tual use, intended frequency of use (indicating degree of intention to use) was found to be a significant determinant.

3. The perception of relative modal convenience was found to be a dominant factor in forming both intentions and actual choices to use transit, and its perception was more stable over time than were the perceptions of other level-of-service measures.

From a practical standpoint, perhaps the single most important development of the study was the simplicity with which the attitudinal variables were defined to produce effective explanatory models. All of the feelings and perceptions variables were constructed as 0,1 variables. Moreover, the 0,1 perceptions variables were found to have superior explanatory power over the more sophisticated variable definitions that were attempted by using relative weights or additional perceptual information. The implication is that the analysis method used here can produce useful results while being relatively easy to apply.

Although the models developed in this study are limited in their application as forecasting tools--primarily because of the categorical nature of the variables and the lack of variables based on objective data that can be transferred from one site to another--they can be used effectively as policy tools in planning and marketing new transportation services. For example, a planner who wished to market a new transit service could ascertain from a behavioral-intentions model that perhaps convenience, enjoyment, anticar sentiments, and being female were important factors in his or her marketing effort to build initial support for the service. Once the service was implemented, the marketing effort could focus more heavily on the convenience of the service, which was found to be the major determinant of actual use.

Clearly, these models need to be developed and tested further to substantiate their validity and usefulness. Similar data sets and models need to be collected and estimated for other sites and the results compared with those reported here. Similar models should also be developed by using objective data and be compared with the attitudinal-based models and evaluated with respect to model cost-effectiveness. Finally, work is needed in the area of attitude formation to gain a greater understanding of the factors that influence variations in attitudes (e.g., across time and individual travelers). Such knowledge would enable attitude changes to be controlled for in the models and make the models more useful for prediction purposes.

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Understanding the Effect of Transit Service Reliability on Work-Travel Behavior

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Research directed at understanding the impact of transit service reliability on work-travel behavior is described. The research focuses on the impact of service reliability on commuter decisions of modal choice and trip departure time. By working with the hypothesis that service reliability is an important attribute in explaining departure time and modal choice, measures of service reliability (tied in many cases to work-arrival-time considerations) are proposed that capture the impact of service reliability on work-travel decisions. The theory is subsequently tested empirically through the estimation of departure-time and modal-choice models by using data collected in the San Francisco Bay Area. Several interesting results emerged from the research effort. First, arrival-time

considerations have an impact on departure-time choice and on modal-choice decisions as well. Second, the arrival-time variables are not highly correlated with existing explanatory variables, which implies that existing travel demand models may not have biased coefficients but will still yield inconsistent forecasts where policy changes alter existing correlations between arrival-time conditions and independent variables in existing models. Finally, the departure-time and modal-choice decisions of commuters appear to be interrelated in a way that suggests that the problem should be structured as a nested rather than a joint choice. The implications of these results and research contributions are discussed, and directions for further research are proposed.

In recent years, increased attention has been focused on the importance of service reliability to the efficiency and attractiveness of transit operations. For the purpose of this research, service reliability is viewed as the variability of service attributes that influence the decisions of travelers and transportation operators. Since the service attribute most often associated with reliability is travel time (wait and in-vehicle time), service reliability can be considered as the travel-time uncertainty for a given trip caused by the variation in travel times experienced in day-to-day travel.

Although it is becoming apparent that service reliability is crucial in influencing both the demand for transit and the net cost of providing transit service (1), little research has been directed at understanding the effects of service reliability on traveler behavior and operator performance. The research described in this paper focuses on understanding the effect of service reliability on traveler behavior. Since commuters constitute the largest single group of travelers (and service reliability is hypothesized to have its most significant impact on this class of travelers), this study is restricted to work-travel behavior. Because work-trip frequency and destination are fixed in the short run, the analysis reduces to a study of the effect of service reliability on commuters' decisions of modal choice and trip departure time.

In developing an understanding of the impact of service reliability on work-travel behavior, a particular objective of this research is to estimate models that can explain the effects of service reliability on modal-choice and departure-time behavior. This would allow planners to conduct policy analyses of how service-reliability strategies affect modal-choice and departure-time decisions, predict peaking responses to service changes, and determine the trade-offs between policies directed at improving service reliability and those designed to improve other attributes of the system.

TRAVELERS' ATTITUDES ABOUT RELIABILITY

Several studies of the preferences of actual and potential transit users have been conducted by transportation planners in efforts to improve transit service, to evaluate demonstrations, and to formulate mathematical demand models. These studies point to the importance that travelers place on reliable transportation services. Reliability is typically associated with the attribute "arriving at the intended time" or "arriving when planned".

The survey results show arriving at the intended time to be among the most important service attributes for all travelers under a variety of travel conditions. For commuters its importance is paramount (2-4). For both work and nonwork trips, arriving at the intended time is considered more important than average time and cost (2), which are generally thought to be the dominant service attributes that affect demand. This result is also apparent in studying users of particular modes (5-8).

