ones require a major rescheduling of activities and trips.

CONCLUSIONS

The topics discussed in this paper have shown the usefulness of the activity-based study of travel at the data-collection, analysis, and modeling stages of transportation planning. The work also has important implications for other aspects of planning, such as policy generation or evaluation. Although some of these techniques (particularly the modeling) are still in the development stage, others are operational and, most importantly, many can be applied to conventional data sources. Travel-survey data contain much information about the timing, sequencing, and linking of major out-of-home activities rarely used in conventional analyses.

The importance of linkages between household members leads to another immediately practicable theme: use of the stage in the family life cycle as a classificatory variable. That this variable accounts for real differences in travel between households has been demonstrated by our (and other) analyses. Moreover, the variable has a dynamic aspect (one can think of cohorts of the population moving between life-cycle groups over time) that lends itself to predictive modeling applications (6).

ACKNOWLEDGMENT

The support of the U.K. Social Science Research Council in funding the work described in this paper is gratefully acknowledged. We also wish to thank the Oxfordshire County Council for making available the results of the Banbury travel survey.

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# Basic Properties of Urban Time-Space Paths: Empirical Tests

RYUICHI KITAMURA, LIDIA P. KOSTYNIUK, AND MICHAEL J. UYENO

**Temporal and spatial characteristics of urban travel behavior as a time-space path are explored. An abstract model that integrates Hagerstrand's prism, the concept of trip linkage, and the intervening-opportunities concept of trip distribution is developed as a tool for this exploration. Empirical examination of hypotheses derived from the abstract model indicates that the probability of permanently returning home is a function of the time when, and the location where, the trip maker's last sojourn (or stop at an activity site) is completed; that the average duration of a sojourn is negatively correlated with the number of sojourns in the path; and that the spatial distribution of sojourn locations depends on the number of sojourns.**

The dominance of the work trip in the development of models aimed at understanding and predicting travel behavior has led to the suppression of the space-time element in these models. The temporal component (time of day) of the work trip is basically constant, as is the spatial aspect in terms of destinations. Travel for other purposes is characterized by countless possibilities of destinations, frequencies, time scheduling, and combinations with other purposes. Only limited research has been devoted to this type of travel behavior because its importance to the planning of roads and highways was not of the highest order and also because it was considered complex.

Recently, however, the importance of considering this type of travel became more obvious when the response to the energy crises of 1973-1974 and the spring of 1979 included travel rescheduling or foregoing discretionary activities and combining trips (1,2). One approach to such aspects of travel behavior is to analyze the behavior in its entirety as a "path" (3) in the time-space dimension. Clearly, an understanding of time-space elements and interactions in travel behavior would be invaluable. Yet currently available analysis methods fail to provide an adequate framework for dealing with the complexity of travel behavior, which is becoming increasingly important.

Research in this field is in the stage of seeking analytic structures, examining alternative hypotheses, and attempting to develop a theoretical framework. Accordingly, the space-time characteristics of travel behavior as a path have been largely unexplored. It appears that the accumulation of relevant empirical observations of the behavior would also be extremely valuable. Such an effort should provide appropriate bases for the model-building effort, just as empirical observations of trip-length distributions, accumulated over decades, have added to researchers' understanding of urban travel patterns.

This paper summarizes the results of a research effort that explored some of the basic characteristics of urban travel behavior represented as time-space paths. The objective of the study is to hypothesize several macroscopically observable properties of the time-space path and statistically examine these hypotheses on an empirical data set. The goal of the effort is to identify a set of fundamental properties of travel behavior with the anticipation that the empirically supported properties would offer guidance for model-building efforts related to complex travel behavior.

As a tool for this exploration, the study developed a simple abstract model of travel behavior that integrates three well-known concepts and frequently practiced approaches: Hagerstrand's prism (3), the concept of trip linkage (4), and the intervening-opportunities concept of trip distribution (5, p. 111). Although highly hypothetical in its nature, the abstract model offers a framework from which certain properties of the time-space path can be inferred. Those inferred properties constitute a set of statistically testable hypotheses. Furthermore, as the assumptions of the simple model are relaxed, these properties can serve as acceptable limits for testing more realistic models.

Since there is no standard terminology on the subject (6,7), we define some key terms used in this study. A (time-space) path is defined as an individual's trajectory in the time-space dimension over a study period. This study deals only with those closed paths that originate and terminate at the home within the study period (a day). The study is abstract in the sense that it focuses on the spatial and temporal aspects of the path while suppressing attributes such as types of activities or modes of travel. Consider a site where a trip maker can pursue one or more out-of-home activities. A site may be a complex of more than one facility in close proximity. A stop made at such a site is called a sojourn, and the site where a sojourn is made is called a sojourn location. A trip is defined as the movement between two successive sojourn locations or between a sojourn location and home. A chain is defined as a series of connected trips that originates and terminates at home. A path can have one or more chains in a day, and a chain can have one or more sojourns in it.

## REVIEW OF SPACE-TIME TREATMENT IN PREVIOUS MODELS

Several research efforts have recently been devoted to the development of a fundamental and coherent framework for analysis of travel behavior, including several analyses of trip linkages (7-12) and time allocation among daily activities (13,14). Although, conceptually, these approaches are not new (4,15-17), they show the promise of overcoming weaknesses that exist in the analytic framework of urban travel demand analysis.

In spite of these developments, relatively little is known of general space-time characteristics of travel behavior presumably because of the absence of simple analytic structures that capture this behavior. Empirical spatial and/or temporal distributions of linked trips have been reported (17-20), but these aggregate observations are not precisely suited to the exploration of individual path characteristics. Many studies of trip linkages or chaining used Markovian models in condensing the abundant information on observed behavior. The Markovian time-homogeneity and history-independence assumptions of those models, however, are clearly too restrictive to be useful if they are applied as a framework for understanding and describing the very fundamental space-time aspects of urban travel behavior [empirical examples of their irrelevance can be found in a report by Kondo (15) as well as in later sections of this study].

The state of the art of utilitarian analysis of travel behavior, on the other hand, appears to be overwhelmed by the complexity of the decision process [perhaps not to the decision maker (10) but certainly to the researcher] as well as the extensiveness and stochastic nature of contributing factors and the large number of possible alternatives involved. Only a few utilitarian analyses have considered travel as a path through space and/or time. A discrete choice analysis of travel patterns by Adler and Ben-Akiva (7) assumed that each path has a certain utility associated with it that could be expressed as a linear function of scheduling convenience, travel expenditure, and destination attributes. The time element, however, was totally implicit in the model; and the scheduling-convenience variable, which could involve certain time factors, was constructed only from the number of activities and from the number of activities per chain. Presumably because of its emphasis on policy analysis, the main concern of the study was the macroscopic description of travel patterns, aggregated over time and space as well as across individual households.

A different type of model was developed by Horowitz (8,11) that may be described as a hybrid of a discrete-choice model and a stochastic-process model. The model development starts with a time-dependent utility of destination location j when visited from location i by mode m. The history dependence of the behavior is incorporated by a parameter that represents the number of trips made up to the time point of concern. The household is the behavioral unit of the study, as in the study by Adler and Ben-Akiva (7). The temporal continuity condition, however, is not apparent in the model. The activity duration is not a component of the utility function, at least in an explicit form. The temporal characteristics of the behavior are again deemphasized, and it is difficult to identify space-time properties of the path from the model.

