Integrating Driver Information and Congestion Pricing Systems

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A great deal is known about both congestion pricing systems and driver information systems in isolation. Unfortunately, very little is known about the joint implementation of such systems. This is particularly troubling because a number of integrated systems are now being considered. Questions that must be answered when designing an integrated driver information and congestion pricing system are discussed. The reason why it is important to consider interactions between the two component subsystems is illustrated using a simple example.

Currently, interest in congestion pricing appears to be particularly intense, despite failed attempts at it during the past 30 years. Many believe that congestion pricing may turn out to be very important to the ultimate success of intelligent vehicle/highway systems (IVHS) and vice versa. There are at least three reasons for this.

First, it is clear that demand management strategies must be included in IVHS. Efforts to develop IVHS technologies usually have been justified on the grounds that they would increase the efficiency and capacity of the existing transportation network and thereby reduce congestion, fuel consumption, and related environmental impacts. However, there is increasing concern that the benefits of IVHS may not be as great as originally anticipated. For example, any increase in capacity—whether the result of electronic toll collection, traffic control (such as ramp metering or in- or out-of-vehicle route guidance), or improved incident management—will be met by an increase in the number of trips and vehicle miles traveled. The likelihood that people will take more trips or change their mode of travel has created concern that augmenting supply via IVHS will conflict with the Clean Air Act Amendments. As a result, many have begun to argue for IVHS-related demand-management techniques (i.e., techniques aimed at influencing the intensity, both over time and space, of transportation demand). One of the most important of these techniques is congestion pricing.

A second reason is that congestion pricing may improve the performance of IVHS. IVHS policies that should work well in an ideal world may be ineffective where there is unpriced congestion. To the extent that tolls properly price congestion, they could improve the performance of IVHS overall.

Finally, congestion pricing may be more palatable as part of an integrated IVHS. Recent attempts to market congestion pricing to the public have relied on introducing congestion pricing for new highways or bridges that are already planned as toll facilities, adding time-of-day variation to the toll structure of an existing bridge or place where traffic bottlenecks. Options include electronic toll collection technology and opening high-occupancy vehicle lanes to nonqualifying vehicles that are willing to pay a fee (1-3). It may be easier, however, to get people to accept congestion pricing if it is introduced along with an advanced traffic management system or an advanced driver information system (ADIS). That way people would think they are receiving something concrete in return for additional tolls.

For these reasons, people have argued for integrating congestion pricing and IVHS. Advocates of integration include users of the highway system, environmentalists, traffic engineers, and policymakers. In fact, several integrated systems recently have been or are about to be proposed.

Although there have been some papers written on the topic, little is known about how congestion pricing should be integrated into IVHS or what the impacts of it will be. It has been argued intuitively that information systems would perform better in the context of congestion pricing, because the latter would lower congestion levels and thereby increase capacity on routes for rerouting (4). Similarly, combining information and pricing could result in synergistic effects; greater improvements may result than would have if each policy were implemented alone (5). Only two examples of quantitative work on this topic were found in the literature (6,7). Although interesting, the analyses are somewhat limited; primary attention is given to examining whether gains from joint pricing and information are greater than gains that would follow if the policies were applied separately. The results are either greater (superadditive), less (subadditive), or independent.

Several key assumptions were made, including the following:

- Information is supplied before any travel begins.
- Capacity is constant on a give day (i.e., incidents last throughout the peak period), and
- The system is in equilibrium every day (even given the day-to-day changes in capacity).

The purpose of this paper is to explain (a) why it may be possible to use integrated driver information and congestion pricing systems to reduce congestion and its negative impacts, (b) what types of decisions need to be made when designing such a system, and (c) why it is important to consider interactions between the two subsystems. First, the role of driver information systems and congestion pricing systems is discussed. Various types of systems that can be used, and the possible advantages and disadvantages of each are considered. Then a simple analytic model is used to illustrate the importance of considering interactions between the two subsystems. Finally, future topics for research are outlined.