It should be recognized that, although the results of these surveys identify the importance of reliability-related attributes to the traveler, they do not provide data from which to assess the impacts of these attributes on traveler decision making. Thus, although it is a significant finding that travelers rank reliability-related attributes as extremely important, the survey results are limited in that they identify the need to establish a consistent set of reliability measures and analyze the impact of service reliability on travel behavior but are insufficient to provide an accurate assessment of this relation.

PREVIOUS RESEARCH

In the limited empirical work that has been directed at understanding the impact of service reliability on work-travel behavior, the departure-time decision has been modeled as conditional on modal choice, and the impact of service reliability has been examined separately for each decision level.

Early attempts to include objective measures of service reliability in modal-choice models ran into difficulty because of problems encountered in collecting accurate data (9). The inclusion of scaled reliability variables in modal-choice models has resulted in statistically significant coefficients for the reliability variables and has improved the predictive power of the models (3,10). However, the use of scaled variables poses serious questions about the validity of transferring the model for forecasting in other areas and also makes it difficult to evaluate policies of reliability improvement and to measure trade-offs of reliability investment versus investment in other transit improvement strategies. Since objective measures are likely to be monotonically related to scaled measures, past research provides motivation for developing relevant objective measures of service reliability and for measuring their impact on work-travel decisions.

Departure-time research has examined more closely the trade-off between travel times and work arrival times. Empirical work has been restricted primarily to automobile travelers, but important advances have been made in (a) the finding that travel-time uncertainty affects the probability of late arrival, (b) differentiation between traveler sensitivities to early and late arrival at work, and (c) recognition of the impact of work arrival flexibility and occupation on perceived trade-offs between travel time and schedule delay (11-12). (Schedule delay is defined here as the difference between actual arrival time and official work start time.)

Despite these accomplishments, there remain several obstacles that must be overcome. Although the significance of the trade-off between mean travel time and work arrival time has been demonstrated to some degree, the effect of travel-time uncertainty has not been completely considered, particularly in relation to traveler sensitivities to early and late arrivals that are caused by uncertainty in travel times. In addition, the potential interdependency of the decisions on modal choice and departure time has been virtually ignored. Finally, past research has been restricted primarily to a study of automobile travelers. The effect of service reliability on transit use and user departure-time decisions has not been examined.

This research effort was aimed at extending the study of service reliability and work-travel behavior by considering the interdependencies of the mode and departure-time decisions, explicitly accounting for travel-time uncertainty in these travel decisions, improving the definition of perceived loss associated with varying arrival times, and expanding the choice set to include a study of automobile, transit, and carpool commuters.

THEORY OF ROLE OF SERVICE RELIABILITY IN CHOICE OF MODE AND DEPARTURE TIME

For a given mode m and departure time d, each traveler will experience a particular travel-time distribution for his or her commute. Assuming that a commuter leaves home to travel to work at roughly the same time each day, this travel-time distribution translates directly to an arrival-time distribution at work. (The study of the commuting trip was restricted to a study of home-to-work travel only, partly because of a lack of available data on the return trip.) If we define T as the traveler's mean arrival time at work and T* as the traveler's official work start time, then a typical arrival-time distribution for a given mode and departure time might be similar to the distribution shown in Figure 1, where $F_m(t|d)$ is the probability of arriving at time t given departure time d and mode m. The figure suggests that individual commuters generally choose to arrive most of the time at or before their official work start time and usually do arrive sometime before the official start time.

Figure 1 is just an example of an individual's possible arrival-time distribution; different commuters will experience different arrival-time distributions. There would clearly be a different distribution for every combination of mode and departure time facing an individual, although it is possible that, whereas the parameters of a distribution may change, the distributional form may not vary.

In current models of travel behavior (which typically use the concept of utility theory and linearity in the parameters of the utility function in defining the impacts of service attributes), only a measure of mean travel time is included in the utility expression. Although it is apparent that there may be varying expected arrival times at work and a great deal of uncertainty about that arrival time, the specification used in current models of travel behavior does not explicitly account for either of these effects and their implications for the traveler. By not including measures that consider arrival-time implications, current models implicitly assume that travelers arrive at work when they want to and are "risk neutral" toward uncertainty in their arrival times. This implies that, for equivalent travel times, arriving at work extremely late or extremely early with equal probability is valued the same as arriving on time with certainty, which is clearly unrealistic for the majority of commuters. It also implies that travelers are indifferent as to alternatives that have the same mean arrival time but varying arrival-time distributions.

The question that arises is, Assuming that service reliability is an important input to the traveler decision-making process, how can we model this effect on commuter choice?

An appealing approach is to relate the arrival-time uncertainty to the commuter's perceived loss associated with different arrival times, since this would be a way to represent the importance of arriving at the intended time. To represent perceived loss, the notion of an arrival-time loss function is introduced.