Although the traditional trip-distribution analysis has completely left out the temporal aspect of travel behavior and the continuity condition of trips, time-budget analyses (16,17) have not meaningfully incorporated the spatial aspect. Although effort has been made to represent the continuity condition, the main emphasis of recent developments is still placed on the atemporal distribution of trips. In spite of Hagerstrand's conceptualization of time-space paths, it appears that no effort has been devoted to exploring the space-time aspect of urban travel behavior.

## ABSTRACT MODEL OF THE TIME-SPACE PATH

An abstract model that integrates Hagerstrand's prism, the concept of trip linkage, and the intervening-opportunities concept of trip distribution was developed as a tool for extracting space-time properties of time-space paths. The basic assumptions of the model are as follows:

1. The movement of people is one-dimensional, or the study area can be represented as a linear city;
2. Opportunities are homogeneously distributed in the linear city at a constant density; and

3. The speed of travel is invariant regardless of time and location.

These assumptions, similar to those found in Burns (21), offer the ideal situation where the Hagerstrand's prism represents the domain of possible trajectories that one can follow given an origin coupling constraint that one cannot leave home until a certain time of day (21) and a destination coupling constraint that one must return home by a certain time of day.

The abstract model involves another assumption regarding the distribution of trips or sojourn locations: The trip maker pursues out-of-home activities whenever there are acceptable opportunities within the feasible region of the time-space coordinates. The probability of acceptance of an opportunity is assumed to be constant.

Thus, the model depicts activity linkage in a probabilistic manner that may well replicate observed behavior. The behavioral implications of the model, however, are rather limited. The activity decision is assumed to be sequential, as opposed to simultaneous activity planning where most of the activities for the day are prescheduled (12). Certain aspects of the behavior are thus not represented by the model. For example, the model does not represent the empirically observed interdependency (13) in temporal scheduling of activities. However, the purpose of the model is not to replicate travel and activity choice behavior, and the model is kept intentionally simple for this reason. In its present form, the model does not incorporate the type of activities or the time when the trip maker leaves home. No assumptions are imposed regarding the duration of out-of-home activities. It should be emphasized, however, that the model is not intended to be descriptive or predictive. Rather, it is developed as a conceptual framework to extract in an abstract manner some specific aspects of travel behavior. Its possible behavioral weakness is acceptable as long as the model serves this purpose.

## FORMULATION OF HYPOTHESES

Four basic hypothetical properties of the time-space path that can be immediately inferred from the abstract model are discussed here. Most of the discussion is limited to the one-chain path--i.e., the path that involves only one closed series of trips that originates and terminates at home. Some generalizations are discussed later in this paper. As is apparent from the model development, the model is directly applicable to the paths that consist of discretionary sojourns.

The first property of the path derived from the model, or hypothesis 1, is as follows: The conditional probability of returning home, given that a sojourn is completed at time t at a given location, is an increasing function of time. As a special case, suppose that the probability of making another sojourn depends only on the acceptability of reachable opportunities. Then the conditional probability exponentially increases with time.

The number of reachable opportunities decreases linearly as time proceeds (21). Then, if one applies the intervening-opportunities concept, the conditional probability of not finding an acceptable activity location within the prism is given by

$$P(t) = \alpha \exp(\ell\gamma v t) \quad 0 \leqslant t \leqslant T \tag{1}$$

where

$\alpha$ = a constant = $\exp(-\ell\gamma vT)$,
$\gamma$ = density of opportunities,
$v$ = speed of travel,
$\ell$ = constant acceptability parameter of the opportunity model, and
$T$ = time component of the destination coupling constraint (the origin coupling constraint is expressed as $t = 0$).

One can expect that, if the trip maker does not find a location for an activity within the prism, he or she will return home. This gives the rationale for the second half of the hypothesis. In spite of the simplicity of the underlying discussion, the above result has important implications for the modeling effort, specifically the implied rejection of the Markovian time-independent properties.

Next, consider a generalization to the case where there exists some minimum time requirement for engaging in out-of-home activities. Attention is paid here to the possible case in which a trip maker may not have enough time left to engage in an activity even when an acceptable opportunity is reachable. If that is the case, one would expect the trip maker to return home. Let $t^m$ be the minimum time required for an activity (this is generally different from the activity duration and varies depending on the nature of the activity and possibly on the attributes of the trip maker). Thus, it would be appropriate to assume some distribution function for $t^m$. Let $F(t^m)$ be the distribution function of the minimum time for the activity. Then the probability of being engaged in this activity is the joint probability of finding an acceptable opportunity within the reachable opportunity volume and having sufficient time left for the activity at that location. The probability of returning home, in turn, is expressed as

$$P^h(t,x) = 1 - F(T - t - x/v) + e^{-\ell\gamma v(T-t)} \int_0^{T-t-x/v} e^{\ell\gamma v t^m}\, dF(t^m) \quad 0 \leqslant t \leqslant T - x/v \tag{2}$$

where x represents the location of the trip maker at time t in terms of the distance from home. Examination of the above equation shows that $P^h(t,x)$ is an increasing function of t regardless of the distribution of $t^m$.

The formulation of Equation 2 also provides the second hypothesis: Suppose that the minimum time duration for an activity can be represented by a random variable from a distribution $F(t^m)$. Then, given that a sojourn is completed at time t and location x, the conditional probability of returning home increases with x, the distance from home, as well as with time t.

This can be seen by taking the partial derivative of Equation 2 with respect to x:

$$\partial P^h(t,x)/\partial x = (1/v)(1 - e^{-\ell\gamma x})[dF(u)/du]\Big|_{u=T-t-x/v} \geqslant 0 \quad x > 0 \tag{3}$$

for any distribution function F and any t. The probability of returning home is affected by both the time when, and the location where, the transition to the next sojourn occurs. The temporal and spatial dependency of this probability appears to be a critical element in the analysis of time-space paths.

Knowing that the conditional probability of returning home is an increasing function of time, one also obtains hypothesis 3: The average per sojourn of the sum of travel time and sojourn duration decreases as the number of sojourns in the path increases.

Proving fully this empirically observed (22) property requires an involved analysis of the process. Since this paper is concerned with the qualitative characterization of the time-space path, however, the following simplified illustration will serve the purpose.

Suppose that a trip maker who left home at time t = 0 has completed the first sojourn at location x. Let $s_1$ be the sum of the first travel time and sojourn duration. Since the probability of pursuing another activity decreases with time (hypothesis 1), the probability of pursuing another activity decreases as $s_1$ increases. Therefore, the expectation is that $s_1$ will be larger when the trip maker returns home after the first sojourn than in the case where he or she continues on.

One can apply the same logic to conclude that the sum of the first n trip times and the sojourn durations is larger when the out-of-home path terminates after the nth sojourn, compared with the case where it extends to pursue another activity or more. Then, introducing the assumption that the unconditional distribution of sojourn durations does not depend on t, or that at least its mean does not increase with t as suggested by empirical observations (23), leads to the statement given in hypothesis 3.

The property reflects one aspect of the intricate interrelationships among several attributes of the path--i.e., the number of activities, activity durations, travel cost, and spatial distribution of activity locations. In the utilitarian analysis of the path, each of these attributes will enter into the utility function in an interactive manner. This hypothesis depicts a trade-off that may exist among those elements.

