NETWORK-BASED CONSTRAINTS-ORIENTED CHOICE SET FORMATION USING GIS

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This paper is concerned with choice set formation in the intraurban context where choice alternatives explicitly involve the spatial dimension. Its purpose is to develop an operational method using GIS for generating more restrictive spatial choice sets through incorporating the spatio-temporal constraints and cognitive constraints of an individual into the framework. The main construct proposed, which was formulated in set-theoretical terms, is the cognitive feasible opportunity set (CFOS). A set of network-based GIS procedures were developed using ARC/INFO GIS to operationalize the formulation. An example drawn from a travel diary data set collected in Columbus, Ohio, is used to examine implementation issues. The paper concludes that, without a realistic representation of the travel environment, the spatial configuration of choice sets and the alternatives they contain could be very different from what individuals actually experienced in their daily lives.

1. INTRODUCTION

As the geoprocessing capabilities of GIS become more powerful and detailed data of the urban environment in digital form become more available, methods for tackling problems in disaggregate travel modeling not possible in the past have become feasible today. This paper

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focuses on one particular aspect of disaggregate travel modeling which will benefit substantially from the use of GIS. This is the problem of choice set formation in the intraurban context where choice alternatives explicitly involve the spatial dimension (for example, destination choice).

Difficulties in delimiting spatial choice sets have long been recognized (Burnett, 1980; Hanson, 1980; Landau et al., 1982; Thill, 1992; Timmermans and Golledge, 1990). A major difficulty concerns the proper size and scope of choice sets. In some studies choice sets are so broadly defined that many alternatives they contain are not feasible due to the spatio-temporal constraints an individual faces (e.g. Adler and Ben-Akiva, 1976; Southworth, 1981). Choice sets may also contain alternatives unknown to an individual because of the limited knowledge about the opportunities in the urban environment. An individual may not have the mental capacity to evaluate the large number of alternatives often contained in choice sets (Golledge et al., 1994; Bovy and Stern, 1990; Fotheringham, 1988a; Gärling and Golledge, 1989; Halperin, 1985). Further, there was no effective means for representing elements of a realistic urban environment in the choice set formation process. These include the uneven spatial distribution of alternatives, differences in the speed of movement, and effect of the network geometry of the transportation system. Since mis-specification of choice sets introduces biases in parameter estimates and errors in predicted choice probabilities, many have emphasized the importance and need to develop better methods for choice set formation (Horowitz, 1985; Pellegrini et al., 1997; Thill, 1992; Thill and Horowitz, 1997a,b; Williams and Ortuzar, 1982).

The purpose of this paper is to develop a method for generating more restrictive and relevant spatial choice sets for non-routine discretionary activities through incorporating the spatio-temporal constraints and cognitive constraints of an individual into the framework. The main construct proposed is the cognitive feasible opportunity set (CFOS), which contains spatial alternatives familiar to the traveler and can be reached within given spatio-temporal constraints. The formulation is based on the time-geographic construct of the space–time prism and the cognitive map of individuals about the urban environment (Burns, 1979; Gärling et al., 1994; Golledge and Stimson, 1997; Hägerstrand, 1970; Landau et al., 1982; Lenntorp, 1976; 1978; Parkes and Thrift, 1975). A set of GIS procedures were developed using the

ARC Macro Language (AML) in ARC/INFO GIS to implement the formulation. An example drawn from a travel diary data set collected in Columbus, Ohio, is used to illustrate how the formulation is operationalized in a GIS. Discussion of this example reveals many important implementation issues. While the value of formulating probabilistic choice-set generation models is acknowledged, as asserted by Thill and Horowitz (1997a,b), the concern of this paper is largely on developing an operational method. This work is therefore a first step towards the long-term goal of integrating mathematical modeling and GIS methods in spatial choice modeling. Further, the formulation discussed here represents a restrictive specification in which only the constraints are included. A full formulation of a choice set generation model would include other elements such as a random utility function incorporating attributes of alternatives and a choice probability distribution.

2. PAST IMPLEMENTATION OF PRISM CONSTRAINTS

While there are some previous attempts to operationalize the space–time prism (e.g. Kitamura *et al.*, 1981; Kondo and Kitamura, 1987; Landau *et al.*, 1982; Lenntorp, 1976; 1978; Nishii and Kondo, 1992; Villoria, 1989), they largely use mathematical and geometrical methods which have a number of limitations. First, the complex travel environment was not represented realistically when using these methods. Mobility and travel speed were assumed to be uniform throughout the urban environment. In the real world context, however, travel can only take place along channels of movement and is therefore confined by the geometry of the transport network. Legal speed limit and variations in traffic condition also affect travel speed throughout the network (Burns, 1979; Miller, 1991; 1994). Means for better approximating travel speed and conditions as they are experienced by individuals in real life situations are needed. Since elements of a real travel environment like segment-specific travel speed, the effect of one-way streets and delays at intersections can be represented in a GIS network data model, the application of a network-based method enables more realistic approximation of prism constraints. This paper therefore adopts a network-based approach to prism constraints and choice set formation in which travel is physically

confined by the geometry of the transport network. Segment-specific travel speed is implemented through specifying the appropriate arc attributes in a detailed street network database using GIS.

The difficulty is similar in the case of realistically representing the location and spatial distribution of destination alternatives. The number of alternatives in the urban environment is so large that many past attempts to operationalize prism constraints had to reduce the dimensionality of the problem by dividing the study area into a limited number of traffic analysis zones (TAZs) (e.g. 35 zones in Landau *et al.*, 1982). Spatial structure of the alternatives in this situation is therefore qualitatively very different from the real choice environment as experienced by individuals, since individuals do not normally perceive spatial alternatives as areal aggregates (instead, a node-based perceptual structure was observed in Golledge, 1978; Hirtle and Jonides, 1985). The problem may be serious when the spatial boundary of the perceived choice set of an individual does not correspond to the boundaries of traffic analysis zones (e.g. a choice set may span several different TAZs). Choice alternatives specified in terms of TAZs delimited *a priori* may not be able to reflect some critical choice factors present in the decision-making process of an individual. Since spatial alternatives are largely perceived in terms of point locations, a punctiform representation of activity locations is a more realistic portrayal of the spatial distribution of alternatives (Miller, 1991). In this study, a punctiform representation of urban opportunities is implemented in which spatial alternatives are represented by point locations specified in terms of geographic coordinates. Distance and travel time between any two locations are calculated on a point-to-point basis using the intervening network nodes and arcs. These are more precise distance measures than distance between centroids of traffic zones. The punctiform representation also enables the direct enumeration of the number of opportunities contained in choice sets, and the visualization of their spatial distribution in relation to the locations actually chosen by an individual.

