Framework for Assessing Benefits of Highway Traveler Information Services

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The problem of estimating traveler benefits from an information system that is capable of forecasting traffic conditions on the roads of a network with a variable degree of accuracy is considered. Unlike the cases that have already appeared in the literature, in which furnishing actual times eliminates all uncertainty out of drivers' behavior, here the uncertainty about the occurrence of a particular traffic condition may simply be reduced instead of being completely eliminated. The primary purpose is to propose a methodological framework that can evaluate the benefits from the introduction of information services in highway networks. Given certain behavioral aspects of the traveler decision-making process, the focus is on quantifying what travelers gain by having perfect or partial information about highway traffic conditions. The secondary purpose is to use the proposed methodology to determine the optimal number of travelers to whom information on travel conditions should be provided.

Intelligent transportation systems (ITSs), which encompass advanced surveillance, communication, control, and computing systems and engineering management methods, are envisioned to be able to increase safety, reduce congestion, and improve the productivity of transportation systems. Within ITS advanced traveler information systems (ATISs) are envisioned to provide travelers with information on the status of highways either before they depart from their homes and workplaces or enroute so that they can make informed route choices and minimize their travel times. The information given to a traveler may involve transmission of observed travel times or forecasted future traffic conditions in the network so that congested areas can be avoided. Embryonic systems of traffic information dissemination and traveler guidance, such as Metro Traffic and Shadow Traffic, are already operational in metropolitan areas. The impact of traffic information on travelers' behavior, and subsequently on transportation network performance, is not obvious and must be researched.

Most research on the effectiveness of information systems has been undertaken in the area of evaluating the benefits from correcting drivers' perception (or misperception) of actual road link travel times (*1*). It assumes that drivers choose their routes on the basis of perceived travel times. As drivers assign themselves over the network an equilibrium point is reached when drivers cannot further decrease their perceived travel times by unilaterally changing routes. This assignment is deemed inefficient because drivers may be choosing inefficient (high-travel-time) routes since they are not aware of the conditions on all available alternatives. Most of the papers reviewed previously (*1*) conclude that substantial savings might be achieved if information on actual travel times on links is given to drivers so that an equilibrium traffic assignment based on actual rather than perceived travel times can be reached.

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THE PROBLEM

The problem considered in this paper is that of estimating traveler benefits from an information system that is capable of forecasting traffic conditions on the roads of a network with a variable degree of accuracy. Unlike the cases that have already appeared in the literature, in which furnishing actual times eliminates all uncertainty out of drivers' behavior (perception of travel times), here the uncertainty about the occurrence of a particular traffic condition may simply be reduced instead of completely eliminated.

The primary purpose of this paper is to propose a methodological framework that can evaluate benefits from the introduction of information services in highway networks. Given certain behavioral and attitudinal aspects of the traveler decision-making process, the paper focuses on quantifying what travelers gain by having perfect or partial information on highway traffic conditions.

The secondary purpose of the paper is to use the proposed methodology to evaluate the value of information to address the impacts of market penetration of information services on travelers' behavior and network performance. Primarily, the methodology is used to determine the optimal number of travelers to whom advanced information on travel conditions should be provided.

It is expected that the cost of ITS technologies will substantially decrease with the mass production of devices such as transponders that can receive and send traffic information. This low cost could make ITS technologies widely available to travelers. In the beginning travelers who are using ITSs and services will benefit greatly because they will be able to take advantage of the real-time (or near-real-time) information on traffic conditions obtained via these systems. However, as the number of ITS users increases, alternate routes may also become congested, diminishing the benefits of information that may eventually disappear.

It is incorrect to view ITS as a panacea for transportation ills and to assume that when all travelers are given access to the same network information they all will be better off than they were when they had only historical information or no information at all. In a congested network a change in the traveler assignment pattern caused by providing information may substantially change the total network travel times. In turn this can increase an individual traveler's average travel time compared with that in the situation when he or she chooses routes on the basis of historical information or no information. There is a threshold point at which giving information to an additional traveler will make him or her worse off. This threshold point may designate the optimal market penetration, defined as the number of users who will benefit when given information. Beyond this point having the information is disadvantageous for travelers. Moreover, travelers with no information may do better than those with information.

The information dissemination impacts are analyzed first for a simple network and then for a more complex network in which two traveler services provide information to subscribers in either a cooperative or a noncooperative manner. The impact of introducing travel information on network performance is not well understood and is far from obvious. The understanding of the value of information concept and the ways to estimate the gains from using an information service are critical for the successful development of an ATIS.

DECISION-MAKING UNDER UNCERTAINTY: AN EXAMPLE

Two routes, designated Routes A and B, shown in Figure 1 are available to drivers commuting from Origin O to Destination D. The travel time experienced by drivers depends on the traffic conditions that are encountered on the routes. From past experience a traveler characterizes traffic conditions as either normal or congested. In traffic engineering parlance these conditions can be thought of as levels of service A, B, or C for normal traffic and D, E, or F for congestion. The travel times experienced by the average driver are 22 min under normal conditions and 58 min under congested conditions for Route A and 31 min under normal conditions and 39 min under congested conditions for Route B.

