# Experimental Investigation of Route and Departure Time Choice Dynamics of Urban Commuters

HANI S. MAHMASSANI AND DOUGLAS G. STEPHAN

**The interaction between departure time and route switching in response to experienced congestion in a traffic commuting system is investigated using an experimental approach in which actual commuters interact over a period of seven weeks in a simulated commuting system. This experiment extends previous observational work along this line by incorporating the route choice dimension, which is essential to an understanding of user choice dynamics in congested urban systems. Another important feature of this experiment is the consideration of two groups of commuters with different information availability levels interacting in the same system, thereby allowing the analysis of the effect of information on user behavior and performance. The implications of the findings for the design of information-related strategies for the relief of congestion in urban networks are also discussed.**

Urban transportation planning methods have generally been concerned with a static description of link flows on a network, where flows and travel times are assumed to be invariant over the duration of the peak period, under presumed user equilibrium conditions. The primary dimension of choice thus available to tripmakers is route choice, as users are assumed to select routes in such a way as to achieve equilibrium conditions whereby no user can improve his or her travel time by unilaterally switching routes. An important dimension of choice that is missing in this framework is trip timing, which determines the time-varying flow patterns on the network. The variation of flows and travel times within the peak period has been documented in several studies (*1*, *2*). Furthermore, the interaction between trip timing and route selection is an important element in the analysis of time-varying flows in congested urban networks.

It is thus increasingly apparent that existing urban transportation planning methods are not adequate to address certain classes of operational problems where the time-dependent behavior of flows and the daily variation of these flows in response to congestion patterns and management strategies are of critical importance. The need for operational models that can support the design and evaluation of strategies for coping with congestion in urban networks provides an important motivation for the study of the dynamics of user decisions. This need is timely in light of the mounting national awareness of the rapidly deteriorating traffic conditions in urban areas, as well as the potential of strategies that rely on recent developments in information and communication technologies, including in-vehicle navigation and guidance systems. In addition, the preponderance of certain classes of practical problems, such as major freeway and arterial reconstruction activities that necessitate the loss over significant periods of critical capacity on vital arteries, calls for methods to predict the impact of such reductions and of possible mitigation strategies.

In the past five years, there have been several theoretical contributions to the solution of time-varying departure patterns that satisfy dynamic user equilibrium conditions; the vast majority of these have considered the highly idealized situation of a single origin-destination pair connected by a single route with an intervening bottleneck (*3*–*7*). Extensions that consider both departure time and route choices in similarly idealized situations have also been developed (*8*, *9*). All these formulations were, however, limited to the solution of time-varying departure patterns (on one or more routes) at some "final" equilibrium state; they were not particularly well developed on the behavioral side, for the sake of analytical tractability and for lack of an observational basis for more elaborate behavioral theories. Perhaps the most advanced on the user decisions side is the work of Ben-Akiva et al. (*9*, *10*), where a well-structured decision framework, though still lacking an observational basis, is articulated in the context of a stochastic user equilibrium formulation that can be solved numerically.

There have been several models of the static decisions made by individual tripmakers, particularly of trip timing, where the problem is viewed as one of selecting a discrete alternative among the possible set of discretized departure time alternatives (*11*–*14*). Relatively few studies have addressed the route choice decision from a behavioral perspective; some of these are reviewed in the recent contribution by Ben-Akiva et al. in an intercity context (*15*). An interesting application to bicycle path selection in an urban context, using a stated preference experimental

Department of Civil Engineering, University of Texas at Austin, Austin, TX 78712

approach, has also been presented (*16*). The joint departure time and route choice selection problem has recently been addressed by Abu-Eisheh and Mannering (*17*), using a small sample of university employees whose actual decisions are assumed to reflect prevailing equilibrium conditions in a relatively lightly congested system.

None of the preceding studies have addressed the day-to-day mechanisms by which individual tripmakers may adjust their decisions, in the short term, in response to perceived and experienced congestion in the traffic system. Simple learning rules by which users adjust their anticipated travel times on alternate routes, given their prior experiences with the system, were proposed by Horowitz in a theoretical contribution to the stability of stochastic user equilibrium in an idealized two-link network (*18*). Alternative rules for departure time adjustment were explored by Mahmassani and Chang (*19*) in the context of a simulation framework to study the dynamics of the interaction between commuter decisions and congestion in traffic systems. An essential element in the further development of knowledge and methods in this area, however, is the observation of actual user behavior as it interacts with the traffic system's performance. Recognizing that the complexity of this dynamic interaction seriously reduces the ability of conventional survey methods to obtain the data that would be necessary for such investigation within practical resource limitations, an experimental approach was recently proposed by Mahmassani, Chang, and Herman (*20*). It consists of observing, over several weeks, real commuters interacting through a computer-simulated traffic system. Decisions supplied daily by the participants, acting independently, form the input to a traffic simulation model that yields the respective consequences (arrival times) of these decisions. Feedback from the simulated results is supplied to the commuters who provide decisions on the next day, and so on. This nonprohibitive alternative to large-scale field experiments allows insights into the overall system's dynamic properties and provides a basis for theoretical development and model specification and testing.

In previous papers, two such experiments have been reported (*20–22*). Both consist of an identical commuting corridor with a single highly congested route, where users have a choice of departure time only. The two experiments differ in the information available to users on the system's prior performance. In the first case, all commuters are provided only with limited information on their own arrival time on the previous day. In the second, they are provided with complete information on the previous day's performance, in the form of arrival times for all possible departure times. In addition to the overall evolution of the system, including spatial and temporal convergence behavior under the two informational scenarios, exploratory analyses of the dynamics of individual user behavior have been reported in the previous papers (*20–22*). Formal econometric models of the departure time adjustment mechanisms and associated trip time prediction rules operating at the individual level have also been developed on the basis of these two experiments (*23–26*), and further model development and hypothesis testing is still ongoing with regard to the complex dynamic processes governing commuter decisions.

Having developed and refined the experimental methodology in a single route context, it is natural to extend its application to more complicated situations encountered in actual commuting, particularly those allowing users a choice of route in addition to that of departure time. A third experiment has therefore been conducted for this latter situation, thereby allowing the investigation of the dynamics of user choices along these two interacting dimensions in congested commuting systems. In this third experiment, participants are divided into two information availability groups (limited vs. complete) operating side by side in the same system, providing the opportunity to examine the effect of information when the latter is provided to only a fraction of the total population. The results of this experiment are presented in this paper, with regard to the system's overall evolution and convergence patterns, the dynamics of user decisions, particularly switching frequency and the interaction between route choice and departure time switching decisions, as well as the effect of information on these processes. The analysis presented in this paper is primarily exploratory, aimed at providing an overview and general insights into the questions of interest and suggesting hypotheses for more extensive formal model building and testing.

In the next section, the experimental procedure is described, focusing primarily on those details that are different from the previous two experiments and that have a direct bearing on the interpretation of the results. This is followed by a discussion of the system's overall evolution and convergence patterns. The effect of information is then examined, followed by a comparative assessment of system performance by route from the perspective of user equilibrium principles. After that, the main focus is on the analysis of the interaction of route choice and departure time switching decisions. Concluding comments are presented in the final section, along with questions that will be addressed in subsequent modeling work.

## COMMUTING CONTEXT AND EXPERIMENTAL PROCEDURE

The procedure followed in this experiment is essentially similar to that followed in the previous two, which are described in detail elsewhere (*20–22*). The commuting context now consists of two parallel roadway facilities, each nine miles long (with access limited to a finite number of entry points), used by adjoining residents in their home-to-work morning commute to a common destination, such as a city's central business district (CBD) or major suburban industrial park. The two facilities serving the corridor consist of (1) Route 1, a four-lane highway (two lanes in each direction) with a speed limit of 50 mph, and (2) Route 2, a two-lane arterial street (one lane in each direction) with a speed limit of 40 mph. Both facilities are assumed to be of uniform width and geometry throughout their nine-mile length. The two facilities do not intersect, thus no crossing over from one to the other is possible in the same trip. As before, the corridor is divided into nine identical sectors, one mile in length, with the work destination located at the end of sector 9 and sector 1 being the farthest outbound. The commuters' residences are located in sectors 1 through 5 only, with no trips generated from the remaining sectors. For simplicity, it is assumed that the access time from a given residence to either facility is the same.

To achieve a meaningful level of congestion in the system, the total number of trips generated in each of the five residential sectors is doubled from the 400 used in the two previous experiments to 800 tripmakers per sector, or a total of 4,000 trips during the peak period. It should be noted, however, that while two routes exist in this system compared to only one route in the two previous experiments, the overall level of congestion in terms of the ratio of overall volume to the total number of available lanes has increased by one-third. The number of participating commuters was accordingly increased to 200, or double the 100 used in each of the previous experiments. The participants were assigned equally and randomly to the five residential sectors, and the decisions of each participant were treated as those of 20 identical tripmakers for traffic simulation purposes.

All participants were staff members at the University of Texas at Austin. To avoid possible bias due to professional knowledge, none of the participants were recruited from the Civil Engineering Department or the Community and Regional Planning Program. Furthermore, individuals who had participated in either of the two previous experiments were excluded from this one to control for initial bias and learning effects. Participants were selected and instructions given so as to avoid cooperative behavior in the experimental responses, and to prevent access to uncontrolled sources of information. Careful monitoring and subsequent analysis do not suggest any violations of the intended individual, noncooperative character of the decision process.

