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DISAGGREGATE STOCHASTIC MODELS OF TRAVEL-MODE CHOICE

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This paper is concerned primarily with identifying the research and development needed to build general models of mode choice that are based on the modeling of individual behavior. The existing aggregate associative models are discussed in general terms, and their shortcomings are identified. The rationale of disaggregate behavioral models is then put forward, and the potentials of such a modeling technique are discussed. In this discussion, the present state of development of behavioral disaggregate models is indicated. Based on present experience in building these models, a set of research and development tasks is identified as being needed to develop more general operational models of this type. As each task is identified, suggested means of researching the problem are put forward.

•THE ESTIMATION of travel demand is a major part of most urban transportation studies. Because of the increasing complexity of deciding on investment priorities among transportation alternatives and between transportation and other urban and regional concerns, the accurate estimation and prediction of travel demand are becoming increasingly important as aids to the necessary decision-making process. The ability to predict travel demand more accurately is required both for problems within urban areas and for problems in major regional corridors. The existing travel-demand models, which have been developed largely for predicting intraurban travel, cannot meet the accuracy requirements of the decision-makers and policy-makers. As well as being too inaccurate for useful predictions of intraurban travel, these models are completely inadequate for use in predicting interurban travel. As a result of the shortcomings of existing models, there have been numerous attempts during the past few years to develop new strategies and techniques for modeling travel demand.

Within the problem area of travel demand, the specific problem of travel-mode choice, or modal split, is of considerable interest. Almost every transportation study has developed its own modal-split model, whereas models of the remaining elements of travel demand—trip generation, trip distribution, and assignment—are much more standardized. Mode-choice modeling derives a substantial amount of its added interest from the fact that it has considerable potentials in aiding investment decisions among transport modes and can potentially indicate the likely outcome of various decisions affecting today's ailing public transport undertakings. Although numerous modal-choice models have been developed, these models can largely be classified into a small number of categories wherein the properties of the individual models are susceptible to general description.

Recent work in the area of mode choice has produced a number of models that are concerned with determining the probabilities of choices of individuals. These models

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are based on the concept of applying theories, which concern human behavior and choice, to a disaggregate model structure for mode choice. For the most part, these models have been constructed for the work journey into the CBD of a large urban area. In general terms, this technique holds out considerable promise for the more accurate estimation and future prediction of mode choice.

It appears that this technique of modeling travel-mode choice has some considerable potential not only for more accurately estimating and forecasting modal shares but also for increasing basic understanding of the decision-making process involved. Among the additional benefits to be gained from this modeling technique is the ability to measure the comparative evaluation, in the mind of the traveler, of different system attributes. This clearly has a major use in making decisions among transport alternatives, particularly where patronage of a mode is of prime importance (1, 2).

The major concern of this paper is to describe and discuss the major areas of research and development that are currently indicated as being necessary for the realization of the potential of the disaggregate behavioral approach to modal-choice modeling. The first part of this paper is concerned with a classification and description of existing aggregate modal-choice models and with the identification of the major problems connected with these models. The second part of the paper describes a number of disaggregate behavioral models of mode choice that have been developed and details the potentials of the technique. It should be possible to realize these potentials when these models are generalized. The third part of the paper identifies and discusses the various problems that need to be solved if fully operational models of this type are built. These problems concern the identification of the best system, the user, and environmental characteristics for use in such models; the appropriate values for system characteristics; and some problems resulting from the complex trip patterns that are commonly encountered in urban areas. An outline of the needed research for the solution of each problem is given.

REVIEW OF MODAL-CHOICE MODELING

Modal choice, or modal split, is one of 4 models in the conventional urban transportation planning (UTP) process. This set of 4 models, which is collectively called the UTP package, has been reviewed in a number of papers (2, pp. 196-197; 3, 4). The limitations of this package, as a total travel-demand prediction tool, have been dealt with elsewhere at some length (2, pp. 197-199; 5, 6). Apart from the problems that arise within the UTP package as an entity, modal-split models have a number of specific disadvantages, stemming largely from the evolution of modeling requirements.