Further, there are several difficulties associated with the geometric method used to implement the space–time prism in the past. When the area an individual can reach within the spatio-temporal constraints (called the potential path area (PPA) in time-geographic literature) was derived geometrically, only the home and the workplace were used

as the focal points. The PPA derived by this method thus takes the shape of a spatial ellipse whose geometric properties are determined by the two constraining locations and a given amount of travel time (e.g. Kondo and Kitamura, 1987; Nishii and Kondo, 1992; Stopher *et al.*, 1996). While the ellipse may be a good approximation of the PPA in metropolitan areas where mobility is relatively uniform, it is highly unrealistic in other urban contexts. Using a network-based method will ensure that the PPA generated will be shaped by the geometry of the transportation network instead of producing an unrealistic spatial ellipse. Another concern is that besides the home and workplace locations, many other activities have some degree of spatio-temporal fixity which imposes additional constraints on the feasible alternatives of an individual (Cullen *et al.*, 1972; Stephens, 1975). Interdependencies and linkages among activities may also render some locations which are highly inaccessible from the home base very accessible from other activity locations (Golledge and Stimson, 1997; Hanson, 1980; Kitamura *et al.*, 1990). The PPA for a particular activity is therefore context-specific. It has to be identified in relation to other activities the individual has to perform on the day. This study extends the conventional framework to allow for the constraining effect of fixed locations other than the home and workplace through activity linkages.

Another limitation of past attempts is their failure to move beyond objective spatio-temporal constraints to incorporate the constraining effect of individual cognitive factors into the framework. These factors include an individual's knowledge of various areas of a city, familiarity with potential activity locations, and tendency in locational preference or aversion. In normal circumstances, for instance, an individual will not consider unknown destinations as alternatives even if these opportunities can be reached within specified spatio-temporal constraints (Fotheringham, 1988a; Golledge *et al.*, 1994). In this paper a constraints-oriented approach to choice set formation is proposed which also incorporates a cognitive component.

3. A CONSTRAINTS-ORIENTED FORMULATION OF
THE COGNITIVE FEASIBLE OPPORTUNITY SET

In this section, a formulation of a spatial choice set called the cognitive feasible opportunity set (CFOS) is described. Derivation of the set is

not only based on consideration of spatio-temporal constraints, but also takes the restricting effect of cognitive factors into account. The framework extends the work of Miller (1991) and Golledge *et al.* (1994) who identify the subset of all alternatives that the traveler can reach within given spatio-temporal constraints using a GIS method. Whereas Miller refers to it in terms of its spatial expression as the potential path area (PPA), Golledge *et al.* (1994) called it the feasible opportunity set (FOS).

Consider an individual s who has a daily activity program consisting of a set of n out-of-home activities. Among these activities, some need to be performed at locations fixed to the individual (e.g. workplace, child's school or family doctor), while others can be undertaken at locations which the individual can choose (e.g. gas stations or grocery stores). These latter activities are referred to as "flexible activities". As individual s considers the location for pursuing a flexible activity a, many locations in the universal choice set U will not be relevant in the decision-making process. Among all activity locations in U, only those at which activity a can be performed will be considered. Let U_a denote this activity-specific subset of the universal choice set U. We use spatio-temporal constraints and cognitive variables to further restrict U_a for the derivation of the cognitive feasible opportunity set $CFOS_{sa}$. The $CFOS_{sa}$ is defined as the subset of U_a for individual s for activity a which contains the locations that can be reached within the individual's spatio-temporal constraints and are present in that person's cognitive map of the environment. Each element in the set has a non-zero probability of being evaluated and chosen by the individual.

A formulation of the $CFOS_{sa}$ in the case where only one flexible activity a is to be pursued between two fixed activities f_i at location i and f_j at location j is first provided as follows. Feasible location k for activity a can be identified by specifying the following constraining variables: $t_i =$ the latest ending time of the activity at location i, which is the origin of the trip; $t_j =$ the earliest starting time of the activity at location j, which is the fixed activity location after k; $v =$ the average travel speed on the transport network (this will be modified later to accommodate segment-specific travel speed); $d_{ik} =$ distance from the first fixed location i to location k; and $d_{jk} =$ distance from the next fixed location j to location k. Possible activity locations (k, t) in space–time for activity a which lie within the three-dimensional space–time

prism or potential path space (PPS) can be defined as:

$$\text{PPS}_{sa} = \left\{ (k,t) \middle| t_i + \frac{d_{ik}}{v} \leq t \leq t_j - \frac{d_{jk}}{v} \right\} \tag{1}$$

To incorporate the effect of store hours, minimum threshold activity duration required for activity a, R_{sa}, and delay times at location l, D_l, into this simplistic definition of the space-time prism or potential path space, the maximum activity duration for activity a at location k is first identified as:

$$T_{sak} = \left(t_j - t_i - \frac{d_{ik} + d_{jk}}{v} - \sum_l D_l \right), \tag{2}$$

where $t_j - t_i$ is the total time available for activity participation and travel between fixed activities f_i and f_j, $(d_{ik} + d_{jk})/v$ is the total travel time needed to travel from location i to k and from k to j, and the term $\sum D_l$ represents the total delay time incurred at various locations $l = i, j, k$ (for the case with many flexible activities, k becomes $k_1, k_2, \ldots, k_n$). The total delay time represents the total amount of time spent on changing transport mode, waiting, parking, and other non-travel times consumed in transit (see Villoria's, 1989 discussion on stochastic delays). The effect of store hours and minimum threshold activity duration can further be represented by another constraint:

$$t_o \leq t_k + R_a \leq t_c, \tag{3}$$

where t_o is the time the facility at location k opens, t_c is the time the facility at location k closes, t_k is the time individual s arrives at k, and R_a is the minimum threshold activity duration for activity a. This means that, given the time available for activity participation and travel, location k allows for activity a to be conducted for a duration equal or greater than the minimum threshold duration within the opening hours of its facility or store. The three-dimensional space–time prism can now be specified as:

$$\text{PPS}_{sa} = \{(k,t) | (T_{sak} \geq R_a) \text{ and } (t_o \leq t_k + R_a \leq t_c)\} \tag{4}$$