Figure 2 shows a hypothetical arrival-time loss function l(t) (loss associated with arrival at time t, expressed in units of utility), which is based on the premise that commuters are most satisfied when they arrive at work close to their official work start time. As the commuter arrives increasingly later than the official work start time, the magnitude of the perceived loss increases, representing employment penalties that may be associated with tardiness (e.g., loss in pay, poor reputation, and negative impact on promotion). It is presumed that the penalties for being a few minutes late will be far less severe than those for arriving 15-30 min late.

Perceived loss is hypothesized to increase with early arrival as well, since the commuter could have used the extra time as leisure time at home, which is likely to be valued more than being at the office. It is important to note, however, that the magnitude of the slope of the loss function for lateness is expected to be larger than that for earliness, reflecting perceived penalties for late arrival at work that are greater than perceived penalties for not maximizing leisure time at home. It is assumed that overtime benefits, such as compensatory pay, are not available.

The loss function in Figure 2 represents just one possible functional form. While each individual has only one mean arrival-time loss function, there is reason to believe that the parameters (and form) of the loss function will vary according to each individual's occupation (i.e., clerical, management,

Figure 1. Typical commuter arrival-time distribution for a given mode and departure time.

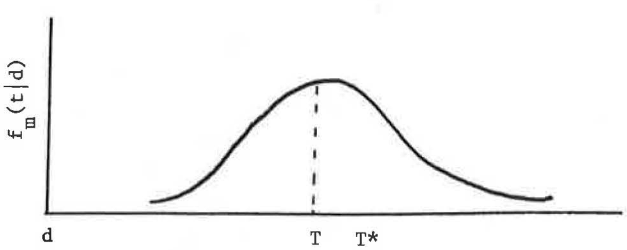
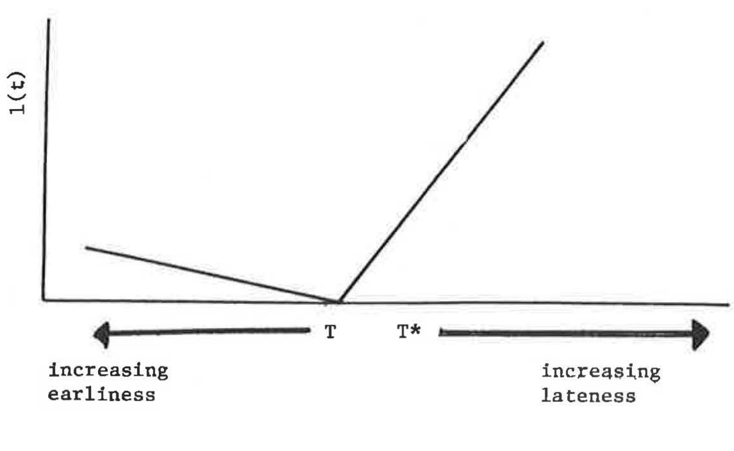


Figure 2. Arrival-time loss function.



etc.) and work flexibility. For example, a member of the clerical staff on hourly wages will have a much higher perceived loss for late arrival than a manager who works for a firm that operates a flexible-work-hours policy.

The effect of service reliability on the process of modal and departure-time choice can be defined as the expected loss for each choice alternative by using a commuter arrival-time loss function and by representing the uncertainty of arrival time by a probability density function of the arrival-time distribution. Assuming that the modal-choice decision has been resolved at the time at which a departure-time decision is made (although the choices may be interdependent), the choice of departure time can be structured conditional on modal choice being fixed. The impact of service reliability on departure time could then be defined as follows:

$$E(l|d,m) = \int_d^\infty f_m(t|d)l(t)dt \quad (1)$$

where $l(t)$ is the loss associated with arrival at time t. The expected arrival-time loss could be included in the utility specification for departure-time choice, which would result in a new departure-time utility specification.

Because of the assumed sequential structure of the problem of modal and departure-time choice, output from the departure-time model forms inputs to the modal-choice model. The information required at the modal-choice level is the optimal departure time for each mode, since travelers presumably make modal-choice decisions on the basis that they will choose to depart at the time that maximizes their departure-time utility for each mode being considered.

For the logit model form (which is used in this research), the optimal departure-utility inclusive terms to be input in the modal-choice model are derived from the departure-time model and can be expressed as follows (13):

$$D_m{}^* = \underset{d=1,I}{\mathrm{Max}}\, U_{d|m} = \log\left[\sum_{i=1}^{I} e^{U_{i|m}}\right] \quad (2)$$

where I is the number of alternative departure-time choices and $U_{i|m}$ is the utility for departure time i given mode m.

It should be noted that, although D* includes the effect of service reliability on work-travel time, there may be cases where commuters are sensitive to travel-time uncertainty even though the expected loss associated with arrival time is quite low. This situation might arise in the case of a traveler who likes to be in control of his or her own schedule. For this type of person, not knowing when the vehicle will arrive at the destination may be very upsetting, even though there is nothing pressing when the traveler reaches his or her destination (14,15). Furthermore, traveler exposure to infrequent but excessively long delays may also affect modal-choice decisions. These effects are represented as separate modal-reliability attributes.

