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An investigation of the reliability of real-time information for route choice decisions in a congested traffic system

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Abstract. This paper investigates the reliability of information on prevailing trip times on the links of a network as a basis for route choice decisions by individual drivers. It considers a type of information strategy in which no attempt is made by some central controller or coordinating entity to predict what the travel times on each link would be by the time it is reached by a driver that is presently at a given location. A specially modified model combining traffic simulation and path assignment capabilities is used to analyze the reliability of the real-time information supplied to the drivers. This is accomplished by comparing the supplied travel times (at the link and path levels) to the actual trip times experienced in the network after the information has been given. In addition, the quality of the decisions made by drivers on the basis of this information (under alternative path switching rules) is evaluated ex-post by comparing the actually experienced travel time (given the decision made) to the time that the driver would have experienced without the real-time information. Results of a series of simulation experiments under recurrent congestion conditions are discussed, illustrating the interactions between information reliability and user response.

1. Introduction

Continuing concern over growing urban and suburban congestion has motivated considerable interest in the use of advanced information processing and communication technologies to manage traffic and advise tripmakers in order to improve the efficiency and quality of vehicular flow in traffic networks. In the past decade, various efforts have been initiated worldwide to improve the information available to drivers in the urban transportation system.[1–10] Several methodological approaches have been proposed for assessing the effectiveness of in-vehicle information strategies in reducing traffic congestion and examining the interactions among key parameters of the system, such as nature and amount of information displayed, market penetration, and congestion severity.[11–15] However, a critical factor that affects the longer term effectiveness of such Advanced Traveler Information Systems (ATIS), particularly in-vehicle route guidance schemes, remains to be investigated. This factor is the accuracy of the information provided to the participating drivers, whether in the form of the trip times on alternative paths or of a recommended path, and the resulting reliability of this information as a basis for route choice decisions made by individual drivers. This issue arises primarily from the dynamic nature of the driver-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 "recommended" path predicated on current link trip times may turn out to be less than optimal as congestion in the system evolves. Furthermore, there are strong indications that drivers may not switch to an alternate path unless they can expect a meaningful improvement in travel time. The assessment of the accuracy and reliability of the information supply strategies and forecasting methodologies is quite important for the evaluation of the ability of the dynamic (real-time) in-vehicle guidance system to improve route selection decisions.

This paper introduces a framework to evaluate the reliability of information supply strategies used in ATIS and applies it to a simulated traffic corridor network through the use of traffic probes. The dependability of the trip time information given to equipped drivers and the quality of their subsequent decisions are investigated in this simulated context, in which individual drivers make their route choices based on trip time information on prevailing traffic conditions only. No attempts is made to forecast link trip times over a given time period or to predict what the situation downstream would be by the time the driver receiving the information reaches it.

In the next section, the modelling framework is discussed, starting with a depiction of the commuting context, followed by the formulation of behavioral rules. The mechanism for operationalizing traffic probes is then presented. The section ends with an overview of the simulation-assignment model used. The simulation experiments are described next, including the specific levels considered for each experimental factor and a discussion of the reliability measures to be quantified. The simulation results are then discussed, followed by concluding comments.

2. The modelling framework

The model used to perform the simulation experiments is an extension of the corridor simulation-assignment model developed by Mahmassani & Jayakrishnan[11] and modified by Mahmassani & Chen[12] to include pre-trip path selection in addition to en-route switching decisions. A traffic probing mechanism has been devised and included in the model to evaluate the reliability of the supplied information on prevailing link trip times.

2.1. *Commuting context*

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 nine miles long, and each is discretized into nine one-mile segments, with cross-over links at the end of the third, fourth, fifth, and sixth miles to allow switching from any facility to any of the other two (see Fig. 1). Commuters enter the corridor through ramps feeding into each of the first six one-mile segments on each facility and commute to a single common destination downstream (such as the Central Business District or a major industrial park).

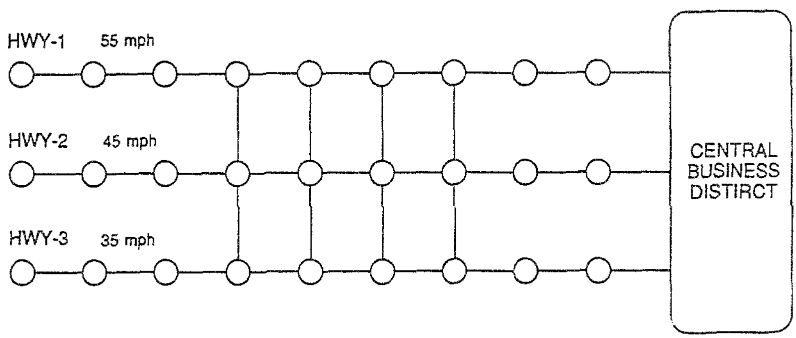

Fig. 1. Commuting corridor with 3 parallel facilities.

Of the three major facilities, hereafter referred to as Highways 1, 2 and 3, Highway 1 has the highest free mean speed of 55 miles per hour, followed by Highway 2 (45 mph) and Highway 3 (35 mph). All the crossover links have a free mean speed of 45 miles per hour. In all experiments, 1800 commuters depart from each of the first six (residential) sectors towards the destination. The departures are spread uniformly over a 20-minute period, with the loading periods for each sector staggered with a time lag of five minutes between adjacent sectors, with sector 1 starting first. Departing rates are 60 vehicles per minute for Highway 1, 20 vehicles per minute for Highway 2, and 10 vehicles per minute for Highway 3 for each sector. Note that this assignment constitutes 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.