These hypotheses suggest that the spatial distribution of sojourn locations may also vary depending on the number of sojourns. From Hagerstrand's prism concept, it can immediately be seen that the distance to the farthest location that can be visited in a path is negatively correlated with the sum of out-of-home sojourn durations. That maximum distance, under the assumptions postulated here, can be expressed as a linear function of the total out-of-home sojourn duration. Now, one can reasonably assume that the total sojourn duration is positively--but not necessarily linearly (hypothesis 3)--correlated with the number of sojourns in the path. Therefore, the distance to the farthest location that can be visited in a path is negatively correlated with the number of out-of-home sojourns and also with the total sojourn duration. One may interpret the property as an expression of the trade-off between space utility and time utility.

The additional restriction on the feasible region of the path will naturally affect the distribution of activity locations. The following inference can be drawn from this: The larger the number of sojourns in the path, the more concentrated the sojourn locations generally tend to be. The discussion below illustrates this for a simplified case.

In addition to the assumptions stated earlier, suppose that the sojourn duration is a constant rather than a random variable. If one applies the intervening-opportunities model, the spatial distribution of the first sojourn location ($x_1$), given that one has left home, is expressed by a negative exponential function:

$$dF(x_1) = K\beta \exp(-\beta x_1) \quad 0 < X_1 \leq L(1) \tag{4}$$

where

$\beta = \ell\gamma$,
$K = 1 - \exp[-\beta L(1)]$,
$L(1)$ = maximum distance reachable when only one sojourn is made = $(T - d_1)v/2$, and
$d_1$ = duration of the first sojourn.

The probability of returning home after the first sojourn is expressed by using Equation 1 as a function of $x_1$:

$$P^h(x_1) = \begin{cases} \alpha \exp[\beta(x_1) + (d_1 + d_2)v] & 0 < x_1 \leq L(2) \\ 1 & L(2) < x_1 \leq L(1) \end{cases} \tag{5}$$

where $\alpha$ is as defined earlier, $d_2$ is the duration of the second sojourn, and $L(2) = (T - d_1 - d_2)v/2$. Then the distribution of the first sojourn location from which no further activities are pursued is

$$dF(x_1)P^h(x_1) = \begin{cases} K\alpha\beta \exp[\beta(d_1 + d_2)v] & 0 < x_1 \leq L(2) \\ K\beta \exp(-\beta x_1) & L(2) < x_1 \leq L(1) \end{cases} \tag{6}$$

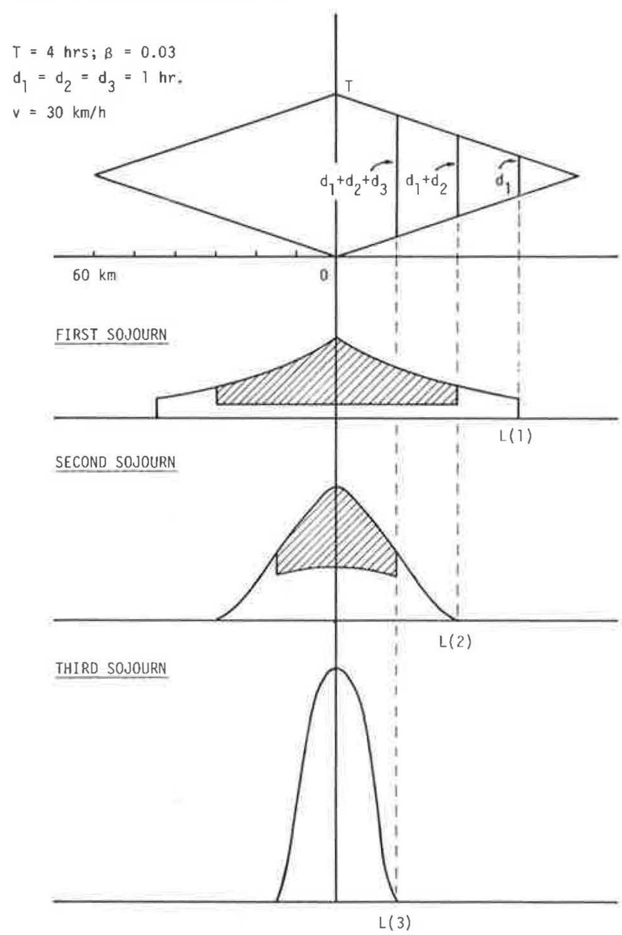
The distribution of the first sojourn location from which further activities are pursued is given as

$$dF(x_1)[1 - P^h(x_1)] = \begin{cases} K[\beta e^{-\beta x_1} - \alpha\beta e^{\beta(s_1+s_2)v}] & 0 < x_1 \leq L(2) \\ 0 & L(2) < x_1 \leq L(1) \end{cases} \tag{7}$$

These two distributions are shown in Figure 1.

The distribution of the first sojourn location varies depending on the number of sojourns--in this case, exactly one or more than one--and the locations are distributed closer to home in the latter case. After manipulating the distribution of the second activity location by using the intervening-opportunities concept, the same logic can be applied to show that the above tendency holds for the second

**Figure 1. Distribution of sojourn locations in a hypothetical linear city.**




Note: The hatched area indicates the distribution of sojourn locations from which next sojourns are made.

location or farther for the nth location in general. The figure illustrates this for up to n = 3.

This discussion is based on the assumption that the opportunities are homogeneously distributed. The conclusion that the distribution concentrates around home as the number of sojourns increases thus cannot be generalized. Therefore, more generally, hypothesis 4 can be stated as follows: The distribution of sojourn locations (or trip destinations) depends on the number of sojourns in the path. It should be noted that this hypothesis is derived for an extremely simplified case. More rigorous theoretical support of the hypothesis requires an involved analysis that is unwarranted in view of the study objective. The obvious dependence of a sojourn location on the previous sojourn location, however, suggests that the hypothesis applies to a more general case where the sojourn durations are random at least for relatively small n.

MULTIPLE-CHAIN PATHS

The above discussion assumed for illustrative simplicity that a path consists of a single home-based chain of trips. Since hypotheses 1-3 are induced on the basis of either the conditional probability of permanently returning home or the total number of out-of-home sojourns and their durations, they apply to multiple-chain paths without modifications. At the same time, this implies that the abstract model has not distinguished between single- and multiple-chain paths.

One approach to multiple-chain paths within the present framework is to assume the existence of additional constraints on the time-space path. Given that a certain set of locations is visited, travel cost almost always decreases by consolidating trips into one chain. As the earlier discussion has indicated, the volume of reachable opportunities keeps on decreasing as time proceeds. In light of these factors, it would seem more logical for a trip maker to make only one trip chain. Therefore, one can expect that, when a path involves more than one chain, there are certain constraints that prevent the consolidation of activities into a single chain; e.g., activities are available only during certain time periods or the trip maker must return home to perform some household tasks. Thus, one may conjecture that, given the number of out-of-home sojourns, the number of home-based chains in a path is positively correlated with the magnitude of constraints under which the trip maker acts. The conjecture follows after one introduces to the abstract model an additional assumption that a trip maker prefers less travel expenditure.

Consideration of travel behavior in a more realistic context, however, leads to additional statements regarding the number of chains in a path. Adler and Ben-Akiva (7) hypothesize that the utility of an activity would be greatest if it were pursued separately from other activities, since one can then select the best arrangement for the activities. The Adler and Ben-Akiva model has a structure that represents the trade-off between the increased utility of the activity and the increased travel expenditure. This utilitarian approach thus suggests that the number of chains is negatively correlated with the valuation of travel expenditure relative to the utility of activities perceived by the trip maker. Pursuing activities separately, at various times of the day, requires the constant availability of expedient transportation. From this, it follows that, for a given number of sojourns, the number of chains is positively correlated with the mobility of the trip maker [the discussion here is critically different from those by Bentley and others (6) and Hemmens (23) in that this study is concerned with trip consolidation given the number of sojourns to be made in the day]. These conjectures are more behavioral, and no clear-cut theoretical support can be obtained from the abstract model. The next section of this paper examines these conjectures together with the four hypotheses. After they are statistically tested, the abstract model can be extended to enrich its behavioral implications.