DESIGN OF AN INTEGRATED DRIVER INFORMATION AND CONGESTION PRICING SYSTEM

When designing an integrated driver information and congestion pricing system, it is necessary to consider the role of each of the two component subsystems and the details of how each works.
Roles of Subsystems

The best way to design an integrated system follows three steps: First, consider the specific goals of the system (i.e., what type of congestion is to be reduced). Second, consider what changes in behavior could achieve those goals. Third, consider how the two component subsystems could be used to bring about the desired changes in behavior.

The first step involves distinguishing between two different types of congestion, nonrecurring and recurring. Nonrecurring congestion, which does not follow a regular day-to-day pattern, is caused by incidents, such as accidents or breakdowns. In contrast, recurring congestion follows a regular pattern; it is caused by the normal dynamics of traffic flow.

The composition of congestion has been investigated by several researchers; most of their figures indicate that both types of congestion are substantial. According to one study, 64 percent of the total delay due to congestion is incident related and 36 percent is due to recurring congestion (8). It is generally believed that an integrated system should be developed to reduce both types of congestion, if possible.

The second step involves distinguishing between default behavior and adjustment behavior. Default behavior is that which is exhibited by a majority of travelers who make a particular trip repeatedly, such as a trip from home to work. Under those circumstances, travelers are likely to develop a habit with regard to the various choices related to that trip, including the decision to travel and the choice of destination, mode, route, and departure time. These habitual choices, in the short-run, will be adhered to with little variability from day to day. On occasion, however, immediate or real-time adjustments will be made to the default pattern that do not arise simply from natural fluctuations in travelers’ behavior and their environment. Travelers make adjustments in response to severe weather, for instance, or to reports of excessive congestion or accidents on their default routes. Adjustment behavior includes pretrip changes regarding decision to travel or the choice of destination, mode, route, or departure time as well as en route changes in destination, mode, and route.

At least in principle, changes in both default and adjustment behavior can affect both nonrecurring and recurring congestion. Of course, all changes in default behavior affect recurring congestion, and many changes in adjustment behavior can influence nonrecurring congestion. What is less obvious is that changes in default behavior can have an impact on nonrecurring congestion in a number of ways. For example, the frequency and the magnitude of incidents (and hence the level of nonrecurring congestion) is probably a function of the level of recurring congestion and therefore can be influenced by changes in default behavior. Furthermore, changes in adjustment behavior can have an impact on recurring congestion because people do not always behave in their own self-interest. Some travelers may, for example, routinely choose a slower route to work because they are unaware of a better alternative.

With this in mind, the third step involves determining how congestion pricing and information subsystems can be used to influence default and adjustment behaviors. In general, both subsystems can be used to influence both types of behavior.

The most popular application of such information systems is their use in influencing adjustment behavior. Indeed, it is clear that information can be used to influence pretrip and en route adjustments (9).

Less widely discussed is the fact that information systems can be used to influence default behavior. How information might be used to affect default behavior, total travel costs, and the travel costs of individuals has been examined by several researchers (10).

Traditionally, discussions of congestion pricing have focused on how it might be used to influence default behavior. Tolls can be used to alter individuals’ decision to travel and their choice of destination, mode, route, or departure time. A majority of early studies avoided the task of modeling these various responses using a generic demand curve. Papers that analyze actual responses include a seminal work that investigated the departure time response to a time-varying toll (11). This study is of particular relevance given current interest in congestion pricing, which is largely based on pricing certain times of the day. Another paper studied the route-choice response to pricing (12).

Finally, it is easy to see how, with the advent of various new technologies, congestion pricing might be used to influence adjustment behavior. First, if drivers are made aware of the toll levels before they begin their trips, they can make various pretrip adjustments. In addition, applying differential pricing to several alternative routes could be used to modify en route decisions.

Types of Congestion Pricing Systems

Congestion pricing systems vary in both their spatial and temporal structure. The authors summarize some of the more important characteristics of these systems; a more complete discussion is available elsewhere (13).

