Comparative Assessment of Origin-Based and En Route Real-Time Information Under Alternative User Behavior Rules

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The effects of real-time traffic information, supplied at the origin of the trip or along the way (en route), on the system's performance under alternative behavioral rules governing path selection in the network are examined in this paper. Simulation experiments are performed to investigate the effect on overall system performance as well as the incidence of benefits (costs) across user information groups of four experimental factors: (*a*) behavioral rules, governing users' response to real-time information, (*b*) sources of information, consisting of point-of-departure or in-vehicle (or both), (*c*) prevailing "initial conditions" in the system, and (*d*) market penetration (i.e., the fraction of users with access to real-time information in the network). The results of these simulation experiments provide insights into the effectiveness of real-time advanced driver information systems on systemwide performance and on its critical determinants. The results confirm a priori expectations that the existence of benefits as well as the relative effectiveness of origin-based versus en route information is highly dependent on the initial conditions prevailing in the system as well as the behavioral rules governing path selection. Extreme behavior by users (with frequent switching in myopic response to any gain, no matter how small) could lead to severe worsening of traffic conditions under real-time information from either source. On the other hand, switching according to a boundedly rational model incorporating a threshold improvement in trip time is more likely to lead to meaningful systemwide benefits.

The supply of real-time traffic information to tripmakers through various possible forms of advanced driver information systems (ADIS) is increasingly looked to as a means of reducing traffic congestion in urban networks (*1*). The effectiveness of different types of ADIS and alternative information supply strategies depends on the complex interactions between user decisions and the network's performance. Questions regarding user behavior as it pertains to different types of ADIS do not appear to have received much attention to date, although they will be critical to the successful implementation of these systems.

In this paper, concern is with two principal behavior aspects of real-time ADIS. The first consists of the mechanism or choice rule governing path selection in response to real-time information on the current trip times on competing paths. The second concerns market penetration, or the effect of the fraction of users in the network with access to such information. While models are proposed and illustrated for the first phenomenon, with respect to the latter, sensitivity analysis is performed and overall system performance and effectiveness is examined for different levels of market penetration.

Another principal focus of this paper is the comparison between two sources of information with different technological and cost characteristics: point-of-departure information versus in-vehicle (en route) information. In both cases, the user would have access to real-time information on current conditions on the various network components. However, in the former, the information influences the driver's initial choice of route (and possibly his or her time of departure), whereas in the second case the driver is already on an initially selected route after having left his or her origin. The analysis focuses primarily on the a.m. home-to-work commute (though a similar treatment could be developed for the p.m. peak period). The point-of-origin information then becomes equivalent to information that one would consult at home, and which can therefore be supplied through existing media, primarily television or telephone lines (connected to a home terminal). On the other hand, in-vehicle information would require the kind of telecommunications and microprocessor technologies and infrastructure contemplated in the various proposed and prototype ADIS systems (*1*). The relative effectiveness of these two sources of traffic information has extremely important technical and policy implications, given the significant differences in the size of the respective investments required by each source. In other words, which of the two sources, taken separately, leads to greater improvement in system performance, if any? If origin-based information is provided, how much additional improvement could be attained by continued en route information availability?

The above questions are explored in the context of numerical simulation experiments in a commuting corridor. Several key factors that determine the answers to these questions are identified and illustrated, particularly the sensitivity of the results to (*a*) the underlying behavioral rules governing users response to the supplied information, (*b*) market penetration, or the fraction of the population with access to the information, and (*c*) the prevailing "initial conditions" in the system, and the corresponding availability of improvement opportunities via flow redistribution among alternate routes.

The simulation experiments are performed using a modeling framework previously developed by Mahmassani and Jayakrishnan (*2*). A corridor network structure is considered, consisting of three principal highway facilities offering several switching opportunities. Only auto drivers are considered, though the behavioral framework could be extended to include transit users. As noted, the illustration is limited to the a.m. home-to-work commute.

In the next section, some aspects of the behavioral framework for the user response models are discussed, and specific

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decision rules are formulated for this purpose. The simulation experiments are then described, including an overview of the simulation model used and a detailed discussion of the specific levels considered for each experimental factor. The simulation results are then discussed, followed by concluding comments.

BEHAVIORAL FRAMEWORK AND RULES

General Behavioral Considerations

The effectiveness of information technology to achieve traffic control objectives depends on (*a*) the existence of improvement opportunities in prevailing traffic conditions, (*b*) the nature and type of information available to different segments of the user population, and (*c*) users' behavior and response to the supplied information.

Mahmassani and Jayakrishnan (*2*) have classified information strategies into four generic categories:

1. Descriptive, stored information, such as a static map that displays only stored information on (fixed- or time-dependent) trip times on the various network links.
2. Descriptive, real-time information, where the trip times are updated on a real-time basis to indicate prevailing congestion on the various network links.
3. Descriptive, real-time information with individual optimization, in which the link-level information could be processed either on board or centrally to compute the current shortest path from the present position to the desired destination of given driver.
4. Controlled guidance, under which the instructions given to users reflect a central controller's system-level objectives, subject to certain constraints to prevent unreasonable penalties to any individual tripmaker.

User behavior and response to the supplied information is the result of a complex process involving human judgment, learning, and decision making in a dynamic environment. This process depends on the type and nature of the information provided, in addition to the individual characteristics and preferences of the tripmaker. In all four cases identified above, user response can be viewed in terms of four choice dimensions: (*a*) acquisition of the equipment, (*b*) consultation of the information system, (*c*) compliance with its instructions, and (*d*) trip decisions and actions (behavior). Of course, these dimensions take place over varying time frames.

Acquisition of the on-board equipment is a long-term decision, reached by the user after some deliberation involving the trade-off of perceived benefits with monetary costs. This decision can undoubtedly be modeled adequately in a standard random utility maximization discrete choice framework.

Consultation of the equipment is a real-time decision, made along and possibly also at the beginning of the trip. The consultation decision is likely to be governed by different behavioral mechanisms for each of the preceding generic types of information systems and strategies. For example, a static map with historic information only (the first strategy) is not likely to be consulted (for path selection purposes) other than at the beginning of a trip or to find an alternate path along the way if actual congestion exceeds anticipated congestion. [Operationally, this choice can be modeled as follows. Let TT_{in} denote the actual trip time experienced by user i up to node n, and ATT_{in} the initially anticipated trip time up to that node. If $(TT_{in} - ATT_{in})$ exceeds a certain threshold, then the driver will consult the video map to identify a suitable alternative.] On the other hand, a controlled guidance system (the fourth strategy) is likely to be consulted on a virtually continuous basis. The underlying behavioral process for the second strategy is likely to be closer to that for the first strategy, whereas the third strategy is likely to be closer to the controlled guidance case. In all cases, the consultation decision is influenced by longer-term processes, particularly user perceptions of the reliability and usefulness of the system, formed mostly by learning through one's own experience with the system, as well as reports by friends, colleagues, and popular media.

The third choice dimension is referred to here as compliance. It is a real-time decision, definitely influenced by the above-mentioned longer-term learning phenomena that form user perceptions. This dimension is not directly applicable to the first two information supply strategies. It is most applicable in the fourth strategy, where specific route guidance instructions are provided, with the controller's intent that they be followed by the motorists. In this case, compliance will be a critical factor in overall system effectiveness. For the third strategy, the applicability of this dimension depends on the specific information displayed. If it consists of just (current) trip times on alternate paths, then it is not clear what compliance would refer to. On the other hand, if a single path is displayed, because it has been determined to be the shortest or otherwise "best" according to some criterion (or as a result of an on-board expert system recommendation), then compliance could be defined relative to that recommendation.