The introduction of additional coupling constraints, as suggested by the first conjecture, increases the number of prisms and reduces the feasible region of the path, as is often illustrated (3,21). Hypotheses 1-4 still apply to the multiple-prism case, with slight modifications, as long as all prisms originate and terminate at the home base. The feasible region of a path that involves nondiscretionary activities such as work and school is defined by applying a prism to each discretionary segment of the path (3,21). The hypotheses presented above, therefore, apply to each prism of those paths as well. New aspects are the non-home-based chain (e.g., office-based chain during the lunch break) and prisms that originate and terminate at different locations. This calls for modification of the hypotheses, especially hypothesis 4, if the statements are to be made for the entire path. For practical purposes, however, dealing with respective prisms would be sufficient.

Before the findings of the empirical analysis are presented, some limitations must be discussed. The first problem is that the prism is not observable. In the review of previous travel-behavior models presented earlier in this paper, it was assumed that the origin and destination coupling constraints are known constants. Of course, this is not the case in empirical data analysis. A trip maker may have several prisms that restrain his or her path even when he or she does not pursue activities that are obviously nondiscretionary. The distribution of opportunities, another determinant of the path, is not incorporated in the analysis. In addition, this study does not explore the behavioral distinctiveness of trip makers. Although the results presented in the next section generally strongly support the hypotheses, these limitations must be kept in mind.

EMPIRICAL RESULT

The empirical analysis of this study was conducted by using the 1965 Detroit Area Transportation and Land Use Study (TALUS) data set. The characteristics of the area are discussed elsewhere (24). The data set consists of a household sample of trip records that include information on the entire set of trips made by each member of the household on the survey day and socioeconomic information on the individual and the household. In this study, approximately 10 percent (32 100) of the original trip records were sampled according to residential locations. The sampling used nine geographic areas, selected to represent a wide spectrum of socioeconomic status. The only individuals used in the analysis were those who (a) pursued at least one out-of-home activity on the survey day, (b) had a closed home-based path, (c) had at least one car available to the household, (d) held a driver's license, (e) were at least 18 years old, (f) made the trips by car (either as a driver or a passenger), and (g) made all trips within the three-county-wide study area. Such aspects as mode choice are not explored in this study. The sample includes 4736 individuals who satisfy all these conditions, and unless otherwise mentioned the results presented below are for the 1806 trip makers whose paths do not contain work trips. Eighty-one percent of those individuals were not in the labor force. A one-day period starting at 2:30 a.m. and ending at 2:29 a.m. is used as the study period.

An overview of the data set is presented in Table 1 in terms of the number of chains and the number of sojourns on the survey day. Whereas approximately one-third of the 1806 individuals made only one nonwork, out-of-home sojourn, about 45 percent of the sample made three or more sojourns. The multiple-sojourn chain is a quite common phenomenon among this sample of 1806 individuals: Among those who made more than one sojourn, 78 percent (or 936 trip makers) had at least one multiple-sojourn chain. Other overall statistics of interest are as follows: Average number of trips per trip maker = 4.51, average number of sojourns per trip maker = 2.85, average number of chains per trip maker = 1.66, and average number of sojourns per chain = 1.72.

There is no notable difference in Table 1 between the aggregate statistics for trip makers who made no work trips and the 2930 trip makers who made work trips. The marginal distribution of the number of chains, however, shows a significant difference between the two groups. The group with no work trips has a higher representation of paths with larger numbers of chains (three or more), whereas the second group has a higher-than-expected frequency of two-chain paths. This is intuitively agreeable, since one can expect that the second, nonwork activity is quite often pursued separately, after the trip maker returns home from work. The contingency table formed by the two column-total rows is highly significant ($\chi^2$ = 82.2 with 3 df). No notable difference was found in the distribution of the number of sojourns between the two groups. Overall statistics for the second group are as follows: Average number of trips per trip maker = 4.40, average number of sojourns per trip maker = 2.82 (1.39 when work is excluded), average number of chains per trip maker = 1.57, and average number of sojourns per chain = 1.79.

Figure 2 shows the relative frequency of returning home permanently for the day, given that a sojourn is completed outside the home base within respective 1-h time periods. The observed relative frequency serves as an estimate of the conditional probability of returning home, a critical element in stochastic analysis of the path. In general, the figure, with its clearly increasing frequency of returning home as time proceeds, supports hypothesis 1. The increasing tendency shown in the figure was tested by weighted least-squares regression using logit, which is defined as $\ln(f_i/f_i')$ where $f_i$ is the observed frequency of returning home during time period i and $f_i'$ is the observed frequency of not returning home. The result naturally yielded a highly significant positive coefficient of time (t-statistic = 3473 with 18 df).

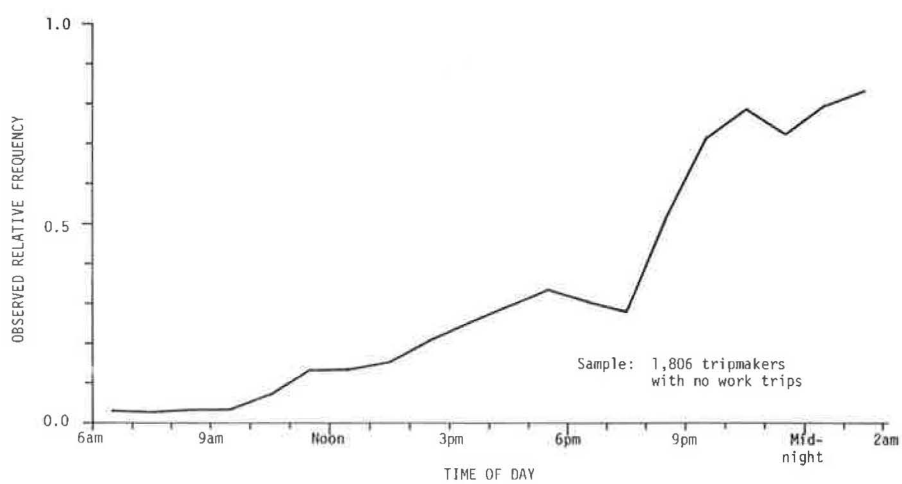
A "dip" in the early evening periods, however, is notable. This is presumably a result of after-dinner activities such as social visits and shopping. As Damm (13) noted, human activity can be allocated by considering several time periods of the day, each of which is perceived to have distinguishable characteristics and to be appropriate for a particular set of activities. The model used here is obviously too abstract to represent such an aspect of human behavior, although some immediate modifications, such as time-dependent opportunity density, would replicate the observation. However, the central focus of hypothesis 1--that the relative frequency of returning home is a function of time--is clearly indicated in the result. It demonstrates explicitly, yet simply, the temporal dependency of the behavior, expanding the body of empirical evidence (17,23). The result also indirectly supports the assumption used by Nystuen in the development of his simulation model (25): that the utility of returning home increases as time proceeds.

Figure 3 shows a spatial, as well as temporal, dependency of the probability of returning home.