In terms of spatial structure, congestion pricing schemes can be either areawide or facility based. The most popular approach to implementing congestion pricing outside of the United States has been areawide. The Singapore system charges for entry into the central business district (CBD) during the morning peak and for exit in the afternoon. The well-known (though short-lived) Hong Kong experiment with congestion pricing subdivided the city districts into several zones, and commuters were tolled as they crossed zone boundaries according to a time-varying schedule. The Norwegian cities of Oslo and Bergen constructed cordons around their CBDs that charge time-invariant tolls but are able to implement peak-period price differentials. Moreover, planned schemes in London and Cambridge, England, and Stockholm are based on one form or another of areawide pricing (14). In the United States, on the other hand, much more attention is being given to facility-based approaches to congestion pricing. One reason is that such approaches are believed to have the best chance of gaining public acceptance, because with such an approach toll-free options are preserved. Another reason is that much of the congestion occurs on suburban connectors, which are not well suited for being charged under areawide schemes.

In terms of temporal structure, congestion pricing systems can be static or dynamic. Static tolls repeat themselves from day to day (or from week to week, if for example the Monday travel pattern is observed to differ strongly from the Friday pattern), even though they may be time-varying (i.e., have different values at different times of the day). Dynamic tolls include all forms of pricing; their temporal toll structure on a given day depends on actual traffic flow or congestion levels. Systems of all three types have been proposed to date, but only static systems have been implemented this far.
It is also important to observe that both static and dynamic systems can be either continuously varying, interval based, or constant within a given day. That is, the toll can change continuously over time (e.g., second by second), can change a few times and remain constant for the intervals between such times, or can remain constant throughout the day. All of the static systems implemented to date have been interval based.

In our view, not all types of congestion pricing systems can be used to influence all types of behavior. For example, using congestion pricing to influence en route choices is very different from using it to influence pretrip choices. A continuously varying dynamic toll is probably not an appropriate way to influence pretrip adjustment behavior. If tolls change continuously, people would expect the tolls to change from what they were before they reach the toll facilities and might ignore them. On the other hand, congestion pricing in principle can be used to influence en route decisions almost continuously. It is not clear, however, whether such a system would be acceptable to the majority of travelers, who might object to not being able to know in advance what they will be required to pay for using a particular route.

Using congestion pricing to influence en route decisions is very different from using it to modify default behavior. In the case of default behavior, it makes sense to consider the response to the toll in the long term. In the case of adjustment behavior, it only makes sense to consider the immediate response. As a result, en route adjustments can be elicited in a variety of different ways. First, one might consider marginal cost pricing. One determines the financial impact of each driver's behavior on the total cost to society and charges accordingly. Because it is not clear that charging marginal fees on a one-time basis results in the adjustment desired, one can consider what tolls would effect the desired behavior. One could charge a toll that no one would be willing to pay on all of the alternatives that are being discouraged at a particular time. Or, one could charge a toll that is meant to encourage desired adjustment behavior by charging a toll that is placed appropriately within the value of time distribution (so that the right number of people go each way).

Types of Driver Information Systems

Just as there are several ways to implement congestion pricing, many different driver information systems also have been proposed. To some extent, the differences among them are determined by the technologies they employ. For purposes of this study, however, it is more important to consider the four functional differences (10,15,16) among them.

First, driver information systems may vary in the information they provide. That is, they can provide either status or guidance information. In addition, the information they provide can be historical, current or predictive. The exact nature of the information influences how people respond to them in real time and during the long run.

Second, the spatial structure of driver information systems can vary in important ways. In particular, they can vary by geographic extent or coverage (including whether both pretrip and en route information is available) and in their specificity (i.e., whether information is provided to individual vehicles or whether the same information is provided to all of the vehicles in a given area). The spatial structure will largely determine the resolution of the ADIS (i.e., how specific the system can be in influencing traffic patterns).

Third, different driver information systems may have different temporal structures. Most important, the frequency with which the information is updated can vary, which too can affect resolution of the ADIS. One study has shown that temporal structure can have a considerable effect on whether the system experiences overreaction effects (15).

Finally, it is possible to design driver information system with a variety of different objectives. The general objective usually is to minimize some individual’s or group’s travel cost. However, the group is defined can significantly affect the ultimate operation of a system. Possible groups include those vehicles at a particular information provision point; all vehicles within x km of a particular point; all vehicles currently within the network; and all vehicles currently within the network, plus those forecast to be within it in the next t min.

