Title

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Abstract

This working paper is a preliminary review of the state of the art in the study of the economics of traffic information. The focus is on the different methods used to model the decision process of drivers in a traffic system, and on the effect of traffic information on this process. In addition, the review includes the characterization of information in terms of content and accuracy. The purpose is to develop an understanding of the market for different types of traffic information. The paper also includes some preliminary models that can be used to model the demand and supply of traffic information, including its temporal and spatial characteristics.

Keywords: Advanced Traveler Information Systems, Benefit Cost Analysis

Executive Summary

With congestion increasing significantly on our roadways, and major adjustments (e.g. the automated highway system) still years away, the throughput of vehicles on our existing system must somehow be increased. Traffic information has been shown by many studies to increase a system's throughput of vehicles by approximately 5-15%, depending on multiple factors. With this working paper we will review the literature presently available regarding the economics of traffic information and the influences affecting the improvements which might result.

One focus of this paper is the behavior of traffic information providers in gathering and distributing the information. A second focus of this paper is on the different factors which affect the human decision process employed by drivers and the effect of traffic information on this process. In addition a number of important findings in fields related to transportation and economics are explored for potential applications to traffic information.

The first area of concern explored is the prospective behavior of information suppliers in the marketplace. A previous study is expanded upon to show that information suppliers might tend to cluster their services in a private market. The maximum benefits which could be received by the entire society from traffic information providers are thus not attained, and the potential improvements resulting from public involvement are explored.

The human decision process is then explored for means of representing the benefits received by consumers of traffic information. Probabilistic theories (e.g. game theory) are used in attempt to model the decisions made by informed and uninformed drivers. From these models conclusions are made about the factors impacting the overall benefits received from the use of traffic information. In addition these benefits are compared to trends likely for the costs of an information system, leaving suggestions as to what level of information would be most productive toward society. The system-optimal level of characteristics describing an information system (e.g. accuracy, frequency of updates) are shown to be affected by the costs of attaining these levels and the benefits which the system's users can be expected to receive.

After attempting to model the human decision process, the individual factors which have been found to affect this process are described. The impact that each characteristic, either of the driver or the environment which the driver is in, is described. These factors are then shown to be combined in a manner unique for all drivers to form what has been referred to as a threshold for diversion, which affects each individual driver's willingness to alter his route or departure time. These changes are what is necessary to reduce the congestion on freeways resulting from excessive demand or capacity-reducing incidents.

Finally the different analytical tools in use today with traffic studies are described along with the adjustments which can be made for direct use with traffic information. These tools (e.g. a queuing curve) can be used to measure the direct impact of certain parameters upon the movement of traffic with information. In addition the impact that each of the previously described factors has on the movement of vehicles can be visualized easier with these tools.

With this information and the research surrounding it it is hoped that the behavior of today's traffic information providers can be understood better. The demand for traffic information by drivers, network operators, goods distributors, etc. can be explored to determine what type of benefits can be realistically expected from our information systems. In addition we might be able to prescribe the actions with regard to public funding and provider behavior through

which we could achieve these benefits.

1. Introduction

As more roadways become saturated with traffic each year, traffic information systems are being looked upon as solutions in more cities. Traffic information systems are used to inform drivers and system managers of periods when capacity on one route has been reduced (due to an incident) or when an alternative route might be quicker due to the level of demand on the primary route. Examples of such systems available today include the SmartRoute systems in Boston, the TravInfo system in the San Francisco/ Bay Area, and the use of the Internet for the Los Angeles metropolitan area (Liebesny 1992; Yim 1996). In nearly every city information is gathered by some means to be distributed over radio reports.

Numerous studies in recent years have explored the many aspects influencing the economics of the traffic information industry. One important aspect of information economics is the behavior of travelers. A better understanding of such could be gained through surveys or observations of traveler responses. Another form of research has used computer simulation to estimate the travel-time benefits attainable with different levels of market penetration. A third form of research involves analytical tools (such as queuing analysis) to represent the impact of different information systems. Each of these areas will be discussed extensively in this report.

In addition to these studies, a number of historical studies in the fields of communication technology and decision theory will be discussed. We will show how we may borrow from their knowledge to understand our world better.

We will show how we plan to use the findings from these studies to gain a clearer understanding of the information industry. With this understanding we plan to address two important issues, namely: i) why the members of the information industry (suppliers and customers) behave as they do, and ii) what kind of changes (with policy, equipment, etc.) might be useful to increase the benefits which society gains from these services.

2. Foundational Research

To analyze the economics of traffic information, it is first necessary to understand the forces which make participants behave as they do. With most goods produced for consumption, it is the desires of the suppliers and customers to maximize their individual benefits which cause each good to be produced and priced at a certain level. The principle behind the customers' demand curve is that they would ideally "pay" a specified amount (often a function of price and transportation costs) for a good which provided them with a certain benefit. With traffic information, this benefit can be seen as a function of the travel time saved with information.

Traffic information is different from most goods, however, in that the cost of "transporting" the information is negligible. Whereas most fixed goods require a trip to the store, information is available at one's fingertips. In addition, fixed goods tend to provide individual benefits independent of the overall level of consumption. Traffic information differs in that the direct benefits of information are inversely proportional to the amount of people receiving the information (due to the buildup of traffic on the alternate route). It should also be noted here (and discussed later) that traffic information can be shown clearly as providing benefits to drivers who are not direct customers. (Diverting vehicles from congested roads can reduce significantly the travel times of other vehicles.) As a result society receives many external benefits not affecting the price which individual customers would be willing to pay. These benefits might be captured as a means for justifying public financing.

A supply curve would represent the level of information (area covered, accuracy and frequency of reports, etc.) which a supplier would produce if he were to generate a specified amount of revenue (from public funding, private customers, etc.). This price would resemble the costs necessary for gathering the information, as the goods need not be transported to a common point such as the market. An illustration of these curves can be seen in Figure 1. One large objective of our research is to attempt to describe the forces behind these curves. Together they influence the level of information which would ideally be produced by a free market.