The potential path area (PPA) is the two-dimensional representation of this potential path space PPS_{sa} in planar geographic space. Graphically, PPA is the area delimited by projecting the space–time prism onto the earth's surface (Burns, 1979; Lenntorp, 1976; Miller, 1991). It contains all locations within reach by the individual who faces constraints as expressed in equation (4) and wants to pursue flexible activity a between two fixed activities. The feasible opportunity set (FOS), which is the set of feasible alternatives delimited by the potential path area (PPA), is therefore:

$$FOS_{sa} = \{k \mid (k, t) \in PPS_{sa}\}. \tag{5}$$

To incorporate the effect of cognitive constraints into the specification of the feasible opportunity set FOS_{sa}, the cognitive opportunity set COS_{sa} for individual s pursuing flexible activity a must be specified. Two important aspects of the cognitive environment of an individual are: (a) spatial knowledge or familiarity with various areas of the city, and (b) locational preference or aversion which indicates the tendency for an individual to prefer or avoid certain areas of the city when pursuing a particular activity. This is a simplified specification of the COS_{sa} for the present purpose. More comprehensive formulation needs to be constructed in future studies. This cognitive opportunity set is defined as:

$$COS_{sa} = \{m \mid m \in F_{sa} \text{ and } m \notin P_{sa}\}, \tag{6}$$

where F_{sa} is the set of spatial alternatives known to the individual as defined by some measures of familiarity or awareness (Gale et al., 1990). P_{sa} is a set which contains spatial alternatives which the individual will not considered due to locational aversion and preference (Gärling et al., 1989). It contains elements which need to be excluded when forming the choice set. This COS_{sa} therefore contains spatial opportunities which are familiar to and will be considered by the individual. The cognitive feasible opportunity set $CFOS_{sa}$ of individual s pursuing flexible activity a can now be specified as the intersection of FOS_{sa} and COS_{sa}:

$$CFOS_{sa} = \{c \mid c \in (FOS_{sa} \cap COS_{sa})\} \tag{7}$$

Elements of the CFOS_{sa} are both reachable within the individual's spatio-temporal constrains and familiar enough so that the probability of being evaluated and chosen is not zero. The size of the CFOS_{sa} can be used to find the number of alternatives for activity a:

$$N_{sa} = \sum_c \lambda_{ca} \quad \text{where } \lambda_{ca} = \begin{cases} 1 & \text{if } c \in \text{CFOS}_{sa} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

As Landau *et al.* (1982) and Burns (1979) suggest, the number of alternatives in the choice set (N_{sa}) can be used as a measure of the effect of constraints or the accessibility to urban opportunities for individual s (see its application in Kwan, 1998). This formulation can be extended for cases where there are more than one flexible activities between two fixed activities. Consider, for instance, a number of flexible activities $a_1, a_2, \ldots, a_n$ to be performed at locations $k_1, k_2, \ldots, k_n$ between fixed activities f_i and f_j. The potential path space as specified by equation (1) would become:

$$\text{PPS}_{sa1 \ldots n} = \left\{ (k_n, t_n) \,\middle|\, \left(t_{n-1} + \frac{d_{n-1,n}}{v} \right) \leq t_n \right\}, \tag{9}$$

where

$$t_i + \frac{d_{ik1}}{v} \leq t_1 \quad \text{and} \quad t_n + \frac{d_{nj}}{v} \leq t_j,$$

and t_n is the time of arrival at location k_n for activity a_n, and d is the distance between consecutive locations as specified by the subscripts, with i and j as the constraining starting and ending locations. Similarly, stores hours, minimum activity duration and delay times for each of these flexible activities can be incorporated into equations (2) and (3). As far as the individual can find locations for these flexible activities, the basic form of equations (4)–(8) do not change except that the constraints are now applied to the sum of relevant variables for individual activities (e.g. the sum of travel time cannot exceed the total travel time available).

Finally, we extend the formulation for network-based implementation as follows. First, the compact notations for representing location in linear space such as i, j and k can be given two-dimensional connotation so that $i = (x_i, y_i)$, $j = (x_j, y_j)$ and $k = (x_k, y_k)$ now represent punctiform activity locations in planar geographic space. When

implemented in a GIS, however, an activity location will be attached to the nearest network node so that i, j and k should be interpreted in the operational context of the network. Further, instead of using average speed v, a time-dependent and segment-dependent travel speed in the network can be implemented by v_{mt}, which represents the travel speed on segment m at time t of the day. Putting these network-based extensions into the equations, travel time such as

$$\frac{d_{ik}}{v} \quad \text{now becomes} \quad \sum_{m=1}^{n} \frac{d_m}{v_{mt}},$$

where the network distance between any two nodes i and k, d_{ik}, is covered by a number of network segments $m = m_1, m_2, \ldots, m_n$, each with a distance of $d = d_1, d_2, \ldots, d_n$ and time-dependent travel speed $v = v_1, v_2, \ldots, v_n$. All other terms involving distance and travel speed can be similarly reformulated for incorporating the effect of network distance and segment-specific travel speed.

Several characteristics of this network-based constraints-oriented formulation of the cognitive feasible opportunity set (CFOS) should now be highlighted. First, the CFOS is individual-specific. Each individual has a distinct pattern of spatio-temporal fixity and cognitive map in relation to the opportunities in the urban environment, and the CFOS for different members of the same household may be different. Second, the CFOS are activity-specific, meaning that only locations with the facilities needed for the pursuit of a particular activity will be considered as relevant alternatives (e.g. grocery stores will not be considered as elements of a choice set for a meal). Third, the CFOS relevant for a particular choice problem depends on the location and nature of the activities before and after it (such as constraining locations i and j in the formulation above). A CFOS is therefore context-specific and contingent upon a unique space–time position in relation to an individual's activity program on a particular day.

4. GIS METHOD AND PROCEDURES

The GIS method outlined in this section was developed for operationalizing the construct of the cognitive feasible opportunity set

(CFOS) in the general form specified by equation (7). The procedures were developed using AML in ARC/INFO GIS Version 7 and involve the following five steps:

Step 1

Digital representations of a detailed street network and layers of relevant urban opportunities are first established in a geographic database. The network database has comprehensive address ranges for geocoding activity locations. Temporal characteristics of the travel environment are also built into the database using appropriate means such as the turntables in ARC/INFO. Other temporal attributes of the urban environment such as store hours are also incorporated. Fixed locations of an individual such as home, workplace, and other fixed destinations are geocoded using address matching operations. Individual spatio-temporal constraints specified by equations (2)–(4) such as the time available for activities and travel and the time an individual is required to be at a certain location will be subsequently built into the GIS.