In keeping with the assumptions of the previous experiments, participants were instructed that they needed to be at work by 8:00 A.M., with no late arrival tolerated at the workplace, which is quite similar to their actual working conditions. The purpose of imposing the identical work start time and no-lateness conditions in this and earlier experiments is to limit nonessential complication in interpreting the results, and to keep the number of participants at a manageable level while allowing a meaningful level of interaction to develop in the traffic system.

In the first two experiments, all users were assumed to have the same level of information availability; thus, no comparative advantage existed in this regard among participants in a given experiment. For instance, in the first experiment, one's own experience in the commuting system was the only source of information available. Thus each participant was provided with the time at which she or he arrived at the work destination given that individual's chosen departure time on the previous day (*20*, *21*). In the second experiment, information was also available from exogenous sources, and participants were supplied with arrival times corresponding to an array of possible departure times (ranging from 7:00 to 7:50 A.M. in five-minute increments) for their residential sector, presented in the form; "If you had left at 7:00 you would have arrived at 7:15" (*22*). The new feature in the third experiment is that both limited (or myopic) and full information availability levels are included. Specifically, in each sector, participants are assigned equally to one or the other information availability group and, accordingly, receive either myopic or full information throughout the experiment. This allows the effect of information availability on performance to be studied and compared for unequally informed individuals operating simultaneously in the same commuting system.

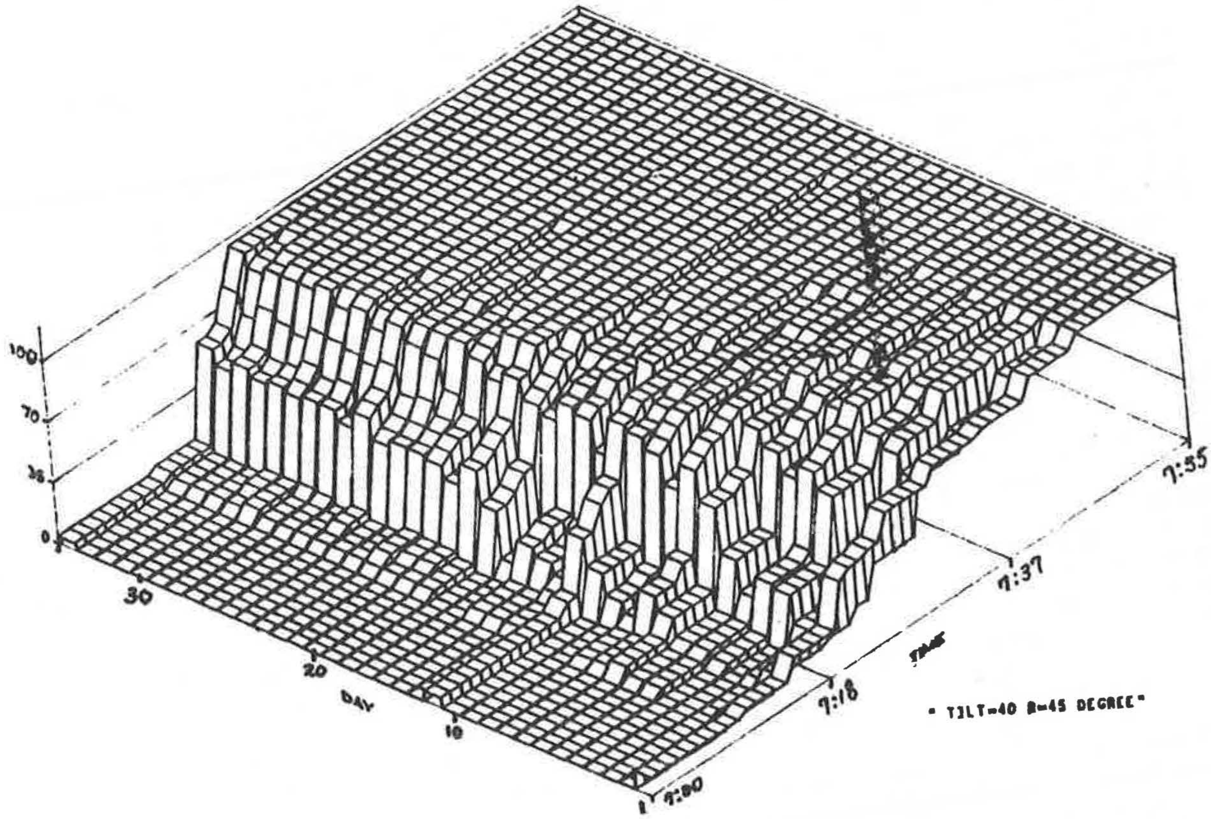
Finally, for completeness, the experimental procedure, beyond the selection of participants and their assignment to the various residential sectors and information groups, is summarized as follows:

1. Supply each participant $i$, $i = 1, \ldots, 200$, with initial information and instructions.
2. On day $t$, all participants supply their departure time and route decisions $DT_{it}$ and $RT_{it}$; these are aggregated by sector into time-dependent departure functions for each route, $D_{krt}(T)$, where $T$ is the time of day, $k = 1, \ldots, 5$ is the subscript for the sector of origin, and $r = 1, 2$ is that for the route.
3. The departure functions are input to a special-purpose, macroparticle traffic simulation model (or MPSM) (*27*), which yields the respective arrival times $AT_{it}$, travel times $TT_{it}$, and other pertinent traffic performance measures. Note that because the two routes do not overlap, each can be simulated independently from the other, given the respective input functions on day $t$.
4. If the maximum experiment duration is reached or steady state is achieved, stop. Otherwise, set $t = t + 1$, supply each participant with information on actual performance on the preceding day, according to her or his information availability group, and go to step 2 for updated departure time and route decisions from the participants.

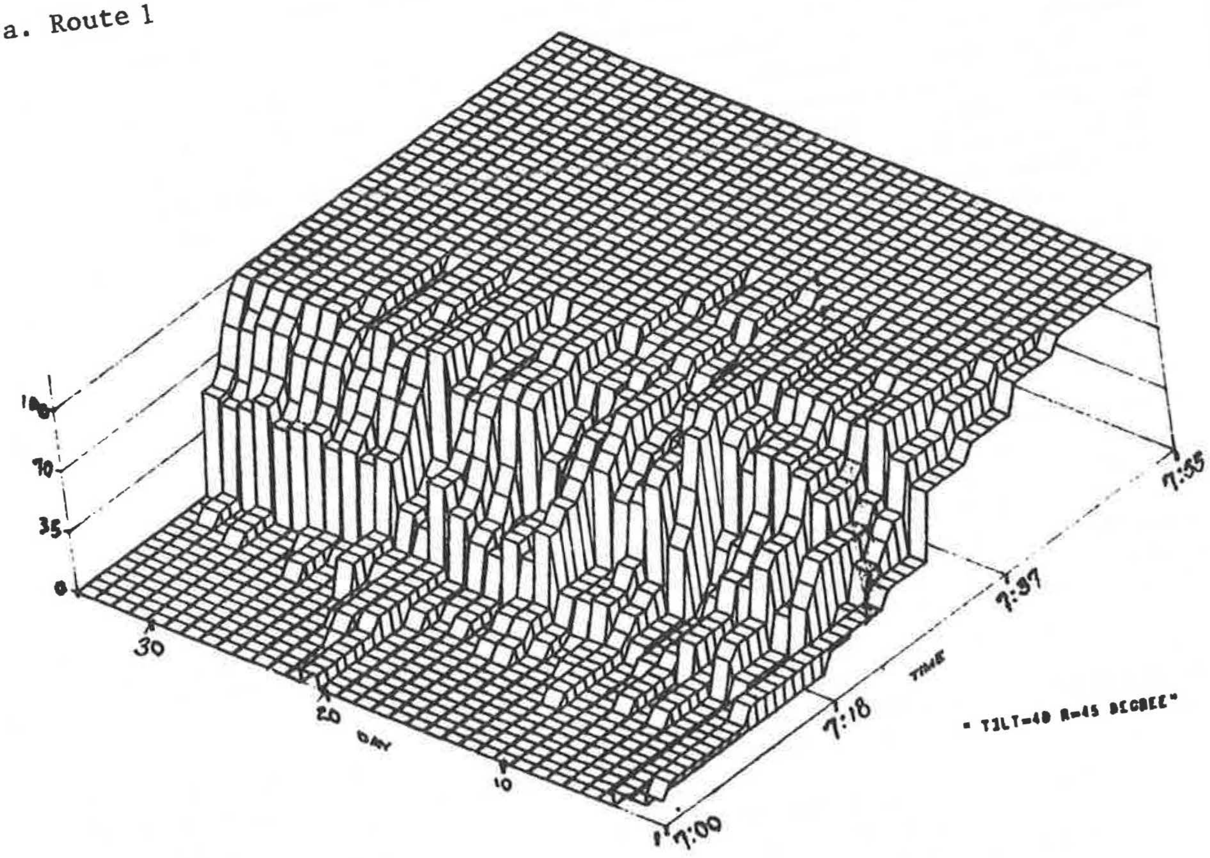
The experimental results are presented next.