From past experience a driver estimates that 60 percent of the time he or she encounters normal traffic. Thus, he or she predicts that normal traffic conditions will continue to appear with a probability of 0.6 and that congestion will be encountered with a probability of 0.4. These probabilities are called *prior probabilities.* The expected travel time on the routes is then calculated as the weighted sum of experienced travel times for each traffic condition, where the weights are the probabilities of occurrence of the traffic conditions. The expected travel times on routes A and B, $E_A(T)$ and $E_B(T)$, respectively, are

$$E_A(T) = (0.6 \cdot 22) + (0.4 \cdot 58) = 36.4 \text{ min}$$

$$E_B(T) = (0.6 \cdot 31) + (0.4 \cdot 39) = 34.2 \text{ min}$$

Based on the criteria of minimization of expected travel times the driver chooses Route B.

It would be advantageous for a driver to obtain advanced information on traffic conditions before he or she chooses routes. For example, a driver who ordinarily travels on Route A would use the information about congestion to avoid Route A and would use Route B instead. This information that eliminates all uncertainty about the occurrence of a traffic condition in the decision-making process is called *perfect* information. (Note that prior probabilities, the percentage of time a traffic condition will occur, cannot be changed; the driver can only receive information about which traffic condition will occur before he or she chooses a route.) The best the driver can do to minimize his or her travel time is to use Route A 60 percent of the time and Route B the remaining 40 percent of the time. The minimum expected travel time that the driver can achieve with perfect information, $E(PI)$, is

$$E(PI) = (0.60 \cdot 22) + (0.4 \cdot 39) = 28.8 \text{ min}$$

Assuming that it is possible to obtain perfect information, the amount a driver should be willing to pay for it is determined as the time savings between the expected travel time with prior information and the travel time with perfect information multiplied by the value of time. In the earlier example the difference is 5.4 min (i.e., 34.2 − 28.8). Assuming that the value of time is \$15/hr (\$0.25/min), the most that a driver should pay per trip is \$1.35 (\$0.25/min · 5.4 min/trip).

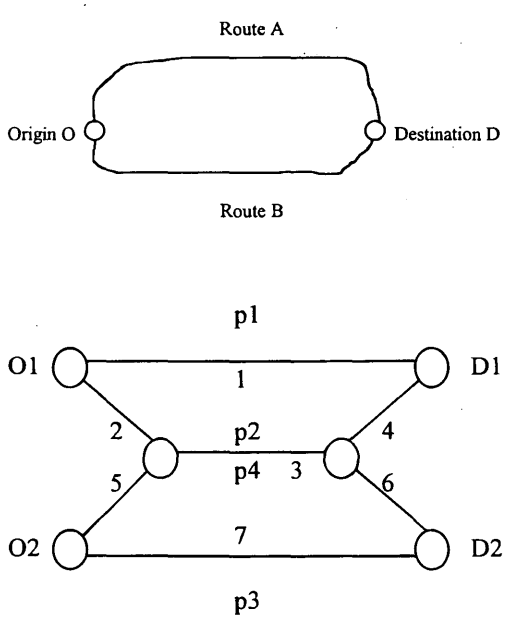

FIGURE 1. Example highway network: (*top*) single O-D pair, (*bottom*) two O-D pairs and two information services.

Formalized Approach

The example given earlier is typical of decision making under uncertainty. Clearly, more than two traffic conditions may exist (e.g., there may also be an incident). In general, a decision maker may undertake action a_k from the set of all possible actions $A = (a_1, a_2, a_3, \ldots, a_n)$. Several states of nature x_i included in the set $X = (x_1, x_2, x_3, \ldots, x_m)$ can occur, each with probability $p_i(x_i)$. For each action a_k that is undertaken when the state of nature x_i occurs, the decision maker receives a payoff (a reward or a loss), $V_{ki}(a_k, x_i)$.

In this example there are two states of nature (normal traffic and congestion), each occurring with a probability of 0.6 and 0.4, respectively, and two actions (choose Route A or B). The payoff $V_{ki}(a_k, x_i)$ is the travel time that a traveler experiences for selecting route k when condition i occurs.

The function $V(a,x)$ represents the set of all payoffs and is called the *gain function*. In the example this function was deterministic, but in general it could be a random variable and most likely a function of traffic volume. When the traffic conditions are broadly defined, as in the earlier example, the assumption that the gain function is deterministic is plausible.