**Table 1. Distribution of trip makers by number of chains and sojourns in path.**

| Number of Sojourns | Number of Trip Chains 1 | 2 | 3 | ≥4 | Total |
|---|---|---|---|---|---|
| **Trip Makers Making No Work Trips** | | | | | |
| 1 | 611 | | | | 611 |
| 2 | 219 | 180 | | | 399 |
| 3 | 98 | 132 | 59 | | 289 |
| 4 | 52 | 78 | 50 | 13 | 193 |
| 5 | 27 | 39 | 28 | 15 | 109 |
| ≥6 | 28 | 57 | 56 | 64 | 205 |
| Total | 1035 | 486 | 193 | 92 | 1806 |
| **Trip Makers Making Work Trips** | | | | | |
| 1 | 966 | | | | 966 |
| 2 | 212 | 506 | | | 718 |
| 3 | 218 | 206 | 69 | | 493 |
| 4 | 75 | 139 | 46 | 12 | 272 |
| 5 | 52 | 76 | 36 | 9 | 173 |
| ≥6 | 76 | 135 | 58 | 39 | 308 |
| Total | 1599 | 1062 | 209 | 60 | 2930 |

**Figure 2. Time variations in relative frequencies of returning home permanently for the day.**



The figure is based on the tabulation of travel records for the 783 trip makers from Warren, Michigan, a suburban middle-income community, by developing a set of five rings for the area and by tabulating sojourn locations according to those rings [a similar set of rings was also developed for the city of Birmingham, Michigan (see Figure 4)]. Since the frequency of trips to ring 5 in the data set was extremely small, rings 4 and 5 were merged and will hereafter be referred to as ring 4. Rings 2, 3, and 4 are approximately 5, 10, and 15 km from the community center, respectively. The tabulation is for trip makers who did not make work trips.

A temporal tendency similar to that in Figure 2 can be found in Figure 3. It also exhibits spatial dependency of the behavior. The observed relative frequency of returning home, given that a sojourn is completed outside the home within respective time periods, generally increases as the distance from home increases. Although a few exceptions can be noted, the figure is strongly supportive of hypothesis 2.

The statistical significance of the spatial and temporal effects shown in Figure 3 was examined by

Figure 3. Space-time dependence of relative frequencies of permanently returning home for the day.

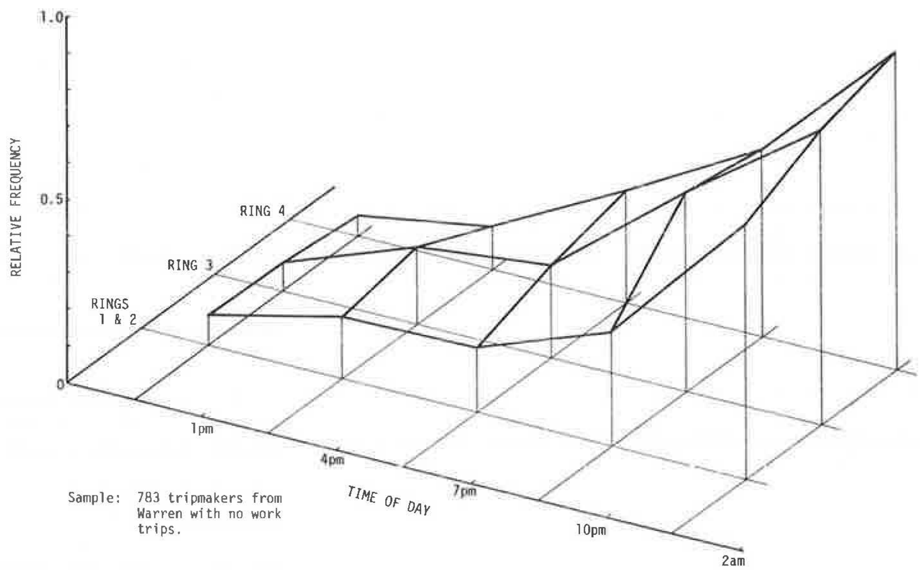
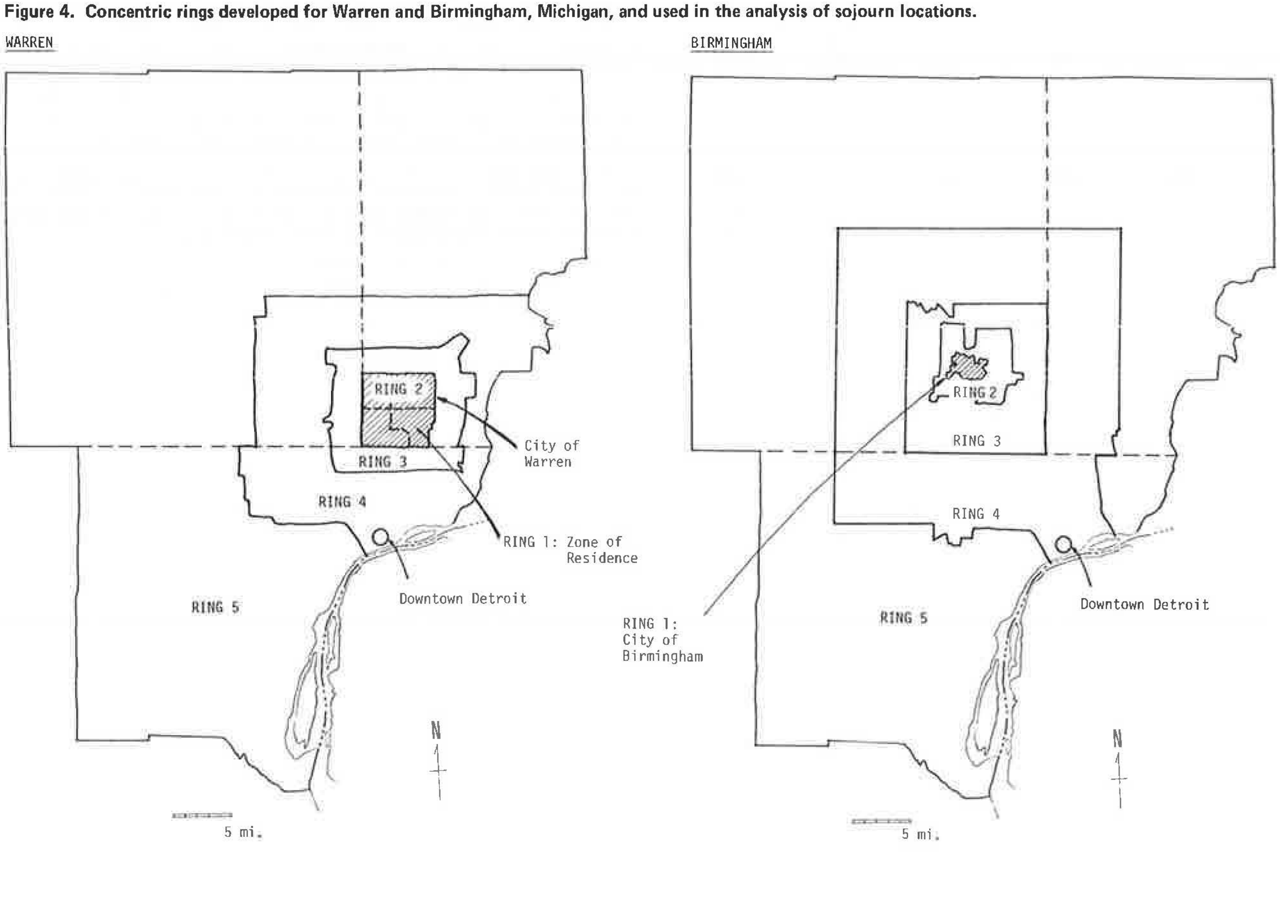



Figure 4. Concentric rings developed for Warren and Birmingham, Michigan, and used in the analysis of sojourn locations.



using logit multiple classification analysis (26). The result indicated that the independent effects of time and location are both significant at $\alpha = 0.001$ (with, respectively, $\chi^2 = 285.5$, df = 4; and $\chi^2 = 15.5$, df = 2). The time-location interaction terms were found to be significant at $\alpha = 0.01$ ($\chi^2 = 24.7$, df = 8).