## SYSTEM EVOLUTION AND CONVERGENCE

Convergence in this system is achieved when the commuters are no longer adjusting their route or departure time choices and the resulting departure time distributions for each route and sector remain the same from one day to the next. In both previous experiments, convergence to a steady state was achieved as of day 20 for the limited information case, and day 29 for the full information case (*20*, *22*). Complete convergence, however, was still not reached in this third experiment after seven weeks (34 days) of administering the experiment. Figures 1 (a, b) and 2 (a, b) show the evolution of the daily cumulative departure time distributions for routes 1 and 2, for sectors 1 and

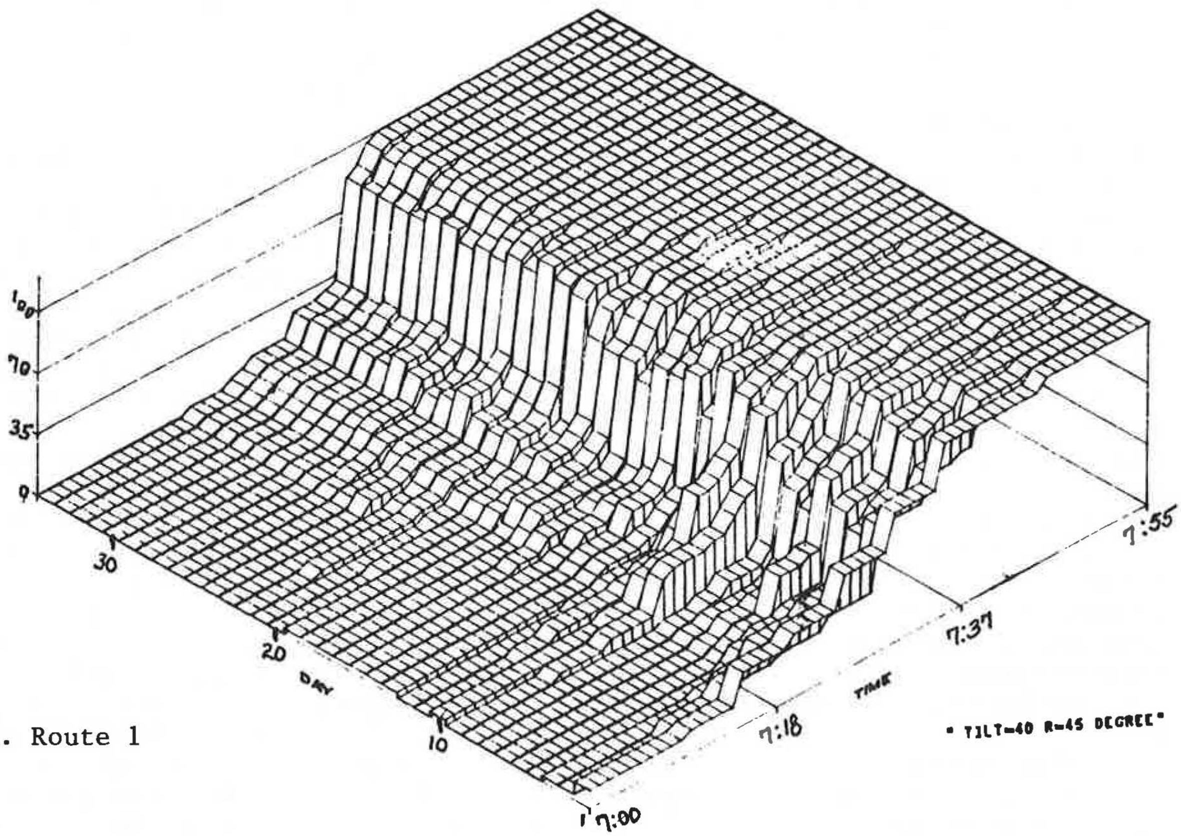



1.a. Route 1

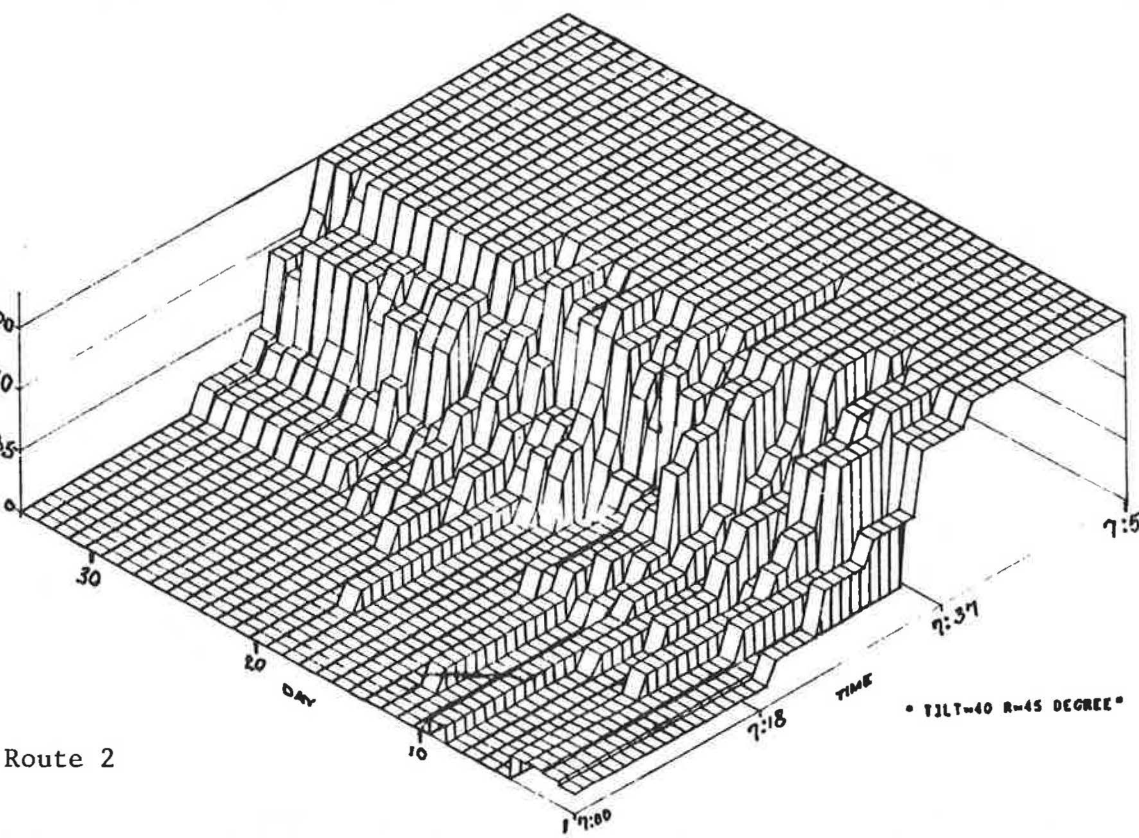



1.b. Route 2

**FIGURE 1 Evolution of daily cumulative departure time distribution for Sector 1.**




2.a. Route 1




2.b. Route 2

**FIGURE 2 Evolution of daily cumulative departure time distribution for Sector 3.**

3, respectively, for the duration of the experiment. Although these distributions had not converged for these sectors by the last day of the experiment, it is clear that the departure patterns on each route were beginning to exhibit markedly reduced changes from day to day toward the latter part of the experiment. Likewise, none of the departure time distributions for any other route and sector combinations had converged as of day 34, though all had stabilized to varying degrees.

Figures 3 and 4 depict the day-to-day evolution of the average travel time and average (of the absolute value of) schedule delay experienced by users in each sector. The schedule delay is defined as the difference between actual and preferred arrival time, the latter having been supplied by each participant at the beginning of the experiment as the desired arrival time in the absence of congestion. These plots further illustrate the dampening of the fluctuation in the average performance of each sector toward the end of the experiment, especially in sectors 1 and 2. Figure 5 depicts the daily percentage of users switching either route or departure time (or both) in each sector, indicating that approximately 11 percent were still switching by the end of the experiment.

The fact that this experiment did not converge, despite the additional time relative to the previous two experiments, which did converge, is due to two primary factors. The first is the increase in overall system congestion, noted in the previous section; the addition of the alternate route and the doubling of the number of participants increased overall congestion in the commuting system on a trips per available-lane basis by 33 percent. Second, the availability of an additional choice dimension to the commuters can be expected to increase the overall level of switching activity and thus the time needed to converge. It is therefore not surprising that this more congested system would take longer to converge, in light of the simulation results presented by Mahmassani and Chang (*19*). Because the experiment was stopped, it is not possible to assert that the system would eventually have converged, although it appears to have been headed in that direction. It is not clear that continuation of the experiment would have added much to the general conclusions and analysis that can be performed on the results attained up to this point. Practicality and cost considerations precluded the possibility of going beyond the seven weeks that were undertaken, especially since serious concerns would arise regarding the goodwill and interest of the participants, thereby jeopardizing the quality of the experimental data.