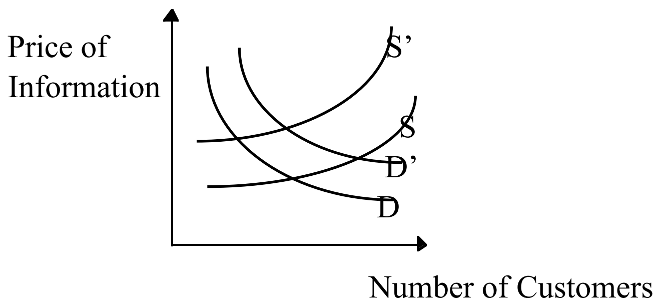

Figure 1. The supply and demand for different levels of information

For example, information of a certain level will be of a certain value to customers (D). Information of a higher level (greater accuracy, more frequent updating, etc.) will be of a higher value (D'); thus customers should be willing to pay a higher price. Similarly, the costs to suppliers for gathering traffic information will increase with the level of information (S' > S). We hope to explain the different factors influencing the level of supply and demand existing on the market.

2.1. Competition among suppliers

The behavior of goods suppliers, a behavior we believe could be extended to that of information providers, was addressed first by an economist, Harold Hotelling (Hotelling 1927). Here it was shown that suppliers of a common good for which there is uniform demand tend to cluster. That is, along a linear market with uniform demand, competing suppliers (both producing the good at equal costs) would ultimately locate themselves adjacent to each other in the center of the market. Because neither provider would be able to increase his revenue by moving, this situation was regarded as a Nash equilibrium, with respect to location. This situation is illustrated in Figure 2.

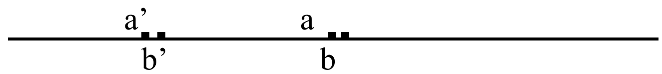

Figure 2. Locations of competing suppliers of goods, at equilibrium (a-b) and non-equilibrium (a'-b').

If either supplier (supplier A) were not located in the middle (rather, at a'), the other supplier (supplier B) could maximize his revenue by positioning himself immediately toward the center (at b'). And so the other supplier (A) would move, the process repeating until both were in the middle, when equilibrium was reached.

This arrangement of suppliers clearly does not sell its goods to its customers at what would be the lowest price possible. When the transportation costs are included for a fixed good, the benefits of the society could be shown to be maximized when the suppliers are distributed throughout the line rather than being clustered in certain locations.

This issue comes of interest with traffic information because it can be shown that information providers will also tend to cluster near the locations of highest demand. Such clustering would in a sense maximize the demand captured (and thus the revenue) for the individual suppliers. As a result, competing providers would be running similar operations in the same locations; the fixed costs necessary to capture this area would be needlessly multiplied. An alternative solution, one which would maximize the public benefit from the service, would call for the distribution of information suppliers such that no overlapping occurred and the maximum demand was captured. The benefits gained by travelers from information would increase, while the costs would be unchanged.

As Hotelling mentioned that this scenario might support the idea of socialism over capitalism, with traffic information it might serve to justify public funding for traffic information. We will later show how studies have also found that benefits of traffic information are consistently received by uninformed travelers as well as the informed. If these benefits are to be captured and priced accordingly, public financing would be necessary at some level. One of the issues at the heart of our study is the precise level of public involvement at which benefits of the system could be maximized.

It should be noted that some thoughts behind this paper were later refuted (D'Aspremont 1979), on the argument that price equilibrium would never exist with suppliers so close, due to undercutting. However, for some sources of traffic information (particularly with radio or television) no direct pricing exists between the suppliers and the customers. In addition, a unique aspect of traffic information is that the customer does not bear the costs of transporting the good between locations. The cost of transporting the information electronically costs very little in both time and money, and as a result, the transportation costs associated with gathering/distribution of information are shared by all customers. As a result, clustering could still exist among traffic information systems, and the involvement of public funding could prove beneficial.

2.2. Modeling the benefits of an informed driver

With regards to the demand for information, much work has been done for other fields of economics which could be applied to traffic information. Many authors, including one of the founders of decision theory, Jacob Marschak, reasoned that the value of information (and thus the demand price) could be set as the average amount earned as a result of that information (Marschak 1974b). In other words, the value of a piece of information could be set as the change in the expected value of the output parameter to be measured. With regards to traffic information, the benefits could be received through a reduction in travel time; the value of the information would be the average reduction in travel time. (Unfortunately with transportation many variables combine to form a utility function which is maximized by drivers. Other factors affecting one's utility, and thus the price, include the familiarity with certain routes or the consequences of being late for an appointment, such as a flight. Factors such as these are often difficult to capture and will be explored later.)

A simple extension of this which appeared in Marschak's paper would involve the payoff matrix given in Figure 3, with states of nature S_1 and S_2 and actions a_1 and a_2 :

	States of Nature	
	S_1	S_2
Actions, a_1	r_1	0
a_2	0	r_2

Figure 3. Representation of a Payoff Matrix

where r_1 and r_2 represent the rewards for certain action-state pairs. For this example assume that the rewards r_1 and r_2 represent the amount of travel time saved by taking the shorter route. Action 1 represents taking the freeway and action 2 the arterial. States 1 (no) and 2 (yes) represent the existence of an incident along the freeway. The payoff matrix shows how rewards would be gained by traveling the freeway when there is no incident and the arterial when there is an incident (causing enough delay to warrant diversion).