Possible Advantages and Disadvantages

With all of this in mind, it is important to compare driver information systems and congestion pricing systems in view of the fact that either can be used to influence both default and adjustment behavior. Which system should be used in each case? It is not yet possible to answer this question with certainty; however, the authors present some of the advantages and disadvantages of each.

Influencing Default Behavior

Information systems are only likely to have a significant impact on default behavior if travelers lack perfect information on alternatives to their current choices. Hence, the extent to which an information system will continue to influence default behavior for the longer run depends in large part on how long it takes people to remember the information they are regularly given. Commuters and other regular travelers may learn relatively quickly or be very well informed already; thus the information system may be necessary in this regard for a relatively short period of time.

From a technical standpoint, however, congestion pricing is likely to influence default behavior effectively. Travelers have demonstrated a sensitivity to prices because almost everyone has alternatives to their default choices. Yet failed attempts to implement congestion pricing in the past have shown that political difficulties remain. One issue is congestion pricing’s inequitable impact on the poor. If fairness theory (17) is applied, congestion pricing is at a disadvantage compared with other traffic restraint policies, such as blanket prohibitions on driving in city centers (13).

Influencing Adjustment Behavior

Although information systems can have a significant impact on both pretrip and en route adjustment behavior, they cannot achieve every desired response pattern. The most important reason for this is that there is no guarantee that travelers will comply with information directives. In particular, an information system can be effective only if the information being provided is perceived as reliable (in that what is predicted occurs) and useful (in that it is in a traveler's own best interest). Otherwise, it may be ignored,
rendering it ineffective (15). Therefore, it probably is not possible to minimize congestion directly using an information system, because to do so would require that some travelers be given information that is not in their own self-interest.

On the other hand, congestion pricing is useful in influencing adjustment behavior, particularly when it is used in conjunction with an information system, because the tolls reinforce information.

However, if the information is both reliable and useful, it should not be necessary to reinforce it. Congestion pricing is necessary only if the information offered is unreliable or it is not useful (in a traveler's self-interest). If the information is unreliable, any tolls are not likely to be accurate. However, if the information simply is not useful, then congestion pricing may be able to achieve objectives that cannot be achieved with information alone. In particular, if information must be "fair," (that is, affect all travelers equally) then information alone is not apt to achieve optimal adjustment behaviors, because such adjustments are likely, to be bad for some drivers and good for others. Congestion pricing, on the other hand, can be used to achieve the optimal adjustments, although it may not be widely accepted.

EXAMPLE OF THE IMPORTANCE OF INTEGRATED DESIGN

Thus far, the authors considered why it might be advantageous to implement an integrated driver information and congestion pricing system and what decisions must be made in the design of such a system. To illustrate why it is important to design the two subsystems simultaneously, a simple numerical example is given to show problems that can arise if the two subsystems are designed independently.

Consider a facility-based congestion pricing system that has static, interval tolls and a driver information system that attempts to minimize the cost of the vehicle currently receiving information by providing predictive, vehicle-specific guidance that is updated continuously. The specific design issue is the location of the toll stations (at either points of entry or exit).

In the absence of incidents, the location of the toll station will have no impact on traffic flow given the static nature of the tolls. However, in the event of incidents and with the use of an information system, vehicles may be advised to switch routes when incidents occur. That may have an impact on the number of people that pay the toll, who pays the toll, and their satisfaction with the system.

Network

Figure 1 shows the network under consideration. Commuters travel from A to C and have the choice of two routes, using either Links 3 and 1 or Links 3 and 2. The free-flow travel times on Links 3, 1, and 2 are 15, 12, and 18 min, respectively. There are potential bottlenecks, modeled as deterministic queues, on Links 2 and 3, which have capacities of 780 and 300 vehicles/hr, respectively. Toll stations are located either at the entrances of Links 1 and 2 (at B), or just after the bottlenecks on those links (at C). The origin-destination flow from A to C is 2,200 vehicles. The capacity of Link 3 is set arbitrarily high; in effect, it is a two parallel-route network, with Route 1 consisting of Links 3 and 1 and Route 2 consisting of Links 3 and 2. Modeling Links 1 and 2 as a combination of a free-flow component of fixed time and a bottleneck of variable time (depending on queue length) is useful and has some empirical validity (18). Such behavior has been observed on urban freeways. In addition, the fixed time component brings the travel time function on a link closer in shape to that of popular speed-density curves. Thus, \( t^*_f = 27 \) min and \( T_c' = 33 \) min. The desired arrival time, \( t^* \), is 8.0 hr.