Since the first major transportation studies were carried out in the mid-1950's, various attempts have been made to build models of the modal-choice process. These models can be broadly classified into 3 principal groups. The earliest models attempted to predict modal choice at an aggregate level by using characteristics of the aggregated areas, such as zones and districts (7, 8, 9, 10, 11, 12, 13). These characteristics constituted socioeconomic measures of the population of the aggregated areas and measures of attraction of these areas in terms of the activity levels of various land uses. Because the models did not contain any characteristics of the modes, they could not respond to changes in these characteristics. Furthermore, because the socioeconomic measures incorporated are generally increasing (e.g., income, car ownership, and level of education), predictions of future modal shares from these models suggest that transit will be used by a dwindling proportion of the population, irrespective of any changes in mode characteristics.

The second generation of models came into existence in the early 1960's and incorporated some measures of the transportation system but still at an aggregate level (14, 15, 16). At first the system characteristics were still intractable because they comprised the fitted function of trip distribution from the gravity model (17). Later models began to incorporate actual system characteristics, such as time, cost, and frequency. An excellent example of this type of model is the diversion-curve model developed by the Traffic Research Corporation (16). However, these second-generation models are all aggregate models and have drawbacks in that they can current overall modeling processes used in such studies. They have been developed to predict individual behavior by assigning to individuals probabilities of using modes in a binary choice situation. It appears that these models can better reproduce existing conditions, regardless of geographic location, and give more reasonable responses to forecasts of mode and user characteristics than models of the type described in the earlier section.

PROPERTIES OF DISAGGREGATE STOCHASTIC MODELS

The models being developed within the second approach discussed in the preceding section are disaggregate stochastic models (2). The models are stochastic in that they predict the probability that an individual will make a specific choice. This probability is assigned on the basis of the consideration of user and system characteristics, and this procedure is most consistent with modern theories of human discrimination and choice (27, 28). These theories state that every human decision is, in essence, probabilistic. In addition to providing a basis in behavior to the concept of stochastic disaggregate models, these theories lead to 2 conclusions that are extremely important in formulating models of this type. First, disaggregate stochastic models of this type can be formulated with a relatively small number of variables required to achieve good predictions. Second, people do not have irrational or unquantifiable biases toward specific alternative choices.

Placed in the context of modal choice, this approach effectively states that an individual will choose a mode with a probability determined by trip considerations and his own scaling of the effectiveness of the alternatives for that trip purpose.

Thus, the stochastic model of modal choice may be considered as a translation of the theoretical elements of decision-making into operational terms. Based on the revealed preferences by travelers in their modal choices, the models distinguish between the attraction and disutility of the system characteristics and user characteristics that affect the preference scale of system attributes. More specifically, the models can incorporate a variety of system characteristics and, provided that adequate quantification can be achieved, may include attributes derived from attitudinal studies (29, 30, 31). These models have several properties that are of help in analyzing modal choice.

First, these models have greater predictive validity than conventional models because they are based on the behavior patterns of individuals rather than on statistically derived correlations in aggregate analysis.

A second property of these models is that they are based on the smallest element of the population—the individual. As such, the large variances attributed to problems of zoning or of aggregation of population attributes are eliminated (5, 32, 33, 34, 35). Thus, the predictions from the models must have much narrower confidence limits than those of aggregate models.

A third property, also stemming from the disaggregate approach, relates to the eventual aggregation that must be used for the models to be applied to large urban areas. Because the models are constructed from the smallest population elements, the level of aggregation can be determined from the models as the precision of measurement required to yield the desired predictive accuracy. In contrast to earlier modal-choice models, a stochastic disaggregate model is a deductive model in that it determines a priori the variables to be measured and the level of aggregation and the groupings for aggregation that are required for operation of the model.

A fourth property of stochastic disaggregate models is that they provide a basis for inferring the relative values that people place on various characteristics of the transportation systems. These values may be derived from an examination of the relative weights of each system characteristic on the choice process described by the model. The behavioral basis of the models requires that, by definition, the values so obtained be behaviorally consistent.

