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Abstract

The space-time prisms envisioned by Hägerstrand enclose the locations a person can reach by taking into account various time constraints. This concept has been applied on occasions to measure accessibility. It was argued that the potential of applying this approach in spatial analysis was limited by data availability and computing power. Taking advantage of technological advances, a procedure utilizing a Geographic Information System (GIS) is developed to locate facilities within space-time prisms. Data from Portland, Oregon are applied to demonstrate how the proposed procedure can be used to measure accessibility to health care facilities. The potential of the procedure for measuring accessibility from the activity-based perspective is discussed.

Key words: Space-time prisms, accessibility measurement, and GIS

INTRODUCTION

Space-Time Prisms

The concept of space-time prisms was originally developed by Hägerstrand (1) as an instrument for understanding human geography. Its most notable application in transportation research is the introduction of constraints into models involving human spatial interaction. Individuals need to perform various activities to maintain existence in society. Although certain activities may occur simultaneously, more often they exclude each other and are executed in a sequence in which each activity has to be carried out within a given duration, at a certain place, and in presence of other individuals. Because spatial movement consumes time and due to the indivisibility of the individual, activities which have fixed execution time or locations limit him from physically participating in events elsewhere. The concept of space-time prisms was developed to visualize and quantitatively determine these possibilities.

The basic form of a space-time prism is illustrated in Figure 1. For the purpose of presentation, movement on the planar space is reduced to the one dimensional horizontal axis that measures distance from a place in space where the person has to stay for a certain period of time. The vertical axis measures time on a 24 hour scale. This prism is formed when an individual faces the constraints that requires presence at that place at time points T_1 and T_2. The projection of the prism on the vertical axis represents the total time budget the person has for traveling and performing the activity at the location. The slopes of the prism are defined by the speed of the travel means the person possesses. The faster the speed the longer the distance can be reached within the same amount of time. The projection of the prism on the horizontal axis delineates what region in space is accessible by the person under the given constraint. Ideally, all locations within the accessible region can be physically reached by the individual, if the person choose to exhaust the total time budget in traveling. However, when durations at any location are considered, being in the accessible region does not guarantee that the location being feasible for the person's task at hand. As noted by Hägerstrand (1), a location has not only spatial coordinates but also time coordinates. For example, there usually is a minimum time required to finish the task occuring at a certain type of facility. A travel time budget can thus be derived by subtracting the minimum duration for the activity from total time budget. It represents the maximum amount of time the person can spend on traveling but still finish the task at the facility. If the person prefers to stay at the facility longer than the minimum duration, a location closer to the origin must be selected. The duration of staying at location can be visualized in the space-time diagram by a "tube" that has a length of the minimum duration along the time axis (Figure 2). The locations not feasible for the person are those "tubes" that are not entirely within the prism.

Applications of the Concept of Space-Time Prisms

The provision of accessibility is a common goal among transportation/land-use policies. One way to measure accessibility is to determine potential opportunities which can be physically reached (2). This is exactly what a space-time prism was designed to determine. Burns (3) used the volume of a prism directly as an indicator of accessibility. He showed that relaxing time constraints increased a person's accessibility more than increasing the average travel speed. Although prism volumes are efficient instrument for measuring physical accessibility, it does not precisely reflect the opportunities within a person's reach. Most of the space within a prism is useless, since activities take place only at discrete locations. Miller (4) pointed out that only the set of relevant activity locations within a prism need to be considered in the measurement of accessibility. His view parallels those from other researchers who measured accessibility by counting the number of opportunities reached within a given travel time (5, 6).

The Objectives

It is obvious that the accuracy of accessibility measurement will benefit from data with high level of spatial resolution. On the other hand, such data require high computational power to manipulate. Since researchers in the past rarely had access to both of these, it can be argued that the existing applications of the space-time approach did not realize its full potential. However, many of the difficulties in applying the concept of space-time prisms have certainly been alleviated. The rapid growth of Geographic Information Systems (GIS) in the past decade not only advanced software efficiency but also made available databases that are suitable for such an analysis. The objective of this paper is twofold. First, a procedure that can be easily implemented in a GIS to find facilities within space-time prisms is developed. Second, a case study is utilized to demonstrate how the proposed procedure can be used to measure accessibility. Data from Portland, Oregon are applied to assess accessibility to health care facilities by auto and transit.