The benefits which come as a result of the use of traffic information, found from the payoff under different scenarios, can be described as follows. Let:

$1-p$ = probability of an incident occurring (S_2)
p = probability of no incident occurring (S_1)

Assume that the probability of an incident is less than one-half, and, on average, drivers would perform better taking action 1 each time. Drivers would become aware of this trend from past experience, and in the event that no updated information is available, would follow this action each time. The average payoff ($= \Sigma_i p_i r_i$) would be:

$$p*r_1 + (1-p)*0 = p*r_1 \qquad \text{(without information) (1)}$$

In the event that information is available, we can assume that the driver will take that action which offers the greatest reward each time. That is, under state 1 (no incident along the highway) the driver will take action 1 (travel the highway). Under state 2 (an incident along the highway) the driver will take action 2 (travel the arterial). In this case the average payoff would be:

$$p*r_1 + (1-p)*r_2 \qquad \text{(with information) (2)}$$

The average benefit of information, seen by subtracting (1) from (2) are found to be:

$$(p*r_1) + ((1-p)*r_2) - (p*r_1) = (1-p)*r_2 \qquad \text{(benefits of information)}$$

Upon simple observation this finding shows us that the benefits which are to be received from a traffic information source are proportional to:

i) the probability of an incident occurring (1-p), and
ii) the average reward which would result from taking the optimal action

As a result one can see that the benefits of an information system are greatest when incidents are more frequent (until taking the arterial becomes better, on average) and when the reward of using the alternate route in this state is greater. With this system we could calculate the maximum benefits to be produced by an information system, if state 2 were to correspond to the existence of an incident significant enough to warrant diversion. The reason for this definition of state 2 results from the fact that benefits are produced when the optimal action for a certain state changes. It is precisely at this point, where diversion is warranted, that the optimal action changes.

2.3. Extensions of game theory

This payoff matrix is similar to another game theoretic representation which involves the actions of more than one party. In the previous payoff matrix, the rewards of certain actions were a function of the prevailing state; in game theory, the rewards are a function of other players' actions. In a sense, this arrangement might seem more logical because the travel times (or rewards) along a certain route are clearly a function of how many other people travel that route. One direct application of this concept was made by de Palma (1993). He assumed that an entire platoon (one of the "players" taking an action) traveling from one origin to one destination would follow the same route, the payoff (or cost) being a function of the other platoons' actions.

This scenario could be applied with the use of traffic information. For a simple case, imagine two sets of drivers (informed, uninformed) traveling along a similar route. The informed travelers' benefits would be a function of the percentage of people between each O-D set which take each route. That is, because the travel time on each route is a monotonic function of the volume using it, the benefits of taking the secondary route, in the event of an incident on the primary route, is a function of the number of vehicles taking a similar action. Complications arise in that the number of vehicles equipped and the capacity reduction of an incident change with every incident; thus the payoff will change. This is information which the informed driver is typically not equipped with when making his decision. In addition, the availability of alternate routes will change from site to site, also affecting the rewards for different actions. In summary game theory would likely be most helpful in simply gaining a picture of the decisions faced by everyday drivers and the effects which these decisions have. The results, however, would be difficult to generalize and transfer between events and locations.

A possible representation of the payoff to individuals under certain conditions (or the expected benefit to be received from information) is given by Hirshleifer & Riley (1992). Shown in Figure 4 is a graph, on which the x-axis represents the probability of state 1 occurring (at x = 1, state 1 occurs; at x = 0, state 1 does not occur). Assume state 1 represents the event of an incident. The y-axes represent the utilities resulting from each action when that state corresponding with the x-coordinate occurs.

The diagonal lines connecting them represent the expected utility which would result from the probability distribution given by each point along the x-axis. When a message gives a certain probability, the best action would be that which gives the largest expected utility. As a new message arrives and gives a new probability distribution, the expected utility corresponding to certain actions will change; the value of this information is the change in the expected utility at this state from the previous state.

For instance, assume that the probability of an incident, apriori, is 1/3. Similar to previous discussion, the optimal action at $p_0 = 1/3$ would be to take the highway, with a utility represented by A. Assume that an information source gives two messages. Under one message, that no incident has occurred, the probability of an incident has fallen to $p_1 = 0.1$. With the second message, that an incident has occurred, $p_2 = 0.8$. Under message 1, the optimal action would be to take the highway (which has the highest expected payoff, B). Under message 2, the optimal action would be to take the arterial (C). The expected utility, given the information, can be found from the line connecting points B and C. Assuming that the apriori probability remains p = 1/3, the benefit resulting from the information would be the vertical distance between A and BC. This diagram can be used to see clearly that:

i) the benefit gained from the information can be seen to increase linearly with the accuracy of each message. As p_1 increases, the line BC rises proportionally, and the distance between A and BC increase proportionally as well.

ii) the benefits gained from increasing the accuracy of all messages, or the overall accuracy of the system, grows even faster.

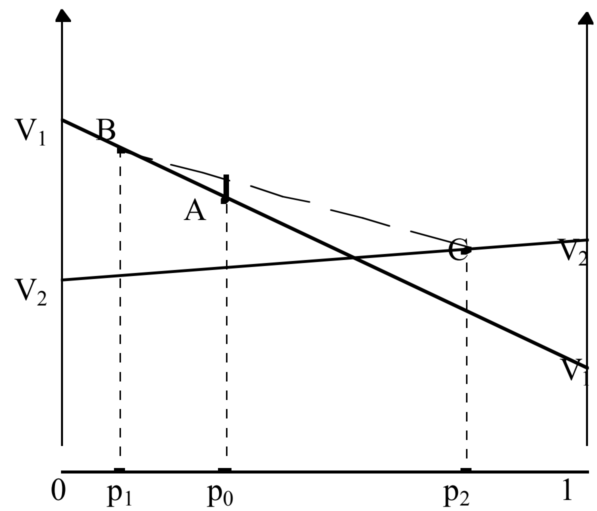

Figure 4. Graph representing the benefits of information in terms of the accuracy of the messages (p_i) and the utilities of different states (V_i). The benefit resulting from the information is proportional to the distance between A, the apriori expected utility, and the line BC, the expected utility after receiving the messages.