In addition to the temporal aspects of system convergence, its spatial characteristics are also of interest. In the previous two experiments, it was observed that sectors in which users are facing greater day-to-day uncertainty and unpredictability, reflected in the day-to-day fluctuations of travel time, required a longer period to converge. Although none of the sectors attained a steady state by the end of this experiment, switching activity can be examined as an indicator of the probable order in which sectors might have converged and of the sector's relative closeness

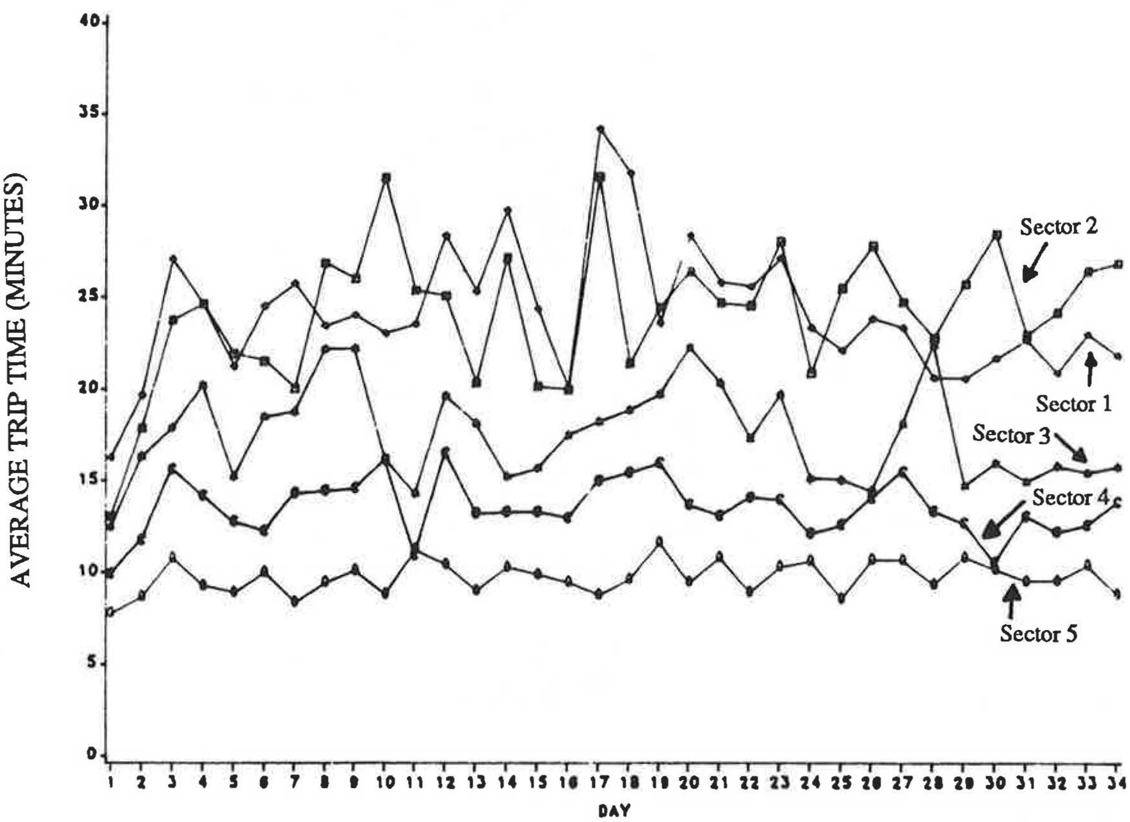



**FIGURE 3 Day-to-day evolution of average trip time for each sector.**

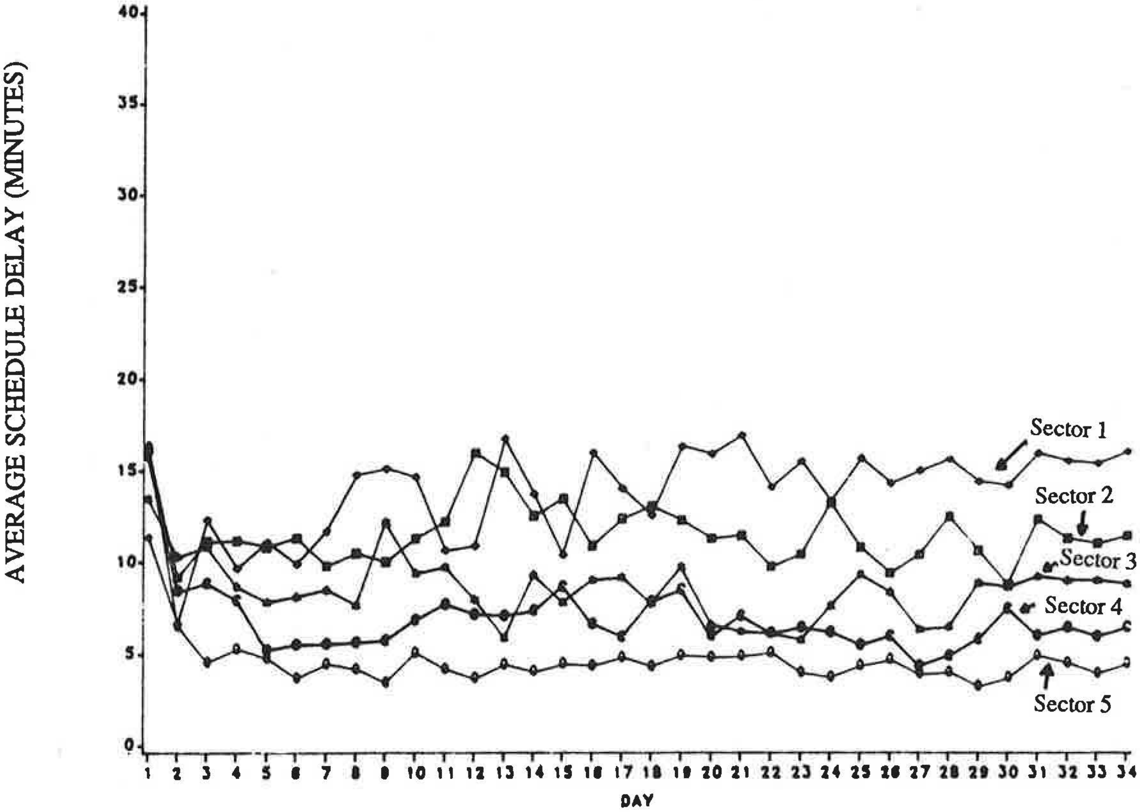



**FIGURE 4 Day-to-day evolution of average absolute schedule delay for each sector.**

to steady state. Figure 5 appears to indicate that sectors 2 and 1 experienced greater overall switching activity than did the other three sectors. A nonparametric test was used to address formally the dependence of switching activity on the sector. The null hypothesis is that switching activity is independent of sector or, more precisely, that each rank ordering of the sectors is equally likely (i.e., not the result of a common underlying order). The test measure is Friedman's statistic, related to Kendall's *W*-coefficient, which measures the agreement of several rank orderings of a given set of objects (*28*). In this case, the rank order of the sectors in terms of switching frequency is considered on each day of the experiment. Letting $R_{ij}$ denote the rank of sector $j$, $j = 1, \ldots, 5$ on day $i$, $i = 2, \ldots, 34$, the calculation of the test statistic can be found in standard textbooks (*28*). Under the null hypothesis, this statistic is $\chi^2$ distributed with 4 degrees of freedom. In this case, the calculated value is 42.2, while the 99.9th percentile value of the $\chi^2$ distribution is 18.5, allowing the clear-cut rejection of the null hypothesis. Thus, as expected, the switching activity varies by sector. The sums of the ranks $R_{ij}$, namely, $R_{\cdot j} = \sum_{i=2}^{34} R_{ij}$, for $j = 1, \ldots, 5$, provide a maximum likelihood estimator of the common underlying rank order of the sectors (*29*). Accordingly, the calculated values are $R_{\cdot 1} = 84$, $R_{\cdot 2} = 57.5$, $R_{\cdot 3} = 134.5$, $R_{\cdot 4} = 114.5$, and $R_{\cdot 5} = 104.5$, indicating that sector 2 ranks highest in terms of the extent of switching frequency, followed by sector 1. The corresponding fluctuation in system performance is depicted in Figures 3 and 4, further corroborating the already mentioned findings of the previous experiments (*22*). The difference is that greater interaction seems to exist in this experiment among the sectors (particularly 3, 4, and 5), reflected in the less clear-cut conclusions, probably due to the higher level of overall congestion in the system.

In the next section, the effect of information availability on the system's evolution and the relative performance of the two user groups are examined.