THE GIS PROCEDURE

Databases

The proposed procedure begins with preparation of databases. An algorithm operating within a GIS then manipulates these databases and find facilities within space-time prisms. The basic data involved in modeling a space-time prism are coordinates of the relevant locations and the times required to travel between locations. Relevant locations include travel origins, locations containing the facilities of interest (e. g., hospitals, shopping centers), and destinations. Origins and destinations are given by the analysts based on the prisms analyzed. For example, the locations at which a person performs activities are the origins and destinations when prisms are used to measure accessibility. If the analyst does not have data on the set of facilities, such databases can be developed from prevalent yellow-page databases. By address-matching in a GIS, yellow-page listings can be converted into a point-based database in which each point represents the location for a relevant facility (7). Miller (4) suggested that a database on the street network be used to characterize both relevant locations and travel time. The network itself is a representation of the surface transportation system. Each network link should be characterized by the travel time required to traverse the entire length of the link. This information usually can be obtained from a traffic assignment analysis. In cases where accessibility by other modes is also the interest, each link should be coded with the types of modes that use this link as well as their travel times. Relevant locations can be approximately represented by the nodes closest to the actual locations, however, the approximation requires these facilities be managed as points in another GIS layer. By overlaying the location layer on top of the network layer, the network node closest to a facilities can be identified. In addition, each network node should also be labeled so that the locations of facilities can be identified at the node layer without referring back to the location layer.

The Algorithm

The algorithm used to find facilities within space time prisms relies mainly on two of the common functions in a GIS, "select by circle" and "shortest path". Given a point in space as center and a radius for searching, "select by circle" returns geographic features that are within the specified circle. "Shortest path" works with a network consisting of nodes and links. It takes two or a series of nodes as input then outputs the shortest path connecting the given nodes on the network. The algorithm is described below according to the space-time prism in Figure 1 in which the person has to return to the origin.

1. Locate the network node closest to the origin. Let this node be the center of the search circle. The radius of the circle is temporally set as (travel time budget / 60) * (average network travel speed / 2). The travel time budget is derived by subtracting the minimum duration for the activity from total time budget. There is no need for precise estimation of the average speed. By trial and error, the most appropriate assumption can be made such that time required to find the final result is minimized.
2. Select network nodes containing facilities of interest within the boundary of the search circle. Name nodes in the selection as “temporary destinations”.
3. For each temporary destination, calculate the network shortest path connecting the origin, the temporary destination, and back to the origin. Evaluate the travel time on the shortest path. If it is longer than the travel time budget, the node is not feasible. If

it is less than the travel time budget, this temporary destination is feasible. Select this node into a selection set and name it "feasible destinations".

4. Find the minimum of the shortest path among all "feasible destinations". If it is less than the travel time budget, it implies that there may still be other facilities outside of this circle that may meet the time constraint.
5. Increase the radius of the search circle by an arbitrary length, d, and select network nodes containing facilities of interest within this circle. Find facilities that are within the bigger circle but not in the initial search circle. This selection is essentially bounded in a ring that has a band width equal to d. This selection becomes the new "temporary destinations".
6. Repeat step 3 and 4 until none of the temporary destinations are in a shortest path that has length less than the travel time budget.

THE APPLICATION

Aggregate Accessibility Measurement: A Case Study

Wachs and Kumagai (6) devised an index of accessibility that basically counts the number of opportunities (e. g., employment or health care services) which can be reached within certain minutes of traveling from the community where accessibility is measured. They applied the indicator to measure accessibility to health care services for two census tracts in Los Angeles. All relevant medical facilities in the study area were first identified and manually plotted on a map. Travel time contours were then plotted on the same map, originating from centroids of the census tracts. The contours enclosed all regions in the city that can be reached within 15 minutes and 30 minutes of travel from each tract. Two sets of contours were plotted, one for auto and the other for transit. Actual travel speeds on all major streets were obtained from field studies to estimate auto travel times. Published bus schedules were used to estimate transit travel times among bus stops. Additionally, walking speed of 3 mph were assumed to estimate the travel times from a centroid to the closest stop and from a bus stop to a facility. Their results (Table 1) show that motorists enjoyed a much greater level of accessibility than transit riders. The authors concluded that this approach can be implemented to evaluate transportation and regional policies in a way different from conventional measures such as traffic volumes and travel times. It helps redirect policy-making toward provision of quality of life, which is essentially different from mobility.