In general, the decision maker–traveler will try to optimize the expected value of his or her gain function. In this particular example he or she minimizes the expected travel time of choosing action k when state of nature i occurs over the set of actions:

$$E[V(a,x)] = \min_k \sum_i p(x_i) \cdot V(a_k, x_i)$$

The expected gain with perfect information $E(PI)$, in which the traveler selects k to minimize $V(a_k, x_i)$ for each x_i, is given as

$$E(PI) = \sum_i p(x_i) \cdot \min_k[V(a_k, x_i)]$$

The value of perfect information to the traveler is based on the difference between the expected travel time with perfect information and the expected travel time with prior information.

More Complex Example

When traffic is forecasted traffic conditions are usually given for each road (or route) rather than as a general statement about network congestion as in the previous example. In the following, more complex example the same two-link network is considered, but now there are four traffic conditions:

1. Both routes have normal traffic (designated N_A and N_B),
2. Route A has normal traffic but Route B is congested (N_A, C_B),
3. Route A is congested and Route B has normal traffic (C_A, N_B), and finally
4. Both routes are congested (C_A, C_B).

Assume that these four conditions occur with the following probabilities:

$p(N_A, N_B) = 0.24$, $p(N_A, C_B) = 0.36$, $p(C_A, N_B) = 0.16$, $p(C_A, C_B) = 0.24$.

The outcome when a traveler chooses Route A or B depends on the conditions as follows:

	Traffic Condition			
Decision to Take	*(N_A, N_B)*	*(N_A, C_B)*	*(C_A, N_B)*	*(C_A, C_B)*
Route A	22 min	22 min	58 min	58 min
Route B	31 min	39 min	31 min	39 min

The expected travel times on route A and B, $E_A(T)$ and $E_B(T)$, respectively, are

$$E_A(T) = (0.24 \cdot 22) + (0.36 \cdot 22) + (0.16 \cdot 58) + (0.24 \cdot 58) = 36.4 \text{ min}$$

$$E_B(T) = (0.24 \cdot 31) + (0.36 \cdot 39) + (0.16 \cdot 31) + (0.24 \cdot 39) = 35.8 \text{ min}$$

A driver is expected to choose Route B, which has the least expected travel time.

The expected travel time with perfect information, $E(PI)$, is:

$$E(PI) = (0.24 \cdot 22) + (0.36 \cdot 22) + (0.16 \cdot 31) + (0.24 \cdot 39) = 27.52 \text{ min}$$

The difference between the expected travel time with perfect and prior information is 8.28 min (35.8 − 27.52). Assuming that the value of time is \$15/hr, the most the traveler should pay for perfect information is \$2.07 per trip (\$0.25/min · 8.28 min/trip).

Formalized Procedure

In the case describes in the previous section the state of each route can be described by random variables X for Route A and Y for Route B. The random variable can assume the state-of-nature normal traffic (N) or congested traffic (C). Then the traffic conditions on the network can be described by using a joint distribution of X and Y, $f_{X,Y}(x, y) = P(X = x, Y = y)$. The payoff $V_{kij}(a_k, x_i, y_j)$ is the time that a traveler experiences when selecting route k under state of nature - (i, j). The gain function $V(a, x, y)$ represents the set of all payoffs.

The minimum expected travel time that a traveler can achieve with prior information is

$$E[V(a, x, y)] = \min_k \sum_{i,j} p(x_i, y_j) \cdot V(a_k, x_i, y_j)$$

The expected benefit of having perfect information when a traveler selects route k to minimize V for each (x_i, y_j) state is

$$E(PI) = \sum_{i,j} p(x_i, y_j) \cdot \min_k[V(a_k, x_i, y_j)]$$

The difference between $E[V(a, x, y)]$ and $E(PI)$ multiplied by the monetary value of time determines an upper bound on what one should pay for perfect information.

INTRODUCTION OF INFORMATION SERVICE

In the second example normal traffic prevailed on either route 76 percent of the time $[p(N_A, N_B) + p(N_A, C_B) + p(C_A, N_B)]$. With perfect information a traveler would be able to predict this condition 100 percent of the time and use the facility that is not congested. The traveler could also benefit from imperfect information, however, as long as route conditions can be predicted better than prior information allows. Information, for example, that correctly predicts traffic conditions 90 percent of the time allows the traveler to take advantage of normal traffic conditions 68.4 percent (0.9 · 0.76) of the time.

Assume that in addition to the prior probabilities on the traffic condition a traveler is given conditional probabilities that describe the past performance of the information system. These probabilities indicate the frequency with which the information service forecasted a particular traffic condition, given that this condition indeed occurred. These probabilities are given in Table 1. The entry of 0.6 (in the upper left of Table 1) indicates that the service forecasted normal traffic on Routes A and B 60 percent of the time when normal traffic acually occurred on the routes. In addition, 15 percent of the time the service forecasted normal traffic on Routes A and B

TABLE 1 Conditional Probabilities

Forecasted	Actual Condition			
Condition	N_A,N_B	N_A,C_B	C_A,N_B	C_A,C_B
N_A,N_B	0.6	0.15	0.15	0.1
N_A,C_B	0.15	0.6	0.1	0.15
C_A,N_B	0.15	0.1	0.6	0.15
C_A,C_B	0.1	0.15	0.15	0.6

when actually a normal traffic condition occurred on Route A but congested traffic occurred on Route B.