CURRENT STATE OF THE ART

The stochastic modal-choice models (see Appendix and 47), developed at present, have been built as binary-choice models by using a variety of statistical tools. These neither be transferred geographically nor readily subdivided; they are extremely sensitive to zoning; and the measurements of trip distances, particularly for short trips, are inaccurate because of the aggregation under which all trips are designated as originating or terminating at a point, the centroid of a zone. Also, these models are deterministic in the sense that they yield modal volumes rather than probabilities of using a particular mode. Deterministic models of this type have wide confidence limits statistically so that they are limited in their usefulness for explaining or predicting.

PRESENT RESEARCH ON MODAL-CHOICE MODELS

In an attempt to overcome some of the problems mentioned in the previous section, recent research has followed 2 directions. The first approach is an attempt to combine trip generation and modal-choice decisions in 1 model (18, 19, 20). A major conceptual problem, in the models developed from this approach, relates to the difficulty of establishing the theoretical structure for a decision-making process or situation. This is compounded when a number of decisions have to be made, some of which are contingent on and some independent of the others. None of the models so far proposed has addressed itself specifically to the elaboration of this multiple and simultaneous decision-making process.

Although these models are conceived only as generation and modal-choice models, to make them operational, and hence to make them even more complex, requires that trip distribution be included. This is necessary because a combination of a modal-choice model and generation model is not defined operationally because the specific trip interchange must be known before values can be obtained for the system charactertistics operating on modal choice and generation.

Finally, several problems are encountered in the estimation processes. Considerable difficulty exists in formalizing mathematically the complex decision-making processes already described. Attempts at doing this have not been conspicuously successful. The statistical reliability of the combined generation and distribution modal-choice model remains to be firmly established. This is due to the complexity of the total choice mechanism and the relative simplicity required for operational purposes as well as the aggregation bias. It is not surprising, therefore, that in a discussion of the statistical reliability of one of these models, the following conclusion was reached (21):

> The high level of residual error in estimating the total choice mechanism (as opposed to a single aspect) should be regarded as a danger signal by the planner. The result implies high uncertainty in our predictions of the effects of changes in the transportation system. When account is taken of sampling errors and errors in predicting independent variables, in addition to the generally low correlation statistics, it is clear that the uncertainty in predicting future origin and destination traffic movements is very great indeed. The planner must therefore be extremely cautious in his decisions and explicitly recognize that his evaluations are subject to this uncertainty.

The second approach to building new models of travel-mode choice is based on the application of theories of individual behavior in making choices and yields, initially, a disaggregate probabilistic model. However, unlike the first approach, these disaggregate behavioral models are conceived of as operating within the same model structure as the conventional UTP package of models.

The main advantage of this approach is that modal choice is analagous to the typical marketplace decision situation (22). The individual buyer, namely the traveler, has to choose between a number of goods or services according to their attributes and his set of preferences. It is felt that the present state of behavioral modeling permits relatively sound operational formulation of this choice process.

This approach represents a major change in emphasis in 2 respects: The models are disaggregate, and they attempt to model individual behavior on the basis of mode and user attributes (23, 24, 25, 26). At present, such models have not been developed specifically as a stage in a transportation study and therefore do not fit well in the tools are probit analysis, logit analysis, and discriminant analysis. These statistical techniques have been used because they seem, to some extent, to reflect the choice situation as it is perceived to exist by the transportation planner.

Four models have been developed by using the theory of discriminant analysis (24, 36, 37, 38). This theory hypothesizes that the total traveling population of a study area can be viewed as comprising two or more distinct subpopulations, divided on the basis of the modes they use. The task of discriminant analysis (39) in this case is to determine a function of user and system attributes that best discriminates between the subpopulations. All four of these models work from sets of binary choices; i.e., they identify a series of populations containing people with a binary choice and operate on these binary choices alone. Thus, the task is to determine a set of discriminant functions, D_{ij} (where D_{ij} is the discriminant function between mode i and mode j), that minimize the number of members of the population that will be misclassified (in terms of their choice of mode) by the model (Fig. 1).