Although their approach was often cited in research literature, it did not gain popularity among practitioners despite the value demonstrated. As noted by the authors, limitations in available data and operational computer programs created difficulty for implementation on a larger scale. The GIS procedure proposed in this paper can be implemented to relieve the limitations and integrate regional transportation models with accessibility assessment. All the manual work involved in data preparation can be efficiently accomplished within a GIS. The facilities enclosed by a travel time contour can be determined by a modified space-time prism in which the trip is not required to return to the origin, and in which the duration of staying at the facility is not considered. Two changes need to be made in the original algorithm to accommodate this. In step 1, the radius of the initial search circle is changed to (travel time budget / 60) * (average network travel speed). It has to be noted that the travel time budget here refers to the travel time that are used to count opportunities (i.e., 15 and 30 minutes). In step 3, for each temporary destination, evaluate the network shortest path connecting the origin and the temporary destination. It is not required to connect back to the origin.

Data from Portland, Oregon are applied to replicate Wachs and Kumagai's work using the proposed procedure. TransCAD (8) is adopted as the platform for its integrated workspace that combines fundamental GIS functionality with network analysis tools. It also provides a macro language for automating tasks (9). Using this language, the algorithm is programmed in a way that no manual interaction is required during the computational process. Two census tracts are selected to assess the difference in accessibility by auto and transit. The first one (census tract number 6602) is located in a suburb southwest of Portland, and the second (census tract number 31903) is located in the city of Tigard. These two tracts are approximately 5 mile apart with Tigard being on the verge of the transit network. For measuring accessibility by auto, the network database is derived from the regional transportation models of the Portland metropolitan area. Each link is associated with peak and non-peak traverse time estimated through traffic assignment analysis. A bus network is created from the transit schedules published by the Tri-County Metropolitan Transportation District of Oregon. Bus stops are first geocoded to represent nodes in the network and the difference in arriving times between two stops measures the travel time on this link. If two or more routes connect at a node, the time lag between two connecting routes is applied as a turn penalty. Data on health care facilities are obtained from a yellow page database (10). The Standard Industrial Classification (SIC) code is the primary key in identifying relevant opportunities (1). Establishments categorized with Industry Group Number, 801, 802, 803, 804, and 806 (i.e., clinics and offices of medical doctors, dentists, osteopathic physicians, other health practitioners, and hospitals, respectively) are included in the analysis as the health care services provided in the physical environment. The locations of these facilities are pinpointed by the address-matching routine in a GIS, which reads the address of a listing and automatically finds the matching street segment in the reference street network. A point is then created, in a separate layer, right next to this segment to represent the location of this facility. After address-matching, all listings of health care providers are converted into a point layer. The auto and transit networks are each overlaid on top of this layer to identify the network intersection closest to a relevant facility. This node is then used to represent the location of the facility and store its attributes. If a network node is identified as closest to more than one facility, the number of health care opportunities is aggregated.

The network nodes closest to the centroids of the two tracts are identified as the origins of the prisms. An average travel speed 40 mph is entered to define the initial search circle. The time selected for analysis is the morning peak period (i.e., 7 to 9 AM). The traverse time on each bus link is based on schedules in this period; auto link traverse times are derived from iterative traffic assignment. The accessibility to health care services by auto and transit is assessed with 15 and 30 minutes of travel time budgets. Because not all of the offsets between facilities and the nodes representing them are small enough to be neglected, adjustments need to be made to account for traveling along the offsets. For auto, one minute is deducted from the overall travel time budget for this purpose. That means the actual budgets entered the analysis are 14 and 29 minutes. Most of the offsets between facilities and transit stops are traversed by foot and walking speed can be assumed to determine the travel time along the offset. However, this is not the approach adopted in this analysis. It is noted that a small amount of error made in the estimation of the offset can severely affect the precision in assessment of accessibility by transit, since it requires a relatively long time to traverse a small distance by foot. The bus network created in this analysis does not include all the potential stops along routes, therefore, the offsets are not precise enough to estimate time incurred by walking. Instead, 15 and 30 minutes budgets are entered the analysis intact and the results should be interpreted as the number of services within 15 and 30 minutes of transit travel, plus a small amount of walking time. The results of the analysis are summarized in Table 2. Health care facilities are grouped into 3 categories, hospital (SIC code 806), clinics of medical doctors (SIC code 801), and clinics of miscellaneous practitioners (SIC code 802, 803, and 804).