These conditional probabilities can be used to update the prior probabilities and obtain *posterior probabilities*. The posterior probabilities represent the percentage of time that a particular traffic condition would occur given that it had been forecasted. The posterior probabilities can in turn be used to calculate expected travel times on the routes.

The following notation is needed before proceeding to solve the problem:

- x, y = traffic condition that occurred.
- m, n = traffic condition that was forecasted.
- $P_{X,Y}(x, y)$ = joint probability of condition x,y occurring.
- $Q_{M,N|X=x,Y=y}(m, n)$ = conditional probability of information service forecasting condition $(M = m,\ N = n)$, given that $(X = x,$ $Y = y)$ occurred.

- $Q_{M,N|X=x,Y=y}(m, n) \cdot P_{X,Y}(x, y)$ = the joint probability of the forecast of condition m, n and the actual condition x, y.
- $Q_{M,N}(m, n)$ = marginal probability of traffic condition $(M = m,$ $N = n)$ being forecasted for all possible occurrences of X, Y.
- $h_{X,Y|M=m,N=n}(x, y)$ = conditional probability of condition X, Y occurring given that the forecast indicated $(M = m,\ N = n)$.

Given this notation the procedure for computing posterior probabilities and expected travel times is as follows:

1. Gather the prior probabilities $P_{X,Y}(x, y)$ and the conditional probabilities $Q_{M,N|X=x,Y=y}(m, n)$.

2. Calculate the joint probabilities for each condition and its forecast, $Q_{M,N|X=x,Y=y}(m, n) \cdot P_{X,Y}(x, y)$.

3. Calculate marginal probabilities, $Q_{M,N}(m, n)$.

4. Calculate posterior probabilities $h_{X,Y|M=m,N=n}(x, y)$ as

$$h_{X,Y|M=m,N=n}(x, y) = Q_{M,N|X=x,Y=y}(m, n) \cdot P_{X,Y}(x, y)/Q_{M,N}(m, n)$$

5. Calculate expected travel times for each x,y using the posterior distributions as

$$E[V(a, x, y)] = \Sigma_k [V(a_k, m, n)] \cdot h_{X,Y|M=m,N=n}(x, y)$$

Numerical Example

Table 2 was developed by using the prior probabilities of traffic conditions given earlier and the conditional probabilities of traffic condition forecasts from Table 1. Table 2 (*a*) shows the joint probabilities for each traffic condition and its forecasts that are obtained by multiplying the prior probabilities by the conditional probabilities. The marginal probability of a forecasted traffic condition, $Q_{M,N}(m, n)$, is obtained by summing the joint probabilities over all actual conditions. For example, the marginal probability that N_A, N_B is forecasted equals 0.246(0.144 + 0.054 + 0.024 + 0.024).

Table 2 (*b*) shows the posterior probabilities that are obtained by dividing the joint probabilities by the marginal probability. For example, the posterior probability of N_A, N_B occurring given that it is forecasted equals 0.585 (0.144/0.246).

TABLE 2 Probabilities of Numerical Example

a. joint and marginal probabilities of actual traffic condition and its forecast

	Actual				Marginal
Forecast	N_A,N_B	N_A,C_B	C_A,N_B	C_A,C_B	Probability
N_A,N_B	0.144	0.054	0.024	0.024	0.246
N_A,C_B	0.036	0.216	0.016	0.036	0.304
C_A,N_B	0.036	0.036	0.096	0.036	0.204
C_A,C_B	0.024	0.054	0.024	0.144	0.246

b. posterior probabilities

	Actual			
Forecast	N_A,N_B	N_A,C_B	C_A,N_B	C_A,C_B
N_A,N_B	0.585	0.22	0.098	0.098
N_A,C_B	0.12	0.71	0.053	0.12
C_A,N_B	0.176	0.176	0.47	0.176
C_A,C_B	0.098	0.22	0.098	0.585

c. minimum time routes, expected travel times, and marginal probabilities

Forecast	Choose Route	Travel Time (min/veh)	Marginal Probability
N_A,N_B	A	22*(0.585 + 0.22) + 58*(0.098 + 0.098) = 29.078	0.246
N_A,C_B	A	22*(0.12 + 0.71) + 58*(0.053 + 0.12) = 31.368	0.304
C_A,N_B	B	31*(0.47 + 0.176) + 39*(0.176 + 0.176) = 33.754	0.204
C_A,C_B	B	31*(0.098 + 0.098) + 39*(0.22 + 0.585) = 32.6	0.246

The route choices resulting in the minimum expected value of travel time for each forecast and the marginal probabilities of the forecasts are given in Table 2 (*c*).