The previous discussion has implications for the validity of existing models of work-travel behavior. An obvious deficiency of current models is that they do not explicitly account for service reliability (and other arrival-time considerations) and hence are clearly not sensitive to policies directed at improving service reliability. For example, if a federal agency is considering sponsoring a program to improve service reliability, there is no existing way of quantifying the expected benefits of such a program or the cost-effectiveness of supporting service-reliability strategies as opposed to fare programs or programs designed to improve mean vehicle speeds.

The omission of service-reliability variables, however, may affect more than just the availability of an analytic tool sensitive to service-reliability policy. When reliability-related variables are omitted, it is possible that the coefficient estimates of other independent variables in the utility expression may differ asymptotically from their true values because of their correlation with omitted reliability attributes (16). If this is the case, when the omitted model is used in forecasting, biases may be present that affect the accuracy of the forecast.

METHODOLOGY

Based on a review of previous research, and through the design and implementation of additional analyses, the final analysis methodology was formulated. A multistage methodology was defined in which examination of service information and loss-function analysis combined to form arrival-time variables that included reliability effects and that, in turn, were studied in the estimation of a departure-time model. Results from the departure-time model were then used in the estimation of the modal-choice model.

A sequential modeling structure was used in which departure-time choice was conditional on modal choice. Separate models were estimated for modal and departure-time choice. This structure was selected because of a belief that the decisions are interdependent in that the departure-time decision is made conditional on a modal-choice decision having been reached.

Departure time was modeled as a continuous choice by using a logit model formulation. Since alternative departure times may not be free of the independence of irrelevant alternatives (IIA) assumption implicit in logit, diagnostic tests of IIA violation were conducted. Multinomial logit was also used to estimate discrete alternatives of modal choice; one would expect there to be less correlation between error terms of the alternative modes than in the case of departure-time choice, although diagnostic tests of IIA violation were conducted on the modal-choice model as well.

The range of departure-time choice was such that expected arrival times varied from 42.5 min earlier than the official work start time to 17.5 min later than the official work start time, to conform with available departure-time data. Modal-choice alternatives were restricted to single-occupant automobile, transit, and carpool.

The Urban Travel Demand Forecasting Project (UTDFP) data set collected in the San Francisco Bay Area was selected for this research effort, primarily because it contains detailed level-of-service data (network-computed, which may introduce some bias) for each individual for various modes at different peak-period departure times, in addition to more traditional travel-behavior and socioeconomic data. The UTDFP sample of 991 observations was reduced for this study by omitting the following:

1. Park-and-ride users (of which there were few),
2. Observations where the respondent's official work hours begin outside the morning peak (because of an interest in studying the morning peak period only),
3. Nonworkers (because this is a study of work travel only) and part-time workers (because they would be facing off-peak return-trip conditions for which data did not exist),
4. Observations where the respondent has an ex-

pected work arrival time more than 40 min earlier or more than 15 min later than his or her official work start time (to eliminate commuters who have regular nonwork activities that result in their extreme arrival-time behavior), and

5. Observations for which data were incomplete.

This resulted in an estimation sample of 425 respondents.

A generalized loss function was estimated by using a small sample of respondents (17). Many of the travel-time data used in this research were derived from previous studies of automobile, transit, and carpool travel or were assumed because of the lack of available literature on the subject. In many cases, previous studies were based on data that did not adequately represent day-to-day service levels experienced by travelers. As a result, the data used in this research suffer from these problems, and a future research priority should be to collect better data on reliability.

Departure-Time Model

The departure-time period of study involved expected arrival times that ranged from 42.5 min earlier than the official work start time to an expected arrival 17.5 min later than the official work start time. Twelve departure-time alternatives were defined for the departure-time model. Each alternative represented a 5-min departure-time interval, and the data input for each alternative represented a discrete approximation of departure attributes for the continuous interval. Since the discrete observation for each interval consisted of information at the mean point of the interval, 12 discrete alternatives were defined as follows: 40E = departure such that the expected arrival is 37.5-42.5 min earlier than the official work start time, 35E = departure such that the expected arrival is 32.5-37.5 min earlier than the official work start time, etc., to 15L = departure such that the expected arrival is 12.5-17.5 min later than the official work start time. It was assumed that the frequency of transit service was sufficiently high during the peak period that transit users were faced with the full set of alternative choices. In cases where headways are long, the departure-time choices of transit users can become somewhat discontinuous.

