Understanding the Competing Short-Run Objectives of Peak Period Road Pricing

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The interest in peak period road pricing has grown considerably in recent years both in the United States and abroad. This increase in interest is usually attributed to worsening congestion and improved electronic toll collection technologies. However, there may be a third reason as well: peak period pricing can be used to generate revenues. This use of peak period road pricing is explored and compared with programs that are designed to minimize social cost. Using some simple examples, it is shown that it is possible to increase toll revenues but at a significant cost to society. In addition, it is shown that most of the revenues and costs can be attributed to the length and end of the toll period.

Peak period pricing has been an accepted part of life in the United States for many years. For example, most long distance telephone companies charge higher prices during the day than they do during the evening and night. In addition, many public transit systems (e.g., the Washington, D.C., Metro) also charge higher prices during the peak period. However, in spite of the urgings of many economists, peak period pricing is not yet in widespread use on U.S. highways.

There are, of course, many reasons for this. In the United States, some of these reasons became evident during the 1970s when UMTA, with the help of the Urban Institute, offered to assist several cities in establishing programs that would demonstrate that peak period pricing could be used to bring congestion levels down to the "socially optimal" level (which is a specific type of peak period pricing that is usually referred to as "congestion pricing"). The response was considerably less than expected (*1,2*). Although three cities did agree to further study (Madison, Berkeley, and Honolulu), all of the preliminary studies ended without requests for further funding because of public opposition. Congestion pricing was perceived as being unfair, discriminatory, regressive, coercive, and antibusiness.

Yet, in spite of these past failures, the United States and other countries are again beginning to consider peak period road pricing. In the United States, the recent Intermodal Surface Transportation Efficiency Act (ISTEA) has allocated funding for up to five pilot congestion pricing programs. In the rest of the world, several such programs are now either under way or in the planning stages. For example, Singapore has had a program in place since 1975 (*3–6*); Bergen, Norway, has had a program in place since 1986; and Hong Kong tested a program from 1983 to 1985 and is now considering a full-scale implementation (*7–12*). The Netherlands had planned on having a full-scale program in place by 1996 and is now considering a somewhat scaled-down program instead (*13*); Cambridge, England, intends to initiate a trial program by 1993 or 1994 and a full-scale program by 1997 (*14*); and Oslo and Trondheim, Norway, and Stockholm and Gothenberg, Sweden, are all considering programs of one kind or another.

Several reasons are usually given for this renewed interest. First, congestion is now much worse than it has ever been in the past. As two-income families have become more prevalent and suburban rings have grown in both absolute population and area, the number of commuters using private automobiles in the United States has increased dramatically. In fact, from 1960 to 1980 the number of people driving to work nearly doubled (at a time when the number of people in the work force increased by only 50 percent). In addition, there has been a continued increase in the amount of truck transport, and hence in highway truck miles, both inside and outside of urban areas. The result is that more than 55 percent of urban freeway travel during the peak period takes place during congested conditions (*15*) and that more than 11 percent of the total vehicle miles of travel takes place during recurring congestion (*16*). Hence, although congestion pricing has been unpopular in the past, it is needed more than ever before. Second, toll collection technology [see for example, Bernstein and Kanaan (*17*)] has now advanced to the point where congestion pricing can be implemented.

However, in our casual conversations with policy makers who are now considering peak period pricing, it has become apparent that there is another reason for this increase in interest. Many of them seem to view peak period pricing as a mechanism for increasing revenues (which should not, strictly speaking, be referred to as congestion pricing). In addition, there may also be increased support for road pricing simply as a means of reclaiming road space for pedestrians [see Goodwin (*18*)].

Not surprisingly, the existing literature does not consider these aspects of peak period road pricing. Instead, it focuses on the inefficiencies that are inherent in (high-volume) roadway travel (*19–28*). Thus, given the possibility that peak period road pricing may be used as a revenue generation mechanism, it is important to consider the impacts of such policies. This paper represents a first step in such an investigation.

We begin by describing the specific setting we consider throughout the remainder of the paper and by discussing the various competing objectives of peak period road pricing. We then consider the impacts of pursuing these objectives, first within the context of tolls that are in place throughout the entire peak period and then within the context of time-varying tolls. We conclude with a discussion of future avenues that still need to be pursued. We should point out in advance that we do not evaluate any specific road pricing programs in this paper. Studies of this kind can be found elsewhere (*29–32*).

