RECENT FINDINGS ON THE BENEFITS OF ROUTE GUIDANCE

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INTRODUCTION

Advanced traveler information systems (ATIS) have gained worldwide interest as a promising technology for improving the efficiency of urban networks and reducing congestion. It is generally anticipated that the provision of route guidance information to travelers will help them avoid congested links in the network, thereby reducing congestion by spreading traffic over space, and possibly time. This proposition has been so well received that technology for ATIS is being developed and tested in numerous locations around the world. There remains, however, a paucity of analysis to demonstrate that the implementation of ATIS will in fact have a significant impact on congested urban networks, and to estimate the magnitude and distribution of its potential benefits. This paper is concerned with an important application of ATIS technology: the management of incidents. Using an idealized traffic corridor and deterministic queueing methods, conditions under which route guidance information is useful are identified. Benefits to traffic guided with ATIS are estimated and system performance is evaluated in diverse environments of non-recurring congestion.

1. BACKGROUND

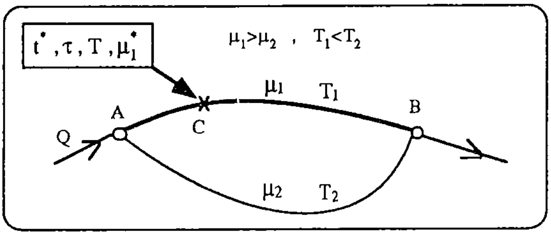
There have been numerous efforts during the last decade to evaluate the benefits of ATIS (see, for example: Kobayashi, 1979; Tsuji et al., 1985; Jeffrey, 1987; Al-Deek et al. 1989; Kanafani and Al-Deek, 1991). The results to date suggest that, by and large, the benefits of route guidance are marginal under conditions of recurring congestion. Experienced travelers, who make up the major portion of traffic in congested urban networks, have sufficient information to manage their route choice under conditions of recurring congestion. This has often been reflected in the estimates of potential benefits from route guidance in the vicinity of 10% savings in total travel time. These results suggest that route guidance is likely to be more useful under conditions of non-recurring congestion, as may be caused by incidents. Under these conditions, the lack of information about the severity and duration of an incident and its location vis-a-vis the rest of the network would leave the traveler insufficiently informed to make appropriate route choice decisions. Furthermore, by extending ATIS information to potential travelers long before they approach incident locations, it may be possible to further reduce potential congestion by altering trip patterns including departure times, thereby spreading traffic over time in addition to space.

In the following paragraphs we describe a deterministic queueing model of a simple corridor in which we simulate the occurrence of incidents of various locations, durations, and severity. We use the model to analyze the benefits from route guidance, and we study the sensitivity of these benefits with respect to the percentage of vehicles that have ATIS equipment on board. In simulating the application of ATIS technology, we assume that it is possible to estimate the flow and the travel time on each link in the network using data collected via traffic surveillance. It is also possible to detect the occurrence of an incident, to estimate its duration and the capacity reduction caused by it. It is assumed in this analysis that vehicles with ATIS will always follow directions to divert to a shorter route. This assumption is not necessary for the model used here and can be easily relaxed.

2. CORRIDOR MODEL WITH INCIDENT

We consider a simple corridor as shown in Figure 1. The corridor consists of two routes connecting points A and B. The first route is a freeway with capacity μ_1 and free

FIGURE 1 CORRIDOR AND INCIDENT PARAMETERS



flow travel time T_1 and the second is an alternate route with free flow travel time T_2 and capacity μ_2, where $\mu_2 \leq \mu_1$. We further consider that $T_1 < T_2$, and we assume, following Kuwahara and Newell, 1987, that these times are independent of flow except under queueing conditions. Thus, in the absence of queues, route 1 is always preferred to route 2.