An immediate implication is that spatial interaction patterns vary depending on time. The intensity of the interaction is also a function of the distance from the trip maker's home to the present location as well as the spatial separation between the present and the next locations. The result implies that one cannot apply a single trip matrix to represent trip makers' movements in general. Each trip maker has a unique trip matrix that depends on the location of his or her residence. The elements of the matrix vary as a function of time, and their rate of change possibly varies depending on the distance from home. The result indicates that, in addition to the cost of travel to a destination location and its attributes, the utility of the destination is also a function of the time of day and the distance from home. The result suggests a new, dynamic approach to spatial interaction analysis [a closely related discussion can be found elsewhere (27)].

**Figure 5. Average sojourn and travel durations by number of sojourns in the path for trip makers making no work trips.**

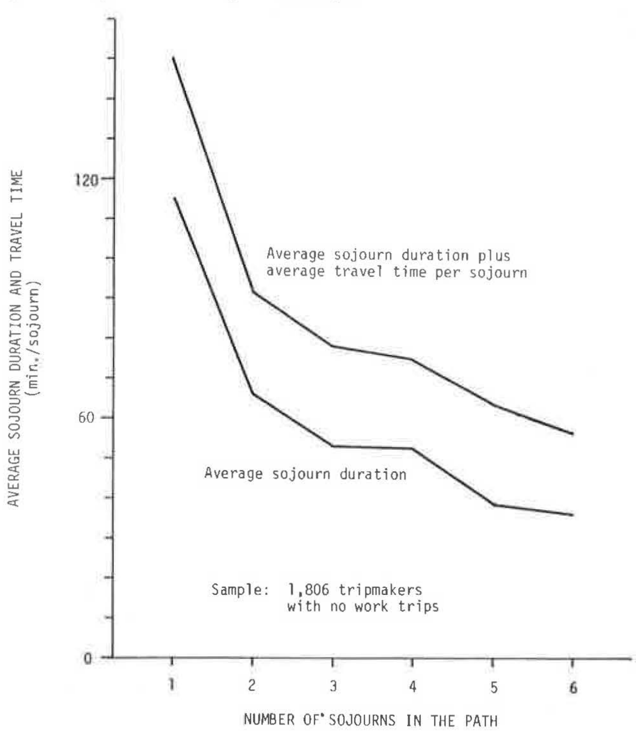



**Table 2. Average travel time spent per sojourn by number of sojourns and chains in the path.**

| Number of Trip Chains | Time per Sojourn by Number of Sojourns (min/activity) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | ≥5 |
| 1 | 34.0 | 22.3 | 21.8 | 19.6 | 20.4 |
| 2 | | 30.3 | 25.5 | 23.4 | 19.1 |
| 3 | | | 28.7 | 23.4 | 18.8 |
| 4 | | | | 18.8 | 20.2 |
| Overall | 34.0 | 25.9 | 24.9 | 22.0 | 19.5 |

Note: Sample = 1806 trip makers who made no work trips.

Another temporal aspect of the time-space path is the duration of sojourns. Figure 5 shows the average travel time per sojourn and the average sojourn duration by the number of sojourns in the path (for the 1806 trip makers with no work trips). The average travel time per sojourn is defined as the total travel time divided by the number of sojourns in the path. Figure 5 supports hypothesis 3 by showing a steady decline in (a) average duration per sojourn and (b) average travel time plus average sojourn duration per sojourn as the number of sojourns increases. Using a Dutch data set, Vidakovic (22) reported a similar result. This tendency is found in the present study regardless of the number of trip chains.

The result can be interpreted as an indication of the trade-off between the number of activities and the time that can be spent for respective activities. This may provide a guideline in formulating a utility function for utilitarian analyses of the time-space path. At the same time, the result offers strong evidence for rejecting the Markovian model structure, where the sojourn duration is essentially independent of the number of sojourns.

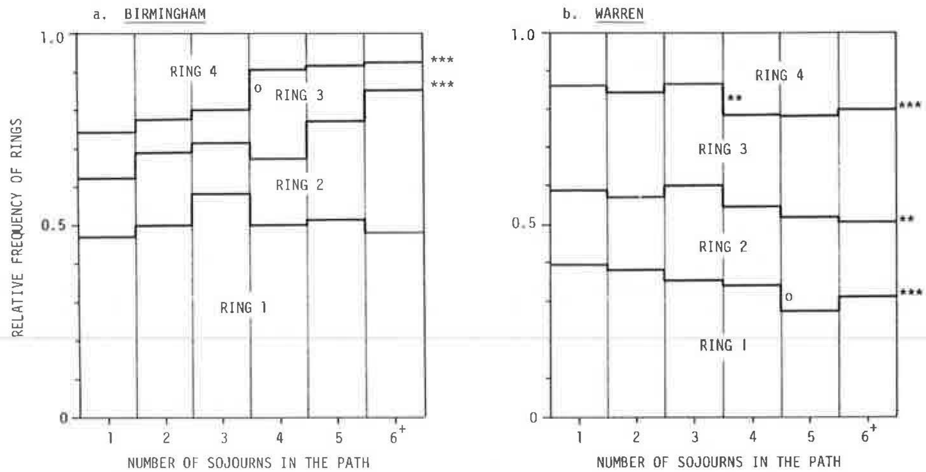
Table 2 gives the average travel time spent per sojourn by the number of out-of-home sojourns and by the number of trip chains in the path. The table provides support for the assertion that a path is more efficient, in terms of travel cost, when more trips are consolidated into a chain. The table shows that, given the number of chains, the average travel time spent per sojourn decreases as the number of sojourns (or number of trips) increases. The table also shows the general tendency that, given the number of sojourns, the average travel time increases with the number of chains or decreases as the degree of trip consolidation increases. The tendency, however, is not clear when the number of sojourns is four or more, presumably because of the small sample size of trip makers with a large number of sojourns.

The table also offers support for hypothesis 4 regarding the correlation between the spatial distribution of sojourn locations and the number of sojourns. When the number of sojourns equals the number of chains (diagonal elements of the table), the average travel time presented in the table represents the average length of home-based trips. A clear tendency found in the table is that the average length of trips to sojourn locations decreases as the number of sojourns increases. Thus, for this special case, the spatial distribution of sojourn locations depends on the number of sojourns in a manner that is compatible with the earlier discussion. The differences among the four average travel times are generally significant.

Hypothesis 4 is more directly examined by using sample subsets that represent both areas for which rings were developed: Birmingham, a high-income community, and Warren, a middle-income community (Figure 4). Figure 6 shows the result. It should be noted that the present result is an extension of previous empirical observations of spatial distributions of sojourn locations (18-20) in that it involves an additional dimension, the relation between the distribution of sojourn locations and the number of sojourns in the path or chain.