Step 2

The second step is to identify network arcs and nodes an individual can reach within the given spatio-temporal constraints. These are the potential paths for pursuing the flexible activities between each pair of fixed activities. In the original time–geographic formulation, a potential path refers to the three-dimensional representation of a feasible trajectory in space–time by an individual (Burns, 1979; Miller, 1991; Lenntorp, 1976). As long as the effect of temporal constraints can be expressed in terms of the interaction between distance and travel speed as described in equations (2)–(4), potential paths can be represented in planar geographic space. Further, since travel can only take place along channels of the transportation network, the projection of an abstract potential path onto real urban environment is represented by the transport links and nodes an individual can reach within the given constraints.

Finding these potential paths or routes is by no means straightforward even using GIS. The difficulty is illustrated in Figure 1 where the problem is to find all possible paths which, starting from fixed location i, allow the individual to reach flexible locations such as k_1 or k_2 and arrive at the next fixed locations j given a certain amount of total
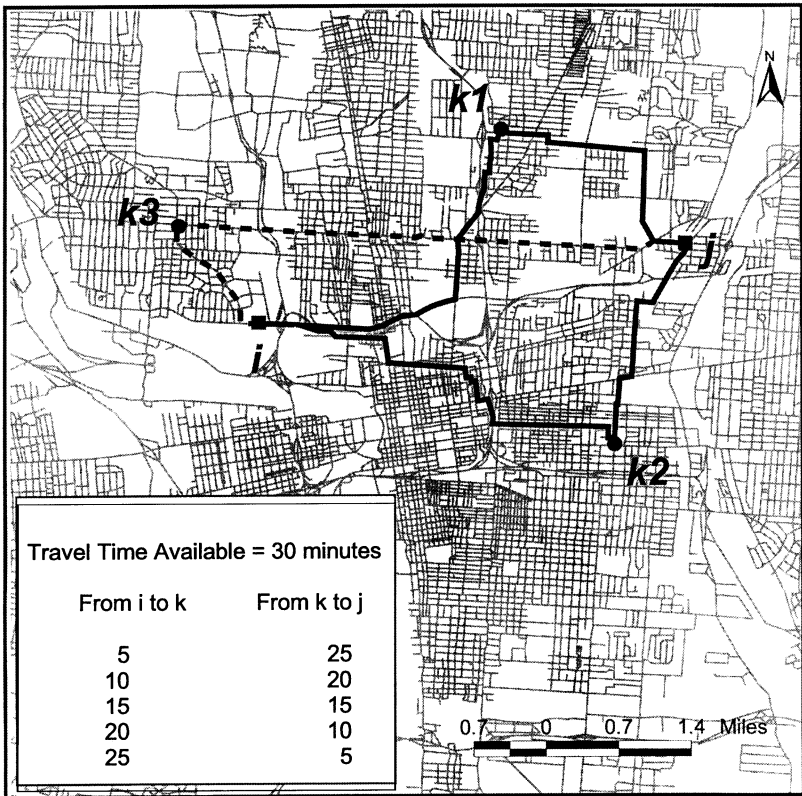
FIGURE 1   The difficulty in finding all potential paths given the time constraint.

travel time. Current GIS software has procedures only for finding the shortest path between two locations or the optimal route connecting a set of locations. If the shortest path algorithm is used given location i and j, only one path connecting them will be found. Since individuals do not necessarily use the shortest path in their travel (Gärling and Gärling, 1988), and most elements of the feasible opportunity set are not located on this route, this method cannot find all potential routes between i and j. If an optimal route algorithm is used, location k_1 or k_2 must be a known location so that the algorithm can determine which three points to connect. Since locations k_1 and k_2, being the locations of potential opportunities, are unknown in the sense that locations

that will satisfy the constraints are not known beforehand, routing algorithms cannot be used to solve the problem either. Further, even if there is an algorithm which can find all possible paths between i and j within the travel time constraint, optimization considerations will lead it to find only routes connecting locations between i and j like k_1 and k_2, but not locations outside their in-between area like k_3 which would still be feasible given the travel time constraints (Figure 1). A possible method for solving this problem developed in this study is outlined as follows.

A given amount of travel time between i and j is first divided into various combinations of travel time from i to k and from k to j with a constant increment (see example in box of Figure 1 where available travel time is thirty minutes). A series of route sets containing all reachable links from either i or j for different travel times are then delimited (for example, the set containing routes which could reach i within five minutes (I_5) and the set containing routes which could reach j within 25 minutes (J_{25})). Another series of route sets is derived by intersecting the appropriate route sets given the total amount of travel time. For example, if the travel time available between i and j is 30 minutes, intersection of the route set which could reach i within 10 minutes (I_{10}) with the route set which could reach j within 20 minutes (J_{20}) generates one route set (A_{i10j20}) which contains feasible links for connecting i, k and j. Symbolically, this can be represented as $A_{i10j20} = I_{10} \cap J_{20}$, and so on. Finally, the set containing all potential routes connecting i, k and j for a given total travel time is generated by finding the union (B) of this series of route sets (A) generated in the last step. Symbolically, this can be represented as $B_{30} = A_{i5j25} \cup A_{i10j20} \cup \ldots \cup A_{i25j5}$. Pseudo codes for performing this procedure on a data file which contains only fixed activities are listed below:

PHASE 0: Initialization

  Step 0.1: For any pair of consecutive fixed activities A and B performed on the same day and by the same person, set the following variables:

   NODE0 = node-ID of the network node nearest to A
   NODE1 = node-ID of the network node nearest to B
   TTIME = total time for travel between A and B
   TOL = the tolerance for network overlap

Step 0.2. If TTIME > 10, set TM = 5 and INCRT = 5 else set
         TM = 2 and INCRT = 2

PHASE 1: Find all potential routes to flexible location k between
         fixed activities A and B
Step 1.1 Set ATIME = TM, BTIME = TTIME – ATIME
Step 1.2 If TM ≥ TTIME, allocation is done. Go to Step 1.7.
         Else do
Step 1.3 Allocate all routes to NODE0 as PP_TM0 with travel time
         ATIME, and allocate all routes to NODE1 as PP_TM1
         with travel time BTIME
Step 1.4 Reselect the overlap PP_TM of PP_TM0 and PP_TM1
         with tolerance TOL
Step 1.5 Kill PP_TM2 and PP_TM1
Step 1.6 Set TM = TM + INCRT, go to Step 1.1
Step 1.7 Append all PP_TM to coverage NETCOV representing all
         PP for the two fixed activities

Step 3
Once all feasible routes for a flexible activity are identified, the PPA
covered by this set of feasible network arcs and nodes can be found by
buffering procedures in GIS. Alternatives which fall within the bound-
ary of this PPA or FOS can be identified either by overlaying the
buffer zone on the coverage of all alternatives, or querying the data-
base directly.