Assume that a fraction of the commuters have access to real-time network traffic information be it from an on-board or a home-based traffic advisory unit. The equipped 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/her destination along alternative paths. A behavioral assumption is made in the definition of available paths in a corridor network such as the one considered here, namely that users perceive and identify a path in terms of its major highway facility, reflecting 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 mode (including the origin), the user effectively considers only three paths, one for each facility.

2.2. *Path selection and switching rules*

Two alternative rules are used for both en-route path switching and initial route selection: 1) a "myopic" deterministic choice rule, and 2) a boundedly-rational rule. Both rules are described in turn hereafter.

Rule R.1. Myopic Switching Rule
This rule simply states that from any given node n, the user will always select the best path (in terms of least cost or least travel time) from the current node to his/her destination. In this simulation context, rule R.1 can be stated in the following form:

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

where

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

An important concept in the above rule is the notion of a current path, which is central to our modelling framework. It assumes that the user has an evoked current path to which he/she 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 alternative parallel arterial. The assumption that drivers follow the 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. A possible more reasonable assumption 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
Under Rule R.2, a user will switch from his/her current path to the "best" alternative only if the improvement in the remaining trip time exceeds some indifference band of trip time saving. This threshold can be expressed either in absolute terms or relative to the remaining trip time. Following Mahmassani and Jayakrishnan[11], a switching rule with a relative indifference band subject to a minimum (absolute) trip time saving can be stated as:

$$\delta_i(n) = \begin{cases} 1 & \text{if } TTC_i(n) - TTB_i(n) > \max[\eta_i(n) TTC_i(n), \tau_i(n)] \\ 0 & \text{otherwise} \end{cases} \quad \text{(R.2)}$$

where

$\eta_i(n)$ is the relative indifference band for user i, as a fraction of the remaining trip time on the current path from node n to the destination, i.e., $TTC_i(n)$, with $\eta_i(n) \geq 0$, $\forall$ i, n;
$\tau_i(n)$ is the minimum improvement in the remaining trip time, from node n to the destination, necessary for user i to switch from his/her current path, with $\tau_i(n) \geq 0$, $\forall$ i, n; and all other terms remain as defined previously.

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 our 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, in order to preserve a meaningful threshold effect and to preclude unintended switchings when $TTC_i(n)$ becomes very small as the driver approaches his/her destination, the absolute band $\tau_i(n)$ is introduced to provide a lower bound. Both $\eta_i(n)$ and $\tau_i(n)$ could either be 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 for a given individual over the duration of his/her commutes. In addition, while $\eta_i(n)$ is allowed to vary across users, $\tau_i(n)$ is taken as a constant τ for all drivers.

As noted earlier, the above 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, which could provide estimates of the remaining trip time on the user's current path as well as identify the "best" path.

2.3. *The simulation-assignment model*

The model is comprised of three main components: the traffic performance simulator, the network path processing component, and the user decision-making component. The first component is a fixed time-step macroparticle traffic simulator. Vehicles on a link are moved individually at prevailing local speeds consistent with macroscopic speed-density relations (modified Greenshield's model). Inter-link transfers are subject to capacity constraints. For the given network representation and link characteristics, the simulator uses a time-dependent input function to determine 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 processing 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 responses of users to the available information according to a set of behavioral rules of the kind described previously. 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 & Jayakrishnan.[11]

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

2.4. *Traffic probing mechanism*

In order to assess the reliability of information provided to motorists and the quality of the decisions made on the basis of this information, a traffic probing mechanism has been devised to emit passive "dummy" (or virtual) cars at decision points to travel downstream to the destination to collect data for the various reliability measures. Under this mechanism, every time an equipped car reaches a node where real-time traffic information is accessible, one dummy car is emitted from that node along each available route leading to the driver's destination, including the driver's current route. The same is applicable to pre-trip information at the origin node.

Once a dummy car is emitted, it moves with the traffic under prevailing traffic conditions and is not allowed to switch routes. It is regarded in the program as a non-equipped car, but it does not take up space nor affect traffic in any way. Even though these traffic probes do not contribute to actual traffic, they do experience the prevailing traffic conditions surrounding them, such as the current traveling speed on the link and the waiting time during node-to-node transfer. From the standpoint of the "real" cars, the dummy cars do not exist.

Various quantities are collected at the end of the trip for every dummy car, as described in Section 3.2.

3. The experiments

3.1. *Experimental factors*

The simulation experiments were conducted with respect to three experimental factors, namely, information source, behavioral rule, and market penetration. These are described in turn hereafter.

Information source
Two information sources are considered: home-based information, consulted prior to actually starting a trip, and in-vehicle en-route information. Four strategies are considered for this factor:

1. no information (base case),
2. home-based pre-trip information only,
3. en-route information only, and
4. both sources are available.

Under strategy 2, path selection is allowed only at the origin. Once the user is actually driving on any given link (including the entry ramp), it is no longer possible for him/her to switch to another facility. Under strategy 3, users only have access to information along the way. They always enter the corridor system through the entry ramp to their individual intended path (assigned as part of the loading pattern) and can switch through crossover links only. Under the last information 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.