The fourth dimension actually includes several possible decisions, with varying time frames for each. The most evident is en route path switching, which is the principal real-time decision targeted by in-vehicle information systems. A second decision consists of initial (home based for the a.m. commute) route selection. This decision can be taken as an immediate response to real-time information consulted at the trip origin (and supplied either through the in-vehicle display or some other in-home medium). However, it is also influenced by the day-to-day experience of the users in the system, which contributes to forming the users' perceptions both over the short-term (day-to-day) and over a longer time frame. A third response consists of trip timing. In the immediate term, the tripmakers can delay, advance, or both the time of their trips, in light of prevailing traffic conditions. From day-to-day, the tripmakers will adjust their departure time, as a result of learning through repeated system usage. The user's preferred arrival time plays an important role in this process. Some equilibrium choices or timing strategies might be reached by individual commuters over time as a result of this process. (Another possible choice available to users in the medium term is that of changing modes, particularly switching from automobile to transit, if adequately available.) Over the medium to long term, changes in activity patterns could take place, reflecting the users' potentially improved ability to schedule their activities using reliable real-time information. Of course, over the very long term, the standard choice dimensions of residential or work locations remain available for users; these are outside the scope of the present discussion.

An important factor that was noted in connection with all of the decisions just outlined is that of the perceived reliability of the information and its resulting credibility. This arises primarily from the dynamic nature of the decision environment and the presence of collective effects in the network as a result of the interactions of a large number of individual decisions. In particular, a "best" path predicated on current link-trip times may well turn out to be less than optimal as congestion in the system evolves. This issue is of particular concern for the third and fourth information strategies defined previously. Of course, it is possible to use predicted trip times for path computations instead of the current actual values. However, the accuracy of the prediction logic would have to be questioned as no such entirely satisfactory prediction techniques are currently available. This is particularly problematic under the fourth strategy (controlled guidance). To what extent will (and can) the anticipated response of users to the supplied guidance instructions be incorporated in the prediction? Naturally, the reliability issue becomes more critical as the fraction of users in the system with access to the information increases, as seen in the simulation experiments presented in the final section of the paper.

The focus of this paper is primarily on the en route path switching decision in real-time, in response to information of the third strategy. In other words, the users are assumed to know the current travel time on the best path from the current node to their destination. The focus is also on the initial path selection decision, at the trip origin, in response to information similar to that available under the third strategy, though it may not necessarily be delivered through an in-vehicle medium, as discussed in the previous section. Only the real-time aspects of these decisions are considered in this analysis; the day-to-day and longer-term aspects will be introduced at a later stage. In addition, the equipment acquisition decision will be indirectly considered by conducting sensitivity analyses with respect to a market penetration parameter.

Next, alternative behavioral mechanisms and choice rules for path switching and initial route selection are formulated. These form the basis of the numerical simulation experiments conducted to compare the relative effectiveness of en route and origin-based real-time information.

Path Selection and Switching Rules

Several alternative mechanisms and behavioral rules with varying degrees of complexity could be formulated for each of the elements identified in the preceding discussion. However, in the absence of definitive observational data, the focus is on simple operational representations that adequately capture the character of user behavior and can thus be used in the context of simulation models to evaluate the overall performance and effectiveness of real-time information in traffic networks. Three distinct alternative rules are proposed hereafter for en route path switching; similar constructs can also be used for initial path selection. The first is a so-called myopic deterministic choice rule; the second is a boundedly rational model of path switching, whereas the third is a standard random utility discrete choice model. These are described in turn hereafter.

Rule R.1. Myopic Switching Rule

By analogy to the standard path choice rule in static network assignment models (*3*), this rule simply states that from any given node n, users will always select the best path (in terms of least cost or least travel time) from the current node to their destination, that is,

$$\delta_{ik}(n) = \begin{cases} 1 \text{ if } TT_{ik}(n) \leq TT_l(n),\ \forall\, l \in P_i(n),\ i \neq k \\ 0 \text{ otherwise} \end{cases}$$

where

$\delta_{ik}(n)$ = binary indicator, equal to 1 if user i selects path k between node n and the destination, and 0 otherwise;
$TT_{ik}(n)$ = current trip time on path k between node n and user i's destination; and
$P_i(n)$ = set of paths between node n and user i's destination.

The assumption that drivers follow the current best path from every node along the way is rather extreme, in that it would lead the user to switch paths in pursuit of any gain, no matter how insignificant.

Rule R.1 can be restated in the following switching form:

$$\delta_i(n) = \begin{cases} 1 \text{ if } TTC_i(n) > TTB_i(n) \\ 0 \text{ otherwise} \end{cases}$$

where

$\delta_i(n)$ = binary indicator equal to 1 if user i switches from the current path to the "best" one between node n and the destination, 0 otherwise;
$TTC_i(n)$ = trip time on the current path from node n to user i's destination; and
$TTB_i(n)$ = trip time on the best path between n and user i's destination.

An important concept in this rule is the notion of a current path, which is central to the modeling framework. It assumes that the users have an evoked current path to which they might exhibit some degree of commitment. In a freeway corridor context, such an evoked path might be strongly associated with the freeway itself or with a major alternate parallel arterial. A possibly more reasonable assumption than the above extreme myopic rule is that driver switching behavior exhibits a boundedly rational character anchored in one's current path. This assumption is operationalized next.

Rule R.2. Boundedly Rational Switching Rule

The notion of bounded rationality in the context of the day-to-day dynamics of departure time and route decisions of urban commuters has been extensively explored by Mahmassani and Chang (*4–7*). It has been applied for the real-time route switching decisions under in-vehicle information by Mahmassani and Jayakrishnan (*2*). This notion can be operationalized using a satisficing switching rule with an indifference band of trip time saving. Users will switch from their current path to the best alternative only if the improvement in the remaining trip time exceeds this indifference band. This threshold can be expressed either in absolute terms, or relative to the remaining trip time. Following Mahmassani and Jayakrishnan (*2*), a switching rule with a relative indifference band subject to a minimum (absolute) trip time saving can be stated as

$$\delta_i(n) = \begin{cases} 1 \text{ if } TTC_i(n) - TTB_i(n) > \max[\eta_i(n) \cdot TTC_i(n), \tau_i(n)] \\ 0 \text{ otherwise} \end{cases}$$

where

$\eta_i(n)$ = relative indifference band for user i, as a fraction of the remaining trip time on the current path from node n to the destination: $TTC_i(n)$, with $\eta_i(n) \geq 0, \forall\, i, n$;

$\tau_i(n)$ = minimum improvement in the remaining trip time, from node n to the destination, necessary for user i to switch from his or her current path, with $\tau_i(n) \geq 0, \forall\, i, n$; and all other terms are as previously defined.

It can be seen that rule R.1 is a special case of rule R.2 with $\eta_i(n) = 0$ and $\tau_i(n) = 0, \forall\, i, n$.

In the model, $\eta_i(n)$ is expressed in relative terms. It can be thought of as the percent improvement in remaining trip time vis-a-vis the current path. Moreover, to preserve a meaningful threshold effect and preclude unintended switching when $TTC_i(n)$ becomes very small as drivers approach their destination, the absolute band $\tau_i(n)$ is introduced to provide a lower bound. Both $\eta_i(n)$ and $\tau_i(n)$ could be either fixed constants or vary from node to node, and possibly over time. Furthermore, they could be related systematically to the socio-demographic attributes of the user. The simulation results presented in this paper assume fixed values for these bands over the duration of any given trip. Furthermore, while $\eta_i(n)$ is allowed to vary across users, $\tau_i(n)$ is taken as constant τ for all drivers.