Step 4
Variables of the cognitive dimension specified in equation (6) are
then incorporated into the geographic database and used for identify-
ing the cognitive opportunity set (COS). One relatively simple
measure is the familiarity index, which measures an individual's famil-
iarity with various areas of the city. For instance, the COS may be
defined as areas of the city with familiarity rating above a certain
level on a rating scale (e.g. Gale *et al.*, 1990 used a nine-point scale,
whereas van der Heijden and Timmermans (1984) used a binary
variable).

Step 5

Finally, the CFOS as specified in equation (7) is delimited by over-laying the FOS and COS identified in Steps 3 and 4 and finding their intersection. The number of spatial alternatives in the CFOS for a particular activity for the individual is found by querying the size of the CFOS.

5. AN EMPIRICAL EXAMPLE

This section reports an example used to implement the GIS procedures outlined in the last section. Data of the case were drawn from a travel diary data set collected by the first author in the city of Columbus in Franklin County of central Ohio in November 1995. Data items used here will be explained below (see Kwan, 1998 for details). A detailed street network and various layers of activity locations in Franklin County, Ohio were also used. The street network is the enhanced network Dynamap/2000 provided by GDT which contains 47,200 arcs and 36,360 nodes of Columbus streets. Data for urban opportunities in Columbus were compiled from various sources including digital and printed phone directories. Activity locations were geocoded using street addresses. These urban opportunities include banks, department stores, gas stations, grocery stores, restaurants and many others.

   The activity program of the person is shown in Table I and Figure 2. The person's home is located in the northeastern part of the city of Columbus called Westerville. On the travel diary day, this person conducted activities at three out-of-home stops which were work, a social event at a church and a meal in that sequence. She returned home after

TABLE I   Activity program of the individual

Stop number	Activity	Location	Spatial fixity rating	Distance willing to travel[a]	Activity start time	Activity end time	Travel time (min.)
0	Home-based	Home	5	N/A	0:00	7:10	N/A
1	Work	Workplace	5	7.5	7:32	17:00	22
2	Social event	Church	5	12	17:17	19:16	17
3	Meal	Restaurant	1	5	19:30	21:00	14
4	Home-based	Home	5	N/A	21:16	0:00	16

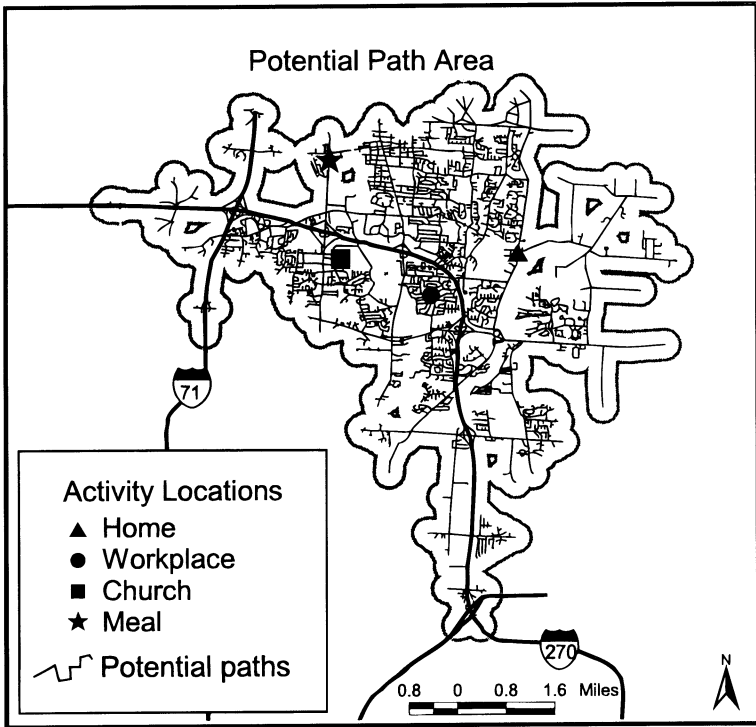[a] Distance willing to travel for a particular activity measured in miles.

FIGURE 2   Potential paths and potential path area for the individual for a meal
destination.

the meal. The problem is to delimit the CFOS for this individual which
includes all feasible alternatives that will enter into the choice process.

Both the home and workplace locations of the person are treated as
fixed locations. Whether the social event or meal was a fixed activity is
identified by a spatial fixity rating (that is, the ease with which the
location for an activity can be changed). On a five-point scale, a value
of one means it was easy to change the location of the activity,
whereas a value of five means it was difficult. For our purpose here, an
activity is defined as locationally fixed if its spatial fixity rating is
higher that three. Data provided by the person indicate that location
for the social event (i.e. church) could not be changed, whereas the
meal location has a spatial fixity rating of one, meaning it was easy to
choose other alternative locations (Table I). So the task is to identify

this person's cognitive feasible opportunity set (CFOS) for a meal location given the constraining locations before (church) and after (home) the activity.

Since the person's actual time budget is not known, it was assumed that, for the purpose of illustration, the time she actually spent on each activity equals the time available for that activity, and the time she actually spent on travel between each pair of activities also equals the time available for traveling between them. Given that the total travel time available from church to the meal location and returning home was 30 minutes, it is necessary to find all feasible routes which the person can reach within 30 minutes. For simplicity's sake, the seven classes of roads in the street network were collapsed into three and assigned travel speed as follows: (a) 55 miles per hour for controlled access freeways (Class 1); (b) 25 miles per hour for state highways and municipal arterials without access control (Class 2 and 3); and (c) 15 miles per hour for other city streets (Class 4 to 7). It was further assumed that delay time in transit is equal to 25% of total travel time available. Then an AML in ARC/INFO was developed to implement the procedures described in Step 2 above to find all potential paths or feasible routes. Potential paths generated by this procedure for the person and activity in question are shown in Figure 2.