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COMPETING OBJECTIVES

Road pricing can have several effects on traveler behavior in the short run. In particular, it can result in changes in route, changes in departure time, changes in mode, changes in the total number of trips taken, and changes in the origin and destinations of those trips. As a result, it can be used to achieve a variety of different ends. (It is for this reason that we generally often use the term peak period road pricing rather than congestion pricing in this paper. We use the latter term only to describe programs that are designed to increase social welfare.) For example, one can imagine policy makers making well-reasoned arguments about why road pricing should be used to

- Reduce social costs (time, money, etc.),
- Reduce out-of-pocket transportation costs,
- Reduce travel time,
- Reduce the number of vehicle miles,
- Increase toll revenues,
- Increase transit revenues, or
- Increase total (toll and transit) revenues.

Furthermore, these objectives could be either general (e.g., reduce the total number of vehicle miles or reduce out-of-pocket transportation costs) or very specific (e.g., reduce the total number of vehicle-miles on the Gotham Expressway or reduce out-of-pocket transportation costs for people earning less than $20,000/year).

In general, the various objectives of road pricing need not conflict, yet in some cases they may be entirely contradictory. For example, it may be possible to both increase toll revenues and reduce social costs. On the other hand, it may not be possible to both reduce out-of-pocket transportation costs and increase total revenues. In either case, it is important that we have some way of comparing these different objectives so that policy makers can make informed decisions.

For the purposes of this paper, we will use a relatively simple technique to conduct the comparison. In particular, we will consider only two different types of policies, one aimed at minimizing social cost (which in the examples that follow is simply the total travel cost minus the toll revenue) and the other aimed at maximizing toll revenues (given certain constraints). For each of these policies we will calculate and compare a variety of different impact measures using some simple examples.

BASIC MODEL: SRD EQUILIBRIUM

We will work with a model of commuter behavior on a simplified transportation network composed of a set of nonoverlapping (i.e., with no arcs in common) paths (P) and a single origin-destination pair (O-D pair). Commuters traveling between this single O-D pair choose both a path (or route), $p \in P$, and a departure time, $t \in [0, T]$.

Although we discuss commuters as if they are discrete entities, we actually work with departure rates. In particular, for each path ($p \in P$) the departure rate on p at time t is denoted by $r_p(t)$, and each possible pattern of departures is described by the vectors $r(t) = (r_p(t) : p \in P)$ and $r = (r(t) : t \in [0, T])$. The total number of commuters between the single O-D pair is denoted by N. Thus, the set of feasible path flow vectors is given by

$$H = \left\{ r : \sum_{p \in P} \int_0^T r_p(t)\,dt = N \right\} \tag{1}$$

The cost on each path (C_p) is a function of the total travel time on the path and the arrival time at the destination (plus any tolls). We assume that the time needed to traverse path p when entered at time t can be modeled as a deterministic queueing process in which

$$D_p(t) = d_p + \frac{1}{s_p} x_p(t + d_p) \tag{2}$$

where

d_p = (fixed) travel time on path p,
s_p = service rate of the queue on path p, and
$x_p(t + d_p)$ = number of vehicles in the queue on path p for a vehicle that enters the path at time t (and hence reaches the queue at time $t + d_p$).

Further, because travelers may arrive early or late, we introduce an asymmetric schedule cost given by

$$\Phi_p(t) = \begin{cases} \beta[t^* - (t + D_p(t))] & \text{if } [t + D_p(t)] < t^* \\ 0 & \text{if } [t + D_p(t)] = t^* \\ \gamma[(t + D_p(t)) - t^*] & \text{if } [t + D_p(t)] > t^* \end{cases} \tag{3}$$

where

t^* = desired arrival time,
β = dollar penalty associated with early arrival, and
γ = dollar penalty associated with late arrival.

Note that we do not include a window of "equally acceptable" arrival times to simplify the analysis that follows. Also note that we will often use the notation F_p to denote the free-flow travel cost on path p (i.e., $F_p = \alpha d_p$).

Using the preceding definitions, we may now define the generalized travel cost as follows:

$$C_p(t) = \alpha D_p(t) + \Phi_p(t) + \tau_p(t) \qquad \forall\, p \in P \tag{4}$$

where α is the value of travel time and $\tau_p(t)$ is the toll on path p at time t (if any). Further, by appropriately defining the min operator [see Friesz et al. (*33*) for details], and letting

$$\mu_p(r) = \min\{C_p(t) : t \in [0, T]\} \tag{5}$$

and

$$\mu(r) = \min\{\mu_p(r) : p \in P\} \tag{6}$$

we can define an equilibrium as follows: A departure rate pattern $r \in H$ is a simultaneous route and departure-time choice equilibrium (SRD equilibrium) if and only if (iff) r satisfies the following condition for all $p \in P_w$, and t:

$$r_p(t) > 0 \Rightarrow c_p(t) = \mu_w(r) \tag{7}$$

That is, we assume that the only flow patterns that can persist are those in which all used path and departure time choices have minimum cost.