A two-phase approach was used to select the most appropriate departure-time model. The initial phase consisted of selecting variables that, a priori, made intuitive sense as explanatory variables of departure time. These variables are defined below:

TIME = total travel time;
EARLOSS = early-arrival expected loss;
LATELOSS = late-arrival expected loss;
FLEXON = 1 if can be late to work (on-time alternative), 0 otherwise;
FLEXLATE = 1 if can be late to work (late alternatives), 0 otherwise;
ADUM = 1 if automobile drive alone is chosen mode, 0 otherwise;
BDUM = 1 if transit is chosen mode, 0 otherwise;
BRIDGE = 1 if transit user who crosses Bay Bridge to get to work, 0 otherwise;
INCOME = 1 if annual earnings \$5000 or less (1972 dollars), 0 otherwise;
AGE = 1 if over 50 years of age, 0 otherwise;
OCC1 = 1 if occupation is professional/technical or management/administration (extremely early alternatives), 0 otherwise;
OCC2 = 1 if occupation is professional/technical or management/administration (slightly early alternatives), 0 otherwise;
ONTIME = 1 if arrival between 2.5 min before and 2.5 min after official work start time, 0 otherwise;
EARLY1 = 1 if arrival earlier than 17.5 min before official work start time, 0 otherwise;
EARLY2 = 1 if arrival between 17.5 and 2.5 min early, 0 otherwise;
LATE1 = 1 if arrival between 2.5 and 7.5 min after official work start time, 0 otherwise; and
LATE2 = 1 if arrival between 7.5 and 12.5 min after official work start time, 0 otherwise.

The variables were generically specified and were introduced one at a time into the departure-time specification. For the addition of each new variable, a logit model was estimated, and the results were examined for statistical significance, proper signs, and the possibility of different independent variables explaining similar effects in the model (by comparing the magnitude and statistical significance of the suspected variables when both were included in the same specification). This process was repeated several times until all variables had been considered. During the initial phase, variables were only entered into alternatives where, a priori, one could justify their presence. A number of constants were also specified in the model to represent omitted effects. Because of the size of the departure-time choice set, departure-time alternatives were assigned group constants.

In the second phase, the variables in the final phase 1 model were individually tested in alternative specifications in an effort to refine the model specification. The "best" departure-time model was selected after the phase 2 analysis.

Tables 1 and 2 give the selected specification and estimation results for the departure-time model. All of the independent variables have the expected sign and are significant (t-statistic with an absolute value of ≥ 1) with the exception of some of the constants.

It was found that the arrival-time variables, EARLOSS and LATELOSS, have significant coefficients and appear to lend additional explanatory power to the departure-time model. Since the arrival-time variables consist of loss derived from arriving at work at a particular time and the uncertainty of arrival about that time, the estimation results imply that the implications of when the traveler will arrive at work and the uncertainty associated with it, as well as the perceived penalties for arriving about that particular time, are a departure-time consideration. However, in separate tests it was found that the effect of loss derived from arrival-time considerations consists primarily of loss derived from arriving at a particular time and much less so from the uncertainty of arrival about that time. This result is somewhat surprising but may perhaps be attributable to the quality of the data used in estimation (leading to lack of variation in the reliability data) or methodological problems rather than an indication that travel-time uncertainty is truly of marginal importance.

A further step in the departure-time research was to compare models estimated with and without the reliability-related variables, EARLOSS and LATELOSS. The estimation results for the model from which reliability-related variables were omitted appear in Table 3 and were compared with the results for the selected model (Table 2).

Table 1. Definition of alternatives for selected departure-time model.

Variable	40E	35E	30E	25E	20E	15E	10E	5E	On Time	5L	10L	15L
TIME	X	X	X	X	X	X	X	X	X	X	X	X
EARLOSS	X	X	X	X	X	X	X	X	X	X	X	X
LATELOSS	X	X	X	X	X	X	X	X	X	X	X	X
FLEXON									X			
FLEXLATE										X	X	X
ADUM									X			
BDUM	X	X	X	X	X							
BRIDGE	X	X	X	X	X	X	X	X				
INCOME						X	X	X	X			
AGE	X	X	X	X	X	X	X	X				
OCC1	X	X	X	X	X							
OCC2						X	X	X				
ONTIME									X			
EARLY1	X	X	X	X	X							
EARLY2						X	X	X				
LATE1										X		
LATE2											X	

Note: X denotes that the variable listed in the stub column of the table is entered into the utility for the alternative listed at the top of the table.

Table 2. Estimation results for selected departure-time model.

Variable	Coefficient Estimate	Asymptotic Standard Error	Asymptotic t-Statistic
TIME	-0.041	0.032	-1.279
EARLOSS	-3.168	2.296	-1.380
LATELOSS	-25.728	23.411	-1.099
FLEXON	1.084	0.227	4.780
FLEXLATE	3.162	0.756	4.184
ADUM	0.496	0.269	1.846
BDUM	-0.794	0.319	-2.487
BRIDGE	2.764	1.063	2.600
INCOME	2.042	1.032	1.979
AGE	1.104	0.308	3.583
OCC1	-0.492	0.277	-1.774
OCC2	-0.575	0.250	-2.304
ONTIME	-3.606	6.894	-0.523
EARLY1	-6.483	8.734	-0.742
EARLY2	-5.874	8.717	-0.674
LATE1	-5.211	4.018	-1.300
LATE2	-2.880	2.062	-1.397

Note: Log likelihood = -820.974, L(constants) = -875.846, L(0) = -1056.082, number of observations = 425, and number of cases = 5100.