Probit analysis (25, 40, 41) is a statistical technique originally derived in work on toxicology. It is based on the premise that, if members of a population are subjected to a stimulus that can range over an infinite scale, the frequency of responses to the stimulus (assuming that the response is a 0, 1 response, i.e., it either occurs or does not occur) will be normally distributed. Thus, if a cumulative plot of members of the population who have already responded is drawn against the value of the stimulus, the curve that results will be a normal sigmoid (S-shaped) curve (Fig. 2). This theory is applied to the modal-choice situation by assuming that the stimulus is made up of the relative disutilities of travel on 2 modes in a binary situation and of the characteristics of the user. The estimation problem becomes one of assigning coefficients, or weights, to the disutilities and user characteristics in the probit equation.

The last of the principal analytical techniques and one that has been used for this type of modeling is logit analysis (26, 42). In its simplest form, the linear logit model states mathematically that the probability of the occurrence of an event varies with respect to a function G(X) as a sigmoid curve called the logistic curve. This model may be written mathematically as

$$P_1 = \frac{1}{1 + e^{G(X)}}$$

which is identical to part of the discriminant analysis model, although it should be noted that the means of evaluating the function G(X) is very different in these 2 cases. This model is applied to modal choice by defining the event mentioned previously as being the choice of 1 mode in preference to the other.

It should be noted that, although probit and logit analysis are mathematically different and are based on dissimilar premises, operationally there is a considerable similarity in the results produced by the 2 techniques. Problems concerning which of the 3 techniques mentioned previously is most appropriate for the building of behavioral modal-choice models are discussed in more detail in the remainder of this paper.

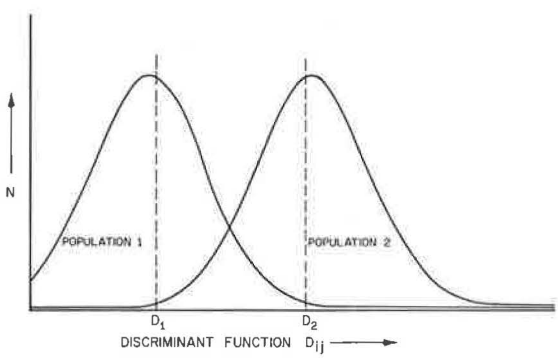

Figure 1. Frequency plot of values of the discriminant function in a binary population.

PROBLEM IDENTIFICATION

In the building of operational disaggregate stochastic models of modal choice, a number of problems are encountered. This section of the paper is concerned with identifying a number of these problems and with proposing possible strategies for solving the problems. Six problem areas are identified as requiring research to develop useful, operational models of modal choice.

The first problem area concerns the parameters needed to describe the transportation systems among which the traveler must make his choice. In particular, the inclusion of some measures, which represent comfort, convenience, and safety, seem desirable but present many problems in the framework of a quantitative model structure. The second problem area concerns the set of user characteristics to be included in the model and the form in which such characteristics should operate in the mathematical function.

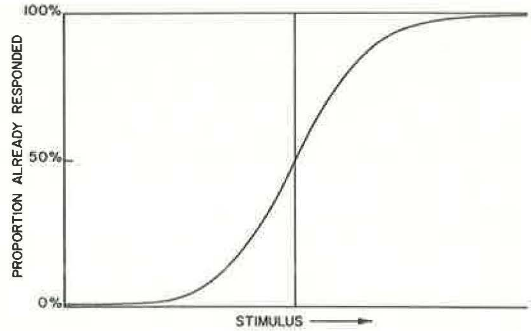

Figure 2. Cumulative plot of response to a varying stimulus.

Third, the various coefficients of the model are likely to depend on the value to be derived from the trip. The determination of a good set of trip classifications related to trip value is clearly needed for the development of these models of modal choice.