## EFFECT OF INFORMATION AVAILABILITY

As explained in the description of the experimental procedure, two user groups were defined on the basis of the level of information made available daily to each group. Differences between the limited information and complete information groups are examined in (1) how well each group performs (in terms of user costs) relative to the other and (2) the extent of the effort that members of each group have to exert in the process. Furthermore, by comparison with the previous experiments, it is possible to comment on the effect of the fraction of the population that has an informational advantage (i.e., is supplied with complete information). In the previous experiments, Mahmassani and Tong (*22*) found that when all users in a system (with a single route) were given complete information, the final

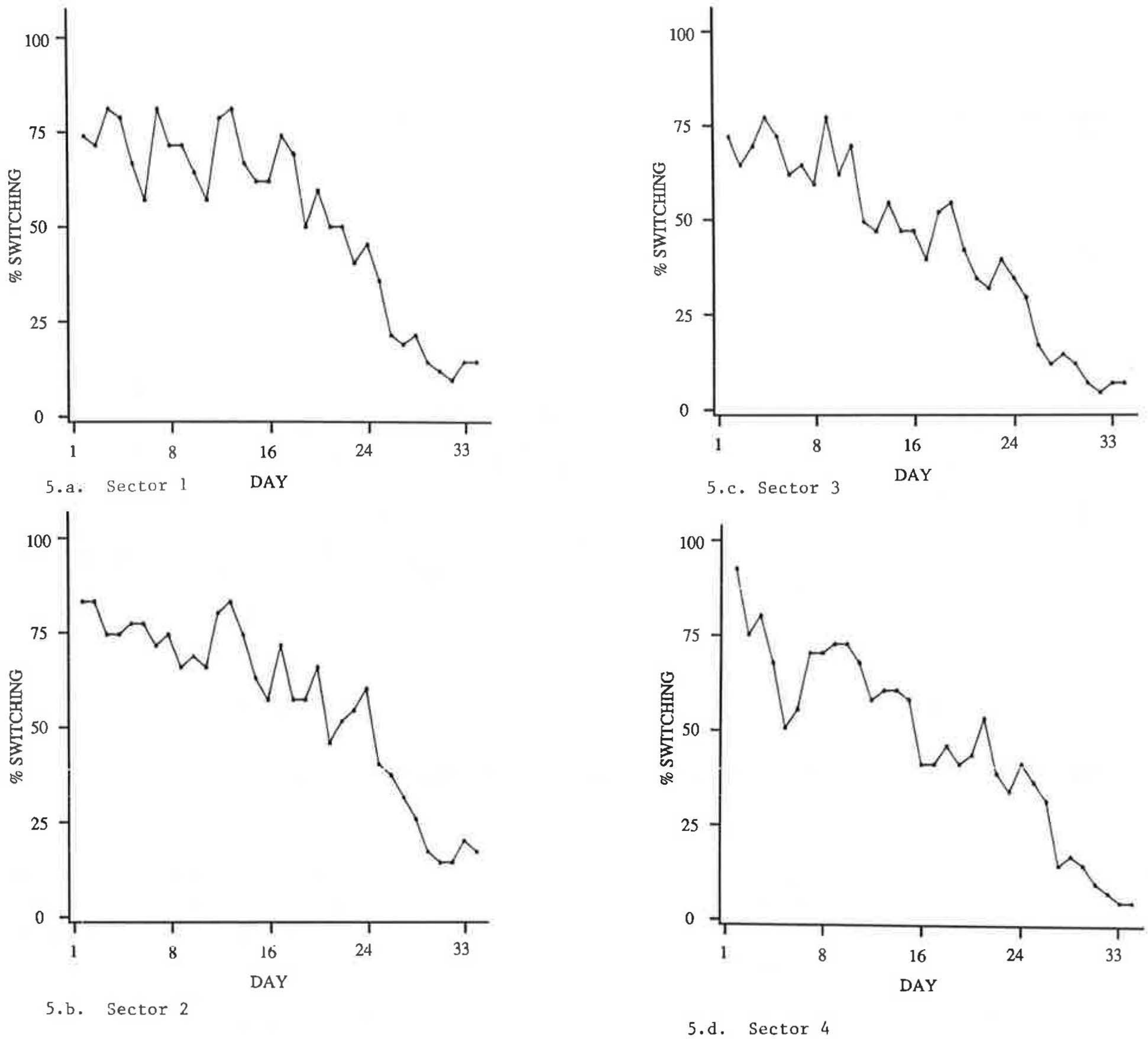
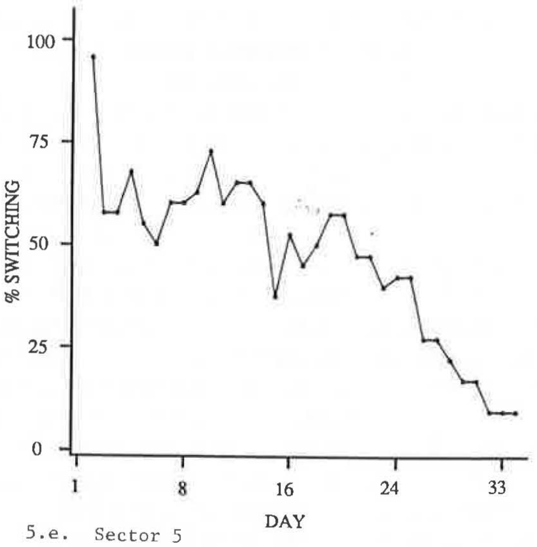



**FIGURE 5 Day-to-day evolution of percentage of users in each sector switching or departure time (possibly both).**

state reached was superior to that attained under the limited information situation. This superiority was established in terms of the average schedule delay and average travel time experienced by users in each sector at steady state. It was also found that this superior performance took a longer period to reach than in the limited information case, with users exhibiting greater overall daily switching activity in search of an acceptable solution.

Because this experiment did not converge completely, there is no "final state" at which to conduct the comparison of the performance of the two information availability groups. Since day-to-day fluctuations had subsided toward the end of the experiment, however, the averages of the performance measures of interest taken over the last four days are treated as representative of the "final state." The average schedule delay and average travel time experienced by the users in each sector (over the last four days) are calculated separately for each information availability group, and are constrasted in Figure 6 (the sector number is shown near each point in the figure). With the exception of sector 3, the performance of the full information group dominated the other. In sector 3, the average travel time is about 19 percent lower for the full information group, although the schedule delay is only slightly higher (by about 2 percent). These findings conform to intuition and are consistent with the earlier results of Mahmassani and Tong (*22*).

Regarding the relative effort exerted by the two groups to achieve the foregoing level of performance, the intensity of daily switching activity can be examined for each group. Figure 7 depicts the day-to-day evolution of the respective fractions of users in each information group that switch either route or departure time (possibly both). The plots suggest that the behavior of the complete information group was approaching convergence more rapidly than that of the limited information group. It is also useful to note that the complete information users in sector 3 constitute the only subgroup that had reached a steady state



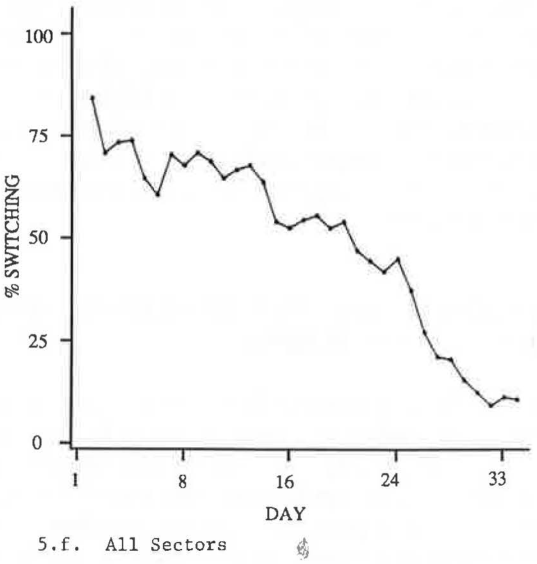




**FIGURE 5** *(continued)*

(i.e., were no longer switching decisions) by the end of this experiment. These results would appear to contradict the findings of the two previous studies, in which providing information to *all* users in the single route system increased overall switching frequency and resulted in longer time to convergence. An important distinction in this experiment, however, is that there are two groups of users with two different levels of information availability "competing" in an interactive system. That the group with more information appears to reach a more desirable outcome at a smaller switching cost than the less fortunate group seems consistent with intuition. Actually, the earlier findings appeared counterintuitive but were explainable upon the realization that no user had an inherent advantage over the other in terms of availability of knowledge about the system's performance. Thus more information to all led to higher expectations and a more persistent search by all *(22)*. Here, more information to only one group allowed that group to outperform the other, resulting in a more rapid decrease in switching activity. This then illustrates that the effect of information depends on the fraction of users with access to this information. Greater diffusion could reduce the competitive advantage that a given level of information might convey.

## PERFORMANCE BY ROUTE

Although it is not possible to test the validity of the standard user equilibrium (UE) conditions in the context of this experiment, it is nevertheless helpful to examine differences in the performance experienced by users on the two available routes. Table 1 presents the average travel time experienced by users (from each sector) on each route, calculated over the four-day final state, as described previously. In all cases, the average travel time experienced on Route 1 is less than on Route 2, which has lower capacity and lower free flow speed. This does not seem to be in agreement with static UE conditions, which require

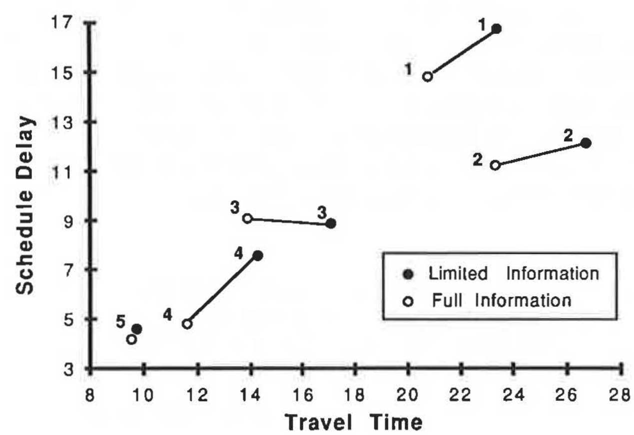



**FIGURE 6 Comparison of average performance of two information availability groups at final state (average over last four days).**

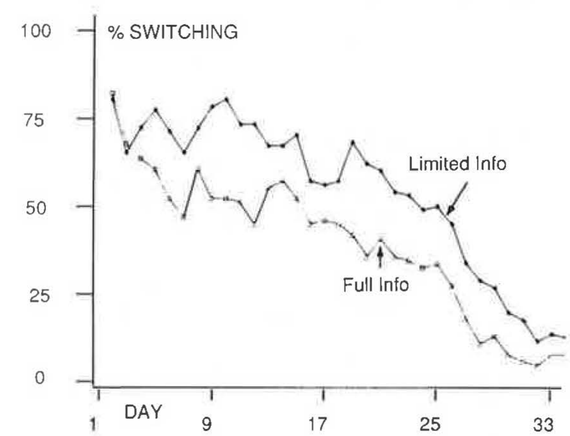



**FIGURE 7 Day-to-day evolution of fraction of users in each information group who switch departure time or route (possibly both).**

travel times on all used alternative routes between a given origin-destination pair to be equal at equilibrium.