Table 3. Results for model from which reliability-related variables were omitted.

Variable	Coefficient Estimate	Asymptotic Standard Error	Asymptotic t-Statistic
TIME	-0.039	0.031	-1.271
FLEXON	1.072	0.226	4.736
FLEXLATE	3.160	0.756	4.181
ADUM	0.648	0.224	2.900
BDUM	-0.724	0.314	-2.304
BRIDGE	2.774	1.062	2.612
INCOME	2.055	1.032	1.991
AGE	1.090	0.308	3.543
OCC1	-0.467	0.277	-1.690
OCC2	-0.564	0.249	-2.261
ONTIME	3.741	0.757	4.938
EARLY1	2.647	0.754	3.510
EARLY2	3.444	0.748	4.605
LATE1	-0.851	0.533	-1.597
LATE2	-0.683	0.500	-1.365

Note: Log likelihood = -822.719, L(0) = -1056.082, number of observations = 425, and number of cases = 5100.

The major difference between the two models is the values of the constants. There is very little change in the coefficient value of the other explanatory variables. What is particularly interesting is that the coefficient for mean travel time changes by only 5 percent. These results present a strong argument that the arrival-time variables in the departure-time model are not highly correlated with variables used in existing models and that most of the implications of on-time arrival and related uncertainty are omitted effects absorbed into constants in existing models. The implications of this finding are that explanatory variables in existing models may not have overly biased variable coefficients because of the omission of arrival-time variables, but existing models will still provide inconsistent forecasts for any policy changes that alter the existing correlation between arrival time and variables in existing models. (It is also interesting to note that a χ^2 test conducted on the hypothesis that the loss variables have coefficients equal to zero could not be rejected at the 0.05 level.)

Statistical tests were conducted to see whether the selected departure-time model differed significantly from a uniform probability departure-time model or from a departure-time model consisting of only constants in the specification. For both the uniform probability model and the model consisting of only the constants, the hypothesis that the model is the same as the selected departure-time model is easily rejected at the 0.05 level, which implies that the explanatory variables are adding statistical significance to the model.

A validation test was also conducted on subsamples of the sample used for model estimation to determine whether the selected model was properly specified. The sample was separated into single-occupant-automobile, transit, and carpool users, and chosen departure times were predicted for each modal group by using the departure-time models. The predictions were obtained by applying the model to each individual in the sample for the purposes of predicting individual probabilities of selecting particular departure times. These results were compared with actual chosen departure times reported in the UTDFP data set and did validate the reasonableness of a selected departure-time model.

Diagnostic tests based on conditional choice (18) were also conducted on the selected departure-time model to determine whether it violated the underlying logit assumption of IIA. The results indicated that use of the logit form to estimate the selected departure-time model cannot be rejected.

Table 4. Definition of alternatives for modal-choice model.

Variable	Automobile	Transit	Carpool
ACON	X		
BCON		X	
COST/WAGE	X	X	X
$\hat{D}$*	X	X	X
SEX	X		
FLEXARR		X	
DENSITY		X	X
CLOTRANS		X	
AUTDRA	X		
AUTDRC			X
AUTWKA	X		
AUTWKC			X
BAY		X	
HOMELOC2		X	
HOMELOC3			X
HEADWAY		X	

Note: X denotes that the variable listed in the stub column of the table is entered into the utility for the modal alternative listed at the top of the table.

Table 5. Estimation results for modal-choice model.

Variable	Coefficient Estimate	Asymptotic Standard Error	Asymptotic t-Statistic
ACON	-0.804	0.659	-1.220
BCON	2.875	0.656	4.378
COST/WAGE	-0.044	0.020	-2.230
D*	0.572	0.292	1.962
SEX	0.513	0.261	1.967
FLEXARR	0.480	0.332	1.448
DENSITY	0.003	0.001	3.071
CLOTRANS	0.874	0.432	2.021
AUTDRA	3.248	0.812	4.000
AUTDRC	1.267	0.680	1.863
AUTWKA	1.432	0.530	2.704
AUTWKC	1.375	0.523	2.629
BAY	1.014	0.532	1.905
HOMELOC2	0.981	0.407	2.411
HOMELOC3	0.386	0.263	1.468
HEADWAY	-0.104	0.037	-2.851

Note: Log likelihood = -299.429, L(constants) = -400.8, L(0) = -450.61, number of observations = 425, and number of cases = 1235.

Modal-Choice Model

A multinomial logit model of modal choice was estimated for the alternatives of single-occupant automobile, transit, and carpool. As in the case of the departure-time model, selection of the "best" modal-choice model specification was based on intuitive reasoning, the coefficients having the expected sign, the statistical significance of the coefficients (in terms of t-statistics), and the overall statistical fit of the model (in terms of log likelihood).