Fourth, frequent questions have been raised concerning what the appropriate values are for the system parameters—those perceived by the traveler, or those measured by an independent observer. Again, this represents a major problem area in developing disaggregate behavioral models.

The fifth problem area concerns temporal and geographic, or spatial, transferability. To develop models that are not restricted in application to specific locations and times of day requires an examination of possible dependencies between coefficient values and the dimensions of time and space and a determination of the means to handle such dependencies that are found to exist. Finally, problems are encountered in determining the ways to handle trip segmentation and a multiple-choice environment. Both of these problems are directly related to the mathematical structure of the model.

These are, in outline, the central problems that must be resolved to achieve operational disaggregate behavioral models of modal choice. Each of these problems is discussed in detail, and possible strategies for solution are indicated in the following sections.

DEVELOPMENT OF A BEHAVIORAL MODAL-CHOICE MODEL

Identification of System Variables

System variables can be classified as either exogenous or endogenous to the decision-maker. The exogenous system variables may include overall travel times, overall travel costs, and travel time reliability. This last refers to all those factors that intervene by adding delays or uncertainty in achieving trip goals. These would include segments of delay and uncertainty such as walking, waiting, transfer, and a built-in unreliability. This unreliability includes a component learned by the traveler from experience with schedule variance or traffic congestion and a component of unpredicted delays arising from system accidents (e.g., vehicle breakdown and weather).

It may be hypothesized that a detailed analysis of system unreliability is equivalent in fact to what is commonly known as convenience. Convenience is understood here as an exogenous property of the system reflecting the extent of impediments to travel and can be measured by the delays that the system imposes on the users and that increase the uncertainty or perceived unreliability of the system.

Safety is not considered to be an independent variable for modeling purposes. As far as it is an objective system attribute, it is already represented in the evaluation of the unpredictability referred to previously. Insofar as it is a projection of the individual anxiety of the traveler onto system characteristics, little additional explanatory power will be achieved by incorporating it.

The exogenous system variables can be treated in several ways with respect to the method of inclusion in a disaggregate behavioral modal-choice model. Most of the models developed in the past have used either ratios of costs and of times or differences of costs and of times. The use of ratios in a behavioral model implies that the decision-maker views time or cost differences on a relative scale, i.e. his decision would be affected to the same extent by a choice of travel times of 10 and 5 min as by a choice of 60 and 30 min. The use of differences, however, implies an absolute valuation of times and costs so that the choice between travel times of 10 and 5 min would now be equivalent to a choice between 60 and 55 min. A third alternative, which has not been examined in detail before, is to use differences relative to the total overall cost or time. This would imply that the choice of the decision-maker is influenced by the absolute value of the cost or time saving relative to the total outlay of cost or time that he must bear if he is going to make the trip. It is clear that this method of inclusion would give rise to significantly different values of the time and cost components of trips, particularly in the case of discretionary trips and of interurban movements where choice is between, for example, air and ground common carriers. Each of these alternatives may be examined both by scaling experiments and by their relative performance in each model in predicting modal choice.

The main endogenous system variable is comfort. This may be treated by carrying out a cross comparison among mode alternatives of their comfort characteristics. The characteristics to be examined would include the space for each passenger, shock and vibration, noise, privacy, and other variables relating to the physiological and psychological characteristics of movement systems. On the basis of available data on acceptable values of these characteristics to users, an interval scale might be developed that would allow measurement of differences among modes in terms of comfort. In addition, an attempt might be made to develop a psychometric ratio scale that, if successful, would generate a single value of comfort that could be used to evaluate any existing mode or a new technology. It should be emphasized that the weighting procedure, referred to earlier, of the comfort variables is fundamentally different from the treatment of comfort as a residual variable.

User Characteristics

When the behavior of individuals is considered in decision-making, it is desirable to consider their individual utility functions. Detailed consideration of these utility functions is not possible, however, so socioeconomic characteristics of the users are generally introduced instead. These characteristics serve as proxies to represent the average behavior of the individual decision-makers.