Although equilibrium was not completely reached in this system, a more important consideration is that the preceding conditions are recognized to be inappropriate for time-dependent flows, where travel times vary within the peak period. Plots of the travel time by departure time on each route (excluded here for space considerations) clearly confirm that different travel times are experienced on each route for different departure times in this experiment. The extension of the UE principle to the time-dependent situation is predicated on the assumption that the decision process involves a trade-off between the travel time and schedule delay associated with a particular joint departure, time-route choice alternative (*3*, *8*). Table 2 presents the average of the absolute value of the schedule delay, also taken over the four-day final state described earlier. The values for sectors 1, 2, and 3 reflect performance that is consistent with such a trade-off, indicating that residents of these sectors who use Route 2 experience a lower average schedule delay than those who use Route 1. No such advantage exists for residents of sector 4, however, who incur an uncompensated higher travel time on Route 2 relative to Route 1. For sector 5, Route 1 simply dominates Route 2 on both cost components, yet the latter still captures a fraction of the sector 5 commuters.

If the utility function of a commuter can be represented as a linear weighted sum of travel time and schedule delay, then the relative magnitudes of the quantities reported in Tables 1 and 2 for sectors 1, 2, and 3 indicate that schedule delay must be valued considerably more highly than travel time in order to satisfy the dynamic user equilibrium conditions (for convenience, assume that users in a given sector have identical utility functions). Estimates for the marginal rates of substitution between the two cost components can be calculated as the ratio of the difference in average schedule delay between the two routes to the corresponding difference in average travel time, yielding −0.17, −0.47, −0.19, 0.0, and 1.52 for sectors 1 through 5, respectively. These values can be interpreted as the minutes of schedule delay one is willing to incur to reduce travel time by one minute. Alternatively, by taking the inverses of these numbers, it can be seen that one minute of schedule delay can be worth more than five minutes of travel time. Furthermore, in both sectors 4 and 5, travel time apparently cannot compensate for schedule delay, suggesting that users may effectively be indifferent to travel time relative to schedule delay. These findings therefore corroborate the results of the previous two experiments. Further insights can naturally be obtained through a more detailed econometric analysis of the individual-level data, which will be addressed in future work. In the next section, the exploratory aggregate analysis is continued, with the focus on the interrelation of route and departure time switching decisions.

TABLE 1 AVERAGE TRAVEL TIME EXPERIENCED BY SECTOR OF ORIGIN ON EACH ROUTE AT FINAL STATE (AVERAGE OVER LAST FOUR DAYS)

| | Route 1 | Route 2 | Both Routes |
|---|---|---|---|
| Sector 1 | 20.2 | 25.5 | 22.1 |
| Sector 2 | 24.5 | 26.2 | 25.1 |
| Sector 3 | 12.5 | 26.9 | 15.5 |
| Sector 4 | 11.4 | 15.8 | 12.9 |
| Sector 5 | 8.9 | 11.2 | 9.6 |

TABLE 2 AVERAGE ABSOLUTE SCHEDULE DELAY EXPERIENCED BY SECTOR OF ORIGIN OF EACH ROUTE AT FINAL STATE (AVERAGE OVER LAST FOUR DAYS)

| | Route 1 | Route 2 | Both Routes Combined |
|---|---|---|---|
| Sector 1 | 16.1 | 15.2 | 15.7 |
| Sector 2 | 11.8 | 11.0 | 11.5 |
| Sector 3 | 9.6 | 6.9 | 9.0 |
| Sector 4 | 6.2 | 6.2 | 6.2 |
| Sector 5 | 3.5 | 7.0 | 4.4 |

## INTERACTION BETWEEN DEPARTURE TIME AND ROUTE SWITCHING

The interaction between the day-to-day adjustments of the departure time and route choice decisions is addressed in this section in an effort to suggest and explore some hypotheses about the mechanisms that govern this behavior. Of particular interest is the extent to which the switching of route and of departure time occur independent of one another. This has methodological implications for the formulation of an appropriate decision structure and model specification, as well as practical implications for the design of control and management strategies.

Table 3 presents the percentage of users in each sector who switched departure time at least $n$ times, with $n = 1, \ldots, 33$. Similar information is presented in Table 4 for those who change route, indicating that more users switched departure time than route and that users switched departure time more frequently than route. Figure 8 depicts the day-to-day evolution of the fraction of participants who switched both departure time and route on a given day and the fraction of those who switched only one or the other (but not both). Clearly, the latter fraction is considerably less than the former on most days. Figure 9 shows the day-to-day patterns of the (marginal) fraction that switched route and of the fraction that switched departure time, further illustrating the considerably higher frequency of departure time changes on a daily basis. The average number of departure time switches made between consecutive route changes is presented in Table 5, indicating an initial reluctance to change routes and suggesting

TABLE 3 PERCENT OF PARTICIPANTS MAKING AT LEAST *n* DEPARTURE TIME SWITCHES BY SECTOR

| n | Sector 1 | Sector 2 | Sector 3 | Sector 4 | Sector 5 |
|---|---|---|---|---|---|
| 1 | 100 | 100 | 98 | 100 | 98 |
| 2 | 100 | 97 | 95 | 100 | 95 |
| 3 | 100 | 97 | 95 | 95 | 92 |
| 4 | 100 | 97 | 92 | 93 | 88 |
| 5 | 100 | 94 | 92 | 90 | 85 |
| 6 | 95 | 94 | 90 | 88 | 82 |
| 7 | 90 | 91 | 82 | 80 | 82 |
| 8 | 88 | 86 | 80 | 78 | 70 |
| 9 | 83 | 83 | 72 | 71 | 68 |
| 10 | 79 | 83 | 70 | 68 | 68 |
| 11 | 79 | 83 | 65 | 68 | 65 |
| 12 | 71 | 83 | 60 | 58 | 60 |
| 13 | 69 | 80 | 55 | 56 | 58 |
| 14 | 67 | 77 | 55 | 56 | 55 |
| 15 | 57 | 69 | 50 | 51 | 52 |
| 16 | 43 | 63 | 40 | 51 | 48 |
| 17 | 40 | 60 | 35 | 44 | 45 |
| 18 | 40 | 54 | 30 | 36 | 42 |
| 19 | 36 | 46 | 25 | 34 | 35 |
| 20 | 31 | 40 | 22 | 29 | 35 |
| 21 | 26 | 37 | 20 | 29 | 28 |
| 22 | 19 | 29 | 18 | 17 | 22 |
| 23 | 17 | 20 | 18 | 15 | 20 |
| 24 | 12 | 20 | 15 | 15 | 20 |
| 25 | 12 | 17 | 10 | 15 | 18 |
| 26 | 10 | 17 | 8 | 12 | 12 |
| 27 | 7 | 17 | 8 | 10 | 12 |
| 29 | 5 | 9 | 2 | 5 | 8 |
| 30 | 2 | 9 | 2 | 2 | 8 |
| 31 | 2 | 9 | 0 | 0 | 2 |
| 32 | 0 | 6 | 0 | 0 | 2 |
| 33 | 0 | 3 | 0 | 0 | 2 |

TABLE 4 PERCENT OF PARTICIPANTS MAKING AT LEAST *n* ROUTE SWITCHES BY SECTOR

| n | Sector 1 | Sector 2 | Sector 3 | Sector 4 | Sector 5 |
|---|---|---|---|---|---|
| 1 | 76 | 63 | 55 | 68 | 50 |
| 2 | 71 | 57 | 50 | 59 | 38 |
| 3 | 55 | 34 | 28 | 46 | 20 |
| 4 | 48 | 31 | 20 | 37 | 15 |
| 5 | 33 | 20 | 10 | 24 | 15 |
| 6 | 29 | 20 | 10 | 15 | 12 |
| 7 | 19 | 14 | 8 | 7 | 8 |
| 8 | 19 | 14 | 2 | 5 | 8 |
| 9 | 10 | 6 | 2 | 2 | 8 |
| 10 | 10 | 6 | 2 | 2 | 8 |
| 11 | 10 | 3 | 0 | 2 | 8 |
| 12 | 7 | 3 | 0 | 2 | 5 |
| 13 | 2 | 0 | 0 | 0 | 5 |
| 14 | 2 | 0 | 0 | 0 | 5 |
| 15 | 2 | 0 | 0 | 0 | 2 |
| 16 | 2 | 0 | 0 | 0 | 2 |
| 17 | 2 | 0 | 0 | 0 | 2 |
| 18 | 2 | 0 | 0 | 0 | 2 |
| 19 | 2 | 0 | 0 | 0 | 2 |
| 20 | 0 | 0 | 0 | 0 | 2 |
| 21 | 0 | 0 | 0 | 0 | 2 |
| 22 | 0 | 0 | 0 | 0 | 2 |

that commuters might first respond to experienced fluctuations in a given traffic system by first changing departure time, keeping the same route as usual. After the first route change, Table 5 reveals that users switched departure time approximately 1.5 to 2.5 times more often than route.