The minimum expected travel time for the average driver is

$$E[V(a, x, y)] = 0.246 \cdot (29.078) + 0.304 \cdot (31.368) + 0.204 \cdot (33.754) + 0.246 \cdot (32.6) = 32.79 \text{ min}$$

This time is obtained by the drivers using Route A when the forecast calls for either normal traffic on both routes or normal traffic on Route A and congestion on Route B (55 percent of the time) and using Route B when the forecast calls for either congested traffic on both routes or congested traffic on Route A and normal traffic on Route B (45 percent of the time).

The use of an information system resulted in the reduction of travel time by 3 min (35.8 − 32.79) compared with the case when only historical (or prior) information is used. The most that a traveler should be willing to pay for the service is his or her value of 3 min.

OPTIMAL NUMBER OF INFORMED TRAVELERS

It would be incorrect to assume that all travelers should be given information even if they are willing to pay for it. A highway network has limited capacity and experiences congestion. As congestion increases so does travel time. If travelers are given information indiscriminately it is possible that the change in commuting patterns will result in higher average travel times on routes, and thus higher individual travel times for all travelers, including those with information.

It is assumed that travelers are minimizing their individual travel times or behave according to Wardrop's First Principle (*2*). An inherent assumption of Wardrop's First Principle is that travelers have full information (actual travel times) about the routes. In the case in which travelers base their route choice on perceived travel times instead of actual ones, the principle states that at equilibrium the traveler cannot improve his or her perceived travel time by unilaterally switching routes. This principle leads to Stochastic User Equilibrium (*3*).

The minimization of individual traveler times must not be confused with the minimization of networkwide travel times, also known as Wardrop's Second Principle (*2*). It is common that in minimizing their individual travel times travelers can indeed increase the total networkwide travel time. In the absence of congestion Wardrop's First and Second Principles yield the same traffic assignment flows and costs.

In this paper it is assumed that travelers have an incentive to purchase information of a given accuracy as long as it can make them better off. This implies that travelers will be able to further minimize their individual travel times in comparison with the case of having only historical (prior) information. Therefore, the optimal (or desirable) number of travelers can be determined by an equilibrium pattern which the travel times for travelers who use the information service are at least as good as those for travelers with historical information. This equilibrium point determines the maximum market share for the information service.

Network Equilibrium

To analyze this problem the networkwide interactions among travelers must be investigated. The network highway links are congested, and the travel time on a link is estimated according to the Bureau of Public Roads (BPR) congestion curve (*4*) of the form

$$t_l = t_0 \cdot [1 + a(\text{link flow/link capacity})^x]$$

where

- t_l = average travel time on link l,
- t_0 = free-flow travel time on link l (the distance divided by the free-flow speed),
- a = marginal increase in link time when accommodating an additional vehicle, and
- x = coefficient.

The link capacities used in the BPR curve were calculated by using the methodologies set forth in the 1985 *Highway Capacity Manual* (*5*) for each road type (arterial and freeway).

Assume that the congestion curves for Routes A and B are

$$t_A = 17 \cdot [1 + 3 \cdot (\text{flow}/2{,}000)^2], \text{ and}$$

$$t_B = 30 \cdot [1 + 3 \cdot (\text{flow}/6{,}000)^2]$$

where Route A and B capacities of 2,000 and 6,000 vehicles per hour, respectively, are calculated for levels of service that represent stable flow. Depending on traffic conditions, normal and congested, each of these curves are divided into two areas. For normal traffic conditions on Routes A and B they are

$$t_A = 17 \cdot \{1 + 3 \cdot [(100 + f_A)/2{,}000]^2\}, \text{ and}$$

$$t_B = 30 \cdot \{1 + 0.3 \cdot [(1{,}500 + f_B)/6{,}000]^2\}$$

For congested traffic conditions on Routes A and B they are

$$t_A = 17 \cdot \{1 + 3 \cdot [(1{,}300 + f_A)/2{,}000]^2\}, \text{ and}$$

$$t_B = 30 \cdot \{1 + 0.3 \cdot [(5{,}100 + f_B)/6{,}000]^2\}$$

The graphical representation of the volume-travel time functions and areas representing normal and congested conditions are given in Figure 2.

If 500 travelers are assigned over the routes the resulting travel times are 21.59 min for normal conditions and 58.31 min for congested conditions on Route A and 30.99 min for normal conditions and 37.84 min for congested conditions on Route B. If normal conditions on Route A prevail 60 percent (24 percent + 36 percent) of the time and congestion prevails 40 percent (16 percent + 24 percent) of the time, the expected travel time is 36.28 min. If normal conditions on Route B prevail 40 percent (24 percent + 16 percent) of the time and congestion prevails 60 percent (36 percent + 24 percent) of the time, the expected travel time is 35.1 min.