The result of the analysis clearly indicates the difference in accessibility to health care services by auto and transit from either tracts. Overall, residents in southwest Portland enjoy better accessibility to health care services by either modes than those in Tigard. The number of health care facilities reached by auto is excessively larger than that by bus from either tracts. This result is similar to that found by Wachs and Kumagai in Los Angeles (6). Although it is not possible to make transit as mobile as auto, the way to improve the transit system for increasing accessibility can be indicated by such an analysis. For example, for the tract in Tigard, there is no hospital available withtin 15 minutes of transit travel. The closest hospital is the Meridian Park Hospital in the city of Tualatin, which requires at least 28 minutes of travel time on bus alone. If it was deemed necessary to provide people in this tract with quick access to at least one hospital by transit, an express route offered by either the transit authority or the hospital could be an option. In addition, it has to be noted that the analysis is based on the morning peak hours, during which buses have shorter headways and the connection between routes is also quicker than the off-peak hours. It is expected that the number of health care facilities reached by transit will decrease in the midday hours. Unfortunately, this is when the non-working population, particularly housewives and children, will most likely be left without a car and would depend on transit to seek for services. This is also when health services are available. The headways of the routes leading to major care providers thus could be adjusted to maintain the accessibility during the off-peak hours.

Individual Accessibility Measurement: A Proposal

The case study in Portland illustrates how accessibility can be measured by locating facilities within certain minutes of traveling. The strength of such a measurement is in its ability to indicate the deficiency of the transportation / land-use systems in an aggregate sense. It is noted that this is not exactly the accessibility defined by Hägerstrand who viewed accessibility as the freedom of individuals to participate in different activities.

Following his viewpoint, individuals, not zones, should be the focal points of accessibility measurement. Kwan (12) summarized the difficulties when aggregate approaches are used to evaluate individuals' accessibility. First, the use of zone centroids as the origins of accessibility measurement inevitably treats every individual in the same zone having same level of accessibility. Second, an individual's daily activity program that impose constraints on the person's movement is not considered. Third, temporal attributes of a facility are ignored. A facility is usually not available 24 hours and the duration a person needs to stay also varies. These three difficulties manifest themselves in the example of housewives and children discussed earlier. The aggregate measurement fails to account for the demographics of an individual household hence the inaccessibility of the non-working members is not revealed. In addition, the availability of medical services to housewives and children is determined jointly by factors such as the list of things they have to do in the course of the day, the availability of a car, the available hours of the health care facilities, and the minimum time required for the service. If these factors were not taken into account, the importance of transit accessibility would be underestimated. On the other hand, the efficiency of the transit system would be overestimated.

Chen (13) addressed these issues by combining an activity-based travel model 14) with Burns' (3) approach and devised a measure of accessibility that relates not only to transportation and land use characteristics but also to the individual demographic characteristics. The travel model took as inputs activity/travel diaries containing household demographics and a series of activities performed by each individual in the household, then rearranged the temporal aspects of these activities (i.e., sequence or execution times) such that the sum of travel times and waiting times for all activities is minimized. If the notion that people strive to realize this optimality, this activity sequence can be a representation of what an individual with the same demographic background and a similar activity program would do. Accessibility is measured by the volumes of prisms calculated based on the gaps between activities and the speed of the transportation means the individual possessed (Figure 3). For example, the axis of prism 1 is equal to the time gap between Activity 1 and 2 (G_1) minus the time required to travel between them (T_1). The slops of the prism is determined by the individual's travel speed. Although the use of prism volumes as the measurement of accessibility is tractable in measuring the individual's potential for interaction after accounting for his/her activity program, it has been noted that the precision of such an approach is affected by the unusable volume in a prism. This fallacy should be corrected by focusing on the discrete locations in the prism where activities can take place.

Figure 4 illustrates how to locate the set of discrete locations in time gap G_1. The parallelogram defines the accessible boundary within which facilities can be physically reached, regardless of the activity duration at the facility. Similar to Figure 2, the facilities not feasible for the person are those "tubes" that are not entirely within the prism. With modification, the proposed procedure can be implemented to locate this set of locations. It requires changes to be made to the first and third steps in the procedure. In the first step, the initial search circle needs to be modified. The midpoint between the origin and destination is used as the center of the initial search circle. The search radius is half the Euclidean distance between the origin and the destination. In the third step, calculate the network shortest path connecting the origin, a temporary destination, and then the destination.