Further inspection of Figures 8 and 9 reveals a marked similarity in the patterns depicted in the two graphs, suggesting a rather high correlation among particular pairs of plotted variables. In particular, the joint switches of route and departure time closely parallel those of route,

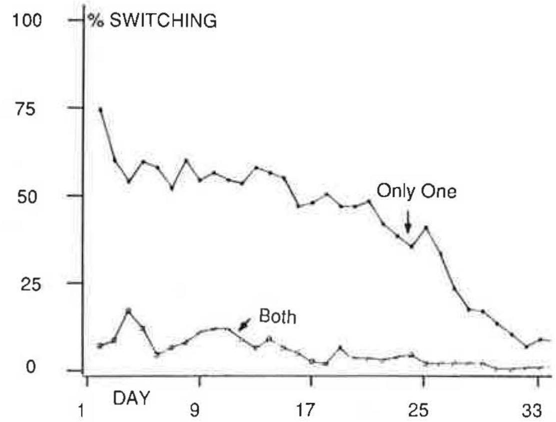



**FIGURE 8 Day-to-day evolution of percent of users switching both route and departure time and fraction switching only one.**

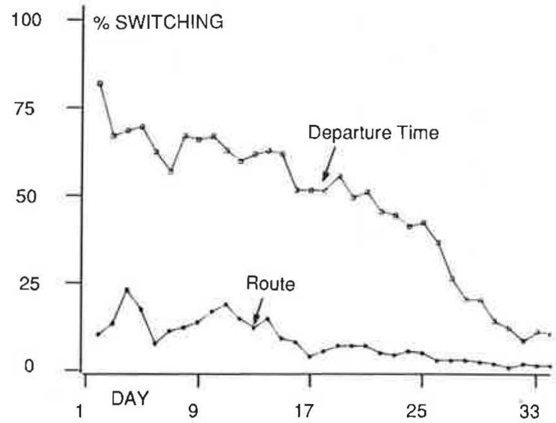



**FIGURE 9 Day-to-day evolution of percent of users switching departure time and fraction switching route.**

whereas changes of only one parallel those of departure time. This interdependence is further explored hereafter. A simple way to assess the validity of the independence hypothesis is to examine the compliance with the fundamental rule of probability that states that the product of the marginal probabilities of two independent events is equal to the probability of the joint occurrence of the two events. Using the sample fractions as estimates of the underlying probabilities, the product of the respective fractions of changing route and departure time is compared with that of changing both, on a daily basis. Figure 10 displays the results. In the figure, the "estimated" fraction is the above product, and the "observed" is the actual fraction in the sample of those switching both. Of course, if the independence hypothesis were to hold, then all the plotted points should lie on the straight line with slope 1. There is a clear, systematic violation of this hypothesis, however, since most points seem to lie above that line.

A more formal test of the aforementioned independence hypothesis can be performed using the chi-squared statistic. Let $N_{ijt}$ denote the number of participants who, on day

TABLE 5 AVERAGE NUMBER OF DEPARTURE TIME SWITCHES BETWEEN $K - 1$TH AND $K$TH ROUTE SWITCH

| K | Number of Partipants Making K Route Switches | Average Number of Departure Time Switches |
|---|---|---|
| 1 | 124 | 3.65 |
| 2 | 109 | 1.81 |
| 3 | 73 | 2.58 |
| 4 | 60 | 1.68 |
| 5* | 41 | 1.66 |

*Less than 20% of the participants had 6 or more route switches

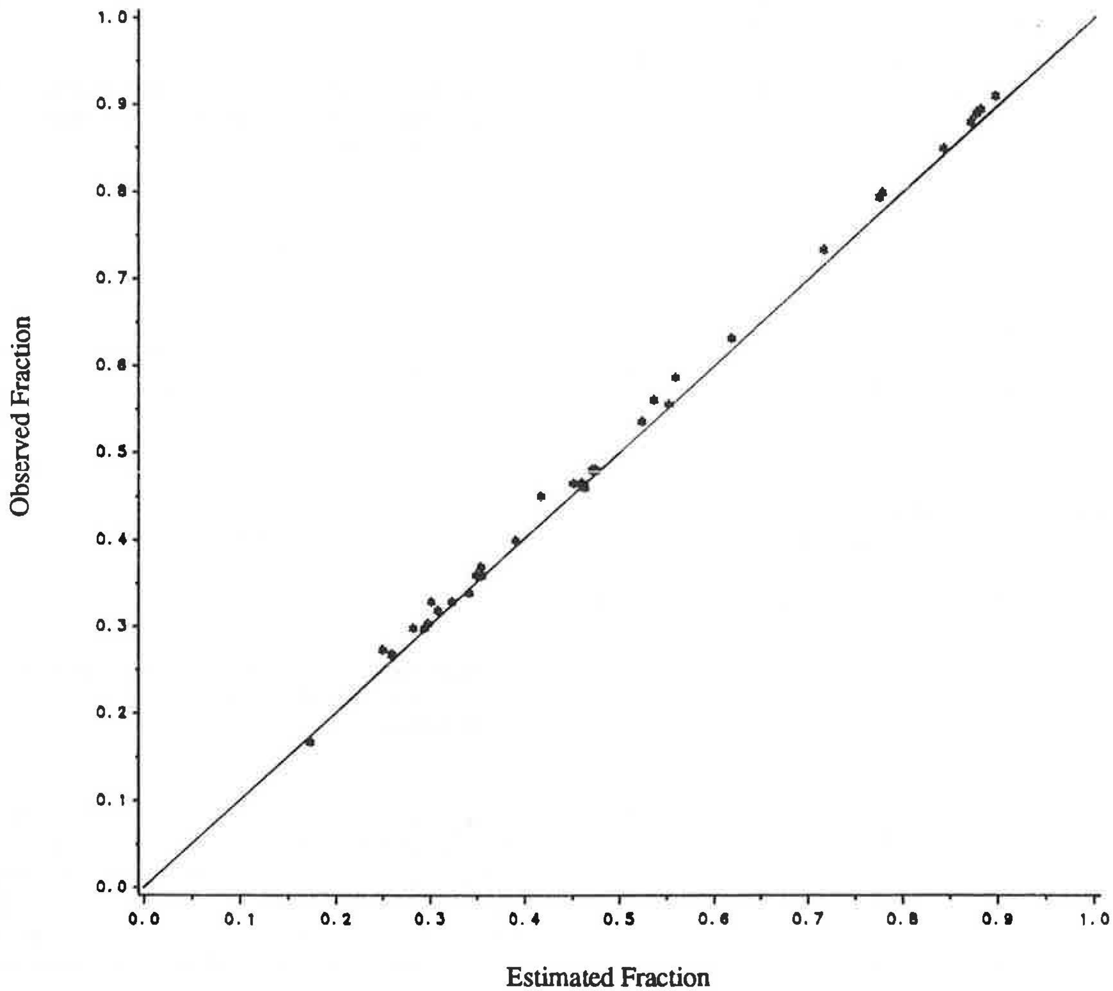



**FIGURE 10 Observed versus estimated fractions in test of independence between departure time and route-switching behavior.**

$t$, make decision $i$ regarding departure time, where $i = 0$ indicates no change and $i = 1$ indicates a change, and decision $j$ regarding route choice (same notational convention as $i$). Then, for a given day $t$ (and dropping the subscript $t$ for clarity of notation), the statistic

$$\chi^2 = \sum_i \sum_j \frac{\left[N_{ij} - \left(\sum_i N_{ij} \cdot \sum_j N_{ij} \Big/ \sum\sum_{ij} N_{ij}\right)\right]^2}{\sum_i N_{ij} \sum_j N_{ij} \Big/ \sum\sum_{ij} N_{ij}}$$

is $\chi^2$ distributed (with one degree of freedom) under the null hypothesis that route switching is independent of departure time switching. Because daily data might result in cells with very few observations, it was necessary to combine the daily data into weekly groups. The results of the test are presented in Figure 11 in the form of a plot of the calculated values of the test statistic for each week of the experiment. Also shown on this plot are horizontal lines corresponding to the 95th and 90th percentiles of the $\chi^2$ distribution (with one degree of freedom). As can be seen, the null hypothesis of independence can be rejected

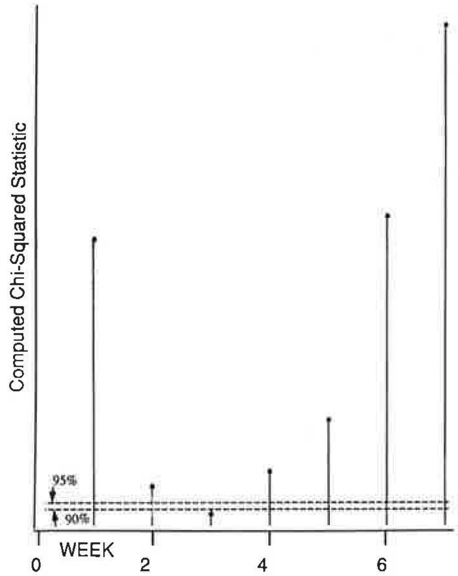



**FIGURE 11 Results of chi-squared test of independence between departure time and route-switching behavior.**

for six of the seven weeks with over 95 percent confidence; the only exception is in the third week, where that hypothesis can be rejected with slightly under 90 percent confidence.