2.4. Costs versus benefits

Unfortunately, as the benefits can be seen to increase linearly with the accuracy of each message, the costs required for achieving such accuracy likely grow at a much faster rate (similar to Figure 5). That is, every degree of accuracy desired for the output likely has an increased marginal cost. (One could justify this from the fact that an errorless system, virtually unachievable, could be represented by an infinite cost.) At some point, the cost of increasing the accuracy would exceed the benefits to be gained from such. As a result, it should be realized that the optimal level of accuracy for messages is likely somewhere below complete accuracy. The cost of devising a perfect system would be too great.

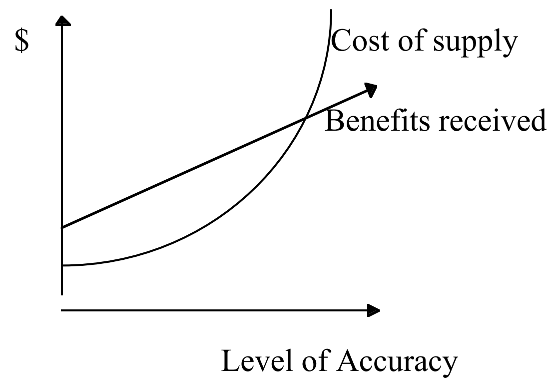

Figure 5. Likely relationship between costs and benefits for accuracy

The cost of information systems is affected largely by the system's ability to handle data. Important thoughts regarding this given by Marschak were in many ways drawn from the contributions of Shannon and Weaver in *The Mathematical Theory of Communication* (Shannon et al. 1962). Important ideas were first addressed here regarding the amount of information. For example, here the amount of information was defined as:

$$H(x) = \Sigma_i -p_i \log(p_i)$$

summed over all messages i of probability p_i. Shannon and Marschak both commented that the larger the number of messages, the larger was the amount of information, and thus the more costly would be the instrument necessary to measure/transfer the information. This trend in costs describes what was explained earlier with the accuracy of messages; it is likely that the number of messages would have to be larger if more accuracy is desired. (Significant improvements in communication technology over recent decades has likely influenced this trend somewhat, but some effect would still be present.)

Fortunately, it should be remembered that more value is not necessarily gained from more information. Shannon argued that the amount of information could not be allowed to exceed the capacity of the channel by which it was being sent, else it would be reduced by errors or ambiguities. From this, Weaver made the natural extension that the capacity of the channel can be assumed similar to the capacity of the audience (or the driver). That is, as many traffic engineers have shown and we will discuss in the following section, the amount of traffic information should not exceed the amount necessary. (For example, the amount of traffic information could include data such as queue length, travel time, cause of an incident, alternate routes available, etc.) Only a fraction of this information is necessary to make an informed decision as to the optimal itinerary.

In addition, human drivers have been shown to be able to handle only a certain amount of information; as the information grows, it may become too complicated. In many instances the increased costs spent to gather more detailed information provide zero benefits. In summary, more information does not always mean more value. In fact, the only instances in which the value of information can be seen as proportional to the amount of information are those instances in which either the state is already known (in which case the value is 0), or when all states are equally likely.

2.5. What can we gain?

In summary, the long-run average value of information, according to Marschak and many others, depends on:

i) the probability distribution of incidents,

ii) the payoff matrix associated with each set of actions and states, and

iii) the rule of action under each message sent.

In a similar manner, Weaver suggested three levels at which information issue could be addressed:

i) how accurately can messages be transmitted?,

ii) how precisely do the transmitted messages cover the desired meaning?, and

iii) how effectively does the received meaning affect conduct in the desired way?

In the following section, the research exploring these issues with respect to traffic information in particular will be discussed more thoroughly.

3. Traveler Behavior

As mentioned earlier, common transportation theory holds that many factors combine in some way to influence the decisions made by drivers. In effect, a utility function consists of a large number of variables, some affecting the overall utility more than others. Naturally the objective of each driver is to maximize his utility (or minimize his disutility, since many measures of transportation are negative, such as travel time) without concern for the utility of others. In many ways this is what makes traffic analysis difficult, in that thousands of participants exist, each with his own objective.

With regards to traffic information, a driver likely holds a preassigned utility for each possible route and departure time based upon his previous experiences. Because a trip-maker generally maintains his itinerary unless his perceptions of alternatives' utilities changes, the objective of traffic information is to make drivers aware of the present situations which might change the ordering of his options' utilities. In this section we will discuss the different components of the normal trip which have been shown to affect drivers' tendencies to use information.

To gain a perspective of the driver's perceptions, Ben-Akiva et al. (1991) predicted that drivers tended to have an information level, I(w), which could be used to judge, from their perceptions, the best option among those available. Drivers would use the experiences of their travel patterns P and the information which they receive from outside sources (radio, route guidance boxes, etc.) to update their information level. With this updated I(w), drivers would then be capable of making a more informed decision as to the optimal route and departure time.

3.1. Factors affecting driver behavior

Within the last decade a number of studies have come out regarding traveler surveys, stated preference models, or, in some cases, observed behavior or field experiments. Such studies have been completed by the likes of Khattak, Mannering, Mahmassani, and others listed at the end. These studies were used to determine the factors affecting drivers' tendencies to use traffic information.

One such variable was the *length of the trip*, or the average travel time. People who often made longer trips were on average more willing to use traffic information and change their route/time, perhaps due to frustration. As a result the benefits of information might be greater in areas known for longer travel.

Another factor in the overall use of (or benefits gained from) traffic information is the *availability of alternates*, in the form of routes or departure times. Information is likely to be most beneficial in the areas which offer alternate routes, for in the event of an incident or severe congestion, drivers will have another option by which their costs could be minimized. With the availability of alternatives, it should also be noted that benefits could be received more frequently (and thus increase on average), as diversion would be more frequent.

One of the limiting factors of the system and our natural desire to achieve the maximum benefits of the system is the *limited processing capacity of human drivers*, or drivers' limited mental representation of the options available. In many cases drivers take a longer route because they have traveled it more often and are more familiar with that route. Taking this one step further, it has been shown that females tend to change routes less frequently than males, perhaps due to a different cognitive map of the routes available or less desire to try new routes.