Behavior rule
In the simulation runs, each user with information is assigned a randomly generated indifference band, η_i, drawn from a triangular distribution with mean $\bar{\eta}$ and range $\bar{\eta}/2$. Since it was found previously that a mean indifference band of 0.2 appears to provide reasonable overall behavior as well as the largest systemwide improvement in travel time[11-12], only two levels of $\bar{\eta}$ are considered in these experiments: 0.0 and 0.2. In the no band case ($\bar{\eta}$ = 0.0), all users are assumed to have a zero band; hence, this case represents the myopic case (Rule R.1). A minimum absolute improvement

threshold, τ_i, set at 1 minute, is taken to be identical across all users with information in the 0.2 band case, whereas in the zero band case, no minimum improvement restriction is imposed. These two levels of the mean indifference band ($\bar{\eta} = 0.0$ and $\bar{\eta} = 0.2$) are implemented for the home-based pre-trip information only strategy (denoted by ($\bar{\eta}_{1i}$), the en-route information only strategy (denoted by $\bar{\eta}_{2i}$), and the strategy where both home-based and en-route information are available. In what follows, denote each case by [$\bar{\eta}_{1i}$, $\bar{\eta}_{2i}$] where a value of 99 indicates that no switching is allowed. Thus, two cases each are considered for home-based pre-trip switchings only and en-route switching only: [0.0, 99] and [0.2, 99] for the former, and [99, 0.0] and [99, 0.2] for the latter. Four combinations of behavioral rules are considered for the situation in which both information sources are available: [0.0, 0.0], [0.2, 0.0], [0.2, 0.2], and [0.0, 0.2]. [99, 99] corresponds to the no information base case.

Market penetration
Five levels of the fraction of users with access to real-time information are 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 the three above-mentioned experimental factors, 41 separate simulation runs were performed, and the reliability of information in each case was evaluated using the performance measures discussed next.

3.2. *Reliability measures*

Several alternative reliability measures with varying degrees of complexity could be formulated to assess the reliability of real-time traffic information.[16] With the built-in traffic probing mechanism in our model, five such measures are extracted and analyzed at the end of the simulation. They are presented in turn hereinafter.

1. *Overall travel time error*
The travel time error for a given path from a given node to the destination is defined as the difference between the computed (a priori) trip time for that path, at a given time, and the actual (ex post) trip time it takes a dummy car emitted at that time to traverse this path, relative to the actual trip time. A positive (negative) trip time error means the information supply strategy that computes trip time using prevailing traffic conditions overestimates (underestimates) the actual time required for the journey. The overall travel time error

averages the trip time error for all dummy cars emitted, i.e., for all decision instances faced by the drivers in the system. It can be expressed as follows:

$$y_j = f\left(\sum_{i=1}^{m} w_{ij} x_i + \theta_j\right) \tag{1}$$

where

$TT_{i,t,k}(n)$ is the computed (a priori) trip time of driver i from node n to his/her destination at time t on path k, k = 1,2,3;
$ATT_{i,t,k}(n)$ is the actual (ex post) trip time of the dummy car emitted for driver i from node n to his/her destination starting from time t on path k, k = 1,2,3; and,
$\alpha_{i,t}(n)$ is a binary variable equal to 1 if driver i is faced with a decision at node n at time t; 0 otherwise.

Note that the factor of 3 in the denominator reflects the existence of three alternative paths at each decision point.

2. *Travel time error on a priori best path*
This measure considers the same travel time error defined above but only for the a priori best path, i.e., the path with the shortest computed trip time. It measures the overall accuracy of the information supplied on the computed (a priori) best paths. This measure is stated in the following form:

$$\text{Travel Time Error on A Priori Best Path} = \frac{\sum_{i,t,n} \frac{[TTB_{i,t}(n) - ATTB_{i,t}(n)]}{ATTB_{i,t}(n)}}{\sum_{i,t,n} \alpha_{i,t}(n)} \tag{2}$$

where

$TTB_{i,t}(n)$ is the computed (a priori) trip time of driver i from node n to his/her destination at time t on a priori best path, $B_{i,t}(n)$, i.e., $TTB_{i,t}(n) = MIN_k(TT_{i,t,k}(n))$;
$ATTB_{i,t}(n)$ is the actual (ex post) trip time of the dummy car emitted for driver i from node n to his/her destination starting from time t on the a priori best path; and all other terms remain as defined previously.

3. *Maximum penalty*
The maximum penalty is defined as the difference between the actual (ex post) trip time on the path actually selected (which could be either the a priori

best or the current path, depending on the behavioral rule) by a driver from a node to his/her destination and the actual (ex post) trip time on the actual (ex post) shortest path from the same node to the destination, relative to the actual trip time on the actual shortest path. This measure is the average of the maximum penalty for all the decision instances that arise in a simulation run, and is operationalized as follows:

$$\text{Maximum penalty} = \frac{\sum_{i,t,n} \dfrac{[\mathrm{ATTS}_{i,t}(n) - \mathrm{ATTB}^*_{i,t}(n)]}{\mathrm{ATTB}^*_{i,t}(n)}}{\sum_{i,t,n} \alpha_{i,t}(n)} \tag{3}$$

where

$\mathrm{ATTS}_{i,t}(n)$ is the actual (ex post) travel time of the dummy car emitted for driver i on the path actually selected by this driver from node n to his/her destination; $\mathrm{ATTB}^*_{i,t}(n)$ is the actual (ex post) travel time of the dummy car emitted for driver from node n to his/her destination on the actual shortest path, $B^*_{i,t}(n)$, i.e., $\mathrm{ATTB}^*_{i,t}(n) = \mathrm{MIN}_k(\mathrm{ATT}_{i,t,k}(n))$; and all other terms remain as defined previously.