The independent variables used in the selected modal-choice model are defined below:

ACON = 1 if automobile drive alone, 0 otherwise;
BCON = 1 if transit, 0 otherwise;
COST/WAGE = total cost/after-tax wage rate;
$\hat{D}$* = log of the denominator of the estimated departure-time model;
SEX = 1 if male, 0 if female;
FLEXARR = 1 if can be late to work, 0 otherwise;
DENSITY = employment density of work location;
CLOTRANS = 1 if choosing a house close to transportation was very important, 0 otherwise;
AUTDRA = automobiles per licensed driver (drive alone);
AUTDRC = automobiles per licensed driver (carpool);
AUTWKA = automobiles per worker (drive alone);
AUTWKC = automobiles per worker (carpool);
BAY = 1 if cross Bay Bridge to work, 0 otherwise;
HOMELOC2 = 1 if home location is central business district (CBD) (transit), 0 otherwise;
HOMELOC3 = 1 if home location is CBD (carpool), 0 otherwise; and
HEADWAY = peak transit headway.

The estimation results for the model are given in Tables 4 and 5. All of the estimated coefficients have the expected signs, and all are statistically significant.

Statistical tests were conducted to see whether the selected modal-choice model differed significantly from a uniform probability modal-choice model or from a choice model consisting of only the constants in the specification. For both the uniform probability model and the model consisting of only the constants, the hypothesis that the reduced model is the same as the selected modal-choice model is easily rejected at the 0.05 level.

The "value of time" is often derived from model results and used as a test of whether the model estimates are plausible. Value of time is computed by examining the coefficients for the variables of mean travel time and travel cost in the model specification. However, for the model structure adopted for this research, the mean-travel-time variable appears in the departure-time model whereas the travel-cost variable is divided by the wage rate and appears in the modal-choice model. Some simplifying assumptions are required to compute the value of time.

The observable utility for modal choice can be written as follows:

$$V_m = \ldots -0.044\ \mathrm{TCPTWR}_m + \ldots\ 0.597\ \hat{D}_m{}^* \quad (3)$$

Since $\hat{D}^*_m = \ln e^{V}\Sigma d|m$, if we assume that all departure-time utilities have the same attributes, then

$$\begin{aligned}\hat{D}_m{}^* &= \ln 12 \exp(\overline{V}_{d|m}) \\ &= \ln 12 + \overline{V}_{d|m} \\ &= \ln 12 + (-0.041\ \mathrm{TIME}_m + \ldots)\end{aligned} \quad (4)$$

Thus,

$$V_m = \ldots -0.044\ \mathrm{TCPTWR}_m + 0.597\,(\ln 12 - 0.041\ \mathrm{TIME}_m \ldots) \quad (5)$$

Now that all variables of interest are in the same expression, the value of time can be derived as

$$(dV_m/dt)/(dV_m/dc) = 0.597(-0.041)y/-0.044 \quad (6)$$

where y is the after-tax wage rate expressed in cents per minute. To convert y to dollars per hour, we multiply by 0.6, which results in

$$\text{Value of time} = 0.597\,(-0.041)\,(0.6)y/-0.044 = 0.334y \quad (7)$$

where y is the wage rate in dollars per hour. This result compares quite favorably with the accepted ballpark commuter value of time of 35-40 percent of the hourly wage rate and helps to support the validity of the estimated models.

Three conditional choice tests of IIA violation were conducted on the modal-choice model, and one alternative mode was eliminated from each test. The null hypothesis is that the IIA assumption holds;

the results showed that, for all tests, the hypothesis cannot be rejected at the 0.05 level.

Reliability-related attributes are represented in the modal-choice decision in the departure-time inclusive term variable ($\hat{D}^*$) and the peak transit headway variable (HEADWAY). $\hat{D}^*$ (which denotes the estimate of D^*) is the term computed from the estimated departure-time model that represents the utility of the optimal departure time for each mode. This enters into the modal-choice model because of the belief that, when a commuter makes a modal-choice decision, he or she takes account of the optimal departure-time circumstances for each mode. Recall that D^* is the log of the sum of the exponentiated utilities for the departure-time alternatives. Thus, D^* includes explanatory effects of work flexibility, occupational characteristics, income, age, Bay Bridge travel, travel time, and arrival-time expected loss as they relate to departure-time choice.

It is well known that transit travel-time variance can be related to the variance of the headway distribution and that headway variance can be related to mean headway. Therefore, it was felt that peak transit headway might be a good proxy for uncertainties independent of arrival-time considerations. Furthermore, it was felt that the frequency of excessively long delays might also be related to the peak transit headways. Thus, peak transit headway was included in the transit alternative to represent those previously omitted transit reliability problems that are not present in automobile-related modes. It was recognized, however, that the headway variable might also serve as a proxy for other omitted transit effects (i.e., discontinuities of transit service) related to transit headway.

Three rather interesting research results emerge from an examination of the modal-choice model. The first is that the model provides insight into the interdependence of commuters' departure-time and modal-choice decisions. For a nested logit model of departure time and modal choice, the coefficient for the inclusive term D^* provides information on the random component in the modal-choice specification, ε_m (19). If the coefficient for D^* is equal to one, Var $(\varepsilon_m) = 0$, and the only random component present in the model is ε_{dm}, the joint random component of the conditional departure-time decision. If this were the case, a joint departure-time and modal-choice structure would be appropriate.