Summary and CONCLUSIONS

As noted by Handy and Niemeier (15), practitioners at Metropolitan Planning Organizations are currently engaged in the search for a practical way to include accessibility assessment as a formal step in their planning processes. The case study in Portland illustrates how the proposed procedure can be implemented within a GIS to accomplish this. The procedure avoids a large level of effort in data preparation and calculation, which is usually the obstacle in bridging the gap between research and practice. Although two databases, the transit network and health care facilities, have to be created for this analysis, such databases are becoming common in practice. There is an increasing number of transit authorities using GIS to plan routes. Geocoded databases of various facilities and services are also becoming available. Evidence can be found on various Web sites that allow users to lookup yellow-page listings then provide driving direction. The strength of the algorithm for locating facilities within space-time prisms is the ease of implementation. Programming is inevitably necessary for automating data manipulation. The algorithm utilizes common GIS functionality to reduce the complexity of the program. The transportation network database is derived from a traffic assignment analysis and is used to estimate auto travel times, thus the measurement of accessibility by auto can be incorporated as an additional step in the conventional 4-step planning process. This provides an alternative performance measure to traffic volumes for evaluating various transportation/land-use policies. If multimodal planning is needed, the analysis of accessibility by transit can also be incorporated. It can reveal the deficiency of the transit system and indicate the potential way for improvement.

In the past decade, conventional travel demand models experienced difficulties in meeting the strict requirement placed by legislation. Activity-based models, which originated from Hägerstrand's initial proposal (1), have emerged as a potential basis for the next generation of transportation forecasting models. Although robust activity-based forecasting systems are not yet available, it is expected that such a system (such as that of Recker (14)) will project travel demand by manipulating data on activity/travel diaries. The proposed procedure holds potential to be used for accessibility assessment in a activity-based framework, since they are both based on the concept of space-time prisms. Before these new models mature, the approach proposed for measuring individual accessibility may be applied with real world data to verify tractability and to formulate a process that combines individual demand forecasting with accessibility assessment.

REFERENCES

1. Hägerstrand, T. What About People In Regional Science? *Papers of the Regional Science Association*, 24, 1970, pp. 7-21.
2. Morris , J. M., Dumble, P. L., and Wigan, M. R. Accessibility Indicators For Transportation Planning. *Transportation Research A*, Vol. 13A, 1979, pp. 91-109.
3. Burns, L. *Transportation, Temporal, and Spatial Components of Accessibility.* Lexington Books, Lexington, MA, 1979.
4. Miller, H. Modeling Accessibility Using Space-Time Prism Concepts Within Geographical Information Systems. *International Journal of Geographical Information Systems*, 5, 1991, pp. 287-301.
5. Sherman, L., Barber, B, and Kondo, W. Method For Evaluating Metropolitan Accessibility. In Transportation Research Record 499, TRB, National Research Council, Washington, D. C., 1974, pp. 70-82.
6. Wachs, M. and Kumagai, T. G. Physical Accessibility As A Social Indicator *Socio-Economic Planning Science*, 7, 1973, pp. 437-456.
7. Lee, M. and McNally, M. G. Incorporating Yellow-Page Databases In GIS-Based Transportation Models. Paper presented at the ASCE Conference on Transportation, Land Use, and Air Quality. Portland, Oregon, May 17-20, 1998.
8. Caliper Corporation. *TransCAD Version 3.0 User's Guide*, Caliper Corporation, Newton, MA, 1996.

9. Caliper Corporation. *GISDK Programmer's Guide*, Caliper Corporation, Newton, MA, 1996.

10. CD USA Yellow Pages USA Deluxe, CD USA Corporation, Omaha, NE, 1997.

11. Office of Management and Budget. *Standard Industrial Classification Manual*. Office of Management and Budget, Executive Office of the President, Washington, D. C., 1987.

12. Kwan, M.-P. Space-Time And Integral Measures Of Individual Accessibility: A Comparative Analysis Using A Point-Based Framework. *Geographical Analysis*, Vol. 30, No. 3, 1998, pp. 191-216.