4. *Opportunity cost*

The opportunity cost here is the travel time the driver would have saved if he/she had switched to the a priori best path. It is thus defined as the difference between the actual (ex post) trip time on the path actually selected by a driver from a node to his/her destination (as measured by the corresponding traffic probe) and the actual (ex post) trip time on the a priori best path, relative to the actual (ex post) trip time on the a priori best path. This measure is the average of the opportunity cost for all the decision instances that arise in a simulation run. Note that this measure is equal to zero for all case runs in which the myopic switching rule is employed, namely [0.0, 99], [99, 0.0], and [0.0, 0.0]. It can be expressed in the following form:

$$\text{Opportunity cost} = \frac{\sum_{i,t,n} \dfrac{[\mathrm{ATTS}_{i,t}(n) - \mathrm{ATTB}_{i,t}(n)]}{\mathrm{ATTB}_{i,t}(n)}}{\sum_{i,t,n} \alpha_{i,t}(n)} \tag{4}$$

where all the terms remain as defined previously.

5. *Quality of decisions*
Decisions made by users during the simulation run can be classified into four categories (see Fig. 2): 1) the user switches to the a priori best path when the a priori best path is the ex post best path (a good decision); 2) the user stays on his/her current path when the a priori best path is the ex post best path (a Type I error); 3) the user switches to the a priori best path when the latter is not the ex post best path (a Type II error); and 4) the user stays on his/her current path when the a priori best path is not the best ex post (a good decision). The fractions of decision instances that fall in each category constitute the principal measures defined here to capture the quality of the users' decisions.

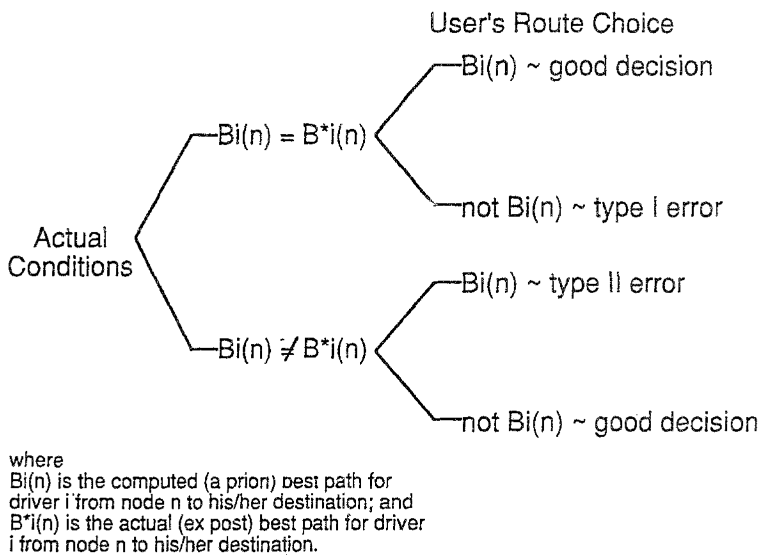

Fig. 2. Quality of decisions.

The above measure are obtained by keeping track of all the information given to users throughout the simulation run and the times needed for the traffic probes to finish their journeys. With these quantities, we can analyze the reliability of the information and the overall performance of the drivers with information as discussed in the following section.

4. Analysis

The results obtained from all the simulation runs, corresponding to the combinations of the three experimental factors described in the previous section, are summarized and presented in Figs 3 through 10. Figure 3 depicts the variation of the average trip time experienced by the users with information (expressed as a percent of the do-nothing base case) with the fraction of the user population with access to information, under either myopic or boundedly-rational switching rules, or both (as in the cases [0.0, 0.2] and [0.2, 0.0]), and along with home-based information availability only, or en-route information availability only, or both information sources. Figures 4 to 7 display the overall results for the first four reliability measures namely overall travel time error, travel time error on a priori best path, maximum penalty, and opportunity cost respectively, for the 40 study cases (excluding the no information base case). In Fig. 8, the number of good decisions actually made by drivers (Categories 1 and 4) as a fraction of the total decision instances are plotted for all 40 cases. Figures 9 and 10 show the variation of the number of Category 2 (Type I error) and Category 3 (Type II error) decisions for all 40 cases respectively, as a fraction of the total decision instances.

Figure 3 indicates that, in general, users with access to real-time information experience smaller improvement in trip time as market penetration increases. In some cases, particularly at the higher market penetration levels, users with information are on average actually doing worse than under the no-information base case scenario. Furthermore, at each level, from 25% to 100% market penetration, users with information are consistently doing better when they are supplied with en-route information only relative to other information sources. The results also suggest that users with information attain

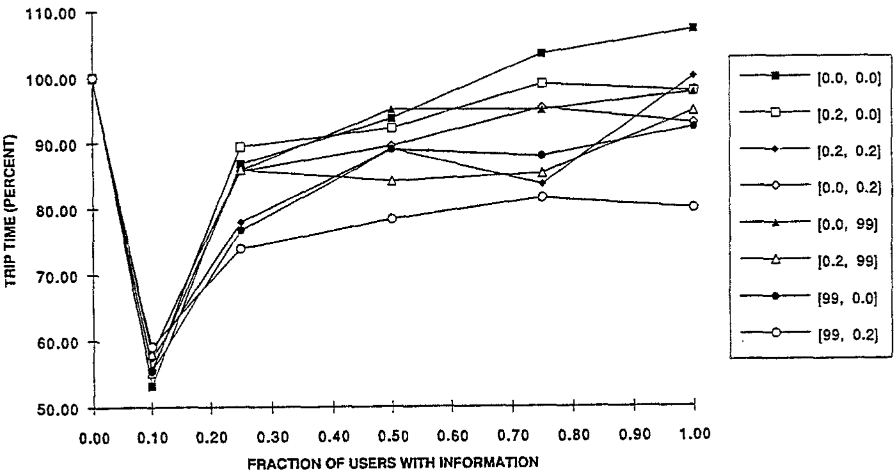

Fig. 3. Average trip time for users with information (as a percent of no information base case).

greater benefits when their behavior follows the 0.2 band switching rule rather than the zero band myopic rule (for the same scenario and information strategy) under most market penetration levels between 25% and 100%.