The user characteristics that are generally considered for inclusion in models of this type are income, age, sex, stage in the family life cycle, and car availability. For stochastic disaggregate models, these characteristics should refer, as far as possible, to the individual and not to the household. Experience of the use of these general categories of characteristics suggests that problems of collinearity may exist among several of the variables listed. This problem may be tackled by the use of techniques such as factor analysis, stepwise regression, and covariance analysis to attempt, as far as possible, to eliminate variables that do not add significantly to the explanatory power of the model.

Previous models of modal choice have largely introduced user characteristics as additive terms along with the system characteristics. This form of inclusion is effectively a behavioral assumption that the choice is made on the basis of system characteristics by themselves, with the addition of an individual bias. This bias is the additive value of the user characteristics included in the model. An alternative assumption appears to be more consistent with behavior theory; that is, the weights (coefficients) attached to each of the system characteristics are dependent on the individual (i.e., the user characteristics). In other words, this assumption implies that an individual bias exists on the importance of each system characteristic rather than on the final choice.

This form of inclusion can be carried out by subdividing the population, on which calibration is performed, into a number of classes representing ranges of each of the user characteristics. Models are then calibrated for each class of the population, and associative relationships are sought between variations in the coefficients of each system attribute and the user attribute values of each class. The extent to which subdivision of the population is possible will inevitably depend on the data sources available and the use to which the model will be put.

Trip Characteristics

When the values attached by each decision-maker to the system atrributes are examined, another source of variation can be hypothesized. This variation relates to the fact that travel can be regarded as a derived demand (42) that is required to permit another activity to be carried out. As such, it seems reasonable to hypothesize that the values of system attributes will be related to the value to be derived by the tripmaker from the activity that he will carry out at the end of his trip. Conventionally, attempts are not made to determine the value derived from an activity, but a proxy—the trip purpose—is used.

In a definition of the trip purposes for disaggregate behavioral models, 2 constraints have to be considered. The first of these is the constraint imposed on the inclusion of trip purposes by the available data. Data available at present are largely work-trip oriented, and, therefore, there is a need for a widening of the data base in this respect. In addition to this, a further constraint is imposed by a consideration of the definition of trip purposes that are currently used in most studies (44). This is an area in which considerable research is needed.

In addition to these principal problems, there are several further problem areas for which some assumptions are necessary so that a viable model formulation can proceed. These problems are outlined in the next section.

Values of System Characteristics

A consideration important in the formulation of a behavioral model is the relation between objective and subjective estimations by the traveler of the system characteristics. The difference between true and perceived values of, say, travel time or costs arise from 2 sources. One is inadequate information about, or experience with, alternative modes. With inadequate information, people will make choices by filling in the necessary judgments on a subjective basis. Obviously, this may bear little relation to objective reality, but it is still the basis for modal choice. The second is a bias that persists even with knowledge of alternatives. By definition, this bias is a stable preference function.

It is obvious that, for predictive purposes, the former process is most critical because it may be assumed that any effects of a stable preference function may be resolved by a simple linear transformation. In fact, model calibration achieves this. The problem caused by lack of information is that a priori there is no way of knowing how these deviations from objectivity are distributed nor at what rate learning modifies the subjective values to make them approach the objective ones. Ideally, if the distribution of subjective values around objective values of the system characteristics are normal, the errors will sum to 0. Alternatively, a consistent relationship between subjective and objective values may be able to be determined. These effects should show up as unexplained variance in the model that, if it were high, would be the basis of a recommendation for extensive analysis in this area.

Environmental Characteristics

The environmental characteristics are those characteristics that are independent of the system and user attributes and can be broadly defined as the temporal and spatial dimensions within which the modal-choice decision is made. The temporal dimension can be typified by the time of day when the trip is made. The time of day can be seen to affect the modal-choice decision process in 3 ways: It will be a partial determinant of system characteristics because of variations in congestion or loading, transit frequencies, and journey speeds and costs; it will also be a partial determinant of trip purpose; and probably the values of time savings in particular will vary with time of day in relation to the possible uses of such time savings.