Several alternative formulations for the indifference bands are possible. For instance, the band could increase at a fixed percentage rate per distance traveled, or according to some systematic process that would capture the dynamic effect of the user's experience in the system. Such increasing bands would reflect the drivers' decreasing propensity to switch as they approached their destinations.

Rule R.3. Probabilistic Discrete Choice Rule

A natural alternative mechanism for path selection at a given node would be a probabilistic discrete choice model, along the lines of those proposed for stochastic network traffic assignment (*8*). For example, the well known multinomial logit form could be used to calculate the probability $P_{i,n}(r|R_n)$ that user i chooses route r from node n to the destination, given a choice set R_n of alternative paths available at that node. This probability would be a function of the utilities $U_{in}(r)$ associated with each route $r \in R_n$. The utilities would be functions of the characteristics of the routes, including the trip time, trip time reliability, schedule delay, and a possible penalty for switching from the current path. Some difficulties do, however, arise in the application of such a route choice rule for repeated en route decisions in the context of a simulation model. The principal concern is that such decisions cannot be assumed to be independent within and across users. Specifications of the utility functions in a way that correctly capture the temporal dependencies within each user as well as across users are likely to be quite cumbersome, and rather difficult to calibrate correctly and implement operationally.

As noted previously, the rules could be applied en route as well as at the trip origin, primarily in connection with descriptive real-time information with self-optimization capability (information supply strategy three), which would provide estimates of the remaining trip time on the user's current path as well as identify the best path (for rules R.1 and R.2). For rule R.3, additional information would be required, though its form and content is not entirely clear. An expert system could possibly provide trip times on a subset of efficient paths, including the current one. All of the above rules can be modified for multiple destinations by adding the appropriate destination subscript.

Departure Time Decision Considerations

The preceding rules are for the path selection and switching decisions, which form the focus of the experiments reported in this paper. Rules for the departure-time decision in response to real-time information have not been investigated nor suggested by researchers, as the effect of real-time information on this choice dimension has not generally been recognized. However, simulation results reported by Mahmassani and Jayakrishnan (*2*) for a particular set of conditions in a hypothetical commuting corridor have suggested that the potential to reduce congestion through peak spreading obtained by trip-time shifting may be quite significant relative to what might be achievable through traffic redistribution over space (i.e., over alternate paths). This point has also been highlighted in a recent Mobility 2000 report (*9*).

As discussed previously, departure time changes could take place both in real-time as well as from day-to-day (and eventually over the long term). On a real-time basis, the user can consult a home-based advisory unit (or TV-relayed information) for current traffic conditions, and decide accordingly to advance, delay, or keep the trip at the same time. Rules with varying degrees of complexity could be formulated for this decision process. Two classes of rules can be suggested for this purpose: (*a*) satisficing rules, that trigger a change when the difference between anticipated and current conditions exceed some threshold; and (*b*) random utility maximization rules whereby users select the departure time that maximizes their utility over all subsequent possible departure times [examples of specifications for the utility functions can be found in Hendrickson and Plank (*10*)].

Of greater concern are the day-to-day adjustments of departure time and the resulting longer-term changes in the temporal loading pattern. Rules similar to those proposed by Mahmassani and Chang (*11,12*) and Tong, et al. (*13*) could be adapted to the situation of real-time information availability. Essentially, such information would be combined with the user's experience with the network to provide the basis for such departure time adjustments (*12,13*). With such rules, the evolution of the system under real-time information could be explored, and the effectiveness and benefits of the latter could be assessed from a long-term perspective rather than simply through the consideration of real-time responses on a given day. Such investigation is outside the scope of the present paper, which considers only real-time path selection responses of commuters. The simulation-assignment modeling framework and the specific simulation experiments conducted for this study are described in the next section.

MODELING FRAMEWORK AND SIMULATION EXPERIMENTS

This section first describes the commuting context and some assumptions pertaining to the definition of alternate paths in the network, followed by an overview of the simulation-assignment methodology. The simulation experiments are then described, including the four principal experimental factors and the corresponding levels considered.

Commuting Context

The model used to perform the simulation experiments is an extension of the corridor simulation-assignment model developed by Mahmassani and Jayakrishnan (*2*). In addition to the existing en route path switching model, it incorporates a new pretrip path selection component to evaluate system improvement opportunities under real-time on-board information, real-time home-based information, or both. The simulation experiments are performed for a commuting corridor with three major parallel facilities, such as freeways or major arterials, for the morning work commute. For convenience and with no loss of generality, all three facilities are 9-mi long, and each is discretized into 9 segments, each 1-mi in length, with crossover links at the end of the 3rd, 4th, 5th, and 6th mi to allow switching from one facility to another (see Figure 1). Commuters enter the corridor through ramps feeding into each of the first six (1-mi) segments on each facility, and commute to a single common destination downstream (such as the central business district or a major industrial park).

In all experiments, 10,800 vehicles are loaded to the corridor over a total duration of 75 min according to a specified time-dependent departure pattern (which is itself an experimental factor in the simulations, as described later in this section). Of the three major facilities, hereafter referred to as Highways 1, 2, and 3, Highway 1 has the highest free mean speed of 55 mph. Highway 2 is the second best, with a free mean speed of 45 mph, followed by Highway 3 (35 mph). All the crossover links have a free mean speed of 45 mph.

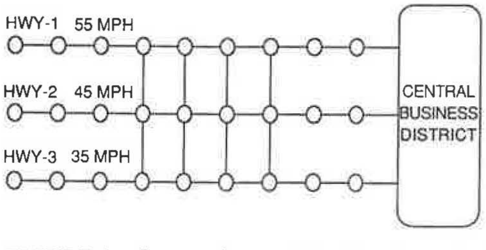


FIGURE 1 Commuting corridor (length = 9 mi).

Assume that a fraction of the commuters have access to real-time network traffic information, be it from an on-board traffic advisory unit or a home-based traffic advisory unit. In particular, the user receives information on the prevailing trip times on all the links of the network. These form the basis for computing the trip times from the user's present location (either at the origin or en route) to his or her destination along alternate paths (i.e., under the third information supply strategy discussed in Section 2). A behavioral assumption is made in the definition of available paths, namely that users perceive and identify a path in terms of its major highway facility. This would result from the extent of a hierarchy in the manner in which users perceive a particular network. Thus a path for the purpose of this analysis consists of a single major facility (to the destination) along with its connecting link. Consequently, at any given node (including the origin), the user effectively considers only three paths, one for each facility. In addition to its behavioral plausibility, this assumption offers the advantage of tremendously simplifying the path processing burden that must be performed by the assignment model (*2*).

To implement the behavioral rules presented in the preceding section (particularly rules R.1 and R.2), a current path is associated with each user, as discussed previously, both at the origin node and along the way. In the latter case, an alternative route consists of a crossover link from the current node to another major highway facility and the remaining portion of that facility to the destination. Thus at every node (including the origin), $TTC_i(n)$ and $TTB_i(n)$, the travel times on the current and the best paths, respectively, are calculated for processing by the user decisions component, as explained in the following.