Supplying real-time information to a fraction of the drivers in the corridor network is intended to alleviate congestion in certain parts of the network by diverting a portion of the traffic to less utilized paths. This diversion would be effective as long as the number of cars that switch over does not worsen traffic conditions on the receiving path beyond a certain level. Therefore, at high levels of market penetration, users with information do not get as much trip time improvement as at low levels of market penetration. By applying an indifference band for switching, the number of unproductive switches induced by the supplied information is reduced, which explains why, at high levels of market penetration, cases with the 0.2 band perform better than those with zero band.

To properly understand and interpret the reliability measures, it is important to realize the nature of the uncertainty in the trip time information supplied. In particular, this information reflects prevailing traffic conditions only and does not involve prediction of what future conditions might be; thus, uncertainty arises from the dynamic nature of traffic evolution downstream caused by both the users (with access to information) who switch routes and those trying to get in the corridor. The reliability measures are intended to assess the quality of this information as a basis for user decisions, given all the interactions that are taking place in the network. As such, these measures reflect the users' response to the information in question.

From a user's viewpoint, initial path selection in the cases where only origin-based pre-trip information is provided could be "unforgiving" in the system under consideration, because the user is assumed to receive no further information that could induce switching along the way. If the path selected is not the best one (either a Type I or Type II error), the user would have no opportunity to correct his/her action for the rest of the trip. On the other hand, when only en-route information is provided, The user may have either one, two, three, or four route switching opportunities during the trip depending on his/her origin. Due to the variability of traffic conditions downstream, having more switching opportunities may help the user correct a "bad" decision made upstream or alternatively get him/her onto a path with a longer trip time, possibly even the worst path (longest trip time). When both information sources are available, the user has the opportunity to select the initial path and up to four chances to switch en-route. Again, with the traffic evolving dynamically, having more switching opportunities does not guarantee a faster journey. In fact, having more route switchings increases the variability and unpredictability of the traffic conditions, thereby possibly worsening the reliability of the information that is inducing the switching.

In Fig. 4 (overall relative trip time error), the trip time computed on the basis of prevailing traffic conditions overestimates the actual time for the trip (positive error) for only two cases: [0.0, 99] and [0.2, 99], at 10% market penetration. In both cases, only pre-trip path selection is allowed. The relatively large positive errors translate into large reductions in trip time for users who follow this information, as evidenced by the corresponding results shown in Fig. 3. The travel time errors for all the cases in which only pre-trip path selection is allowed seems to follow the variation of trip time improvements across different levels of market penetration. This reliability measure becomes more negative with lower trip time improvement for both the [0.0, 99] and [0.2, 99] cases. Moreover, the cases under the 0.2 indifference band switching rule seem to have less negative errors than the corresponding cases under the myopic switching rule.

In the rest of the cases (with en-route information alone or in conjunction with origin-based information), an opposite trend is observed. The travel time error appears to decrease, in absolute value, with lower trip time improvement, i.e., at higher market penetration levels. Furthermore, the errors for these cases are in general larger (in absolute value) than the cases in which only pre-trip information is supplied (at the same market penetration level). The cases under the myopic switching rule exhibit less negative errors than the corresponding cases under the 0.2 indifference band rule. These results are explained below.

When only pre-trip path selection is allowed, the user stays on the selected path for the entire journey, just like the corresponding traffic probe (dummy car). Thus, the travel time error truly reflects its trip time performance. On

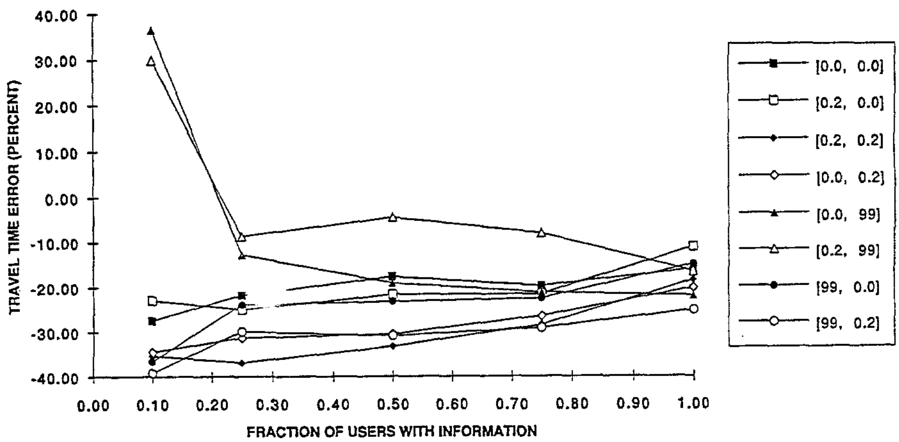

Fig. 4. Overall travel time error (as a percent of actual trip time).

the other hand, when en-route path switching is available, the user has several (up to four) opportunities to switch to other paths, whereas the corresponding dummy cars have to follow their designated paths. As a result, the travel time error need not agree with the user's actual trip time performance.