One could argue that this mental processing could be seen as a cost contributing to the overall cost of the trip. After a certain amount of deliberation the benefits expected from further thought often do not merit the time necessary (the costs of further analysis). As a result, people tend to cut short their route/time deliberation before exhausting all options. In particular, many of the routes available through arterial networks are never considered at all, though they might offer some clear advantage in certain conditions.

On average, most studies have shown that people are willing to *change their departure time more readily* than they are their travel route. This might occur because people are more attached to a certain route, where they perceive themselves as being safer or not being lost. The departure time is not something quite as unique from other departure times.

Another important finding was that the consumer behavior pattern was very different for *morning vs. afternoon peak period* commuters. In essence, afternoon commuters were less willing to change their route between work and home, but were more willing to change their departure time. This result could be explained in that the penalty for arriving home late would likely be much less than that for arriving to work late. As a result, the relative utility placed on maintaining a route versus saving time on an alternate would be higher for afternoon commuters than morning commuters. (A means for representing the number of early and late arrivals at equilibrium, raised by Arnott et al., 1993, will be discussed later.) The value of information could as a result be higher in the morning than in the afternoon, as use of it would be made more readily.

Among other findings were that drivers more willing to change their trip departure time were typically characterized as *young* (perhaps fearing change less). Changes were also more likely if drivers *listened regularly to radio* information (showing that improvements might be beneficial) or if the work arrival time was *flexible*.

One study emphasized that people were willing to change departure time if the *ratio between the actual and free-flow travel times* were higher. This might result from the drivers' frustration levels, feeling that they could be moving faster than the system allowed. Along a similar line, many studies have shown that the reduction of stress or anxiety can be seen as another benefit of traffic information.

With respect to changing routes, drivers were found to be more willing to divert if the congestion on the main route was *incident-induced*. A number of studies have touched on this topic, but if one can imagine, with recurrent congestion the travel times on all routes tend to approach each other (as described by Wardrop's first principle). Thus, the benefits of switching from one route to another (the benefits of information) are expected to be zero. In the event of an incident, however, the difference in travel time between competing routes can become significant, as the service rate of one route changes significantly. As a result the benefit of switching routes (and thus listening to information) increases significantly.

3.2. Combining these factors

The findings of these studies can be used to justify the distribution of the delay necessary for drivers to divert to an alternate route, which was found in previous studies. To be precise, the distribution of the delay time necessary for a certain percentage of travelers to divert was found to resemble an S-curve, similar to that shown below (Huchingson et al. 1979). The number of vehicles changing routes grows at an increasing rate with the delay until a certain level, at which the rate becomes decreasing. The explanation for this trend could be the different values which drivers associated with the different attributes previously discussed.

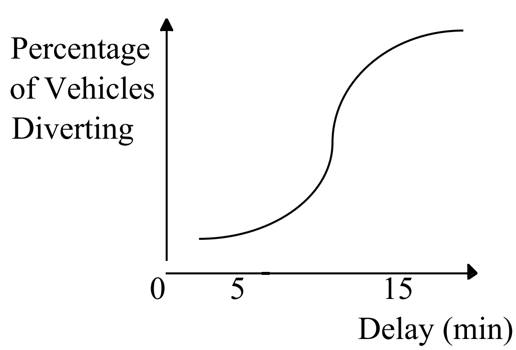

Figure 6. Distribution of delay necessary for diversion among drivers

To be more specific, people hold different values for each minute of late arrival, or the utilities for alternative routes available, which would cause some to change their route or departure time more readily than others. As a result, as the delay increases (or the difference in travel time favoring the alternative becomes greater), more drivers would be willing to divert (and thus more drivers could receive direct benefits from information).

This graph can be seen to represent what researchers define as the threshold necessary for diversion. This threshold represents the amount of delay (or disutility) which would be necessary on a primary route before a driver would divert to an alternate route. When the negative utility of the primary route has exceeded that of the alternate route, one could say that the driver's threshold has been surpassed.

Naturally, because the utilities associated with each attribute differ drastically from driver to driver, this threshold will vary from person to person. Some studies (Hall 1993; Huchingson et al. 1979) have found the threshold among the drivers surveyed or observed to be within the range of 5-15 minutes. As a result of this varying measure, the benefits which would be offered by an information system might be difficult to predict in any conclusive manner. It is conceivable that some average utility value could be associated with each of the multiple attributes of a trip, and with this the benefits which society might gain could be estimated. But questions would exist about how precise the estimate is.

4. Quality of Information

4.1. Attirubutes of an information source

Another area which has been researched, though not as extensively, involves the different measurements of a traffic information provider's output. For example, the measures of an information service include its accuracy, its frequency of update, or the area for which information is collected. One could also choose to divide the information gathering and distribution process into three important components, as described by Khattak, namely the information's content, its medium, and its quality. Changes to any one of these three parameters could impact significantly the message which is perceived by the driver and thus the benefits from this which he is able to gain.

It is logical that individual drivers would care most about the area for which data is being collected. If the route for the trip they are planning (or the alternate routes which are available) is not covered in the area for which information is collected, then clearly no benefits can be gained from the information. Beyond this studies have shown that users of information system tend to value most the accuracy of the system, followed then by the cost of the system, and then by the frequency of updates (Ng et al. 1995).

Different methods could be used to find the optimal level at which these parameters could be met by an information source. Recall that at some level the marginal cost of increasing the accuracy of the information would exceed the marginal increase in society's expected benefit. Hence it would not be wise (from a private or a public operation's perspective) to increase the accuracy beyond this level. Some studies (see for example Arnott et al. 1991), have also shown that the disbenefits of an information system which is not completely accurate can in some cases outweigh the benefits, due to too many vehicles being unwisely diverted, or the diversion period for vehicles occurring too heavily or for too long, etc. Similar relationships could be drawn for each of the variables mentioned, i.e. frequency or area of coverage.