Characteristics describing the spatial dimension appear to be necessary to allow the models to be transferable, in terms of their structure and parameters, over a range of urban areas. These characteristics would be constructed as central measures (i.e., 1 measure of each variable for an urban area) and would stand as proxies for the range of distances, costs, and the like that vary from urban area to urban area. Probable variables that would be used in this manner would be the size, residential density, and age of the city (12, 45).

The extent to which these characteristics can be incorporated in the models will depend on available data. Data restrictions that currently exist would not permit analysis of these problems because most of the available data refer to only 1 city. Similarly, the data restrictions to the morning work trip largely preclude detailed analysis of time of day at present. Again, however, there is a need for further data to assist analysis of this type.

Model Characteristics

Two basic problems need to be tackled in determining the specific form of the behavioral modal choice model. The first of these concerns the structure of trip-making. The majority of transit trips usually consists of 3 segments: access to the transit facility, line-haul, and egress to the final destination. For the automobile, the segments would be line-haul, parking, and egress to the final destination. The problem that has to be considered is how to treat these trip segments in the model. Several possible alternatives include a model based on the line-haul mode only (with average or best system characteristics assumed for collection and distribution), a model in which each possible combination of modes is treated as a separate mode, or an hierarchical set of models that determine the choices for each segment of the trip. These alternatives need to be examined in terms of the operational and conceptual requirements placed on the model.

The second problem concerns the range of choices to be considered in the models. Previous models have been developed as binary-choice models in which it is assumed that the trip-maker reduces his choice problem to a choice between 2 alternatives. The drawback to this approach is the difficulty of identifying which 2 modes represent the final choice of each individual. Alternatively, the models could be developed as multinomial models in which the choices between all possible modes available to the trip-maker are incorporated simultaneously. A theoretical model structure has been developed (42, 46, 48) for modeling a multinomial situation, but its properties, in terms of sensitivities in particular, have not been investigated.

Research is needed here in 2 areas. First, an investigation of the use of the multinomial model is required. Second, research is required to determine the problems involved in the collapse of an individual's choice to 2 alternatives.

Conclusions

Several conclusions can be drawn from the foregoing discussion concerning disaggregate, stochastic, behavioral models of travel-mode choice. First, it is clear that these models can offer several advantages over conventional aggregate deterministic models in estimating and forecasting modal shares. These advantages are principally that the use of choice theory, applied at an initially totally disaggregate level, will lead to models that are spatially and temporally more stable than conventional models. In particular, this leads to a much greater confidence in the resulting forecasts from the models, when used to indicate the likely consequences of particular policies and investment decisions.

Second, although the existing models of this type are restricted both in the type of trips and the variables considered for model calibration, the developmental problems that will be encountered in extending their applicability and usefulness appear to be generally straightforward and readily amenable to solution. In fact, the major problems reside in data collection for tackling these various model developments, and past experience with these models suggests that the data problems are by no means insurmountable.

The third conclusion concerns the information that these models can yield concerning traveler-evaluation of system characteristics. The models already developed have been used to obtain monetary values for the value of travel time. As other system characteristics are explicitly incorporated in the models, other comparative values can also be determined. These values may have considerable use in assisting decision-making on alternative investments in public transport, among other uses. Here it may help to determine whether travelers would prefer more frequent service with higher fares or less frequent service and lower fares, whether they would prefer faster travel or air-conditioning, and so on.

Finally, the successful development of disaggregate, stochastic, behavioral models of modal choice will open up considerable potentials for developing models of the remainder of the travel-demand process on the same basis (2). Considerable understanding of the mechanism of traveler choices will accrue from the modal-choice models, and this understanding can readily be applied to other choice situations with a consequent increase in the accuracy and reliability of travel forecasts.

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APPENDIX

CURRENT STATE OF THE ART

A number of models of modal choice that have been developed, recently, are based on the rationale of disaggregate, behavioral modeling. These models are summarized here. The models may be classified according to the mathematical technique used, i.e., discriminant, probit, or logit analysis.