13. Chen, C. *An Activity-Based Approach to Accessibility*. PhD Dissertation, University of California, Irvine, 1996.

14. Recker, W. W. The Household Activity Pattern Problem: General Formulation And Solution. *Transportation Research -B*, Vol. 19B, No. 1, 1995, pp. 61-77.

15. Handy, S. L., and Niemeier, D. A. Measuring Accessibility: An Exploration Of Issues And Alternatives. *Environment and Planning A*, 29, 1997, pp. 1175-1194.

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FIGURE 1 The Basic Form of a Space-Time Prism

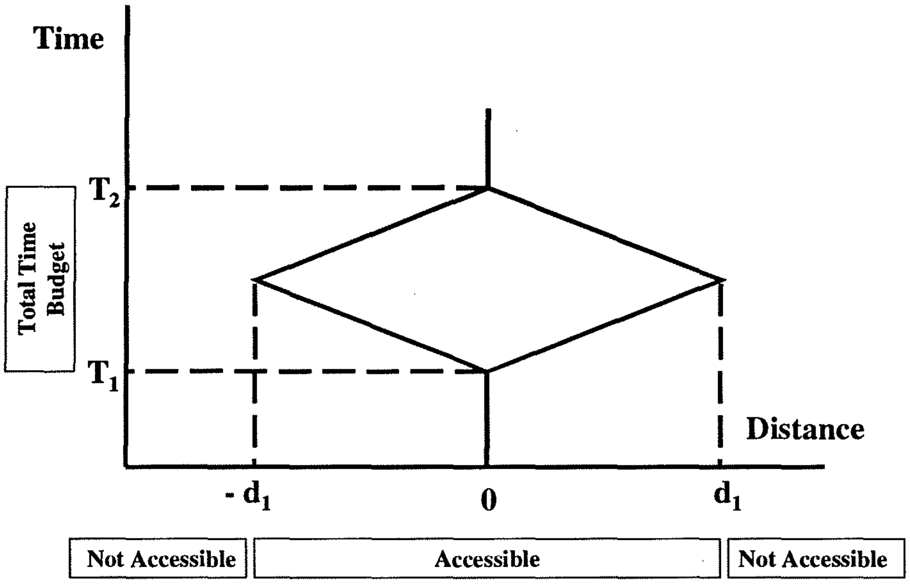
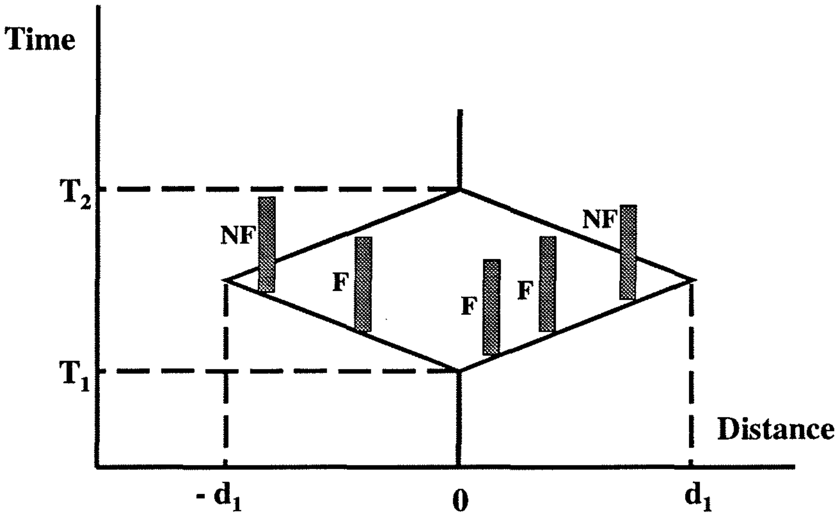