Simulation-Assignment Model

The model is composed of three main components: the traffic performance simulator, the network path search and assignment component, and the user decision-making component. The first component is a special-purpose macroparticle traffic simulator (MPSM), which extends a code previously developed by Chang, et al. (*14*) for the simulation of vehicular movements on highways and arterials. The simulation logic follows that of the magneto-hydrodynamic code developed by Tajima et al. (*15*) for plasma physics applications. It is a fixed time-step simulator. Vehicles on a link are moved individually at prevailing local speeds consistent with macroscopic speed-density relations (modified Greenshield's model in this case). Inter-link transfers are subject to capacity considerations. For given network representation and link characteristics, the simulator takes a time-dependent input function and determines the associated vehicular movements, thereby yielding the resulting link trip times, including estimated delays associated with queueing at nodes. These form the input to the path search and assignment component, which calculates the pertinent path trip times, which are in turn used by the user decisions component. The latter is intended to predict the response of users to the available information, according to a set of behavioral rules of the kind described in the previous section. Another function of the second component is to translate the user path selection and switching decisions into time-varying link flow patterns on the network's links. Further detail on the simulation-assignment methodology can be found in the paper by Mahmassani and Jayakrishnan (*2*).

All simulation experiments were performed on a CRAY X-MP supercomputer to meet the extensive memory requirements associated with applying the behavioral rules at the individual vehicle level and tracking individual vehicle paths.

Experimental Factors

The simulation experiments were conducted to explore the opportunities for system improvement with respect to four principal factors—information source, behavioral rule, loading pattern, and market penetration. These are described in turn hereafter.

Information Source

As mentioned previously, two information sources are considered: home-based information, consulted before actually starting the trip, and in-vehicle en route information. Four strategies are considered for this factor: (*a*) no information (base case), (*b*) home-based pretrip information only, (*c*) en route only, and (*d*) both sources are available. Under the second strategy (*b*), path selection is allowed only at the origin. Once users are driving on any given link (including the entry ramp), it is no longer possible for them to switch to another facility (at least not in response to real-time information in this model). Under the third strategy (*c*), users only have access to information along the way. They always enter the corridor system through their individual primary highway path (assigned as part of the loading pattern) and can switch through crossover links only. Under the last strategy, users have access to real-time information both at the origin and en route, and can therefore select their initial path accordingly as well as switch paths along the way. As explained previously, the relative effectiveness of these two sources of information is one of the principal objectives of this paper.

Behavioral Rule

Only the results for the myopic rule (R.1) and the bounded-rational relative indifference band (R.2) are presented in this paper. In the simulation runs, each user with information is assigned a randomly generated indifference band, η_i, drawn from a triangular distribution with mean $\overline{\eta}$ and range $\overline{\eta}/2$. In Mahmassani and Jayakrishnan's previous simulation experiments (*2*), it was found that a mean indifference band of 0.2 appears to provide reasonable overall behavior as well as the largest systemwide improvement in travel time. Thus only two levels of $\overline{\eta}$ were considered in these experiments: 0.0 and 0.2. In the no band case ($\overline{\eta} = 0.0$), all users are assumed to have a zero band, hence this case represents the myopic case (rule R.1)—users with information will always switch to an alternative path if it offers an improvement in trip time, no matter how small. The minimum absolute improvement threshold τ_i, set at 1 min, is taken to be identical across all users with information, except in the zero band case in which no minimum improvement restriction is imposed.

Two different mean indifference bands were implemented in these experiments: $\overline{\eta}_{1i}$ for the pretrip route choice model and $\overline{\eta}_{2i}$ for the en route path switching model. Hereafter, denote each case by $[\overline{\eta}_{1i}, \overline{\eta}_{2i}]$ where a value of 99 is used to indicate that no switching is allowed. (In the actual computer program, the minimum absolute improvement threshold τ_i was set at a very high value to preclude any switching.) Thus two cases each were considered for home-based pretrip switching only and en route switching only. These are [0.0, 99] and [0.2, 0.9] for the former, and [99, 0.0] and [99, 0.2] for the latter. Four combinations of behavioral rules were considered for the situation where both home-based and en route information are available: [0.0, 0.0], [0.0, 0.2], [0.2, 0.2], and [0.2, 0.0]. Of course, the no-information base case corresponds to [99, 99].

Loading Pattern

One of the principal determinants of the existence of opportunities to improve the overall system consists of the existing network traffic conditions. To capture this effect, three loading patterns were used in the simulation experiments. These are conveniently referred to hereafter as loading patterns 1, 2, and 3. In all cases, a total of 10,800 commuters, split equally among the first six (residential) sectors, share the use of facilities in the corridor during the morning commute. Commuters in each sector depart uniformly over a 20-min period; the loading periods for each sector are staggered with a time lag of 5 min between adjacent sectors, with Sector 1 starting first.

Under the first loading pattern, commuters are split equally among the three highways, departing at a rate of 30 veh/min/sector for each facility. The second loading pattern has departing rates of 40 veh/min for Highway 1, 30 veh/min for Highway 2, and 20 veh/min for Highway 3, for each sector. Under loading pattern 3, 60 vehicles enter Highway 1, 20 vehicles enter Highway 2 and 10 vehicles enter Highway 3, all min/sector. Note that these assignments constitute intended paths for the commuters. If origin-based real-time information is available, the actual initial path selected by commuters with access to such information may be different.

Market Penetration

To examine the effect of this critical parameter, five levels of the fraction of users with access to real-time information were considered, spanning the spectrum from luxury gadget to universal availability: 0.10, 0.25, 0.50, 0.75, and 1.00. As they are generated, individual vehicles are assigned their information availability status randomly and independently according to the above fractions.

Using different combinations of these four experimental factors, 123 separate simulation runs were performed. The results are discussed in the next section.

ANALYSIS OF RESULTS

System performance for each simulation run is evaluated by comparing the average trip time for all commuters in the system to the corresponding value in the base case (the do-nothing case, denoted by [99, 99] in the previous section, with the same initial loading pattern). The average trip times for the base case for loading patterns 1, 2, and 3 are 23.30 min, 21.45 min, and 23.26 minutes, respectively. The clearly superior performance of the system under loading pattern 2 reflects the assignment of vehicles in relative proportion to the individual facilities performance characteristics, as captured here by the free mean speed (recall that Highway 1 has the highest free mean speed). Loading pattern 2 thus appears to provide an assignment of vehicles that is closer to some optimal value than the other two. On the other hand, loading pattern 1 has relatively too many vehicles on Highway 3, whereas loading pattern 3 underuses Highways 2 and 3 while overloading Highway 1.

Figure 2 depicts the variation in total trip time in the system (expressed as a percent of the base case) with the fraction of the user population with access to information, under both myopic and boundedly rational indifference band rules, for each of the three loading patterns, under real-time home-based information availability only. Each case is identified in the figure legend by the notation defined in the previous section. Figure 3 presents similar results for the situation where only en route real-time information is available, whereas Figure 4 presents the results of the simulations under both home-based and en route information availability. Because the total trip times are expressed as a percent of the base case under that particular loading pattern, values exceeding 100 percent indicate a worsening of systemwide performance (compared with the do-nothing case).

To capture the incidence of the benefits (and/or costs) on the user population, Figures 5, 6, and 7 depict the average trip time experienced by those who have access to information in the three cases considered, respectively, again expressed as a percentage of the corresponding average trip time in the do-nothing base case. Figures 8, 9, and 10 present similar information for those trip makers with no access to information. The system's overall performance is examined next, followed by a discussion of the incidence of the benefits and costs on those with and without access to information.