To find the area that can be reached by using these potential routes, a quarter-mile buffer area around each potential route was delimited. This buffering distance is selected because most urban opportunities are accessible within a quarter-mile distance from the adjacent city streets. These buffer areas were finally joined together to form the PPA or FOS for the meal location (Figure 2). Figure 3 shows the universal choice set of all restaurants in Franklin County, Ohio, in 1995 which consists of about 1400 alternative locations. Comparing the 101 alternatives included within the boundary of the FOS delimited, this procedure greatly reduced the size of the choice set.

To find the cognitive opportunity set (COS) as described in Step 4 and 5, two additional pieces of information were used. First, familiarity ratings for various areas of Columbus were collected in the survey using a map of the city overlaid by 30 grid squares covering the entire Franklin County. Subjects were asked to rate their familiarity with the area covered by each grid square on a five-point scale. For the sample person, grids with familiarity rating 1, meaning most familiar,
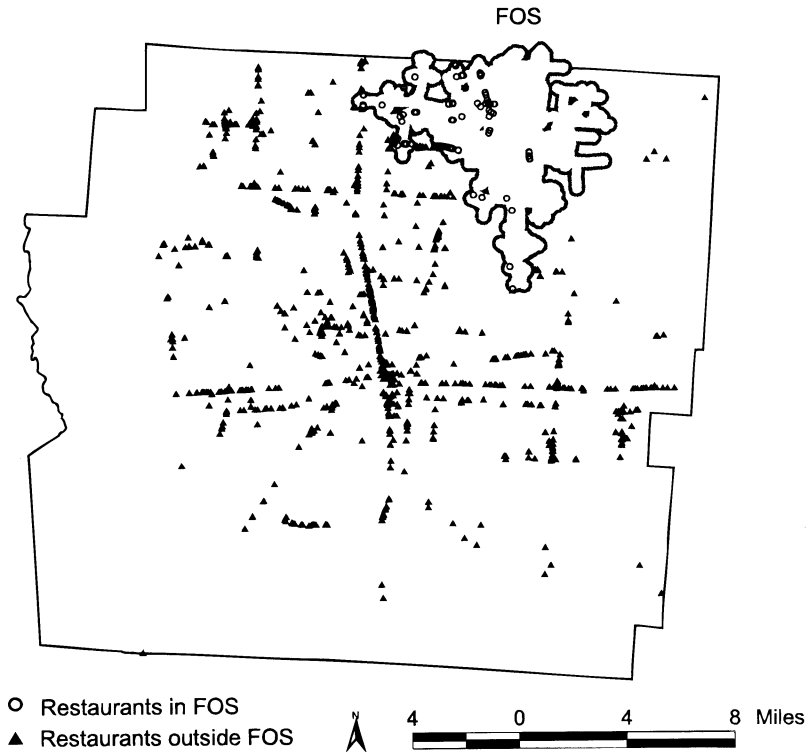
FOS

○ Restaurants in FOS
▲ Restaurants outside FOS

FIGURE 3   Feasible opportunity set for a meal destination for the individual.

are showed in Figure 4. The area covered by these grids was identified
as her COS. Its intersection with the feasible opportunity set (FOS) as
shown in Figure 4, delimited by overlaying operations using the
boolean operator AND on vector polygons in ARC/INFO, defines
the cognitive feasible opportunity set (CFOS). In this case, the CFOS
further reduces the elements of the FOS from 101 to 93 restaurants.

Although this is still a large number of alternatives for choice model-
ing, additional choice criteria can be implemented using GIS. For
instance, on her travel day the person chose an American-style family
restaurant for the meal. An examination of the elements in the CFOS
reveals that it contains only 27 restaurants of this type. Data about the
two preferred alternative meal locations given by the person in the sur-
vey further reveal that other destinations she also considered somehow

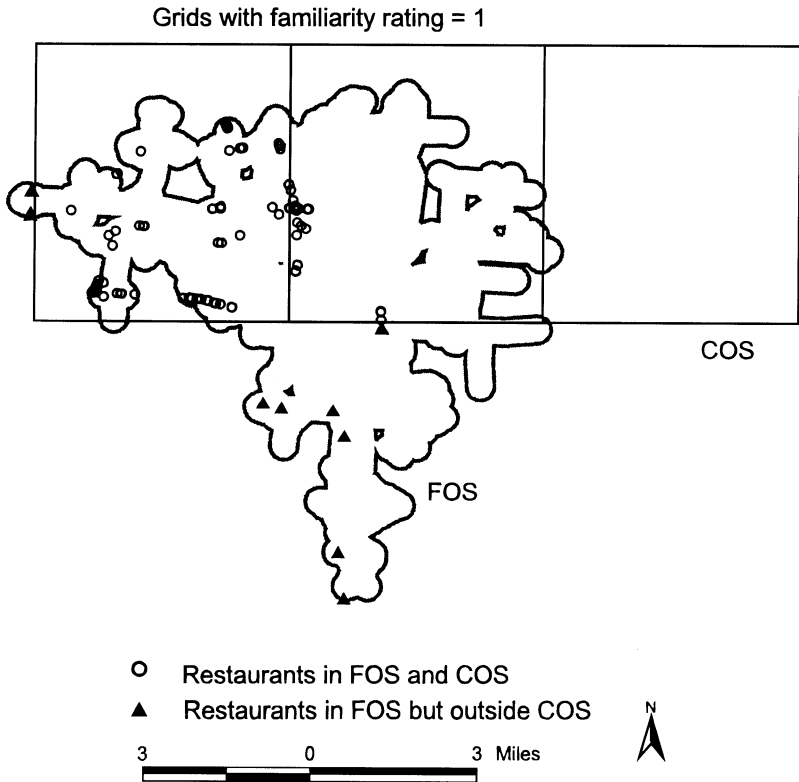Grids with familiarity rating = 1

FIGURE 4   Cognitive feasible opportunity set for the individual.

clustered within a small area of about one square mile around a street intersection. Following the observations of Dijst and Vidakovic (1995) and Fotheringham (1988b), it seems possible that she perceived spatial alternatives in clusters according to their similarities or proximity. If that was the case, a clustering procedure can perhaps be built into the choice set formation process when additional information about the attributes of choice alternatives is not available to the analyst.

6. DISCUSSION AND CONCLUSION

As the example revealed, the spatial configuration and extent of potential paths and the feasible opportunity set (FOS) are heavily

shaped by the geometry of the transportation network, often stretching along routes of high speed of travel (e.g. Interstate 270 in Figure 2) while being more constrained along routes with lower speed. When mobility and travel speed are not equal in all areas and directions in a city, the spatial configuration of the FOS is far from any convenient geometric shapes like the ellipse used to approximate the PPA in past studies. Further, the method of discounting the attractiveness of spatial alternatives based on physical distance used by gravity-type models will need modification for incorporating the effect of variations in travel speed in different parts of a city. Given its ability to represent the complexities and spatial structure of a real transportation network, GIS enables more realistic approximation of spatial choice sets.