The estimated coefficient is equal to 0.572, with a standard error of 0.292. Use of a t-test shows that one can be 85 percent confident that the estimated coefficient differs from one. However, the true standard error of the coefficient for D^* is likely to be higher than 0.292, since $\hat{D}^*$ itself is an estimate subject to error. Nevertheless, it would still seem likely that Var $(\varepsilon_m) \neq 0$. This result suggests that modal and departure-time decisions should be structured as a nested choice rather than as a joint choice.

The second result is inferred from the significance of the headway variable. Recall that this variable is a proxy for transit unreliability independent of arrival-time considerations and the frequency of excessive delays (as well as a proxy for other omitted transit effects). The significance of the headway coefficient suggests that these modal-reliability attributes may have a separate and significant effect on the modal-choice decision.

The third result is derived from examination of the estimated coefficient for the variable FLEXARR in the modal-choice model. This variable represents the individual's perceived arrival-time flexibility. The statistical significance of this variable in the modal-choice model suggests that arrival-time considerations affect modal-choice as well as departure-time decisions.

SUMMARY

This research has focused on understanding the impact of service reliability on work-travel behavior. Since work-trip frequency and destination are fixed, the research problem was narrowed to a study of the impact of service reliability on commuter decisions in regard to modal choice and trip departure time. The problem was further restricted by studying only home-to-work travel, in part because of the lack of available data on the afternoon (evening peak) return trip. By working with the hypothesis that service reliability is an important attribute in explaining departure time and modal choice, measures of service reliability were proposed that capture the impact of this attribute on work-travel decisions. The theory was subsequently tested empirically through the estimation of departure-time and modal-choice models.

A number of conclusions were drawn based on the departure-time model results and related analyses. It was found that reliability-related arrival-time variables have significant coefficients and appear to lend additional explanatory power to the departure-time model. Since the arrival-time variables consist of loss derived from arriving at work at a particular time and the uncertainty of arrival about that time, the estimation results imply that the implications of when the traveler will arrive at work and the uncertainty associated with it, as well as the perceived penalties for arriving about that particular time, are a departure-time consideration. It is also apparent that this effect arises primarily from traveler sensitivity to arriving at a particular time and much less so from the uncertainty of arrival about that time. This result is somewhat surprising but may perhaps be attributable to the quality of the UTDFP data and reliance on previous studies that used inadequate data (either of which might lead to the lack of variation in the reliability data) or other methodological problems rather than an indication that reliability is truly of marginal importance.

Another important finding was that reliability-related arrival-time variables in the departure-time model are not highly correlated with explanatory variables used in existing models and that most of the implications of on-time arrival and related uncertainty are omitted effects absorbed into constants in existing models. This implies that the independent variables in existing models may not have biased coefficients because of the omission of reliability-related arrival-time variables, but existing models will still provide biased forecasts for any policy changes that alter the existing correlation between arrival-time conditions and independent variables in existing models.

Three rather interesting research results emerged from an examination of the estimated modal-choice model:

1. Departure time and modal choice appear to be interrelated in a way that suggests structuring departure-time and modal-choice decisions as a nested choice rather than as a joint choice.
2. It appears that arrival-time considerations affect modal-choice decisions as well as departure-time decisions.
3. The significance of the estimated headway coefficient suggests that additional reliability considerations independent of arrival-time considerations may have a significant effect on modal-choice decisions. However, the explanatory effect of this

variable may also be attributable to other transit effects that were omitted.

Through the development of a sequential departure-time and modal-choice decision structure and the subsequent estimation of departure-time and modal-choice models, the interdependencies of these decisions can be represented in the planning process. This gives planners the capability of predicting both modal shift and peaking responses to service changes.

The estimated models should also enable planners to consider how strategies for improving service reliability affect travel decisions. Since reliability-sensitive variables were not previously included in travel demand models, until now there was no way to analyze the potential impacts of reliability-related policies. Furthermore, use of these models should lead to improved forecasts in general, since the explanatory effect of a previously omitted variable will be included in the model.

Another contribution has been the definition and use of objective measures of service reliability. Past research had demonstrated that the inclusion of scaled reliability variables was statistically significant, but questions were raised concerning the transferability of scaled measures and how they could be used to evaluate reliability improvement policies. The measures developed in this research are not only behaviorally appealing but should also alleviate the problems encountered in the use of scaled measures.

It is important, however, to note that the results and implications of this research should not be interpreted as conclusive but rather as indicative of directions transportation researchers should pursue more vigorously in future travel demand research. In particular, future research should be directed at improving the quality of data collection on reliability, developing simpler measures of reliability, studying how the problem is affected by discontinuities in transit service and return-trip reliability considerations, examining the impact of reliability on nonwork trips, and conducting additional model validation efforts.

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