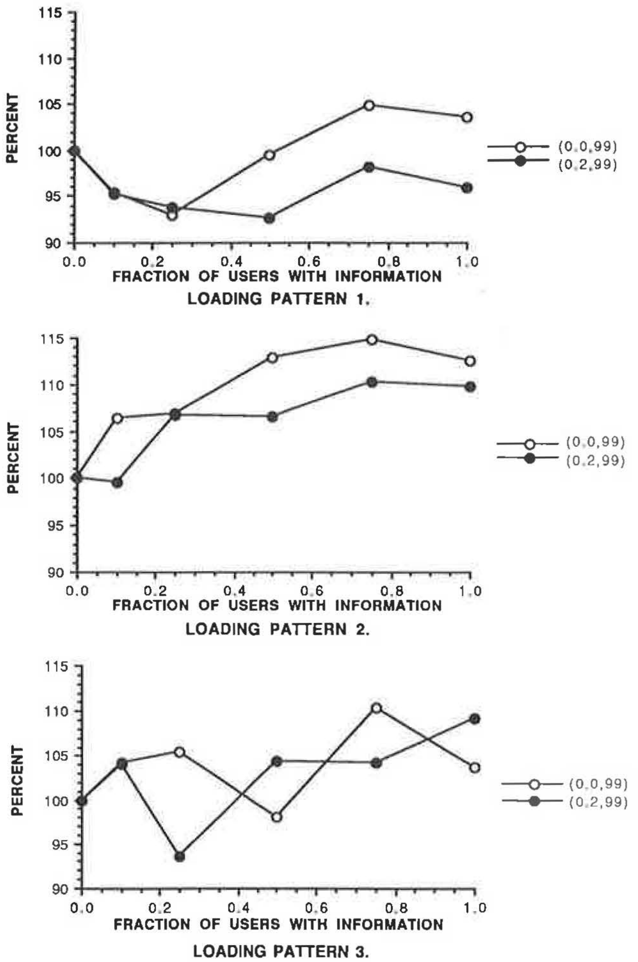


FIGURE 2 Variation of average trip time for all users, as a percentage of no-information base case, under home-based real-time information availability only.

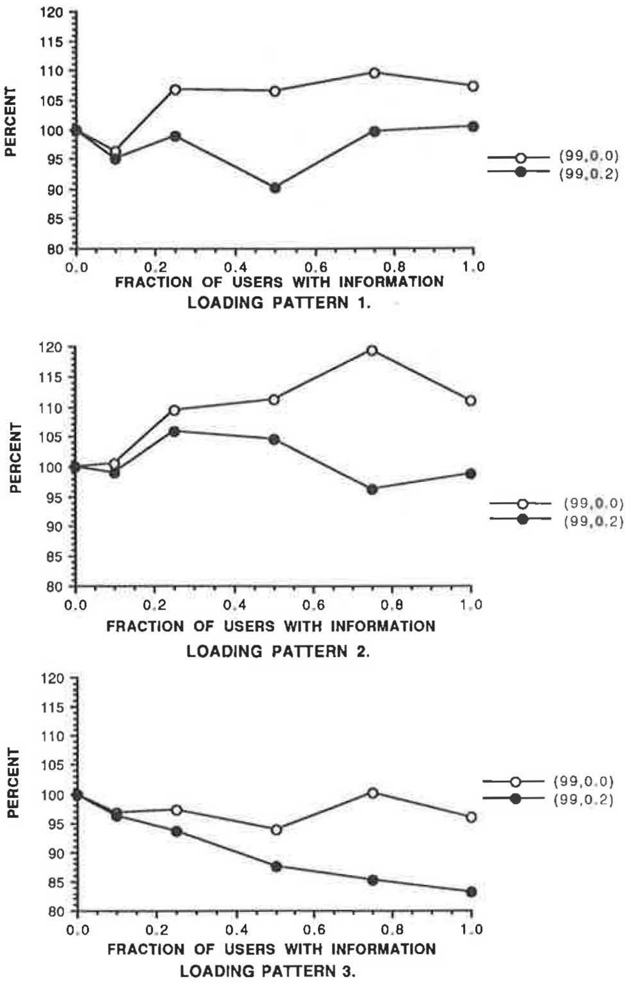
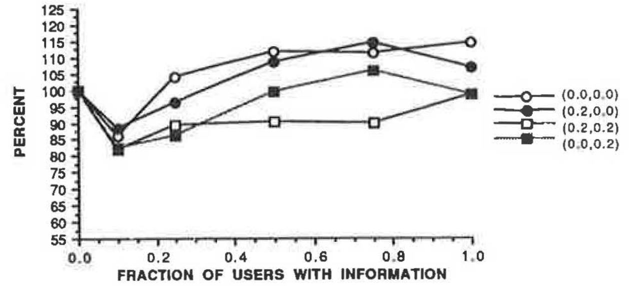


FIGURE 3 Variation of average trip time for all users as a percentage of no-information base case, under en route real-time information availability only.



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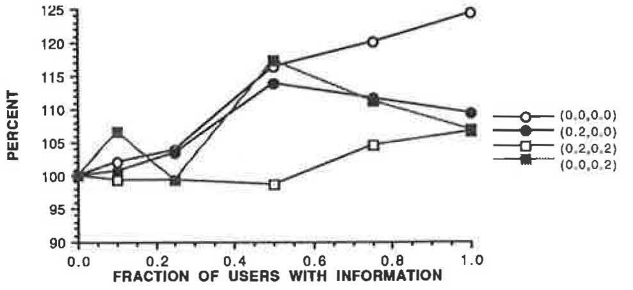

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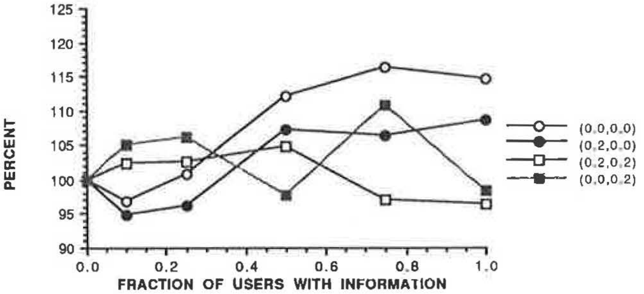

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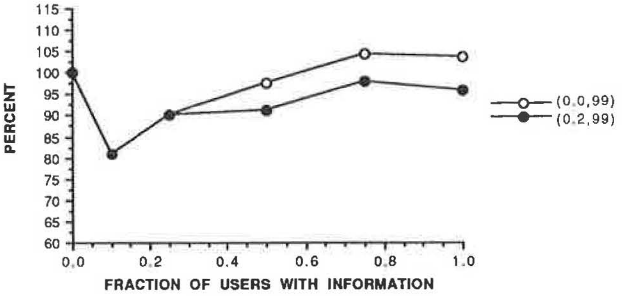
FIGURE 4 Variation of average trip time for all users, as a percentage of no-information base case, under both home-based and en route information.



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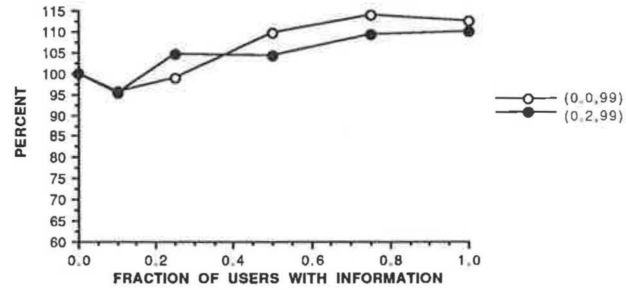

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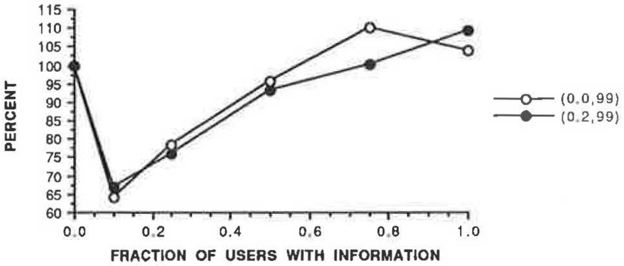

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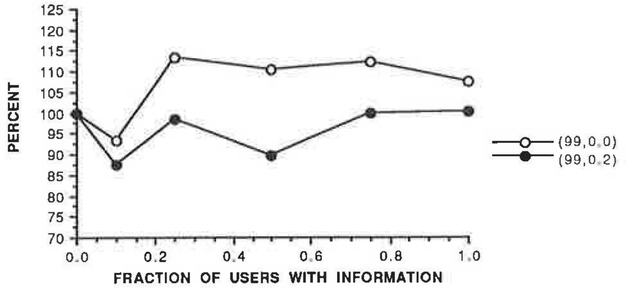
FIGURE 5 Variation of average trip time for users with information, as a percentage of no-information base case, under home-based real-time information availability only.