The computed values of the test statistic also provide a useful measure of the magnitude of the discrepancy between the actual (observed) number of switches in each cell and the corresponding theoretical ones that would hold under the independence assumption. Thereby an informal index of the "extent" of the dependence between the two decisions is provided. Viewed from this angle, the evolution over time of the values shown in Figure 11 reveals a striking pattern whereby route and departure time switching decisions exhibit increasing deviation from independence as the system evolves beyond the third week. In the first week, a large deviation from independence can be detected, followed by two weeks of relatively weaker dependence. Having established the dependence between these two decisions, it is important to attempt to describe how this dependence arises in terms of the underlying behavioral mechanisms. An explanation within an extension of the boundedly rational decision framework proposed by Mahmassani and Chang (*21*, *30*) for the day-to-day dynamics of departure time decision making is presented next.

As noted earlier, the pattern of switching of both route and departure time closely parallels that of route, while the switching of only one of the two choice dimensions appears to parallel that of departure time. These patterns suggest that when users switch route, they also switch departure time. This can be verified by the conditional probability of switching departure time given that a route switch is taking place. These conditional probabilities are presented in Table 6, revealing that approximately 80 percent of the participants also switched departure time the first time they switched route and approximately 70 percent did so on the succeeding route switches. Table 7 further presents the conditional probability of switching departure time given that only one of the two is changed. This probability is well over 90 percent on most days, confirming that route switches are in most cases accompanied by departure time switches.

TABLE 6 CONDITIONAL PROBABILITY OF SWITCHING DEPARTURE TIME GIVEN *K*TH ROUTE CHANGE

| K | Number of Participants Switching Routes for Kth Time | Conditional Probability |
|---|---|---|
| 1 | 124 | 0.81 |
| 2 | 109 | 0.68 |
| 3 | 73 | 0.68 |
| 4 | 60 | 0.70 |
| 5* | 41 | 0.66 |

*Less than 20% of the participants had 6 or more route switches

The behavioral implications of the preceding observations are essentially as follows. When users switch only one of the two available decisions, it is most frequently departure time; when they switch route, they generally also switch departure time. This suggests that user behavior in this context might be governed by a hierarchical structure, with departure time switching taking precedence over the route switching decision. Thus the user's initial response to performance failures is likely to be a switch of departure time; continued failure to achieve satisfactory performance, or a particularly "large" failure, would trigger a more drastic response involving the switching of both route and departure time.

This behavior can be explained within the boundedly rational decision framework presented earlier for departure time decisions (*21*, *30*). It relies on Simon's well-known satisficing decision process proposed as a behaviorally realistic alternative to strict rational behavior (*31*). In its application to departure time decisions, user behavior in the commuting system is viewed as a dynamic boundedly rational search for an acceptable departure time (*21*). The acceptability of a given departure time is determined relative to an aspiration level, operationalized in the form of a dynamically varying indifference band of schedule delay (corresponding to acceptable arrival times).

The extension to the decision context where both route and departure time choices are available to commuters can explain the phenomena discussed earlier. Essentially, user behavior can now be viewed as if governed by two indifference bands $IBD \leq IBR$: one associated with the switching of departure time, denoted by $IBD$, which would be a subset of another interval $IBR$ associated with changing route (and departure time in most cases). Since these would vary across users and over time, $IBD_{i,t}$ and $IBR_{i,t}$ are used to refer to user $i$'s values on day $t$. Thus, letting $PM_{i,t}$ denote the performance measure for a given user $i$ on day $t$, if $PM_{i,t} \leq IBD_{i,t} \leq IBR_{i,t}$, then user $i$ will maintain the same departure time and route on day $t$. If $IBD_{i,t} < PM_{i,t} \leq IBR_{i,t}$, then the user will switch departure time

TABLE 7 CONDITIONAL PROBABILITY OF SWITCHING DEPARTURE TIME GIVEN THAT ONE IS SWITCHING ONLY ROUTE OR ONLY DEPARTURE TIME FOR *K*TH TIME

| K | Number Switching Exactly one for Kth Time | Number Also Switching Departure Time | Conditional Probability |
|---|---|---|---|
| 1 | 195 | 186 | 0.95 |
| 2 | 192 | 169 | 0.88 |
| 3 | 189 | 172 | 0.91 |
| 4 | 186 | 170 | 0.91 |
| 5 | 180 | 167 | 0.93 |
| 6 | 174 | 161 | 0.92 |
| 7 | 170 | 153 | 0.90 |
| 8 | 157 | 145 | 0.92 |
| 9 | 151 | 146 | 0.97 |
| 10 | 141 | 134 | 0.95 |
| 11 | 134 | 129 | 0.96 |
| 12 | 118 | 115 | 0.97 |
| 13 | 111 | 111 | 1.00 |
| 14 | 109 | 107 | 0.98 |
| 15 | 97 | 97 | 1.00 |
| 16 | 87 | 86 | 0.99 |
| 17 | 79 | 78 | 0.99 |
| 18 | 68 | 68 | 0.99 |
| 19 | 54 | 53 | 0.98 |
| 20 | 48 | 48 | 1.00 |

NOTE: Less than 20% of the participants switched exactly one more than 20 times

only; however, when $IBD_{i,t} \leq IBR_{i,t} < PM_{i,t}$, then both route and departure time will be changed. The performance measure has not been specified in the preceding, although the schedule delay is the primary candidate given the previous results on the departure time problem (where travel time was virtually insignificant) and the preliminary results of modeling work on this new data set. It is not necessary to preclude at this point, however, the possibility of using some weighted combination of schedule delay and travel time. Furthermore, note that the effect of repeated failures can be captured in the dynamic equations of the indifference bands, as shown in Mahmassani and Chang (*23*).

The analysis just presented has been repeated separately for each group of users sharing the same information availability status. No particular differences were found between the two groups in the nature of the interrelation between departure time and route switching decisions. These results are not presented here for space considerations, and can be found in a separate report (*32*). As noted earlier, the preceding results constitute a set of hypotheses that will be tested in the context of formal econometric modeling work.

## CONCLUSION

The experiment reported in this paper extends the work conducted to date in this research program in two important directions: (1) the inclusion of the route choice dimension in addition to that of departure time and (2) the consideration of two user groups with different information availability levels interacting in the same simulated commuting system. Naturally, the addition of these features greatly adds to the complexity of the system and to the subsequent analysis of the results. On the other hand, it yields important insights into some of the least studied and least understood aspects of tripmaker behavior in congested urban networks.

This added complexity and the higher congestion level in this commuting system relative to that prevailing in the two previous experiments have resulted in the inability of the system to converge to a steady state where all users are satisfied with the consequences of their departure time and route decisions over an extended experimental period of 34 days. However, a general trend of decreased switching activity over time was exhibited by the users' behavior. Taken with the results of previous experiments, a clearer picture of a traffic system's day-to-day evolution in response to major supply-side changes is beginning to emerge. The effect of information availability on the behavior and performance of given user groups is of particular interest. In this regard, the results of this experiment are to a large extent consistent with a priori expectations based on intuition; that is, users with more information clearly outperform those with limited information when both are competing in the same system. The fraction of total users with particular information levels, however, appears to be a significant determinant of the effect of this information. In the limit, if all users share the same "complete" or "limited" information, a system with complete information may experience greater turbulence in its evolution (*22*). These findings have important implications for ongoing efforts and interest to develop information-related strategies involving communication and information technologies, for the relief of traffic congestion in urban networks. In particular, the type and quantity of information, as well as its distribution across the user population, can greatly influence the resulting impact on the system.

The interdependence between route choice and departure time decisions is another important aspect of user behavior addressed in this paper. The exploratory aggregate analysis considered here points to the precedence of departure time shifts over route shifting in dealing with experienced unpredicted congestion in the system. The explanation for the observed behavior within the previously articulated boundedly rational decision framework appears to be plausible, and preliminary results of model estimation work are confirming this explanation. The insights based on this exploratory analysis form the principal hypotheses guiding the development and calibration of dynamic discrete choice model of user behavior.

Naturally, there are important limitations associated with the general experimental approach followed here, as well as with the particulars of the experiment described in the paper. Regarding the general approach of using real commuters in a simulated system, extensive discussion can be found elsewhere (*20*, *21*, *22*) and is not repeated here. Suffice it to say that this approach can play an important role in the development of theory and behavioral insights that can guide eventual complete or partial field validation. Regarding the specific elements of this experiment, the main new concerns (relative to the previous two experiments) relate to the omission of potentially important attributes that affect route choice. In particular, the visual dimension is missing, thereby excluding the influence of aesthetics. Similarly, pavement texture and condition and the resulting ride quality are other accessory attributes. For all practical purposes, the two routes must be considered as identical in all respects other than their operational characteristics.

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