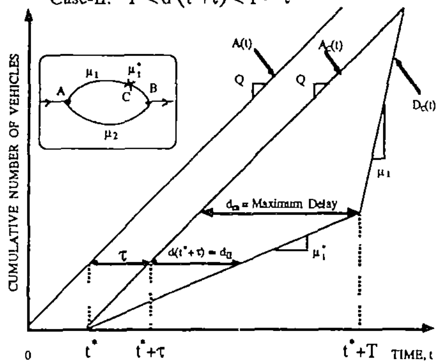
To simulate an incident we need to set down some conditions of the network. First we consider the off-peak case in which the flow, Q, of traffic arriving at A is less than the capacity of the freeway μ_1. We also assume that the location of the incident is such that there is sufficient queueing space upstream of it so that the queue does not back up into junction A. Once travelers pass point A, information from ATIS becomes irrelevant since they would already be committed to one of the two routes. ATIS information will therefore be directed at traffic as it approaches point A. Finally, to simulate and analyze the occurrence of an incident we construct a deterministic queueing diagram for this corridor, as shown in Figure 2. The incident occurs at point C and reduces the capacity of route 1 from μ_1 to μ^*_1. The incident occurs at time t^* and lasts for a duration T. As illustrated in Figures 1 and 2, point C is τ units of travel time away from A along route 1, and $0 < \tau < T_1$.

3. EVOLUTION OF QUEUES WITHOUT INFORMATION

In the absence of ATIS, or any other information about the incident or its impact on travel times, travelers will continue to choose between routes 1 and 2 on the basis of their *non-incident* experience. As mentioned above, this means all traffic at point A will choose route 1. As long as the back-up caused by the incident does not reach point A, the queue will evolve as shown in Figure 2. Traffic arrives at point A according to the arrival curve A(t), and τ units of time later at the incident point C according to curve $A_C(t)$. Note

FIGURE 2 QUEUE EVOLUTION FOR AN OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION

Case-II: $T^* < d(t^*+\tau) < T - \tau$



that the slope of both of these curves is Q, the traffic flow rate. The departure curve $D_C(t)$ shows the departure from the bottleneck. The departure flow rate is initially μ^*_1, the reduced capacity of the bottleneck, and then after the incident is cleared at time t^*+T, is the restored capacity μ_1. Note that Figure 2 illustrates the evolution of the queue for one of a number of possible cases. This is called Case-II and is described by the following condition:

$$T^* < d(t^*+\tau) < T - \tau,$$

where $d(t^*+\tau)$ is bottleneck delay for a traveler who arrives at A at time t^* (when the incident occurs) and uses the freeway to go from A to B, and T^* is the difference between free flow travel times on the two routes, $T_2 - T_1$. The implication of this condition is that if information is available in this case, diversion during some time interval can result in benefits to guided traffic. Also, the above condition implies that Case-II applies for incidents with relatively large durations, i.e., when

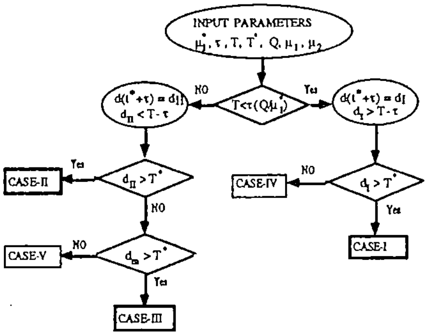
$$T > \tau\left(\frac{Q}{\mu_1^*}\right)$$

The process for identifying cases of queue evolution without information under this incident scenario is illustrated in Figure 3. It is obvious that guided travelers will not gain anything if they divert to the alternate route in Cases IV and V, because the delay never exceeds T^* in these two cases. Therefore, if it is available, information is relevant in three out of five possible cases: Cases I, II, and III. These are used in this study to analyze the benefits from ATIS.

4. EVOLUTION OF QUEUES WITH ATIS

If a user optimal strategy is used to divert ATIS equipped vehicles in Case-II, then there are four possible queue evolutions: NQ1-Case-II, NQ2-Case-II, Q1-Case-II, and Q2-Case-II, see Figures 4-7. In the first two cases the fraction of ATIS equipped vehicles, p, is not sufficient to initiate a queue on the alternate route. The prefix NQ, which stands for "No queue exists on the alternate route," is used to identify these cases. In the last two cases the fraction, p, is large enough to cause a queue on the alternate