Using relevant constraining fixed locations instead of the commonly used home and workplace locations will also increase the chance of generating more relevant and restrictive spatial choice sets. As shown in the example, the actual meal location chosen by the person is in fact closer to the originating fixed location (church) than to either the home or workplace locations (Figure 2). This is indicative of the importance of the imminent choice context in the spatial choice process and suggests that the CFOS is context-specific and activity-specific. It means that the particular CFOS relevant to a particular choice problem is determined by the specific activity in question and the constraining effect of the relevant fixed locations. Approximating the CFOS based upon the home and workplace locations as the only constraining locations is not satisfactory for many out-of-home discretionary activities.

As can be observed in the example, the area of the CFOS may not be proportional to the number of alternatives it contains. This number depends heavily on the location of the constraining fixed activities, as well as the spatial distribution and density of spatial opportunities in the urban environment. The number and kind of alternatives included in a CFOS in suburban locations are very different from those contained in a CFOS with the same area but located close to downtown (as visualization of other cases in the sample has shown). This means that measures of accessibility to urban opportunities should not be based merely on the areal extent of the CFOS even when its area can be identified. Direct estimation of the number of feasible opportunities

is more desirable than its crude approximation by the area of the CFOS. This important point, as Miller (1991) has articulated, can be empirically revealed through implementing the prism construct using network-based GIS methods as was attempted in this paper.

Although rudimentary, incorporation of the cognitive map through using a familiarity rating in this paper represents a first step towards the long-term goal of integrating cognitive factors into choice and travel modeling. Future research needs to find better ways to represent and incorporate these cognitive constraints in spatial choice set formation. Further, it seems that information about the locational preference and aversion of individuals will also be important elements.

For the sake of simplicity in GIS implementation, the constraints-oriented method in this paper is formulated in deterministic and set-theoretical terms. It provides a non-arbitrary and systematic way for delimiting spatial choice sets based on information of individuals and the urban environment. A set-theoretical formulation also facilitates operationalization in GIS because of its straightforward translation into the boolean operations available in most GIS. GIS method in itself, however, does not preclude stochastic formulations of the problem. For instance, Miller's (1994) formulation of a network-based version of the probabilistic Huff model for delimiting market areas has demonstrated the value of this direction. GIS is not only a visualization tool, its geoprocessing capabilities are especially useful for modeling spatial choice or travel behavior (Golledge *et al.*, 1994; Kwan, 1997). It also provides an environment for modeling disaggregate travel behavior in relation to an immense amount of information about the urban environment, including attributes of every road segment and urban opportunity. More importantly, GIS can provide an integrative framework for bringing the objective environment and the cognitive map of the traveler together, thus incorporating these two important dimensions into a unified framework for modeling travel choice and behavior. GIS may enable analysts to achieve predictive accuracy and behavioral realism at the same time through the development of appropriate GIS-based probabilistic spatial models.

Much research is still needed before GIS can be fully integrated into spatial choice modeling. A major obstacle is the lack of efficient algorithms for performing specialized geoprocessing tasks for choice

modeling in most GIS software. The computational efficiency of the operations provided in standard GIS is unsatisfactory especially when dealing with a large amount of spatial data such as that of a street network (specialized packages like TransCAD are exceptions). Using alternative procedures which are computationally less demanding may help. For instance, it was observed that finding the PPA for a location close to downtown Columbus may involve over 20,000 network arcs. Using spatial query methods instead of performing buffering and overlaying to identify the alternatives included in the CFOS saved hours of computing time because they do not involve intensive topological manipulations. However, the lack of efficient algorithms would make it computationally infeasible to attempt solving problems involving spatial combinatorics, such as finding all potential paths or routes for two or more flexible locations between any two given fixed locations. An important area for future research is the development of dedicated and efficient algorithms for specialized GIS operations essential for spatial choice modeling. Another concern is the detailed individual travel data needed for parametizing these GIS-based models, especially information about time budgets and cognitive maps. Much research on effective data collection methods and representation of cognitive maps in a GIS is needed.

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References

Adler, T. and Ben-Akiva, M. (1976) Joint-Choice Model for Frequency, Destination and Travel Mode for Shopping Trips. *Transportation Research Record*, **569**, 136–150.
Bovy, P.H.L. and Stern, E. (1990) *Route Choice: Wayfinding in Transport Networks.* Kluwer Academic Publishers, Boston.
Burnett, P. (1980) Spatial Constraints-Oriented Modeling as an Alternative Approach to Movement, Microeconomic Theory and Urban Policy. *Urban Geography*, **1**(1), 53–67.
Burns, L.D. (1979) *Transportation, Temporal, and Spatial Components of Accessibility.* Lexington Books, Lexington, MA.
Cullen, I., Godson, V. and Major, S. (1972) The Structure of Activity Patterns. In: A.G. Wilson, ed., *Patterns and Processes in Urban and Regional Systems*, 281–296. Pion, London.

Dijst, M. and Vidakovic, V. (1995) Individual Action Space in the City: An Integrated Approach to Accessibility. Paper presented at the Activity-Based Approaches: Activity Scheduling and the Analysis of Activity Patterns Conference, May 25–28, Eindhoven, the Netherlands.

Fotheringham, A.S. (1988a) Market Share Analysis Techniques: A Review and Illustration of Current U.S. Practice. In N. Wrigley, ed., *Store Choice, Store Location and Market Analysis*, 120–159. Routledge, London.

Fotheringham, A.S. (1988b) Consumer Store Choice and Choice-Set Definition. *Marketing Science*, **7**, 299–310.

Gale, N., Golledge, R.G., Halperin, W.C. and Couclelis, H. (1990) Exploring Spatial Familiarity. *Professional Geographer*, **42**(3), 299–313.

Gärling, T., Bränäs, K., Garvill, J., Golledge, R.G., Gopal, S., Holm, E. and Lindberg E. (1989) Household Activity Scheduling. In *Transport Policy, Management and Technology Towards 2001: Selected Proceedings of the Fifth World Conference on Transportation Research*, Vol. IV, 235–248. Western Periodicals: Ventura, CA.

Gärling, T. and Gärling, E. (1988) Distance Minimization in Downtown Pedestrian Shopping. *Environment and Planning A*, **20**, 547–554.