Figure 6a is obtained from the 439 sojourn records of 168 trip makers from Birmingham. The significance of the difference in the relative frequency between two adjacent numbers of sojourns is examined by using the difference in the logit and, when significant, is shown in the figure in terms of the level of significance. The overall tendency in the relative frequency is evaluated by a weighted least-squares regression of logit on the number of

**Figure 6. Distribution of sojourn locations by number of sojourns in a day for trip makers making no work trips.**

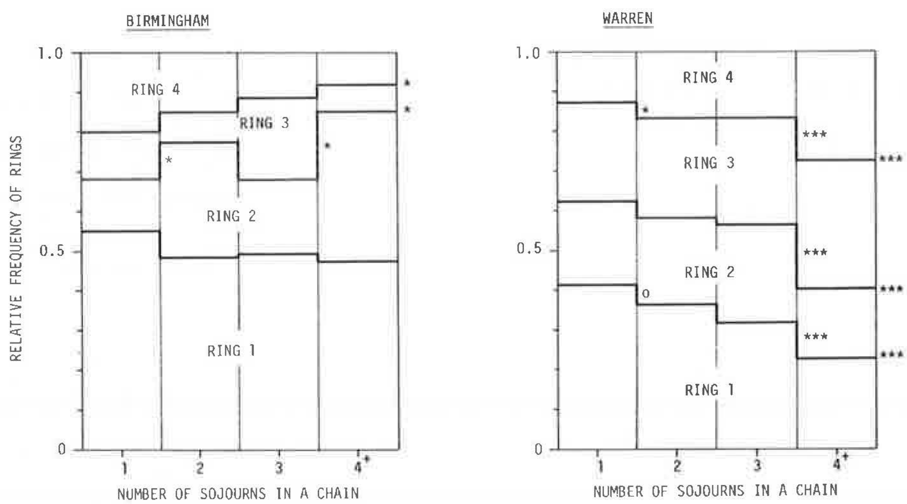



Sample size: 439 sojourns, 168 tripmakers.

Sample size: 2,265 sojourns, 783 tripmakers.

Note: Significance level in the difference of the logits and in the overall increasing/decreasing tendency is shown by:
o for $\alpha$ = 0.10
* for $\alpha$ = 0.05
** for $\alpha$ = 0.01
*** for $\alpha$ = 0.001

**Figure 7. Distribution of sojourn locations by number of sojourns in a chain for trip makers making no work trips.**




Sample size: 439 sojourns, 168 tripmakers.

Sample size: 2,265 sojourns, 783 tripmakers.

sojourns. The figure also shows the significance level of the slope.

Figure 6a clearly indicates that the relative frequency for ring 4, which is the farthest ring and includes downtown Detroit, decreases as the number of sojourns per day increases. The result is again consistent with the earlier discussion. The statistical significance of this decreasing tendency was tested by a rank-ordering method using the logit (28), and the tendency was found to be significant at $\alpha = 0.05$. The weighted least-squares analysis also showed a significant slope (at $\alpha = 0.001$).

Figure 6a shows that the relative frequency of trips to ring 2, the area immediately adjacent to Birmingham, tends to increase with the number of sojourns whereas that of Birmingham itself is relatively invariant. The indication is that, as the number of sojourns increases, the trajectories of trip makers' movements tend to contract into a relatively small area within and around the area of residence (rings 1 and 2 form approximately a rectangle of 13 by 11 km).

The result of the 783 trip makers and 2265 sojourns for Warren is also shown in Figure 6b. The tendency, however, is contrary to that found for Birmingham. The relative trip frequency for ring 4, which also includes downtown Detroit, increases as the number of sojourns increases (significant at $\alpha = 0.001$). On the other hand, those for ring 1 (residence zone of the trip maker) and ring 1 plus ring 2 decrease with the number of sojourns (both significant at $\alpha = 0.01$). It appears that this group of trip makers from Warren tends to make multisojourn trip chains that involve ring 4 [a similar observation can be found elsewhere (19)].

Figure 7 shows the spatial distribution of sojourn locations by the number of sojourns in each chain. The figure for Birmingham again shows the tendency that sojourn locations tend to concentrate around the area of residence as the number of sojourns in the chain increases (significant at $\alpha$ = 0.05). The tabulation for Warren, on the other hand, clearly indicates an increased relative frequency of visits to ring 4 when a chain involves a larger number of sojourns (significant at $\alpha$ = 0.001).

The spatial distributions of opportunities relative to the two areas are, of course, substantially different. Since Warren is located closer to Detroit than Birmingham, its proximity to areas with high opportunity density may be the source of the above divergence between the two. The model of this study can easily be generalized to explain this (note that homogeneity in the opportunity distribution was assumed in the discussion leading to hypothesis 4). Overall, the result here confirms the hypothesis that the spatial distribution of sojourn locations varies depending on the number of sojourns in the path. The result at the same time suggests possible behavioral distinctiveness [e.g., difference in the perceived "action space" (29)] between the two areas, which, however, is not within the scope of the abstract model.

Similar tabulations of sojourn locations are shown in Figure 8 for those trip makers from the two areas whose paths involved work trips. These paths are constrained by more than one prism whose exact size and location in the time-space coordinates are unobservable. Figure 8, which shows the distribution of sojourn locations by the number of sojourns in the path, exhibits a clear tendency that indicates that ring 4, which includes downtown Detroit, gets an extremely large share of the trips made by trip makers who pursue only one sojourn (work) a day. This is an obvious result, since the relative frequency in this case is identical to the distribution of the work locations of these trip makers. The reduced share of ring 4 thereafter (significant at $\alpha$ = 0.001) indicates that the rest of the activities tend to be pursued in the relative vicinity of the area of residence, presumably because sojourn locations are constrained by relatively small prisms, e.g., between work and home. Overall, the result again confirms the dependence of sojourn locations on the number of sojourns. No differences are notable between the two areas for those trip makers who had work trips in their paths.

Unlike the other hypotheses, the first conjecture regarding the number of chains in the path is not directly testable since no measurements are available that represent the magnitude and nature of constraints on the path. Many of the 1806 trip makers who did not make work trips are homemakers. Thus, it is expected that they may have been responsible for larger shares of household chores, especially child care. This would create various types of constraints on the trip maker's behavior (30,31). Therefore, the study took the approach of using the life-cycle stage as a proxy for the constraints and explored its relation with the number of chains. The latter is viewed as a characteristic of the path that represents the magnitude of constraints.

Figure 9 shows the distribution of the number of chains by five life-cycle categories conditioned on the number of sojourns per day (two, three, four, or more). The trip makers in households where the youngest child is between 5 and 17 years old (life-cycle category 3) have a very small frequency of making only one trip chain per day, especially when the number of sojourns is large. This is an expected result, since children of school age would create a larger magnitude of constraints for the caretaker, and it supports the finding of Jones and others (31).

A similar contingency analysis was conducted by using the number of cars available as a proxy for mobility and using income as a proxy for the valuation of travel expenditure. The results are shown in Figure 9, which indicates no clear tendency between income and the number of chains and suggests that the 1965 sample of the 1806 individuals was rather insensitive to the travel cost of intraurban nonwork trips. The tabulation for the number of cars available, on the other hand, exhibits a tendency that indicates that the number of chains in the path increases with the number of available cars. Although the indication is statistically weak, it points out another aspect of urban travel behavior as a time-space path.