FIGURE 3 - CASES OF QUEUE EVOLUTION FOR AN OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION



route, therefore, their names start with the letter Q. The difference between NQ1-Case-II and NQ2-Case-II is that equilibrium can be achieved only in the later, whereas the fraction, p, in the former is less than the minimum fraction, z', needed to initiate equilibrium, where

$$z' = \frac{T\left(1 - \frac{\mu_1^*}{Q}\right) - T^*}{T - \tau - T^*} \qquad \text{Eq(1)}$$

Equilibrium is achieved in both Q1-Case-II and Q2-Case-II. However, because the fraction, p, in Q2-Case-II is large, equilibrium can be reached earlier, i.e., before the incident queue starts to discharge. The minimum fraction, z, of guided traffic needed to achieve early equilibrium is:

$$z = \frac{\mu_2}{\left[\mu_2 + \frac{\mu_1^* T - \tau Q}{T - \tau - T^*}\right]} \qquad \text{Eq(2)}$$

The above expressions for z and z' were derived by Al-Deek (1991).

Cumulative arrival and departure curves are drawn for each case. $A_1(t)$ denotes arrivals at A at time t of traffic using route 1 (the freeway), $A^*_C(t)$ denotes arrivals at the incident bottleneck C when there is diversion to the alternate route, and $A_2(t)$ denotes arrivals to the alternate route. All equipped vehicles are instructed to divert for a period of time, K, until equilibrium is reached or until the freeway reverts to being faster than the alternate route and diversion is discontinued. The length of diversion period, K, is a function of p, the fraction of vehicles equipped with ATIS, with diversion expected to last longer for smaller values of p. In order to maintain equilibrium, the diversion rate has to be decreased. Al-Deek (1991) found that if a queue exists on the alternate route, then the fraction of guided traffic needed to maintain equilibrium equals the ratio of the alternate route capacity to the overall corridor capacity. For example, in Q1-Case-II equilibrium lasts for a period of time ε during which diversion rate equals $p'Q$, where p' is the fraction of guided traffic needed to maintain equilibrium and is given by

$$p' = \frac{\mu_2}{\mu_2 + \mu_1} \qquad \text{Eq(3)}$$

Note that this fraction is not a function of p. However, if equilibrium is to be achieved,