The first reliability measure includes the trip time error on all the alternative routes available to the tripmaker. However, under either of the two behavior rules, a user considers only the current path and the computed (a priori) best path in route choice decisions. This motivates the second reliability measure - travel time error on the a priori best path, summarized in Fig. 5. This figure indicates that these errors are negative for all 40 cases, meaning that the trip time on the a priori best path is underestimated on average. The error for almost all the cases seems to follow the variation of the trip time improvements across different levels of market penetration. With some exceptions at the highest market penetration level, the error increases, in absolute value, with lower trip time improvement, for a given behavior rule and information availability scenario. However, across the various scenarios, the cases with the largest trip time reduction (note in particular the [99.0.2] case), at a given penetration level, exhibit the largest discrepancies (in absolute value) between supplied and actual trip time information. By the same token, most cases under the myopic switching rule exhibit less negative errors than the corresponding cases under the indifference band rule. The results again reflect the interactions taking place in the system between the supplied information and the users' responses to this information, which ultimately determine the reliability of this information.

The results shown in Fig. 6 (third measure of reliability – maximum penalty

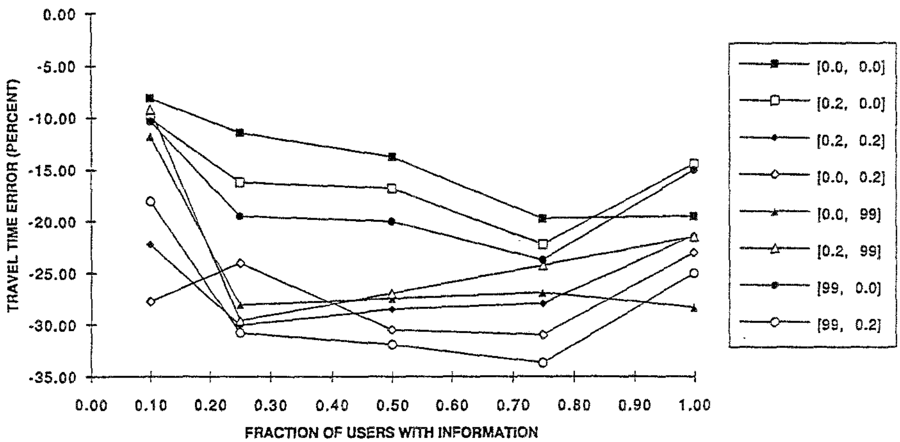

Fig. 5. Travel time error on a priori best path (as a percent of actual trip time).

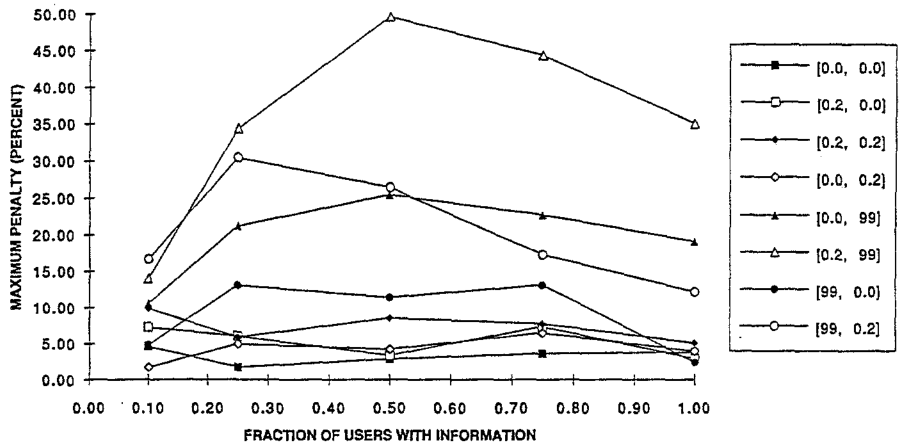

Fig. 6. Maximum penalty (as a percent of actual trip time).

for not following ex post best path) indicate that all the cases with only origin-based information have relatively high penalty, except at 10% market penetration. This means the actual trip times on the selected path are relatively much higher than on the actual (ex post) best path. Nevertheless, the cases at 10% market penetration have relatively low penalty, because the small number of users with access to information is not likely to induce much variability in traffic conditions. Almost all the cases with the myopic switching rule seem to have less negative errors than the corresponding cases with the indifference band rule. The results do not exhibit strong trends otherwise.

In Fig. 7, the cases with [0.0, 0.0], [0.0, 99], and [99, 0.0] are not shown

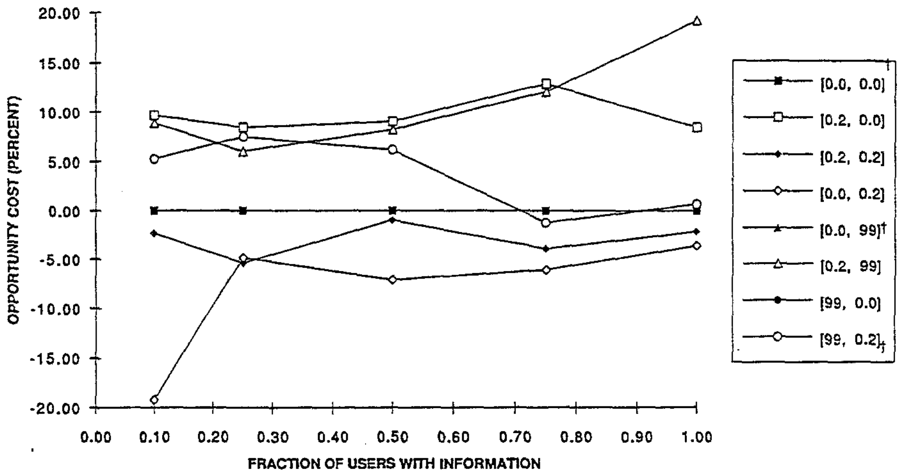

Fig. 7. Opportunity cost (as a percent of actual trip time).