The performance of the system is examined in the presence of incidents. A conditional analysis is carried out that looks at the effects of a single incident, that is, a random, limited time reduction in network capacity. No assumptions are made about the frequency of occurrence of such one-incident days. Furthermore, the impact of the incident on the capacity of the link is modeled as a constant reduction in the capacity of the affected link. The reduction factor, the duration, and the location of the incident are all assumed to be uniformly distributed random variables.

The effect of toll station location on performance is evaluated by examining two situations: one in which the toll stations are upstream of the bottleneck (i.e., at B), and one in which they are located between the bottleneck and the destination (at C). The information system is located at B, in the sense that route guidance is provided at this point to direct travelers to one of the two routes.

Behavioral Model

The behavioral model is based on the assumption that travelers adopt a default behavior that is described by an equilibrium travel pattern. The equilibrium will adjust as a result of the imposition of a congestion pricing policy. Specifically, an extension of the traditional network equilibrium model (19) is used. It is assumed that in equilibrium no traveler can improve his or her total travel cost by unilaterally switching to a new departure time or route (20,21).

An essential feature of this model is the notion of a trade-off between travel time and schedule delay. Those commuters who arrive on time or close to the desired arrival time will have longer travel times than those who arrive early or late. In particular, it is assumed that the travel cost function is given by

\[
C(i) = \alpha \cdot (\text{travel time}) + \beta \cdot (\text{time early}) + \gamma \cdot (\text{time late}) + \text{toll}
\]  

(1)
where \( C(t) \) is the cost for a commuter leaving at time \( t \), and \( \alpha, \beta, \) and \( \gamma \) are the values of travel time, time early, and time late, respectively.

It is also assumed that demand for travel is fixed and that the population is homogeneous. Further, it is assumed that travel time on Link \( i \) is the sum of the time spent traveling at constant velocity along the link, \( T^i \), plus the time spent queuing in bottlenecks at the end of the link, \( T^el \). The bottleneck at the end of the link is represented as a deterministic queue. Thus, if the arrival rate at the bottleneck exceeds the capacity or service rate \( s_i \) of that link, queuing will occur. Given these assumptions, it is possible to find analytic representations of the equilibrium departure rates both with and without tolls (11,22,23). Throughout the analysis, values of time estimated in a previous study (24) are used. It is assumed that \( \alpha = \$6.40/hr, \beta = \$3.90/hr, \) and \( \gamma = \$15.21/hr. \)

When an incident occurs, the information system, if in place, begins operation. It is assumed that travelers follow the route guidance provided at \( B \), which may or may not result in a change in their default route choices.

### Congestion Pricing Scheme

The authors assume that the optimal single-step toll is charged (22,23,25). With such a toll in place, commuters pay a toll, \( \tau \), when arriving at the toll station between the period \([t_i, t'_i] \); at other times during the period of departures, no toll is charged. The equilibrium solutions are identical for the two toll stations, except for the timing of the toll period. The optimal step-toll on each route consists of the set \( \{\tau, t'_i, t'_i \} \) that minimizes total cost.

There are two noteworthy features of the equilibrium travel patterns that arise from the discontinuities in cost introduced by the step-toll. First, at the time that results in arrival at the toll station just before a toll period begins, a gap in departures begins. It lasts until queue lengths have diminished to the point at which travel costs, including the toll, are equal to that of the last commuter. In addition, there is a bulk departure of \( 2s_i \tau_i / (\alpha + \gamma) \) commuters just after the end of the toll period, assuming that the position is random in the bulk (i.e., it averages out over a number of days). Thus, equilibrium is achieved only on the average.