FIGURE 4 QUEUE EVOLUTION FOR NQ1-CASE-II

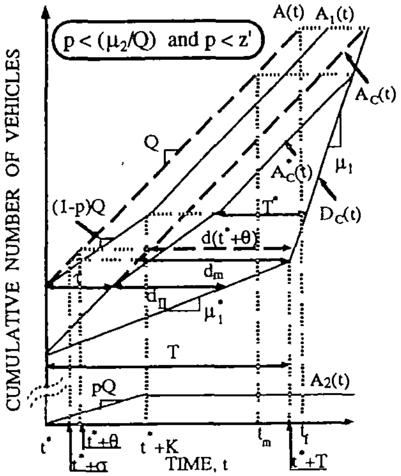


FIGURE 5 QUEUE EVOLUTION FOR NQ2-CASE-II

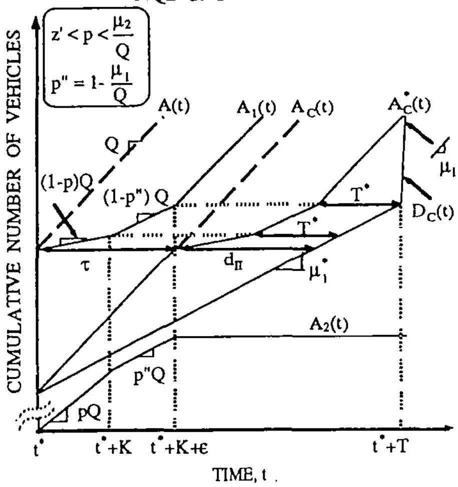


FIGURE 6 QUEUE EVOLUTION FOR Q1-CASE-II

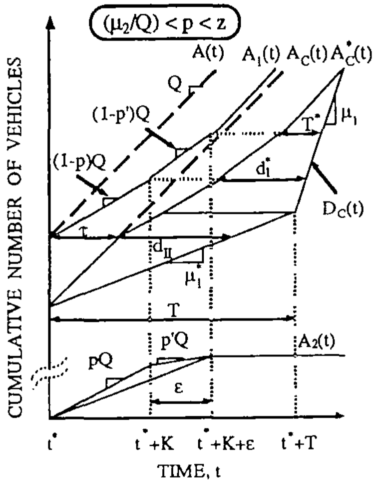
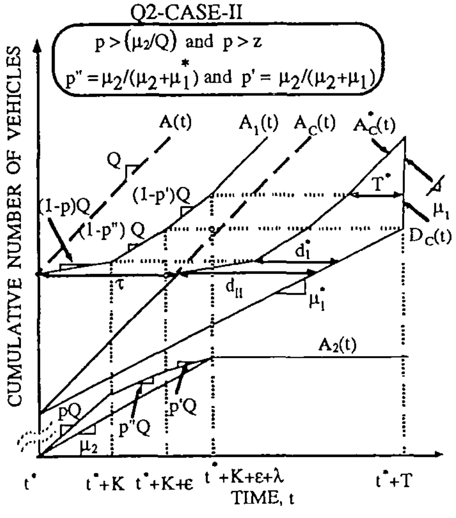


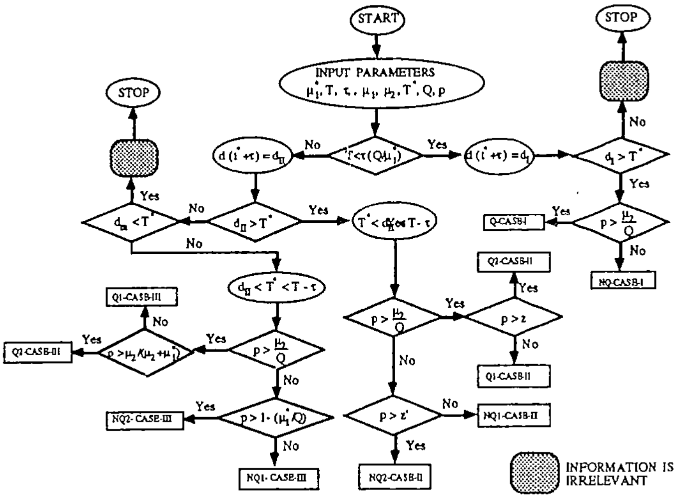
FIGURE 7 QUEUE EVOLUTION FOR Q2-CASE-II



then clearly p must equal or exceed p'. This implies that some equipped travelers will be selected to divert to the alternate route while others will be asked to remain on route 1. This is a non-trivial task, but it is anticipated that it can be achieved with in-vehicle ATIS where communication can be established with individual vehicles as they route in the network.

Application of user optimal strategy to all cases in Figure 3 results in a total of twelve cases of queue evolution as illustrated in Figure 8. For a detailed analysis of queue evolution in each of the twelve cases the reader is referred to Al-Deek (1991).

FIGURE 8 CASES OF QUEUE EVOLUTION FOR AN OFF-PEAK INCIDENT WITH ATIS



5. EVALUATION OF ATIS BENEFITS

In this section we analyze the ATIS benefits to guided and unguided traffic and evaluate the total system benefits. The benefits to guided and unguided traffic are evaluated as a function of the arrival time at point A, the junction of the two routes. The benefits are expressed as a percent travel time savings. Travel time from A to B under incident conditions and in the absence of ATIS is the basis for the calculations of travel time savings. System benefits are the total time savings in the corridor that result from diversion of ATIS equipped vehicles to the alternate route. Next, we illustrate this with a numerical example, then we synthesize the general characteristics of user and system benefits.