because the systemwide opportunity cost is zero. This measure captures the travel time difference forsaken by those users who do not switch to the computed (a priori) best path. Under the myopic switching rule, all users with access to information always switch to the computed best bath. A positive cost means that the user who did not switch to the a priori best path missed an opportunity for a lower ex post trip time. Alternatively, a negative cost implies that the user made a good decision by staying on his/her current path. Note that this measure is calculated only for those users with information who do not follow the a priori best path. According to Fig. 7, users under both the [0.0, 0.2] and [0.2, 0.2] cases experience better trip times when they stay on their current paths. For the other cases, the users would have experienced better trip times by switching to the a priori best paths. The best cases occur for [0.0, 0.2] and [0.2, 0.2], where users' en-route switching follows the boundedly-rational indifference band. The worst cases (high positive opportunity cost) occur when en-route switching is either not allowed, [0.2, 99], or it follows the myopic rule, [0.2, 0.0]. Note that both the current path and the a priori best path may not be the ex post best path.

The above results are confirmed by the fifth set of reliability measures, which captures the quality of the route choice decisions made by users with access to information, as shown in Figs 8 to 10. Figure 8 depicts the variation of the percent of "good" decisions (Categories 1 and 4) actually made by users out of the total decision instances, for each of the 40 cases. The general trend, as expected, suggests a higher fraction of "good" decisions at low levels of market penetration than at the high levels. The worst performance at the high penetration levels occurs in the absence of en-route

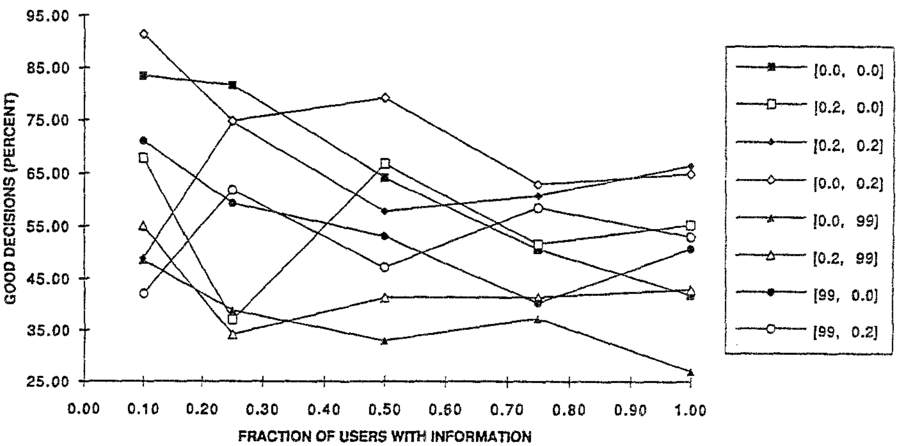

Fig. 8. Decision instances in categories 1 and 4 (as a percent of total decision instances).

information ([0.0, 99], [0.2, 99]), or when en-route switching follows the myopic rule. Conversely, better performance at these levels is observed for the cases where en-route switching is allowed and governed by the indifference band. At very low penetration levels, the indifference band actually precludes some reliable opportunities to improve one's travel time, resulting in fewer "good" decisions than the myopic rule. However, as noted, the situation quickly reverses with increasing market penetration.

Figures 9 and 10 show the variation of the percent of decision instances resulting in a Type I error (Category 2) and Type II error (Category 3) respectively. In Fig. 9, the cases with en-route information and/or boundedly-rational switching exhibit a high percentage of Category 2 decisions (the user does not follow the a priori best path where the latter is best, ex post) at the lowest market penetration level. Of course, Type I errors do not occur for cases with myopic switching only (i.e., [0.0, 0.0], [0.0, 99], [99, 0.0]), since the user never rejects the a prior best path in these cases. The negative correlation between Type I and Type II errors is evident in Figure 10. The general trend in this figure is for fewer Category 3 decisions (the user follows the a priori best path when the latter is not best, ex post) at low levels of market penetration than at high levels. It should be noted that a decision is only considered "good" if the path selected (current or a priori best) by the user is the ex post best path. On the other hand, a user may choose a path that is not the ex post best path and still spend less commuting time than in the no information base case.

When users commit a Type II error in following the a priori best path, it

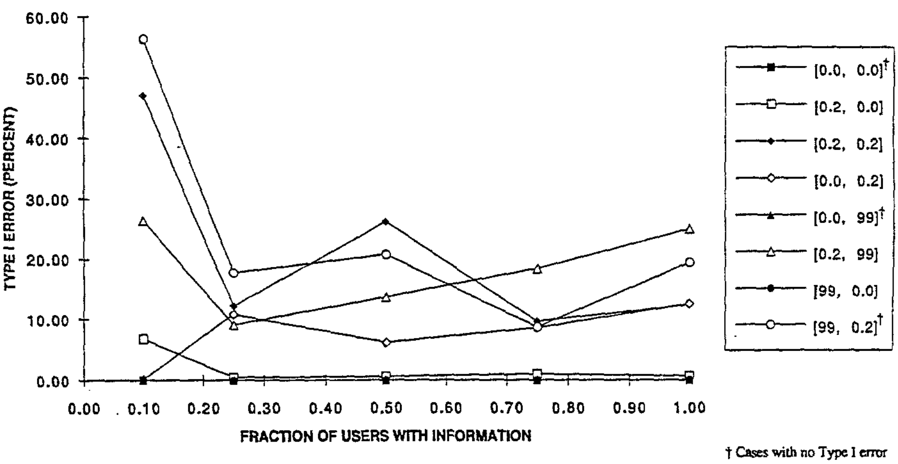

Fig. 9. Decision instances in category 2 (as a percent of total decision instances).