For two routes in parallel, it is necessary to optimally split the \( N \) commuters and maintain equilibrium between routes. This is achieved by applying a uniform toll \( \tau \) on one route in addition to the step toll.

Applying these results to our example gives the results in Table 1. The uniform toll is applied to Route 1, which has the shorter free-flow travel time, and equals $0.22.

### Information System

Again, it is assumed that there is a route guidance system located at Node \( B \) and that this system is perfect in the sense that it "knows" (i.e., can predict perfectly) the end of an incident after it begins. No delay is assumed between the incident's occurrence and the provision of information (i.e., the incident reporting delay is assumed to be zero). Also, it is assumed that all travelers receive information and comply with it. Guidance is based on minimum predicted cost. For simplicity, the effect of the various guided probabilities that represent the fraction of travelers who follow guidance directives is not considered. Because the information system is updated continuously, possible problems related to over-reaction are eliminated (16). However, higher benefits could be obtained with lower guided probabilities, because the system, despite its perfection, does not attempt to minimize system costs.

In the case of congestion pricing, the information is provided on the basis of the total cost, including tolls.

When an incident occurs on Link 1 or 2, the information system begins operation. At that point, the number of vehicles on both of these links and the queue lengths are known. Thus, the exit time of the last vehicle on each link to have passed \( B \) before the incident can be computed. Because the duration of the incident also is known, the exit time for a vehicle arriving at \( B \) on each link can be predicted accurately in the following manner. First, the sum of the arrival time of the vehicle and the free-flow travel time on the link results in the arrival time at the queue. If the last vehicle to exit is still in the queue, then the predicted exit time for the vehicle now at \( B \) is the exit time of the last vehicle plus the service time of the queue. Otherwise, the total service time for the queue is added to the arrival time at the queue. The time of the last vehicle to exit each link is then updated according to the route choice made. If the predicted cost of travel on the default route is greater than that of the alternate route by more than a small threshold (to avoid excessive sensitivity), the vehicle is directed to that route.

### Results

A macroscopic simulation model was used to evaluate the effectiveness of both a driver information system alone and the integrated driver information and congestion pricing system (26). The default route and departure time patterns were calculated using the equilibrium model described above and made discrete for use in the simulation. For each simulation run, a single incident is assumed to occur on either Link 1 or Link 2, which is assumed to affect the capacity of the respective bottlenecks for simplicity. (Alternatively, the free-flow travel time could be assumed to increase as a result of an incident.) The main objective is to evaluate the impact of toll station location on total travel costs, including and excluding toll costs. Because toll stations are placed either at the beginning (\( B \)) or end (\( C \)) of Links 1 and 2, the objective of modeling random increases in travel time on these links is served adequately by restricting the impact of incidents to capacity reductions in the bottlenecks. This restriction on the location of the incident is somewhat unrealistic because, in practice, incidents may occur anywhere along a highway, but the restriction should not affect the results beyond making the incidents more severe than if their location were allowed to vary. (For a given magnitude and duration of incident, more people are affected if the location

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**TABLE 1 No-Toll Equilibrium and Equilibrium with Optimal Step-Toll**

<table>
<thead>
<tr>
<th>Regime &amp; Route</th>
<th>N</th>
<th>EC</th>
<th>Toll($)</th>
<th>( T^+ )</th>
<th>( T^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untolled 1</td>
<td>1634</td>
<td>9.38</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Untolled 2</td>
<td>566</td>
<td>9.38</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tolled 1 Upstream</td>
<td>1620</td>
<td>9.28</td>
<td>3.00</td>
<td>6:33</td>
<td>7:59</td>
</tr>
<tr>
<td>Tolled 2 Upstream</td>
<td>580</td>
<td>9.28</td>
<td>3.22</td>
<td>6:32</td>
<td>7:53</td>
</tr>
<tr>
<td>Tolled 1 Downstream</td>
<td>1620</td>
<td>9.28</td>
<td>3.00</td>
<td>7:16</td>
<td>8:12</td>
</tr>
<tr>
<td>Tolled 2 Downstream</td>
<td>580</td>
<td>9.28</td>
<td>3.22</td>
<td>7:18</td>
<td>8:11</td>
</tr>
</tbody>
</table>
is at the bottleneck instead of upstream of it.) Only summary results corresponding to 100-run simulations for each of the diferent scenarios are provided here; more detail on the simulation results can be found in other work (13) in which modifications to both the pricing and the information systems are discussed.