Systemwide Performance

From a system controller's standpoint, the purpose of home-based real-time information would be to rearrange the loading pattern, through pretrip path selection, in such a way that it becomes closer to the system optimum. However, this information source may not necessarily succeed in improving the system, especially when users select their respective paths according to the myopic rule (R.1), as illustrated in Figure 2. Improvement in system performance is observed for up to 50 percent market penetration, with a high of about 7.0 percent improvement, attained at 25 percent market penetration, and a low of 4.9 percent increase in delay, at 75 percent market penetration under the first loading pattern. Virtually no improvement is obtained under loading pattern 2, with system performance actually worsening by a maximum of approximately 15 percent at 75 percent market penetration. Very little improvement in overall performance is attained when users respond according to the myopic rule (R.1) under initial loading pattern 3. The highest improvement achieved under any market penetration level considered is only 2.0 percent, at 50 percent market penetration. For all other levels, the performance worsens under rule R.1, to a maximum of approximately 10.4 percent.

Under the boundedly rational response rule (R.2), with a mean indifference band of 0.2, Figure 2 indicates that, for loading pattern 1, system performance under origin-based real-time information improves at all levels of market penetration, with a maximum of approximately 7.4 percent. Since loading pattern 2 is closer to the optimum, there appears to be little room for improvement through pretrip path assignment. In fact, although the average trip times get better across the board relative to the myopic cases, they are still worse than the no-switching base case, except at very low levels of market penetration in which only marginal overall improvement is attained. On the other hand, the indifference band buffer under R.2 does not necessarily lead to better overall performance relative to the myopic rule (R.1) for loading pattern 3. A notable instance where it does is at the 25 percent market penetration level, with an overall improvement of 6.3 percent.

Comparing the results in Figure 2 with those in Figure 3, it appears that the system for loading pattern 1 performs somewhat better under origin-based information only than



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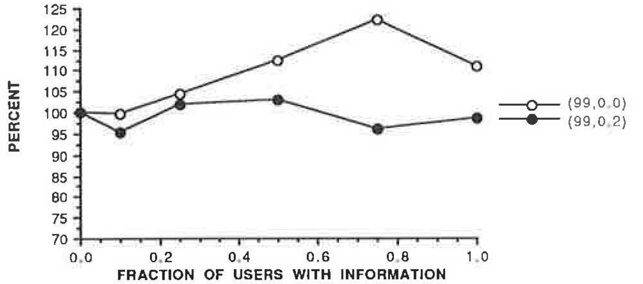

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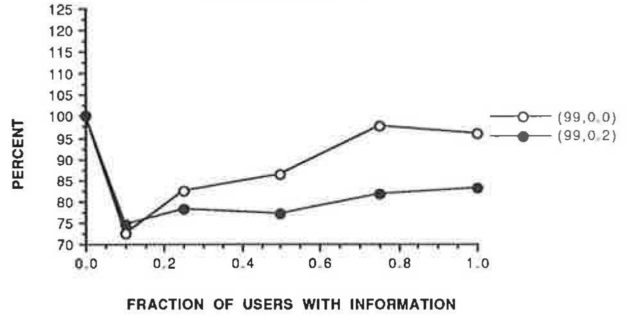

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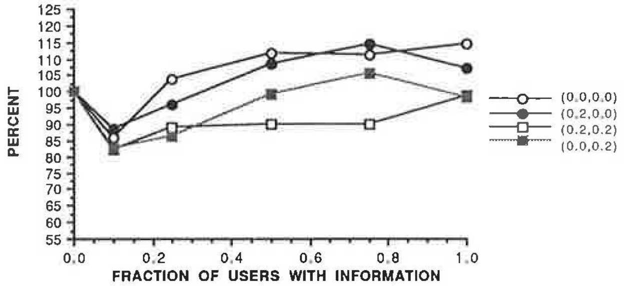
FIGURE 6 Variation of average trip time for users with information as a percentage of no-information base case, under en route real-time information availability only.



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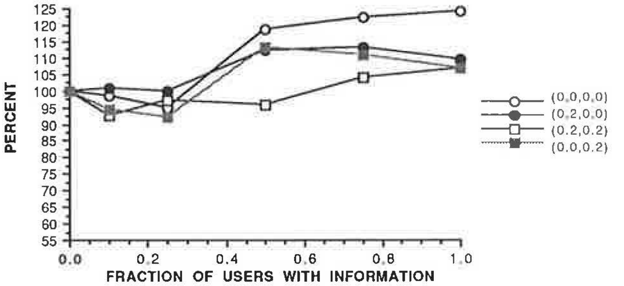

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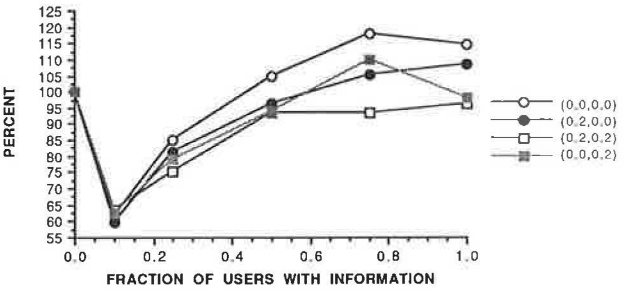

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FIGURE 7 Variation of average trip time for users with information, as a percentage of no-information base case, under both home-based and en route information.

under en route information only. This is true primarily under the myopic rule (R.1), whereas R.2 yields equivalent or slightly better performance under en route switching at lower market penetration levels, but somewhat higher trip times when most users have access to information. On the other hand, the system performs clearly better under en route than under origin-based information for loading pattern 3. One possible explanation has to do with the direction of the changes necessary to improve each of the two loading patterns, which makes them more or less robust vis a vis incorrect or poor switching decisions. For instance, loading pattern 3 is more susceptible to worsening under pretrip path selection only because its improvement would require redistribution of flow from the fastest facility (at free flow), Highway 1, to the other two. Because in the early stages of loading, Highway 1 will still outperform the other two, it will receive diverted traffic from the other two facilities under origin-based information. This diverted traffic will increase congestion downstream on Highway 1, especially as downstream departures start at their already heavy rate under pattern 3. Under origin-based path selection only, no opportunities exist to redistribute flows downstream, precluding the ability to reverse the negative impact of earlier poor switches. On the other hand, to improve loading pattern 1, flow needs to be redirected from the slowest to the fastest facility (at free flow). Therefore, the initial diversion from Highway 3 to Highway 1 under origin-based information would be in the correct direction. Of course, under high levels of market penetration, collective effects lead to reduced effectiveness and possible worsening, even under home-based information only.

Figure 3 also reveals that overall system performance is clearly better when users dampen their response to en route real-time information through a minimum threshold, as in Rule R.2, than when they respond according to the extreme myopic rule R.1. This is true for all three initial conditions considered, but especially for loading pattern 3, for which the improvement continues to increase, albeit at a decreasing rate, with the level of market penetration, up to a systemwide improvement of 16.8 percent over the do-nothing base case. Furthermore, less extreme behavior by users, such as under R.2, tends to dampen the negative impact of the collective effects that appear at high levels of market penetration.