When the model is solved with prior information only, all 500 travelers are assigned to the minimum time Route B, yielding an average travel time of 35.1 min (the minimum of 35.1 and 36.28 min for Routes B and A, respectively). When travelers are assigned by using the posterior information provided by the information service, all 500 travelers use Route A 55 percent of the time [the sum of the marginal probabilities of those choosing route A in Table 2(*c*)] and Route B 45 percent of the time, yielding an average travel time of 31.39 min. This lower travel time is achieved by using the information service to forecast normal traffic on Route A and assigning the travelers over that route during those periods and over Route B when traffic is congested on Route A.

If all 500 travelers were subscribers to the service they would have been better off than if they were using prior information only.

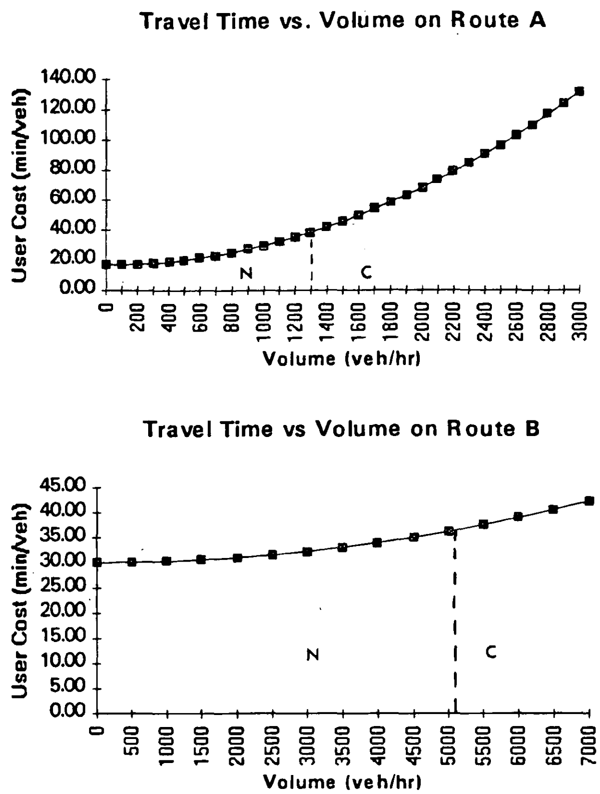

FIGURE 2. BPR congestion curves and traffic conditions.

By using the information their individual time decreased by 3.71 min (from 35.1 to 31.39 min). Finally, when the travelers are assigned with perfect information, all 500 are assigned to Route A 60 percent of the time and Route B 40 percent of the time. Thus, the travel times are further minimized to an average of 28.09 min.

The question that arises is determination of the optimal number of users to be given information. Common sense would indicate that travelers would have an incentive to use the information service only if it did not make them worse off than they were with no service at all. Consequently, the optimal market penetration is determined by a traffic assignment for which the average travel time is no less than that of an assignment obtained without information.

Returning to the previous example, it can be verified that when 800 travelers (instead of 500) are assigned according to the minimum expected travel time, the resulting travel times are 34.818 min when only prior information is available and 35.770 min with the information service (posterior). It is obvious that the switching of commuting patterns caused by the vehicles that obtained information has caused the average travel times on links to become higher than they were in the case in which they had prior information. One may conclude that it is highly unlikely that people will be using the service that makes them worse off (by 0.952 min in this case) than they were before they started using it. Therefore, the number of users to whom information services should be provided (i.e., an equilibrium among users with and without an information service) needs to be determined.

To determine the optimal number of users to be given information, assume that travelers are divided into two classes: those without and those with information, designated *fwo* and *fw*, respectively. The *fwo* travelers will be using only Route B, whereas *fw* travelers will be using Routes A and B in a mixed strategy. It should be recognized that the travel times on routes depend on both types of flows *fwo* and *fw*, because these flows use the routes simultaneously. Since travelers with information *fw* will be using Route A during certain times (i.e., 55 percent of the time), they will be removed from Route B. Thus, the following equation can be set up. The equation determines an equilibrium pattern in which the travel times for travelers who use the information service are at least as good as those for travelers with historical or prior information. The left side of the equation represents the travel times of travelers with historical information, whereas the right side represents the travel times of travelers who use the information service.

$$
\begin{aligned}
&0.4\cdot\{30\cdot[1 + 0.3\cdot[(1{,}500 + fwo + fw - 0.55fw)/6{,}000]^2\}\\
&+ 0.6\cdot\{30\cdot[1 + 0.3\cdot[(5{,}100 + fwo + fw - 0.55fw)/6{,}000]^2\}\\
&= 0.246\cdot\{17\cdot[1 + 3\cdot[(100 + fw)/2{,}000]^2]\cdot 0.805 + 17\cdot[1\\
&+ 3\cdot[(1{,}300 + fw)/2{,}000]^2]\cdot 0.196\} + 0.304\cdot\{17\cdot[1 + 3\cdot[(100\\
&+ fw/2{,}000]^2]\cdot 0.83 + 17\cdot[1 + 3\cdot[(1{,}300 + fw)/2{,}000]^2]\cdot 0.173\}\\
&+ 0.204\cdot\{30\cdot[1 + 0.3\cdot[(1{,}500 + fwo + fw)/6{,}000]^2]\cdot 0.646\\
&+ 30\cdot[1 + 0.3\cdot[(5{,}100 + fwo + fw)/6{,}000]^2]\cdot 0.352\}\\
&+ 0.246\cdot\{30\cdot[1 + 0.3\cdot[(1{,}500 + fwo + fw)/6{,}000]^2]\cdot 0.196\\
&+ 30\cdot[1 + 0.3\cdot[(5{,}100 + fwo + fw)/6{,}000]^2]\cdot 0.805\}
\end{aligned}
$$