With regard to upstream toll station locations, general conclusions based on the 100-run simulation experiments include the following:

• In the presence of incidents, and without information, toll costs are not affected by the incident, because delays due to the incident arise from queuing in the bottleneck, which is located after (downstream of) the toll stations.
• Information always produced improvements in total costs, excluding tolls. In contrast, providing information may result in negative net benefits when toll costs are included. The main reason is that a net increase in the number of toll-paying commuters results from giving information. The net increase occurs when some travelers on Route 1, whose toll period ends several minutes before it does on Route 2, switch to Route 2 (reducing their number compared with those who had no information), followed by the switching to Route 1 of a subset of the bulk on Route 2, which increases the number of toll-paying travelers. Depending on the magnitude of the benefits in total costs excluding tolls, this increase in toll costs may result in negative benefits including tolls.

General conclusions regarding downstream toll station locations include the following:

• An incident may reduce the total number of toll-paying travelers. Incidents reduce the rate at which travelers exit the bottleneck. If the period during which the incident is in progress overlaps the toll period, fewer travelers pass through the toll station during the toll period. Total revenues decrease in this case. Thus, a certain number of commuters who would pay a toll in the incident-free case now exit the bottleneck late enough to avoid the toll. As a result, the costs, including tolls without information, were generally higher for upstream than downstream toll station locations. When information was supplied, these differences were accentuated because information in the upstream case generally increases revenue as well as increases costs compared with the downstream case. In the latter case, the authors observed a negligible increase in the number of toll-paying travelers because of information. Thus, total travel costs, including tolls, invariably decreased with information. Note that because the toll station location is just before the destination at C, equilibrium requires that the ends of the toll period are close to each other, differing only enough to make up for differences in the toll levels on each route. Hence, there is little opportunity to switch to a tolled route from one that is not, or vice versa.
• On the other hand, the time shift in arrivals at the bottleneck caused by the incident may draw travelers into the toll period who do not usually pay the toll, resulting in significantly increased costs for them. This occurs when the incident begins before the start of the toll period and may occur even when information is provided, because some travelers will be between B and C on the incident route when the incident occurs. If the incident ends before the toll period, the number of travelers passing through the toll station is the same as it would be in the case of no incident, because some travelers are drawn into the toll period who do not pay in the latter case, and an equal number of travelers who usually pay arrive at the toll station after the toll period ends.

• Similar to the upstream case, total travel costs excluding tolls always decreased with information.

The observation that higher costs result from giving information, as sometimes occurred with upstream toll stations, supports the authors' original claim that combining pricing and information systems must be done with an eye to the issues that are unique to the combined systems. Although results may be model sensitive, they provide an incentive to look for such phenomena even when modeling conditions are different. The same can be said for the more robust findings regarding downstream station locations, which emphasize the need to consider possible interactions between the two systems. The impact of incidents on revenues, which in turn might spawn acceptability problems on the part of travelers who face unpredictable travel costs, would all have to be taken into account when designing an actual system. Otherwise, independent design of pricing schemes might fail to consider the role of incidents, which are responsible for both the variability in arrival times at the toll stations and the reduced throughput through the station.

CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

The authors have discussed decisions that must be made when designing an integrated driver information and congestion pricing system and have attempted to illustrate the importance of careful design using a simple numerical example. However, it is important to realize that many other issues might arise when driver information systems and congestion pricing systems are implemented together. Future work will examine other issues, whether temporal (i.e., related to how systems are designed to behave in time), spatial (i.e., concerning how systems are designed to behave in space), or demographic (i.e., regarding how systems are designed to behave for different people and vehicles). Various systems will be evaluated on the basis of their acceptability before implementation and their operability after implementation.

REFERENCES


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