4.2. Pricing of attributes

The study by Ng et al. (1995) used surveys distributed to drivers to determine what drivers would prioritize most. But to our knowledge no study has ever attempted to associate different values with different levels of these parameters. For example, how much more benefit (or how much more would people be willing to pay) for information updated every five minutes instead of every ten minutes. Formally known as the trade-off analysis of consumer values (Johnson 1974), surveys could be distributed with a number of different arrangements or costs available. Drivers could be asked to prioritize among these arrangements, with a relative preference among these alternatives being the final result. The perceived utility for each level of attribute could be compared with the necessary costs to determine a level to be designed for. How conclusive these results would be would remain uncertain, but to our knowledge no study has previously been attempted.

To gain a perspective on how the costs may vary, consider the classification given by Ben-Akiva. Information systems are divided here into three categories: historical, current, and predictive. The historical information system uses the results of previous days' travel records (both incident and non-incident) to estimate, on average, what would be the best route and departure schedule to follow. This information can be gained from personal experience and analyzed at little expense. Action under this environment would resemble that of the uninformed driver from equation 1.

A current information system, on the other hand, gives measures of certain variables in the traffic stream near the present time, such as the speed of traffic on certain links. From this data, which is more expensive to gather, guesses could be made as to the optimal trip itinerary. (The accuracy could come of issue here in that it is unknown how long the measured speeds will be maintained along the link.)

The predictive information, which would likely be the most difficult to gather, would require predicting the responses of drivers presently within the system to estimate the future travel times of certain links. These travel times would be those to be incurred specifically by the drivers receiving the information, and for that reason would be the most beneficial. In addition, the future situation depends heavily on the penetration level of the traffic information and also on the response level of the drivers, something which is difficult to know and understand completely. (This difficulty is very similar to that found in the use of game theory.) Therefore, the incorporation of predictive traffic information inherently adds a significant amount of variance to be read into the messages. On a positive note, this variance could be more than offset by the reduced cost of analysis for the drivers who are receiving the information. The ability of information systems to predict the response of traffic is growing considerably; however, it is not often that such information is given to the drivers on the roadway to be used (Yim, 1996). Either way, reports have found that prescriptive information is emerging as an available tool.

One last note regarding these attributes is that because people tend to have different values for different variables, and the benefits for some trips are naturally greater than the benefits for others, a price structure for the information service could be difficult to arrange. In addition, the technology available for information gathering is advancing quickly, allowing the costs of systems to decrease. More importantly, as more drivers become equipped, the benefits received by the informed drivers and the society will change. Further analysis of this will be described in the following section, as found by Al-Deek et al. 1993, but it is safe to say here that:

i) the benefits which the informed driver receives over the uninformed decrease as the percentage of drivers informed increases, and
ii) the overall benefits to society increase up to a certain level of penetration, at which a further penetration results in higher travel times (due to too many vehicles being diverted, known as overresponse)

Because of these trends, the marginal benefits would be difficult to compare with the marginal costs to determine without experiment the optimal level of information penetration.

5. Representations of the Effects of Information

One method which has been commonly used to estimate the benefits of traffic information, particularly in the measure of travel time savings, has been computer simulation of traffic. (For a good collection of studies' findings, see Hall 1993). Most of these studies have shown that the benefits to be achieved through the implementation of information systems is somewhere around the magnitude of 5-15%. In particular, studies have repeatedly shown that the benefits achieved during incident-induced congestion are consistently higher than the benefits during recurrent congestion, likely for reasons discussed earlier.

In this section we will show how different tools of analysis have been used in past studies to represent the effects information can have on the flow of traffic. The tools used in these studies could also prove valuable in economic analyses of traffic information systems.

5.1. A system's ability to handle vehicles

For example, a deterministic queuing curve can clearly display a society's distribution of departure times and a system's ability to handle this traffic (Arnott et al. 1991), as shown in Figure 7. Because the initial departure rate (shown by the slope of AB) is greater than the service rate (the slope of the arrival curve AC) the delay of the queue (shown by the distance between the curves, assuming a travel time of zero) continues to increase until the departure rate is reduced. The total delay experienced is the area within the triangle after the number of arrivals has reached the number of departures, i.e. all vehicles having departed have been served.

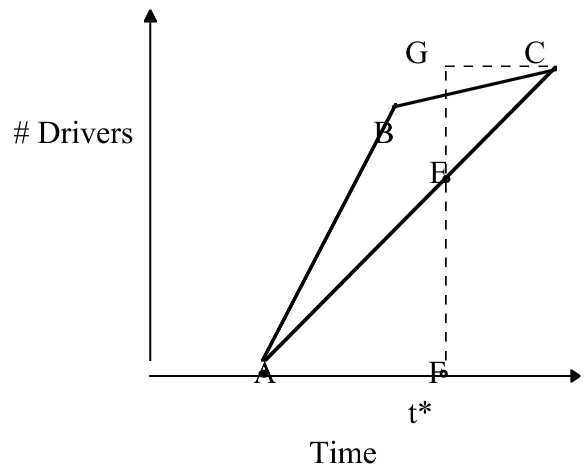

Figure 7. Departure and arrival rates at equilibrium

What is most interesting to gain from this representation is the ratio between the people to arrive late and the people to arrive early, and the adjustments which might be made to some departure times. Remember from before that drivers tend to associate a cost to arriving early or arriving late to their destination (because their time could have been spent more productively otherwise). As such, the cost to a person for arriving at work can be seen as :

$$C(t) = \alpha(\text{trip time}) + \beta(\text{minutes early}) + \gamma(\text{minutes late})$$

where $\beta < \alpha < \gamma$. Assuming that t* represents the time at which arrival to work is desired, it can be shown that the ratio of the total number of "early minutes" (minutes arrival before t*, measured by the triangle AEF) is proportional to the total number of "late minutes" (minutes arrival after t*, measured by the triangle EGC), in the ratio of α/β. That is, if equilibrium has been reached, the total cost to people arriving early is equal to the total cost to people arriving late. In addition, the disbenefit to one person arriving later (just after the last person presently arrives) is greater than the disbenefit of the earliest person's arrival time. Considered to be in equilibrium, no person can improve the cost to the society by adjusting his departure time.