Gärling, T. and Golledge, R.G. (1989) Environmental Perception and Cognition. In Zube, E.H. and Moore, G.T., ed., *Advances in Environment, Behavior, and Design*, Vol. 2, 203–236. Plenum Press, New York.

Gärling, T., Kwan, M.-P. and Golledge, R.G. (1994) Computational Process Modeling of Household Travel Decisions: Conceptual Analysis and Review. *Transportation Research*, **28B**, 355–364.

Golledge, R.G. (1978) Representing, Interpreting, and Using Cognized Environments. *Proceedings of Regional Science Association*, **41**, 169–204.

Golledge, R.G., Kwan, M.-P. and Gärling, T. (1994) Computational Process Modeling of Household Travel Decisions Using a Geographical Information System. *Papers in Regional Science*, **73**(2), 99–117.

Golledge, R.G. and Stimson, R.J. (1997) *Spatial Behavior: A Geographical Perspective*. The Guilford Press, New York.

Hägerstrand, T. (1970) What about People in Regional Science. *Papers of the Regional Science Association*, **24**, 7–21.

Halperin, W. (1985) Spatial Cognition and Consumer Behavior: A Panel Data Approach. Ph.D. dissertation, Department of Geography, University of California, Santa Barbara, California.

Hanson, S. (1980) Spatial Diversification and Multi-Purpose Travel: Implications for Choice Theory. *Geographical Analysis*, **12**, 245–257.

Hirtle, S.C. and Jonides, J. (1985) Evidence of Hierarchies in Cognitive Maps. *Memory and Cognition*, **13**(3), 208–217.

Horowitz, J.L. (1985) Travel and Location Behavior: State of the Art and Research Opportunities. *Transportation Research A*, **16A**, 441–453.

Kitamura, R., Kostyniuk, L.P. and Uyeno, M.J. (1981) Basic Properties of Urban Time-Space Paths: Empirical Tests. *Transportation Research Record*, **794**, 8–19.

Kitamura, R., Nishii, K. and Goulias, K. (1990) Trip Chaining Behavior by Central City Commuters: A Causal Analysis of Time-Space Constraints. In Jones, P., ed., *Developments in Dynamic and Activity-Based Approaches in Travel Analysis*, 145–170. Adlershot: Averbury.

Kondo, K. and Kitamura, R. (1987) Time-Space Constraints and the Formation of Trip Chains. *Regional Science and Urban Economics*, **17**(1), 49–65.

Kwan, M.-P. (1997) GISICAS: An Activity-Based Travel Decision Support System Using a GIS-Interfaced Computational-Process Model. In Timmermans, H.J.P. and Ettema, D.F. ed., *Activity-Based Approaches* and *to Travel Analysis*, Pergamon, New York.

Kwan, M.-P. (1998) Space-time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. *Geographical Analysis*, forthcoming.

Landau, U., Prashker, J.N. and Alpern, B. (1982) Evaluation of Activity Constrained Choice Sets to Shopping Destination Choice Modelling. *Transportation Research A*, **16A**(3), 199–207.

Lenntorp (1976) *Paths in Time-Space Environments: A Time Geographic Study of Movement Possibilities of Individuals*. Lund Studies in Geography B: Human Geography, Gleerup, Lund.

Lenntorp (1978) A Time-Geographic Simulation Model of Individual Activity Programs. In Carlstein, T., Parkes, D. and Thrift, N., eds., *Timing Space and Spacing Time Volume 2: Human Activity and Time Geography*. Edward Arnold, London.

Miller, H.J. (1991) Modelling Accessibility Using Space-Time Prism Concepts within Geographic Information Systems. *International Journal of Geographical Information Systems*, **5**(3), 287–301.

Miller, H.J. (1994) Market Area Delimitation within Networks Using Geographic Information Systems. *Geographical Systems*, **1**, 157–173.

Nishii, K. and Kondo, K. (1992) Trip Linkages of Urban Railway Commuters under Time-Space Constraints: Some Empirical Observations. *Transportation Research B*, **26B**(1), 33–44.

Parkes, D.N. and Thrift, N. (1975) Timing Space and Spacing Time. *Environment and Planning A*, **7**, 651–670.

Pellegrini, P.A., Fotheringham, A.S. and Lin, G. (1997) An Empirical Evaluation of Parameter Sensitivity to Choice Set Definition in Shopping Destination Choice Models. *Papers in Regional Science*, **76**(2), 1–22.

Southworth, F. (1981) Calibration of Multinomial Logit Models of Mode and Destination Choice. *Transportation Research A*, **15**, 315–325.

Stephens, J.D. (1975) Daily Activity Sequences and Time-Space Constraints. Ph.D. Dissertation, Department of Geography, Michigan State University, Lansing, Michigan.

Stopher, P.R., Hartgen, D.T. and Li, Y.J. (1996) SMART: Simulation Model for Activities, Resources and Travel. *Transportation*, **23**, 293–312.

Timmermans, H. and Golledge, R.G. (1990) Applications of Behavioral Research on Spatial Problems II: Preference and Choice. *Progress in Human Geography*, **14**, 311–354.

Thill, J.-C. (1992) Choice Set Formation for Destination Choice Modeling. *Progress in Human Geography*, **16**, 361–383.

Thill, J.-C. and Horowitz, J.L. (1997a) Travel-Time Constraints on Destination Choice Sets. *Geographical Analysis*, **29**(2), 108–123.

Thill, J.-C. and Horowitz, J.L. (1997b) Modeling Non-Work Destination Choices with Choice Sets Defined by Travel-Time Constraints. In Fischer, M.M. and Getis, A., ed., *Recent Developments in Spatial Analysis–Spatial Statistics, Behavioral Modeling and Neurocomputing*. Springer-Verlag, Berlin.

Van der Heijden, R.E.C.M. and Timmermans, H.J.P. (1984) Modelling Choice-Set-Generating Processes via Stepwise Logit Regression Procedures: Some Empirical Results. *Environment and Planning A*, **16**, 1249–1255.

Villoria, O.G.Jr. (1989) *An Operational Measure of Individual Accessibility for Use in the Study of Travel-Activity Patterns*. Ph.D. Dissertation, Department of Civil Engineering, Ohio State University, Columbus, Ohio.

Williams, H.C.W.L. and Ortuzar, J.D. (1982) Behavioural Theories of Dispersion and the Mis-specification of Travel Demand Models. *Transportation Research B*, **16**, 167–219.