Conceptually, providing users with both origin-based and en route information would be similar to attempting to modify

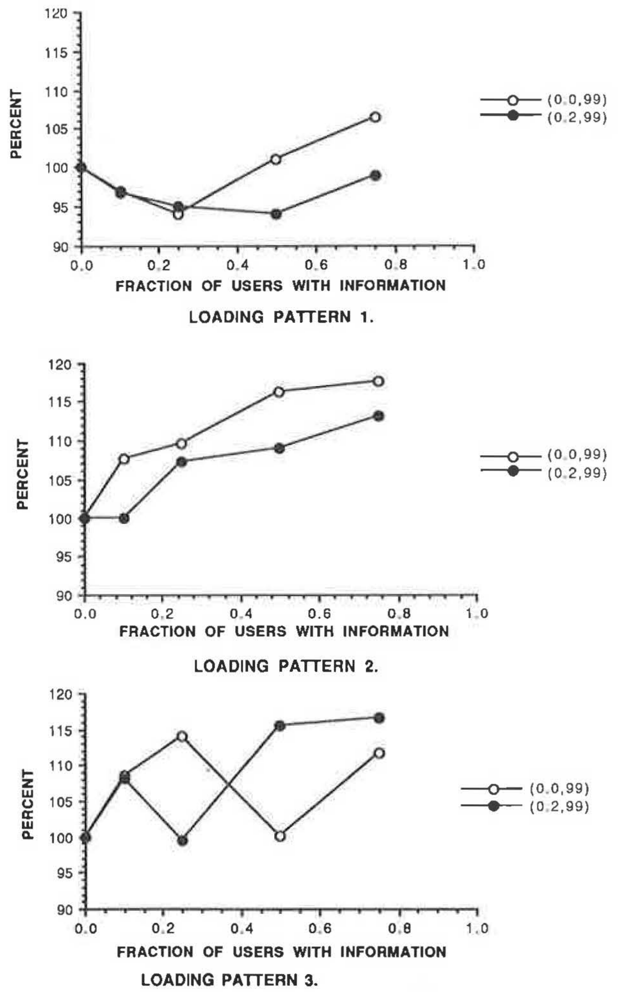


FIGURE 8 Variation of average trip time for users without information as a percentage of no-information base case, under home-based real-time information availability only.

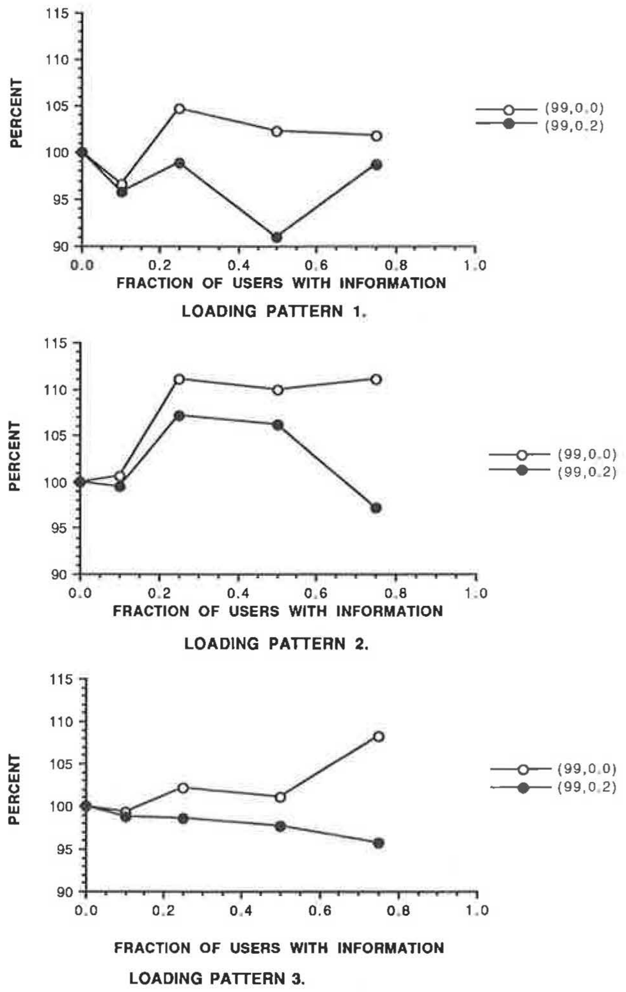


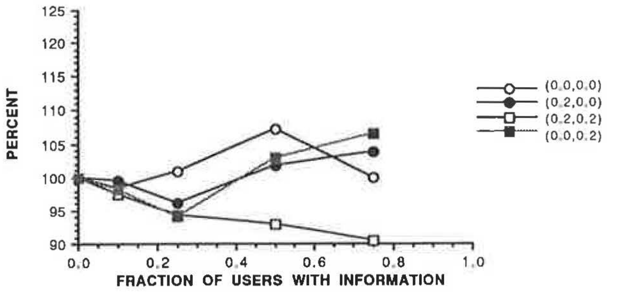
FIGURE 9 Variation of average trip time for users without information as a percentage of no-information base case, under en route real-time information availability only.

the initial conditions (loading pattern) through pretrip switching of users with information, and then seeking to improve the system further by en route switches. However, the analysis of the results presented for en route switching only (Figure 3) have indicated that systems with initial conditions close to the optimum leave little room for improvement, as in the case of loading pattern 2, and may actually get worse, especially at high market penetration levels. Therefore, providing both sources of information appears to reduce the potential effectiveness of either source taken individually, as shown in Figure 4. In many cases, for all three loading patterns, especially under extreme user behavior (rule R.1), the potential negative effects of the two sources appear to be compounded. The worst case is attained at 100 percent market penetration under loading pattern 2 using the myopic rule for both initial and en route switching, with approximately 24.2 percent increase in systemwide trip time. In general, better systemwide system performance is attained when path switching behavior is dampened by an indifference band, both initially as well as en route (i.e, the [0.2, 0.2] case).

Incidence of Benefits and Costs

One of the fundamental issues that transportation systems engineers and policy makers have to deal with is the incidence of the benefits and costs of information on users with and without access to such information. The associated equity issues may well be among the toughest obstacles facing the implementation of advanced driver information systems. With this in mind, average trip times have been computed separately for users with and without information for all the cases considered. The results are summarized in Figures 5, 6, and 7 for those with information and in Figures 8, 9, and 10 for the other group, as noted previously.