## CONCLUSIONS

After integrating several well-known concepts into an abstract model, this study has inferred and empirically examined several hypotheses that focus on the temporal and spatial aspects of urban travel patterns. The empirical results indicate that the relative frequency (or estimated conditional probability) of a trip maker returning home is, in general, an increasing function of the time when and the location where the transition occurs. Another temporal aspect of the path is the dependence of the average sojourn duration on the number of sojourns in the path. The results also showed the dependence of the spatial distribution of sojourn locations on the number of sojourns. A strong correlation was

**Figure 8. Distribution of sojourn locations by number of sojourns in a day for trip makers making work trips.**

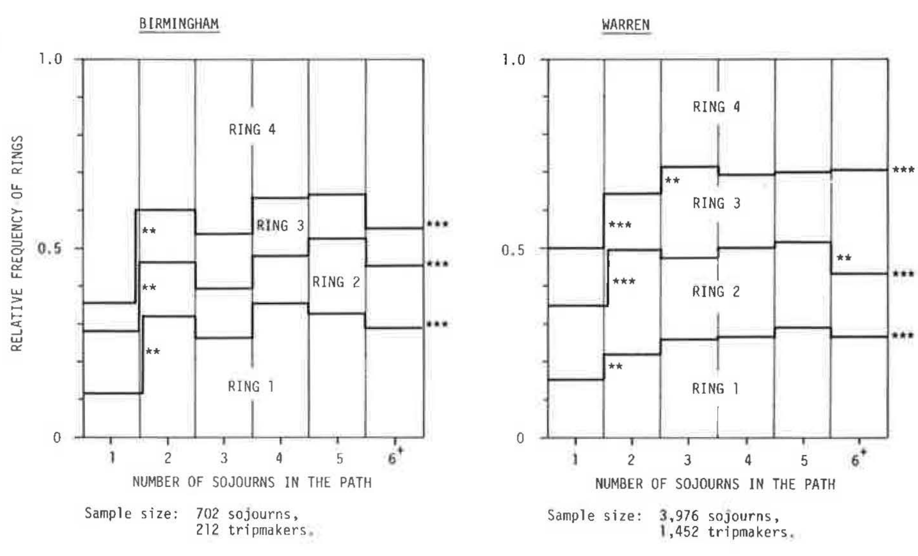
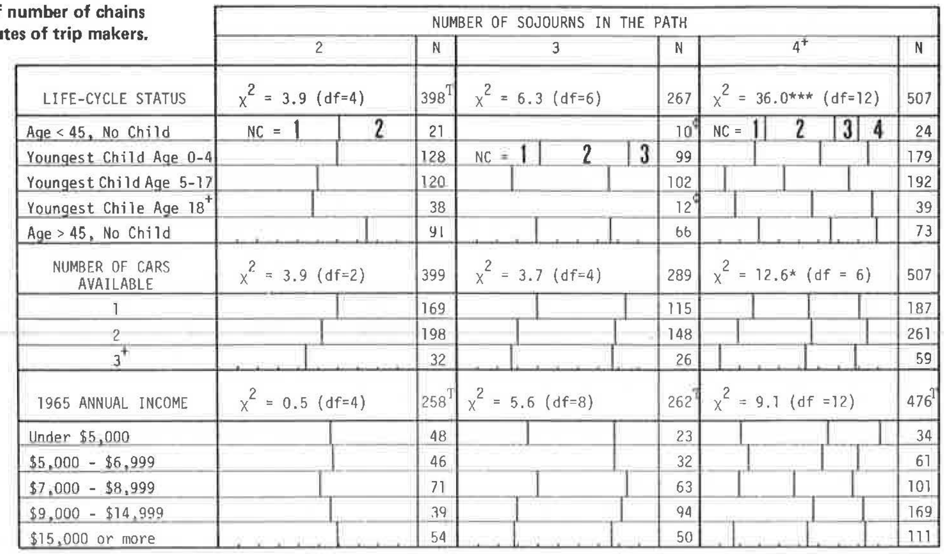


Figure 9. Distribution of number of chains by socioeconomic attributes of trip makers.




Sample: 1,195 tripmakers with no work trips and with more than one sojourn.

NC: Number of chains in the path.

TTripmakers with unknown socioeconomic attributes are eliminated.

ΦThe row is excluded from the analysis due to the extremely small sample size.

found between the number of chains and trip makers' life-cycle status, which suggests varying magnitudes of constraints under which those segments of the population act.

The model developed here can be classified as a stochastic-process model. Thus, the study's first implication is the explicit rejection of the Markovian assumptions often used in analyzing trip-changing behavior. The temporal-spatial dependence found above is not compatible with the Markovian time-homogeneity assumption. The dependence of spatial distributions of sojourn locations on the number of sojourns and the interrelationship between sojourn duration and the number of sojourns all imply that the Markovian history-independence assumption is inappropriate when applied to this behavior.

On the other hand, certain aspects of travel behavior may be well represented by a Markovian model. For example, an empirical tabulation presented by Bentley and others (6) indicates that the number of sojourns in a chain can be represented by a geometric distribution that assumes a Markovian decision process in trip making. Although our results do not support the application of the Markovian models in the time-space framework, further examination of travel behavior may find relevant and useful applications of those models. The above findings also indicate the direction in which the Markovian models can be modified for better representation of travel behavior.

The findings of the study also have certain implications for the utilitarian approach to the modeling of trip behavior. The negative correlation between the number of sojourns and the average sojourn duration is suggestive of a trade-off between these two factors, both of which would be important components of the utility function. The dependency on time and location of the transition frequencies to home indicates that the utility of an activity may be best specified as a function that involves those two factors. The temporal and spatial elements are probably key components of the utility function.

Spatial and temporal aspects of travel behavior are inseparable, perhaps simply because the path evolves in the time-space dimension. Patterns of spatial interaction will vary depending on time, whereas travel decisions will vary depending on the location where they are made. The spatial and temporal characteristics of a path also depend on other characteristics of the path, such as the number of sojourns. Obviously, many intricate relations are embedded in the observed time-space path.

This study has shown that a simple, abstract model can be used in unwinding these relations so that some may then become observable. The basic space-time characteristics illustrated in this study may guide further quantitative modeling efforts and delineate empirical analysis of the complexity of travel behavior.

ACKNOWLEDGMENT

Portions of this study were supported by a National Science Foundation grant to the University of California at Davis.

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# Implications of the Travel-Time Budget for Urban Transportation Modeling in Canada

A. CHUMAK AND J.P. BRAAKSMA

**The travel-time-budget concept, which examines regularities in the allocation of travel time in urban areas, is investigated. Previous analysis of three U.S. cities suggests that the daily travel-time budget is approximately 1.1 h/traveler. The objective of this research is to (a) verify the theory in Canada and (b) determine the practical implications for transportation planning. Analysis of home interview surveys in Calgary, Toronto, and Montreal supports the conclusions previously developed in the United States. A detailed analysis of the Calgary data indicates that the travel-time budget is not affected by such factors as mode of travel, trip purpose, automobile ownership, or location of residence with respect to the central business district. Several practical applications of the concept are developed, including a procedure for conducting an independent validity check of conventional travel forecasts. This process is very simple to conduct and allows forecasts to be verified by using a different model. The travel-time budget is also a useful tool for developing equilibrium travel forecasts. Equilibrium models relate travel demand to available capacity and may reduce the demand for nonessential trips during peak periods. Further research is recommended on the application of the travel-time budget to other aspects of urban travel forecasting, including traffic assignment, modal split, and evaluation of personal mobility.**

Since the early 1950s, several transportation planners and economists have suggested that individuals allocate a certain budget for the purchase of transportation goods and services. Tanner (1) produced the first empirical evidence to support the hypothesis that households allocate a fixed portion of their income for transportation.