5.1. Numerical Example

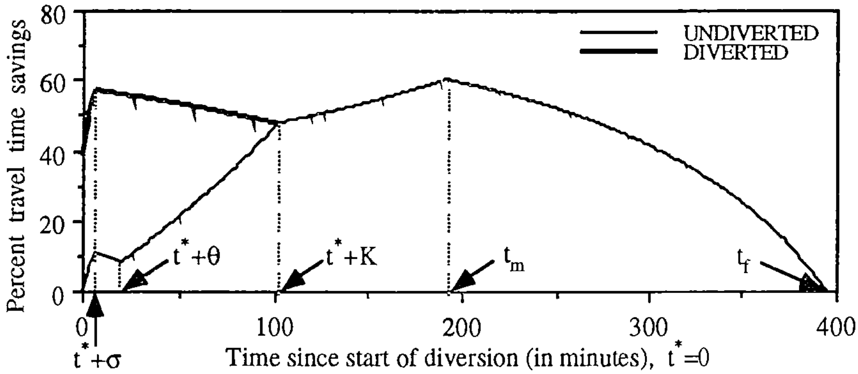
We consider a three lane freeway with a lane capacity of 30 vehicles per minute, (μ_1 =90 vehicles per minute). The alternate route has a capacity μ_2 of 40 vehicles per minute. Demand Q is equal to 80 vehicles per minute. Trip time from A to B using the freeway, T_1, is 15 minutes, while T_2 is 25 minutes. An accident occurs on the freeway at point C at time t^* during off-peak conditions. It takes 10 minutes to travel from A to C when there is no queue between A and C, τ=10 minutes. The accident blocks two out of three lanes and results in a 75% loss in capacity of the freeway. Furthermore, it is estimated that it will take 60 minutes to clear the accident, T=60 minutes.

Following the procedure described in Figure 8, we find that NQ1-Case-II applies when the fraction, p, of vehicles equipped with ATIS is less than 0.5; Q1-Case-II applies when $0.5 < p < 0.75$; and Q2-Case-II applies when $0.75 < p < 1.0$.

5.2. User Benefits

A dynamic profile of travel time savings to guided and unguided traffic for NQ1-Case-II is shown in Figure 9. To explain the trend in time savings we refer to the

FIGURE 9 USER BENEFITS DURING DIVERSION FOR NQ1-CASE-II

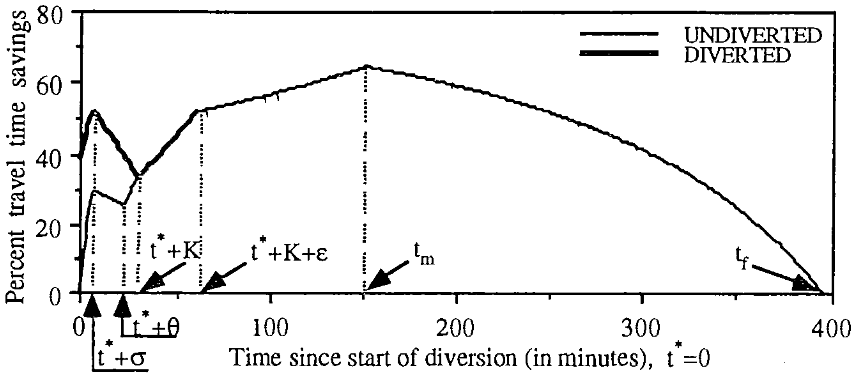


queueing diagram of this case, previously illustrated in Figure 4. Maximum delay, d_m, occurs at time $t^*+\sigma$. Benefits to guided traffic are increasing with a peak during time interval $[t^*, t^*+\sigma]$ because ATIS equipped vehicles are shifted from the freeway, where the queue is building up, to the alternate route where there is no queue. Benefits to diverted traffic are declining in time interval $[t^*+\sigma, t^*+K]$ because guided traffic is being shifted from the freeway where the incident queue is diminishing, to the alternate route where there is no queue. As expected, benefits to unguided (undiverted) traffic are increasing during time interval $[t^*, t^*+\sigma]$ because as more guided traffic diverts, delay on the freeway decreases. The drop in benefits to unguided traffic during time interval $[t^*+\sigma, t^*+\theta]$ is explained as follows: in the absence of ATIS, unguided traffic departs the incident bottleneck while the queue is discharging, while if there is ATIS unguided traffic departs the incident bottleneck while the queue is building up. Queueing delay at the incident bottleneck is a function of the history of the arrival curve, $A_1(t)$. This explains why benefits are not restricted to travelers arriving during diversion time K, but also apply to travelers arriving after diversion ends, regardless of whether they are equipped with ATIS or not. The numerical example illustrates that maximum benefits are not necessarily gained by guided travelers who divert; instead, the maximum benefits are gained by travelers arriving after diversion ends. The queue discharges faster with ATIS than without it as shown in Figure 4, therefore, delay on the freeway decreases at a faster rate and benefits to travelers arriving at A in time interval $[t^*+K, t_m]$ increase with a peak at time t_m. Since the queue would have diminished completely at $t_f+\tau$ anyway, no benefits are gained to travelers arriving at A beyond time t_f.