The method by which this tool of analysis can be seen as beneficial in the analysis of information economics is that, under reduced capacity due to an incident or congestion, the arrival rate (slope AC) will drop. As a result the number of vehicles arriving late will increase, and the number of vehicles arriving early will decrease. Because the cost of arriving late is greater than the cost of arriving early ($\gamma > \beta$) the cost to the system will increase. The objective of the information system is to inform drivers of this unexpected situation such that they may change their departure times or route to minimize the cost of arriving late.

5.2. Parameters of individual incidents

Depending on the distance between the location at which a change of route is possible and the expected duration of the incident, one may or may not receive benefits from an information source. In estimating the benefits which can be received from information systems, this tool has been used by others (Al-Deek et al. 1993) to distinguish those scenarios in which ATIS can be beneficial from those in which it can not.

Al-Deek et al. also showed how different factors affecting the use of information can impact the overall benefits received by society. For example, the percentage of vehicles equipped with information devices can be denoted as p. The larger is the value of p (up to a certain level), the faster the rate at which vehicles will be diverted to the alternate route. The faster the rate at which vehicles are diverted, the sooner will the travel times on the alternate routes become equal. Clearly, the faster equilibrium is reached, the greater are the benefits to the entire system. (Vehicles are moving away from the congested route, which has a higher marginal cost.) When travel times on competing routes have become equal, vehicles will be diverted at a reduced rate to maintain equilibrium. The upper limit for the increase of benefits with p exists because if p is greater than the critical level, vehicles will be diverted at a rate too high for the alternate route.

The overall travel time savings for the system can be seen in Figure 8 as a function of the percentage of vehicles equipped, where the benefits increase until $p = p_c$, in this figure 0.5.

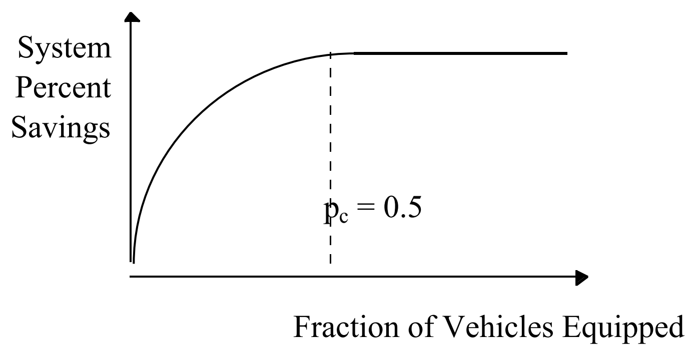

Figure 8. Relationship between system savings and percent of vehicles informed

We should also note here that the benefits to the informed drivers exceed those of the uninformed drivers only until equilibrium has been reached. From this time on, the benefits of the reduced travel time (equal for both routes) are received by *all drivers*. Upon closer analysis, the benefits of the informed, particularly in comparison to the uninformed, will be greatest immediately after diversion has begun, gradually decreasing in comparison until equilibrium has been reached. A picture of this relationship, also borrowed from Al-Deek et al., can be seen in Figure 9. The fact that during a significant portion of an incident's duration the benefits received by uninformed drivers equal those of the informed drivers might also be used to justify public funding for these systems. In addition, as the penetration of information increases (allowing equilibrium to be reached quicker), the benefits of the informed driver will decrease relative to the uninformed driver.

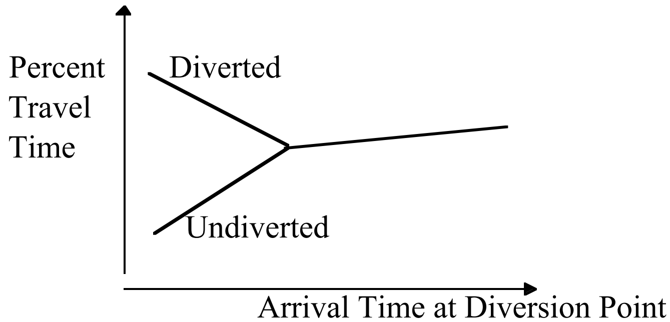

Figure 9. Distribution of benefits between informed/uninformed drivers

Mention should also be given to the fact that the number of vehicles optimal for diversion (p_c), such that equilibrium can be maintained between the two competing routes, can vary significantly. To be specific, the level of diversion which would be optimal would be a function of the severity of the incident (or the capacity reduction along the primary route), as well as the capacity along the alternate route. As a result, for an information system advising drivers in a prescriptive manner is much more complicated than advising in a responsive manner, and thus the benefits which a society could achieve are difficult to actually maximize.

Clearly the amount of work which has taken place in this area of information economics has not received the amount of attention that traveler behavior has. However, it should be stressed that it is these tools which allow us to represent and analyze the results which traveler behavior can have on an overall system. And it is these findings which allow us to perceive the methods by which improvements could be made to the system and what expense or attention should be given to such. From these tools the benefits of traffic information can best be estimated.

6. Discussion

Whether the discussed research involved a survey to map participants' feelings, or methods for representing the movement of informed drivers, the results can help us to understand better the market for information technology.

In particular, market trends exist which cause information providers to position themselves in certain locations or during certain time periods. Information consumers have established many trends which might show us how information could be packaged such as to generate maximum benefits. We will restate the important findings in the following section in hope that these findings can be combined to lead us in the right direction.

6.1. Differences among drivers

First, in attempt to measure the benefits of information, or demand resulting from the benefits perceived by drivers, we must incorporate several factors. The desire of a driver to use information, by changing routes or departure time, is often a function of:

- the availability of alternate routes (making each market very unique)

- importance of arriving on-time versus a bit late
- length of the trip
- level of anxiety/stress
- mental representation of the alternatives available
- source of information regarding situation (self-observation vs. radio, etc.)
- and many other factors, as described earlier

Each of these factors contributes to a utility (or disutility) function U(x), and the driver likely chooses that time-route itinerary maximizing the utility associated with the trip. In many cases, such as those involving heavy congestion but no alternatives, the option of best utility might be to avoid the trip altogether.