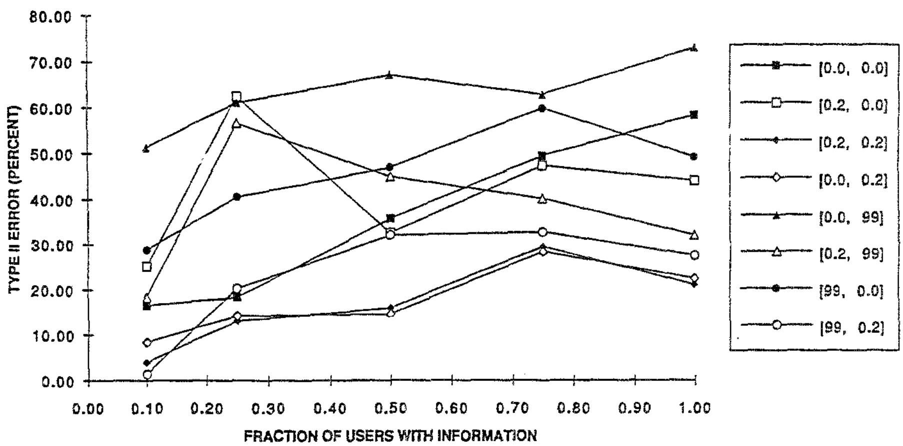

Fig. 10. Decision instances in category 3 (as a percent of total decision instances).

is useful to ask how severe the resulting penalty might be. An upper bound is given by the maximum penalty measure discussed earlier and depicted in Fig. 6. For instance, whereas about 58% of all decisions under the myopic behavioral response to both sources of information, [0.0, 0.0], result in Type II errors at full market penetration (Fig. 10), Fig. 6 indicates that the corresponding penalty does not exceed 5% of the actual trip time. Nevertheless, this particular case ([0.0, 0.0] at 100% market penetration) is one of the worst in terms of travel time improvement for users with information (Fig. 3). On the other hand, the corresponding maximum penalty for the [99, 0.2] case (indifference band switching in response to en-route information only) is over 10% of the actual trip time at full market penetration (Fig. 6). Yet, this case achieves the best performance in terms of trip time improvement. The reason lies in the relatively smaller fraction of decision instances where this penalty is incurred (about 27%). This illustrates a case in which a small penalty incurred with a high frequency greatly underperforms one in which a larger penalty is incurred with a smaller frequency. It also highlights the necessity to consider several measures simultaneously in order to form a meaningful picture of the reliability of alternative information supply strategies.

Following similar logic, the penalty incurred by users who commit a Type I error in not following the a priori best path is given by the opportunity cost measure depicted in Fig. 7. For instance, while the [99, 0.2] case has a relatively high frequency of Type I errors, the corresponding opportunity cost is very close to zero at the higher levels of market penetration, which is consistent with the generally better performance in terms of trip time improvement under this strategy.

5. Conclusions

Care should be exercised in interpreting the above reliability results and attempting to generalize their applicability because they are based on simulation experiments that are limited to a particular network configuration under a certain loading pattern (initial conditions), as well as to particular information strategies. The complex interactions between the information supplied and the users' responses taking place dynamically in the network preclude easy interpretability of the results. Nevertheless, several conclusions can be made with varying degrees of generalizability.

- It is difficult to objectively characterize and measure the reliability of real-time information in an ATIS independently of the users' responses to this information, as these responses ultimately determine the actual trip times in the system.
- Care should be exercised in interpreting seemingly objective measures of reliability, such as discrepancies between computed (supplied) and actual trip times. The quality of the decisions actually made in response to the information should be taken into consideration in assessing the effectiveness of a particular information strategy. These decisions obviously depend critically on the behavioral rules governing the users' responses.
- In general, information strategies consisting of supplying path trip times computed on the basis of currently prevailing traffic conditions do not appear to be particularly "reliable" according to several objective error measures. As expected, the reliability of such information tends to decrease with increasing market penetration of the technology, as the larger fraction of users who respond to the information generates rapid changes in traffic conditions and growing discrepancies between actual and supplied trip times. However, such information may still lead to profitable decisions that ultimately yield some travel time improvement.
- As a corollary to the above result, some form of coordination (by a central controller) is desirable in the provision of information in an ATIS, and a virtual necessity when the fraction of equipped vehicles in the population exceeds a certain level, possibly as low as 25%.
- Other than at low market penetration levels, myopic user responses to the supplied information tend to exacerbate the unreliability of the supplied information, when compared to the boundedly-rational indifference band rule. Furthermore, by allowing such a band to govern their decisions, users on average improve the quality of these decisions, committing fewer Type II errors than myopic users. In addition, the opportunity cost associated with these errors is so small, on average, that a meaningful improvement in overall trip time is obtained.

Given that the issue of reliability of particular information strategies cannot be separated from the users' behavior and the manner in which the supplied information is computed, much work remains to be done in this regard. In particular, an observational basis is needed to study the behavioral aspects of the problem, particularly the rules governing the short-, medium-, and long-run responses of the users. In addition, more "intelligent" information strategies need to be explored, involving predictive algorithms with multiple data sources.

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