It should be noted that guided travelers are always better off than unguided travelers during diversion period K, and so all guided traffic is diverted during this period. The maximum length of diversion period K in this numerical example occurs when p is very small ($p \approx 0$) and is equal to 305 minutes, while the total time during which there are benefits ($t_f - t^*$) is equal to 395 minutes. The numerical example illustrates in this case that at best during 77% of the time guided travelers can be better off than unguided travelers.

User benefits for Q1-Case-II are shown in Figure 10. Benefits to guided and

FIGURE 10 USER BENEFITS DURING DIVERSION FOR Q1-CASE-II

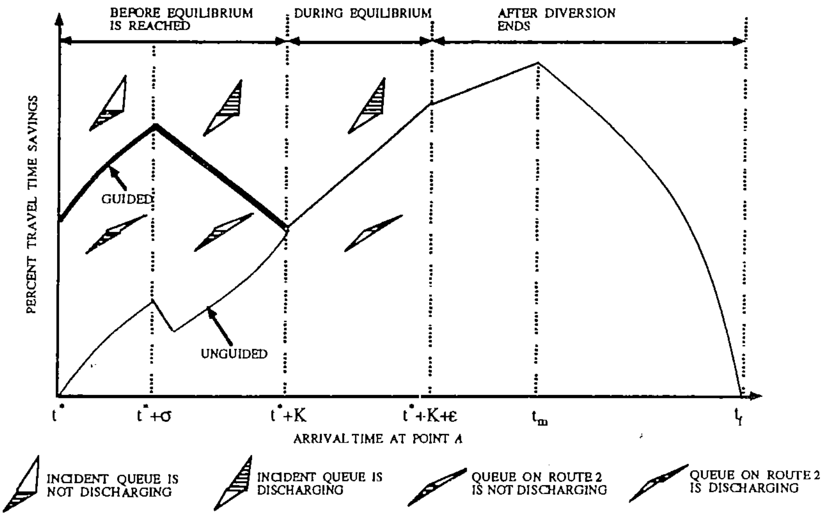


unguided traffic are identical during equilibrium, i.e., during time interval $[t^*+K, t^*+K+\varepsilon]$. The maximum length of diversion time K in this case occurs when $p=0.5$ and is equal to 61 minutes, while the total time during which there are benefits ($t_f - t^*$) is equal to 395 minutes. Therefore, in this case, at best during 15% of the time guided travelers can be better off than unguided travelers. Clearly, there is a drastic drop in benefits to guided travelers when there is a transition from NQ1-Case-II to Q1-Case-II.

Analysis of all the different cases has shown similar trends in the user benefits. This suggests the general characteristics of user benefits described in Figure 11 which can be summarized as follows:

1. As long as the incident queue on Route 1 has not begun to discharge, i.e., as long as $t \in [t^*, t^*+\sigma]$, ATIS benefits to both guided and unguided traffic increase with the arrival time at A.
2. When the incident queue on Route 1 begins to discharge, the benefits to guided traffic start to decline until either equilibrium is achieved or diversion ends, i.e., at time t^*+K. The reason for this decline is that diverted traffic is shifted to Route 2, where either the queue is not discharging or it does not exist. The benefits to unguided traffic increase until either equilibrium is achieved or diversion ends.
3. As long as equilibrium is not reached guided traffic is always better off than unguided traffic. Once equilibrium is reached, the benefits to guided and unguided traffic become identical. The benefits continue to increase until equilibrium ends because the queue on Route 2 is discharging faster than the queue on Route 1.

FIGURE 11 GENERAL CHARACTERISTICS OF *ATIS* USER BENEFITS



4. The chance of guided traffic being better off than unguided drops drastically in cases where a queue forms on the alternate route.
5. A traveler arriving after diversion ends will gain benefits regardless of whether or not he is equipped with ATIS. The magnitude of these benefits are sometimes larger than that accrued to a guided traveler diverting before or during equilibrium.