The 4 discriminant models, referred to in the paper were developed by Quarmby, Mongini, McGillivray, and the Illinois Institute of Technology Research Institute. Quarmby (24) and McGillivray (37) each propose a discriminant function that effectively comprises system characteristics and user characteristics, although Quarmby used differences in system characteristics and McGillivray used ratios of system characteristics. Both models added user characteristics as linear terms in the discriminant function. Mongini (36) used just time differences in his pilot study but suggested that other elements of the total disutility of travel should be incorporated. IIT Research Institute (38) used a series of associative and correlation tests to determine variables to be included, and this resulted in a total of 39 variables describing user and system characteristics in various ways.

The use of a discriminant analysis results in the formulation of a discriminant function that, for the models developed by Quarmby, McGillivray, Mongini, and IIT Research Institute, may be generalized as

$$D_{ij} = F(X_{ki}, X_{kj}) + G(Y_m)$$

where X_{ki}, X_{kj} are the values of the kth attribute of modes i and j respectively; Y_m are the user attributes; $G(Y_m)$ is a function $\sum_{m=1}^{b} \beta_m Y_m$; $F(X_{ki}, X_{kj})$ is either a function $F(X_{ki}, X_{kj}) = \sum_{k=1}^{n} a_k (X_{ki} - K_{kj})$ or a function $F(X_{ki}, X_{kj}) = \sum_{k=1}^{n} a_k (X_{ki}/X_{kj})$.

The model is used as follows: If D_{ij} is less than a value D_1 (Fig. 1), the individual is classified as a user of mode 1; and, if D_{ij} is greater than a value D_2, he is classified as a user of mode 2. If D_{ij} lies between D_1 and D_2, the probability that the individual is a user of mode 1 can be shown to be

$$P = \frac{1}{1 + e^{D_{ij}}}$$

so that the resulting modal-choice model could be written as

$$P_1 = \begin{cases} 1 & D_{ij} < D_1 \\ 1/(1 + e)^{D_{ij}} & D_1 < D_{ij} < D_2 \\ 0 & D_{ij} > D_2 \end{cases}$$

where P_1 is the probability that an individual will choose mode 1.

Both Lisco (25) and Lave (41) used probit analysis as the basis of the calibration of of modal-choice model. Using this theory, Lisco and Lave each proposed a probit equation of the following form:

$$Y = \sum_{k=1}^{m} [\alpha_k (X_{1k} - X_{2k})] + \sum_{\ell=1}^{n} [\beta_\ell (Y_\ell)]$$

where the X's and Y's are as defined for discriminant analysis.

The system characteristics in both cases include travel costs and travel times, and the user characteristics include family size, income, sex, and age in Lisco's model and sex and age in Lave's model. Lave also attempted to include a measure of comfort in his model.

The probit equation is used for modal choice in the following manner: The value of the probit, Y, represents the number of the standard deviations away from the mean of a normal distribution. If standard statistical tables of the cumulative normal distribution are used, the probability, corresponding to this number of standard deviations from the mean, can be determined. This probability represents the probability that the individual being considered will choose mode 1.

The last of the 3 analytical techniques is logit analysis. This technique was used by Stopher (26). The modal-choice model that he developed used 2 system characteristics—cost and time—and one user characteristic—income—in the following form:

$$G(x) = \alpha_1(c_1 - c_2) + \alpha_2(t_1 - t_2) + \alpha_3$$

where α_1, α_2, and α_3 are each a function of income, and the c's and t's are the costs and times of travel by the 2 modes considered.

When the function G (X) has been calibrated by determining the values of the α's, the function is substituted in the equation of the logit curve, and p_1 is then the probability that an individual will choose mode 1.

Apart from the models described here, a number of additional models have been developed, many of them as a basis of further experimentation with the techniques. However, the models described here are sufficient to indicate the basic types of models that have been developed by using the disaggregate-behavioral approach.