Figures 5, 6, and 7 suggest that average users with access to information (from either source) will reduce their trip time in all cases considered at low market penetration levels. The relative advantage gained by users with information appears to be highest when access to such information is limited to about 10 percent of the commuter population. This improvement in the trip time of those with information was achieved



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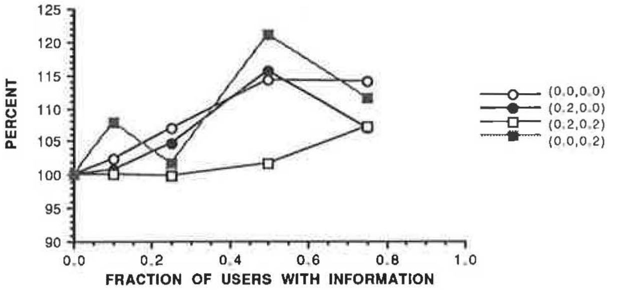

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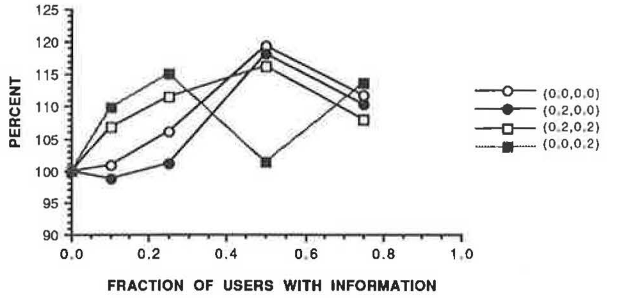

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FIGURE 10 Variation of average trip time for users without information as a percentage of no-information base case, under both home-based and en route information.

at low market penetration levels even when systemwide performance actually worsened. However, as more users have access to information, their trip time savings decrease. In some cases, especially under loading pattern 2, users with information actually experience longer trip times than they would have under the no-information base case. Furthermore, it appears that the closer the initial system is to the system optimum (e.g., loading pattern 2), the lower is the market penetration level beyond which even users with information actually do worse than under no-information (this level is about 15 to 20 percent for loading pattern 2, under either source of information).

Under departure pattern 3, whereas no meaningful systemwide benefits were achieved with home-based information only, the informational advantage resulted in very significant savings at low penetration levels. The most improvement of any case was achieved by those with such information under this loading pattern (40.1 percent reduction in trip time at 10 percent penetration). However, these benefits diminish dramatically as market penetration increases, resulting in an eventual worsening at market saturation. Under loading pattern 1, users with information experience less benefit than under pattern 3 at the 10 percent penetration level. However, this benefit does not decrease as fast with increasing market penetration.

In most cases, home-based information only yields greater savings to those with access to it than en route information only at low market penetration levels (not to exceed 15 to 20 percent for the scenarios simulated in this paper). However, the benefits of the home-based only information source rapidly become diluted as market penetration increases, and eventually become nonexistent or negative as one approaches market saturation. On the other hand, the benefits of the en route only source (to those who have access to it) appear to be somewhat more robust with respect to increasing market penetration. Nevertheless, beyond some level that is highly dependent on initial conditions, these benefits may disappear or turn negative.

When both sources of information are used by commuters, additional benefits, relative to those achievable under either source separately, accrue to users with information at low market penetration levels. However, the benefits are far from being additive. The incremental benefits are rather limited to a few percentage points (relative to the base case). However, these benefits rapidly decrease with market penetration, and are often less than those attainable under one source only.

The results of Figures 8, 9, and 10 for users without information reveal that only in a few cases does this group actually experience a reduction in average trip time (relative to the no-information base case). Most of these cases occur under loading pattern 1. Moreover, in several cases, this group does somewhat better at higher market penetration levels, as the larger number of those with information divert to the supposedly better paths, leaving mostly the uninformed drivers to experience the benefits of reduced congestion on the relieved facilities. However, this does not occur in all cases, and appears to be dependent on initial conditions in the system. Furthermore, benefits which may accrue to the uninformed drivers are typically quite small.

CONCLUSIONS

The simulation experiments presented in this paper are limited to a particular network configuration under three different initial conditions (loading patterns), as well as to particular real-time information supply sources and strategies. As such, considerable caution must be exercised in interpreting the results and before attempting to generalize their applicability. Nevertheless, important and useful insights have been obtained into the effects of real-time information advisory sources on overall traffic system performance, some of the critical factors that influence this performance, and the dependence of these effects on the behavioral mechanisms governing the response of users to the supplied information.

It is important to recall the nature of the information supplied to users. Descriptive real-time information on currently prevailing link trip times coupled with a capability to compute self-optimized paths were considered. Under home-based information, this capability is available at the origin of the trip, before the driver actually gets on the network. With en route information, trip times for paths from the driver's current node to his or her destination are updated on a quasi real-time basis. It is important to keep in mind in interpreting the results of the simulations, the trip times used in the calculation that form the basis of the user decisions are those that are currently prevailing in the network. Of course, these may or may not be the travel times actually experienced by the users when they traverse these links. In other words, no attempt is made to predict what the travel time will be on a given link in the future, taking into account the path choices of the users in response to the supplied information.

It was strongly suggested in the results that the overall effectiveness of real-time information in a network is highly dependent on the prevailing initial conditions, and the extent to which these offer opportunities for improvement. It appears that the closer the system is to the optimum, the higher the likelihood that information from either source may actually worsen systemwide performance. Under loading pattern 2, the best average systemwide trip time is 20.66 min, and the worst is 26.65 min, as opposed to that for the no-switching base case, which was 21.45 min. On the other hand, meaningful improvement was obtained when the initial conditions were further away from the optimum. For instance, under loading pattern 3, the best system performance attained was 19.36 min, which outperforms the best case under loading pattern 2.

The relative effectiveness of home-based versus en route information is also highly dependent on initial conditions, and on the manner in which the present system may be suboptimal. For instance, it was seen that when the fastest facilities (e.g., freeways) are underutilized, origin-based information could be effective. When the reverse is true, initial switching appears to be effective only at very low market penetration levels, and en route information seems to be much more effective. Actual systems are likely to be more like loading pattern 3—to overutilize faster facilities—suggesting that en route information would be preferable from a systemwide standpoint. Of course, this conclusion does not take into account the longer term adjustments that might take place through day-to-day changes in route and departure time. Apparently, if present conditions are already close to the optimum, then the indiscriminate provision of information, both origin-based as well as en route, may actually worsen conditions through users' overreaction and myopic shifts.

Again, it is important to emphasize the limitations arising from the particular network configuration considered, and the manner in which the information was provided to the users in our simulations. However, the results do suggest the need to carefully consider several important parameters and factors in the ongoing research and development efforts pertaining to advanced driver information systems. In particular, the following four items should be highlighted because of the results of our experiments, as well as those that are beginning to emerge in related research.

1. The importance of initial conditions in determining the potential effectiveness of real-time information strategies has been highlighted in previous research by Mahmassani and Jayakrishnan (*2*), and Mahmassani, et al. (*16*). The present results further confirm this conclusion and offer insights into how the character of the initial conditions affects the impacts of information strategies from different sources. Additional effort should be directed at characterizing present conditions in congested networks, especially in terms of how tripmakers actually utilize the components and facilities of these networks.

2. The potential negative effects of extreme behavior in the users' response to the supplied information are further documented in our results. The existence of benefits from advanced driver information systems obviously depends on the manner in which users respond to the information. Allowing for bands or thresholds in one's decision to switch to a presently better alternative clearly improves systemwide performance as well as the benefits that might accrue to those with the informational advantage. Although this matter is not under the system controller's direct control, it can be influenced through the design of the supplied information itself as well as though possible education of the driving public. Ultimately, it is likely that users themselves will reach their own conclusions about appropriate switching rules, through repeated experience with the facility. The dynamics of the formation of such indifference bands constitute an important subject of additional research, which could benefit from previous work on the day-to-day dynamics of commuting decisions through the use of laboratory experiments (*7*).

3. The need for coordination in the provision of information beyond a certain market penetration level is strongly suggested by our results. This point has been recognized in proposals for ADIS implementation programs (*1*). Our results suggest that the level beyond which coordination is needed may be as low as 10 or 20 percent, depending on initial conditions.

4. The nature of the information supplied to the motorists should receive considerable attention. As emphasized throughout, our results are predicated on current trip times and no attempt is made at prediction. However, the strong interrelation among supplied times, user decisions, and traffic conditions makes the prediction problem and the design of information supply strategies rather complex. This item also ties in with the preceding one regarding the development of coordinated information and control strategies.

ACKNOWLEDGMENTS

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