5.3. System Benefits

System benefits are shown as a function of, p, the fraction of vehicles guided with ATIS, in Figure 12. It is illustrated that system benefits increase with p as long as p is less than some critical value, p_c, where $p_c = \mu_2/Q$. Note that p_c equals 0.5 in this numerical example. System benefits become independent of p and level off when a queue forms on the alternate route, i.e., when p is larger than 0.5 in Figure 12. This implies that system benefits are maximized when p equals p_c.

The sensitivity of system benefits to p is investigated throughout the rest of the cases (shown in Figure 8) and the results are as follows:

- System benefits increase with p as long as it is insufficient to initiate a queue on the alternate route, but system benefits level off for $p > p_c$, as illustrated in Figure 12.
- System benefits will also level off when there is no queue on the alternate route and p is sufficient to achieve equilibrium, see Figure 13, (a different numerical example is used in this figure).

The findings imply that if the system management has the choice, then there is no need to equip more than p_c of the vehicles with ATIS. Hence, a strategy can be applied where no more than p_c is diverted to the alternate route. Under this strategy, benefits to the system and to ATIS equipped travelers are maximized simultaneously. However, if more than p_c is equipped with ATIS, then this strategy might be inequitable for those who are equipped but not diverted. In a sense this is a limitation of the ATIS technology in

FIGURE 12 SYSTEM BENEFITS VERSUS "p"

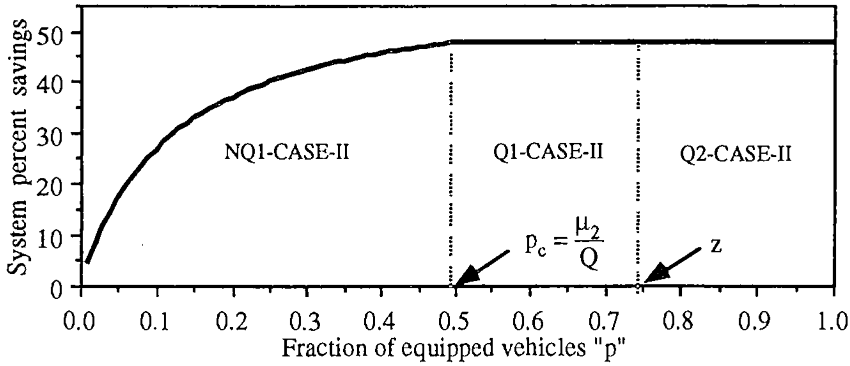
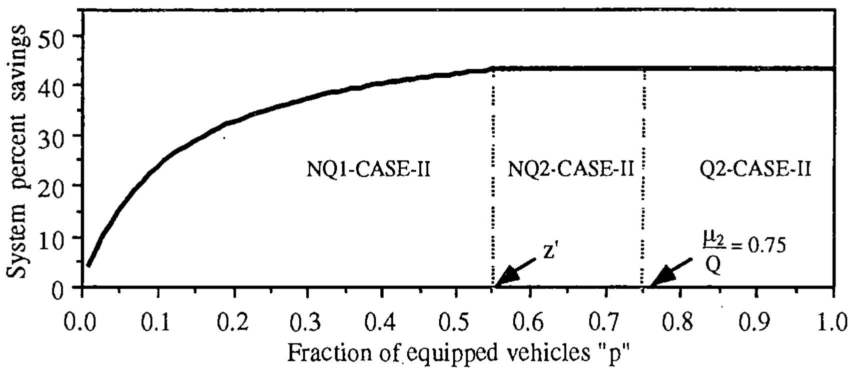


FIGURE 13 SYSTEM BENEFITS VERSUS "p"

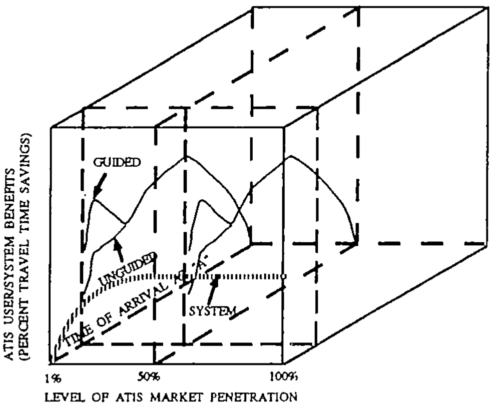


corridors where the overall capacity of alternate routes is small relative to corridor demand.