Given that $fwo + fw = 800$, solving this equation yields flows for *fwo* and *fw* of 57.957 and 742.043 vehicles, respectively. The travel assignment times are equalized at 34.882 min. This result implies that approximately 742 vehicles will have an incentive to subscribe to the service, but only if it were free.

The resulting average travel time as a function of traffic volume for each information distribution strategy is given in Figure 3. There are three information distribution strategies: (a) all travelers have only prior information, (b) an information service gives information on traffic conditions to all travelers indiscriminately, and (c) the information service is provided to a selected group of travelers, whereas the rest of the travelers use historical information. The number of users with information indicates the optimum market penetration because the average travel time between an origin and a destination cannot be further improved by giving information to an additional traveler.

Figure 3 shows that up to a volume of 700 vehicles/hr, if all travelers are given the information an average traveler will experience a shorter travel time compared with that in the case in which he or she were to use prior information. After that volume the information should be given to only a portion of the total travelers. For example, for a volume of 900 vehicles/hr, the information should be given to 748 vehicles. This results in an equilibrium time of 35.080 min/vehicle. (Note that if the information is given to all 900 vehicles the average user cost would increase to 37.515 min.) For a volume of 1,000 vehicles/hr the number of travelers with information will be 755 vehicles/hr. It is apparent that the 11.1 percent inverse in volume (i.e., from 800 to 900 vehicles) will increase the market penetration of the service by 0.9 percent (i.e., from 748 to 755 vehicles). Thus, the majority of additional travelers will be given no information.

Further Extensions

The framework is also applied to a more complex network consisting of six nodes (two origin–destination pairs and two through nodes), seven links, and four paths. The network is shown in Fig-

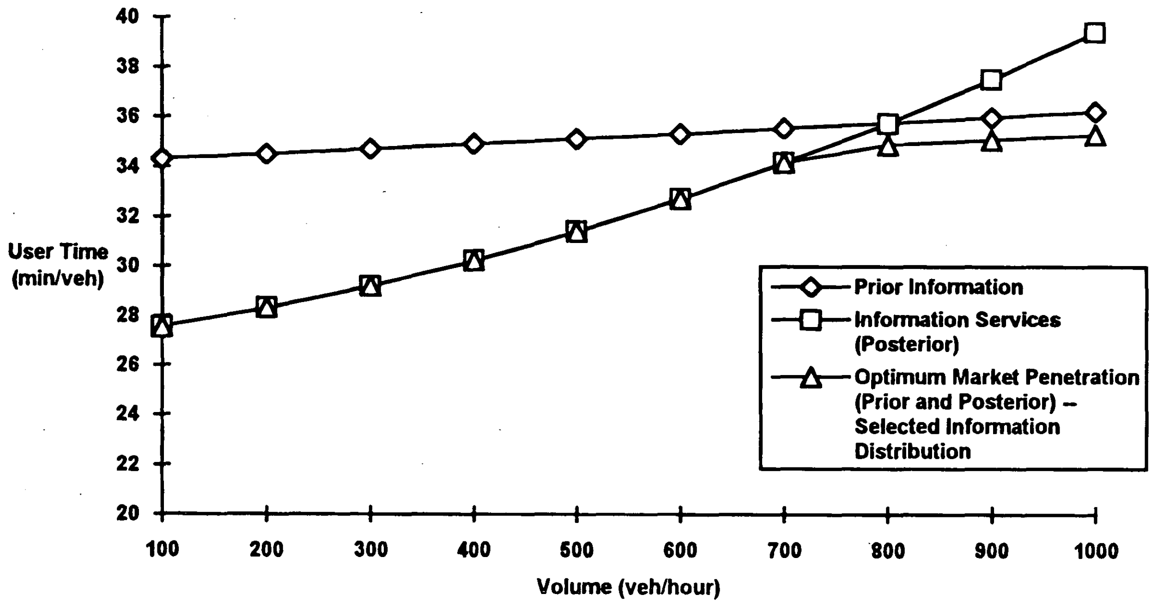

FIGURE 3. Travel times under various information distribution strategies.