FIGURE 2 Feasible Locations within a Space-Time Prism



F: Feasible **NF: Not Feasible**

FIGURE 3 Prism Volume as Measurement of Accessibility

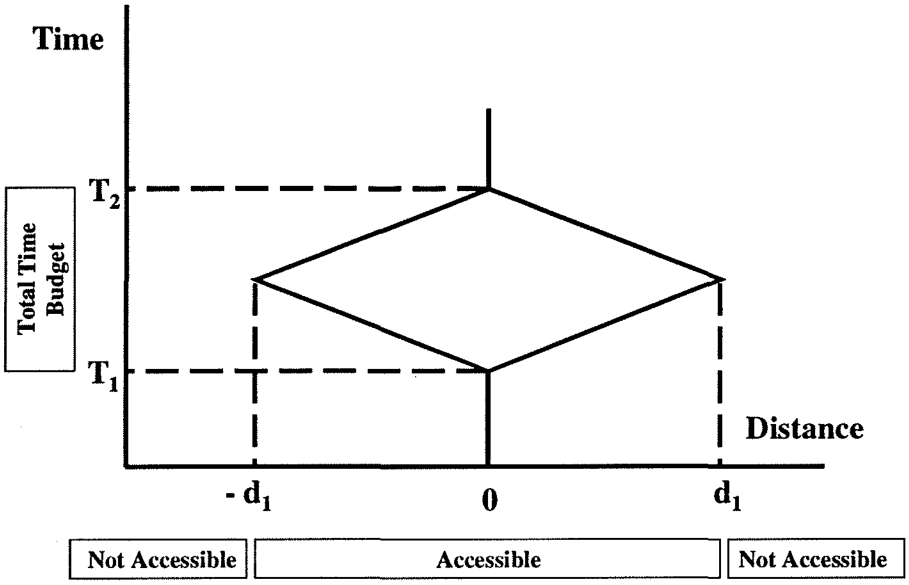


Figure 1 The basic form of a time-space prism

FIGURE 4 Feasible Locations as Measurement of Accessibility

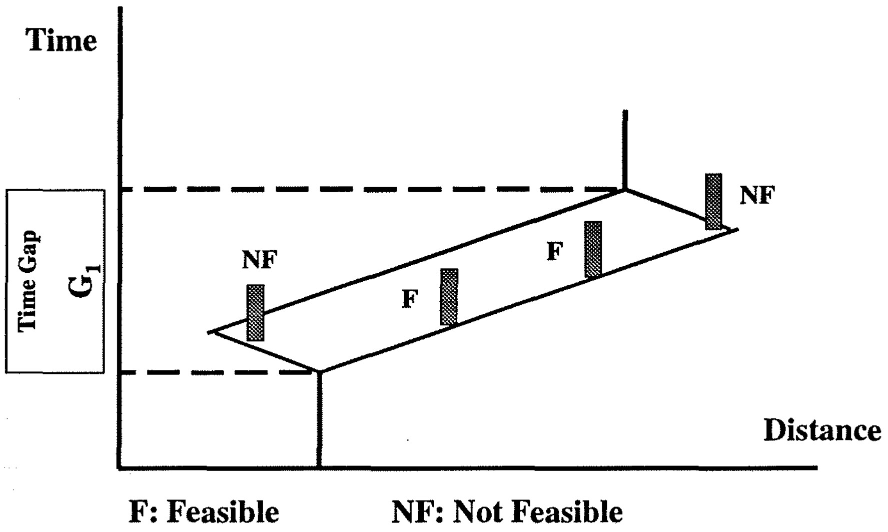


TABLE 1 Accessibility to Health Care Opportunities for Two Selected Census Tracts in Los Angeles

15 MINUTES				
ORIGIN	SOUTH CENTRAL LOS ANGELES (TRACT 2392)		BELL GARDENS (TRACT 5341)	
MODE	AUTO	TRANSIT	AUTO	TRANSIT
HOSP_CLINC [a]	335	11	285	18
GENERAL [b]	40	2	41	0
TOTAL [c]	375	13	326	18

30 MINUTES				
HOSP_CLINC	1534	112	1529	36
GENERAL	143	14	149	1
TOTAL	1677	126	1678	37

[a] Number of hospitals and clinics reached
[b] Number of general practitioners reached
[c] Total number of hospitals, clinics, and general practitioners reached

Source: Wachs and Kumagai (6)

TABLE 2 Accessibility to Health Care Opportunities for Two Selected Census Tracts in Portland, Oregon

15 MINUTES				
ORIGIN	SW PORTLAND (TRACT 6602)		TIGARD (TRACT 31903)	
MODE	AUTO	TRANSIT	AUTO	TRANSIT
HOSP [a]	14	1	5	0
MEDICAL [b]	179	17	141	19
MISCELL [c]	309	42	203	32

30 MINUTES				
HOSP	32	3	30	2
MEDICAL	467	52	420	49
MISCELL	635	124	570	112

[a] Number of hospitals reached
[b] Number of medical clinics reached
[c] Number of miscellaneous clinics reached