5.4. Synthesis of User and System Benefits

The results of user and system benefits of ATIS are represented by the three dimensional Figure 14. The left side plane is a dynamic profile of the user benefits: it tracks percent time savings on a real time basis. The different levels of market penetration, i.e., fraction of vehicles equipped with ATIS, are represented by the parallel left side planes. If these planes are overlaid on top of each other, the three dimensional figure is reduced into a two dimensional figure where the percent savings are plotted versus the arrival time at point *A*. System benefits for a certain level of market penetration are found by integrating travel time savings to guided and unguided traffic over time. This integration reduces the three dimensional Figure 14 into a two dimensional figure as shown by the front face which illustrates a sketch of system benefits plotted against the level of market penetration of ATIS.

FIGURE 14 MODELING USER AND SYSTEM BENEFITS
OF ATIS UNDER INCIDENT CONDITIONS



Finally, it is clear that increasing the proportion of guided traffic improves equity by narrowing the gap in travel time savings between guided and unguided traffic and consequently equalizing the distribution of travel time savings among all system users. However, as the proportion of guided traffic increases, the advantage to guided traffic having ATIS and the disadvantage to unguided traffic not having ATIS decreases. This has a counter-effect on the incentive to have ATIS. Furthermore, system benefits saturate at a certain level of market penetration, chosen arbitrarily as 50% in Figure 14. This saturation reflects operational limitations of the highway facilities such as bottlenecks and the limited number and capacities of feasible alternate routes, as well as the lack of incentive for unequipped travelers to have route guidance information.

6. CONCLUSION

This research represents a modest first step toward understanding the role of route guidance in incident management. It provides a comprehensive analysis of the most relevant parameter which influences the benefits of route guidance: the fraction of vehicles equipped with ATIS. The critical value of this fraction that causes queues on the alternate routes does not depend on the incident parameters but it only depends on the corridor parameters: the capacities of the feasible alternate routes and the travel demand. Consequently it should not be difficult to estimate this value in real life networks. The critical fraction equals zero when there is no alternate route and equals one in corridors with several major arterials, usually parallel to the main facility, and can absorb the corridor demand without being congested. The capacity that is used in calculating the critical fraction should be the total unused or available capacity of all the feasible alternate routes. It is not sufficient for an alternate route to be operationally feasible but it also needs to be institutionally feasible. In testing a few real life networks for this purpose, one may find that there are not many routes which qualify.

The benefits to guided traffic decrease when the proportion of guided traffic exceeds the critical value and system benefits also level off once this value is exceeded. Therefore, if the system management has the choice, there is no need to equip more than the critical fraction of vehicles with ATIS. Hence, the benefits to the system and to the ATIS equipped travelers will be maximized simultaneously. Also, system benefits do not increase with the proportion of guided traffic in cases where equilibrium can be achieved.

In conclusion, route guidance has a significant role in the management of off-peak incidents where uncongested alternate routes are likely to be available. During the peak period, the alternate routes are usually congested. If an incident occurs during the peak period and ATIS equipped vehicles are diverted, they join existing queues on the alternate routes. Benefits of diversion, however, are likely to be marginal under these conditions. Furthermore, system benefits are reduced further because of the disbenefits caused to travelers originally using the alternative routes where guided traffic is diverted. This suggests that ATIS enroute guidance is more useful in the management of off-peak incidents. In today's urban networks, nearly half of the incidents occur during the off-peak period. For the incidents that occur during the peak period, the need is to spread traffic over time rather than space. This can be achieved through departure time switching. Here, the role of ATIS is thought to be more useful before starting a trip rather than enroute. Pre-trip traffic information permits the most flexible decisions by trip makers. Travelers can switch routes, departure times, and possibly modes. This area is yet to be investigated and is an interesting subject for future research.

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