ure 1(*b*). For the purpose of simplifying the discussion of the results it is assumed that the network is symmetric (i.e., Links 1 and 7 are identical and Links 2 and 4 are identical to Links 5 and 6). Two paths are available for travel from each origin to a destination. Paths P1 and P3 consist of Links 1 and 7, respectively, whereas Paths P2 and P4 consist of Links 2, 3, and 4 and Links 5, 3, and 6, respectively. The prior and posterior probabilities of normal and congested traffic occurring on Paths P1 and P2 and Paths P3 and P4 are assumed to be identical to those given in Tables 1 and 2 for Routes A and B. It is also assumed that there are two information services available to travelers: Poly-Traffic serving the O1–D1 pair and Shade-Traffic serving the O2–D2 pair. There are 500 vehicles/hr between each origin and destination.

The results presented in Table 3 indicate that when the services made their decision as to whom to give information and what commuting strategies to suggest independently from each other, they gave the information to all 500 vehicles from each origin. The vehicles ended up with the strategy of choosing Paths P2 and P4 55 percent of the time and Paths P1 and P3 45 percent of the time. Since the services made their decisions in a vacuum, they did not consider the possible strategies of their opponents. Thus, they perceived that the resulting vehicle travel times would be 31.39 min.

TABLE 3 Optimal Market Penetration and Travel Times Under Various Information Dissemination Strategies

Information Type	Select Routes	Users with Information Service (veh/hour)	Expected Travel Time (min/veh)	
			Perceived	Actual
Prior	P1 and P3 100% of the time	0	35.1	35.1
Posterior -- No Cooperation between Services	P2 and P4 55% of the time, and P1 and P3 45% of the time	1,000	31.39	38.91
Posterior -- Cooperation between Services	P2 and P4 55% of the time, and P1 and P3 45% of the time	748	34.69	34.69

However, since Link 3 is shared by Paths P2 and P4, the congestion on Link 3 caused by an additional 1,000 vehicles going over it 55 percent of the time resulted in an actual travel time of 38.91 min. This decision to suggest to all vehicles to choose the same commuting strategy made all vehicles worse off than they would have been if they had stayed on Paths P1 and P3 100 percent of the time. Had they stayed on Paths P1 and P3, as they would have under prior information, their travel times would have been 35.1 min.

When the services either cooperated with each other or attempted to predict each other's responses in terms of a likely strategy, the optimal assignment indicated that they each gave information to use Paths P2 and P4 55 percent of the time to only 374 vehicles. This resulted in a travel time of 34.69 min. The remaining 126 vehicles from origin O1 were not given information and thus stayed on Path P1 100 percent of the time. The remaining 126 vehicles from origin O2 stayed on Path P3 100 percent of the time.

Future Framework Extensions

The framework presented in this paper can be expanded to take into account traveler utilities rather than travel times. The utility, in addition to travel time, may include other impedances such as out-of-pocket cost and other qualitative measures of a commute such as the scenery along the route, perceived safety of the surrounding area, and so forth.

The paper assumed that drivers have linear utilities (i.e., they place the same value on 1 min saved on a 22-min trip as well as on a 58-min trip). This is a rather strong assumption, because people value time savings higher on a shorter trip than on a longer trip (*6*). A candidate nonlinear utility function that can be used in the framework has been provided elsewhere (*6*). The process of deriving nonlinear utility functions has been given previously (*7*).

The framework can also be expanded to take into account the fact that more than two traffic conditions can arise (and be perceived by a driver) on the route. In addition, instead of using discrete distributions a continuous probability distribution can be used to describe traffic conditions. Consequently, the payoffs can be expressed as expected values of a random variable, the traffic flow. Various methods for estimating congestion functions need to be incorporated into the model as well.

The framework presented here is rather aggregate. It does not recognize the time dimension of a decision-making process. The methodology presented needs to be expanded to take into account the dynamic aspects of decision making. There needs to be a feedback loop between the traffic conditions arising at various links in the network at various moments in time and travelers' decisions.

CONCLUSIONS

A framework was presented for assessing the benefit of information from an ATIS. It provides transportation professionals with a tool to evaluate the value of an information service and to compare it with the case in which only historical information was available. In addition, the framework can be used to evaluate the value of the information service in comparison with the case in which travelers have perfect information. The methodology can also be used to estimate the characteristics and accuracy of the information service. For example, given a certain target market penetration, the methodology can be used to determine the system accuracy (i.e., probabilities of detecting traffic conditions) so that an average potential user receives a certain level of benefits. The method can be further improved by considering additional traffic conditions that occur on the routes. More appropriate congestion functions can be derived and used in the method. The procedures presented in this paper can be used within a more comprehensive framework that uses state-of-the-art traffic assignment techniques of mathematical programming and simulation to better ascertain both the potential value of information to customers and the optimal number of people to whom the information should be given. Finally, the framework may complement behavioral studies that determine travelers' attitudes toward various types of information delivery technologies.

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