Unfortunately, what makes all of these factors difficult to weigh is that every driver likely has his own parameters for his utility function, and thus the threshold, the level of travel time delay on a primary route for which diversion begins being considered, varies between different drivers. As a result, the marginal number of drivers willing to divert with each minute of delay is a function of the delay. This causes the benefit resulting from information to vary from one scenario to the next, making estimations complicated.

A similar element of the industry which compounds this problem is the distinctions among users in the market. As surveys have shown (Ng et al., 1995), commercial vehicle operators (or dispatchers) would be willing to pay more for services than individual drivers. A suggestion for the market's reaction to this might include two different types of service, one a commercial premium service available to operators and the other a more generic, public service available to individuals. This segmentation would prevent the diminishing of the larger users' benefits which would result from wider usage, as discussed earlier. Furthermore, a pricing system could be implemented to capture the benefits received more readily.

Unfortunately, it has been repeatedly shown that the level of diversion which is user-optimal is rarely, if ever, the same as that which is system-optimal. Because every driver is trying to minimize his own costs, drivers will lean toward the user-optimal diversion and prevent the maximum benefits of the system from being attained. Different types of information services could control outputs to influence driver behavior in the desired manner. For example, information services could give route guidance, in hope that drivers will follow the service's suggestion and travel what could be the system-optimal route. On the other hand, systems could give data about the network, such as the travel time on each link, and allow each user to make his own decision. In this scenario, information would most assuredly lead to the user-optimal diversion. An important issue we hope to address in the future is what arrangement would be received best by the system's users while maximizing benefits.

Also important in deciding the proper format of information is the capacity of individual drivers to process the information. In many instances the traffic information given over the radio can be quite confusing to the average driver. Consumers have consistently been shown to have a limited processing capacity (or attention span) for product information. Drivers perhaps consider the effort necessary to analyze this information to be a cost toward their utility function. Even more apparent is that the excess costs directed toward gathering more detailed information may not provide benefits worthy of the necessary costs.

6.2. Costs and benefits of a system's attributes

With information systems the marginal benefit received from each information gatherer (e.g. a loop detector) is likely a decreasing function. Assuming that detectors would first be placed near the locations of heaviest travel or highest demand, each successive detector should serve a smaller percentage of travelers and thus produce lower benefits. However, the average cost of each detector is likely also a decreasing function; the electronic cost of transmitting the information is negligible, and the processing and labor necessary for data can be seen as fixed costs to be spread over detectors. At some point the marginal cost of adding one detector or gathering more information would likely exceed its benefits. In some situations as well, the benefits might be limited by the amount of time available on a radio or television commercial. Another objective of our research is to determine where this level lies for different environments.

Similar relationships also exist for independent parameters of an information service, such as the accuracy or frequency of incident reports. We also plan to address these issues with our research and discuss how the costs associated with these parameters affect the level of information which would be optimal.

In another light, we mentioned earlier that the information which could be given by a payoff matrix based upon the details of the choices. It can be shown that benefits can be received from more detailed information only when the optimal response of the informed individual changes under certain conditions. Imagine the simplest system (analogous to one described by Marschak 1974b), in which the only information necessary is whether the delay on the primary route is greater/less than the difference in travel time from the alternate route. For a more concrete example, imagine route 1 normally takes 20 minutes and route 2 30 minutes. The only information necessary, for user-optimal diversion, is: Is the delay greater than 10 minutes? If so, it is unnecessary to incur the cost of determining the actual delay (or the queue length, or the expected duration, etc.), because it would not affect the decision made (or the benefits received) by the consumer.

Unfortunately it is possible that more detailed information might be necessary to some extent due to different drivers having different thresholds for diversion. In addition, the predictive variables such as the actual delay or the number of vehicles which will use information are not deterministic, and due to their randomness, the benefits to be achieved from information can only approach the maximum. This randomness is also similar to the uncertainties of game theory resulting from the variability of incident severity, the availability of alternates in certain situations, and the size of the informed "platoon".

Finally, traffic information has been consistently shown to provide the maximum benefits in certain markets. In particular, incident-induced congestion has shown room for significant benefits, resulting from the fact that the system once in equilibrium is now not. In addition, information has been shown most beneficial in areas where alternative routes are available; with such, drivers are capable of changing their actions in the event of unforeseen circumstances.

A third scenario in which benefits could be greater would be those segments which involve the highest demand among travelers. An interesting scenario arises due to this in that multiple information gatherers tend to cluster around those areas showing the highest demand. As a result, the benefits received from these information services could be cut significantly. This result could lend itself to the support of information financing by public entities rather than private providers. It is hoped that with a clearer understanding we can organize our traffic information system such as to minimize the "losses" which might result from such arrangements.

7. Future Research

With the expansion of highways no longer an option, traffic information systems are being viewed in many cities as a primary means of reducing the costs of congestion. The objective of this paper and the research surrounding it is to gain an understanding of the factors influencing the benefits resulting from information systems. With this we hope to address the different methods for financing and operating these systems such as to generate the maximum benefits for the system while spreading the costs equitably. The important issues which have been addressed in this paper, and to which we hope to pursue answers as we continue our research, include:

i) How can we model the cost to information providers of supplying the network? What are the economies of scale, and at what level do the costs exceed the benefits?

ii) What are the external factors, such as available communications, that limit the productivity which can be gained from information systems?

iii) What type of decision network (e.g. game theory) should be used to model the decisions which drivers (informed and uninformed) face in setting their itinerary?

iv) How can we measure the benefits (or disbenefits) received by the network, in addition to the travel time savings? How are these benefits divided between direct and indirect consumers of information, or how should the financing necessary for traffic information be divided between public funds and private consumers?

These questions do not deserve simple answers, but with a better understanding we may be able to increase the benefits of our present roadway system significantly.

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