Although it can be quite difficult to solve for SRD equilibria [see Bernstein et al. (34)], for this simple model earlier works (23,35) present an analytic solution. For the case when $\tau(t) = 0$ (i.e., the no-toll equilibrium), they demonstrate that the equilibrium can be characterized as follows:

$$t_q = t^* - \left(\frac{\gamma}{\beta + \gamma}\right)\frac{N}{S} - d \tag{8}$$

$$t_{q'} = t^* + \left(\frac{\beta}{\beta + \gamma}\right)\frac{N}{S} - d \tag{9}$$

$$t_q = t^* - \left(\frac{\beta\gamma}{\alpha(\beta + \gamma)}\right)\frac{N}{S} - d \tag{10}$$

$$r(t) = \begin{cases} s + \dfrac{\beta_s}{\alpha - \beta} & \text{if } t \in [t_q, \tilde{t}) \\ -\dfrac{\gamma_s}{\alpha + \gamma} & \text{if } t \in [\tilde{t}, t_{q'}] \end{cases} \tag{11}$$

$$C = \left(\frac{\beta\gamma}{\beta + \gamma}\right)\frac{N}{s} \tag{12}$$

where

- t_q = time that the queue begins to form,
- $t_{q'}$ = time the queue falls to zero, and
- $\tilde{t}$ = departure time that leads to an arrival at t^*.

Patn subscripts were omitted for the sake of clarity.

COMPARING OBJECTIVES: PERMANENT TOLLS

With this as background we now turn to the question at hand. That is, we now consider the differential impacts of the socially optimal and revenue maximizing tolls. We begin with a very simple case for which we need only consider the effects of the revenue maximizing toll. This enables us to easily illustrate the magnitude of these effects. Specifically, in this section we consider the case in which there is a toll in place throughout the entire period (i.e., a permanent toll), and we assume that this toll does not vary with the flow level [for a discussion of the use of step tolls see Bernstein and Smith (36) and for the case of tolls that vary continuously with flows see Dafermos (26)]. We also limit ourselves to a simple example in which commuters traveling between a single origin and a single destination choose both their departure time and whether to use the single highway (which can be tolled) or the single local road (which cannot be tolled). Finally, we assume that the system reaches an equilibrium in which both paths are used.

Using the results above and letting $\eta_p = \gamma/[s_p(\beta + \gamma)]$, we can write the equilibrium cost (as a function of the number of users) on the highway as

$$C_h(N_h) = F_h + \eta_h N_h \tag{13}$$

and for the local (free) road

$$C_l(N_l) = F_l + \eta_l N_l \tag{14}$$

where

- N_h = number of users on the highway,
- N_l = number of users on the local road, and
- $N = N_h + N_l$.

Thus, in this case, the equilibrium condition is given by

$$\underbrace{F_h + \eta_h N_h + \tau}_{C_h} = \underbrace{F_l + \eta_l(N - N_h)}_{C_l} \tag{15}$$

which implies that $N_h = (F_l - F_h - \tau + \eta_l N)/(\eta_h + \eta_l)$.

Because we know that the socially optimal toll is zero in this case, we can turn directly to determining the revenue maximizing. The toll revenue maximization problem is given by

$$\max_{0 \le \tau \le (F_l - F_h + \eta_l N)} N_h \cdot \tau \tag{16}$$

Substituting in for the equilibrium value of N_h yields the following equivalent problem:

$$\max_{0 \le \tau \le (F_l - F_h + \eta_l N)} \frac{F_l - F_h - \tau + \eta_l N}{\eta_h + \eta_l} \cdot \tau \tag{17}$$

Hence, the revenue maximizing toll is given by

$$\tau_{tr} = \frac{(F_l - F_h + \eta_l N)}{2} \tag{18}$$

and

$$N_h^{tr} = \frac{(F_l + F_h + \eta_l N)}{2\eta_h + 2\eta_l} \tag{19}$$

with the toll revenues given by $R_{tr} = \tau_{tr} N_h^{tr}$.

We can now gain some insight into the effects of the revenue maximizing toll by considering a numerical example. Using the values of α, β, and γ estimated elsewhere (37) (i.e., $\alpha = 6.40$, $\beta = 3.90$, and $\gamma = 15.21$), and setting $N = 5{,}000$, $s_h = 6{,}000$, $s_l = 4{,}000$, $d_h = 0.333$, and $d_l = 0.50$, we find that the equilibrium cost when there is no toll is \$4.11 with 3,825 commuters using the highway. With the revenue maximizing toll of \$2.47 in place, the equilibrium cost increases to \$5.56 with only 1,913 commuters using the highway. This means that the revenue maximizing toll results in a 35 percent increase in commuting cost (assuming that toll revenues are not redistributed) and toll revenues of \$4,725. Each dollar increase in toll revenues therefore costs society \$1.53. Hence, although toll agencies may be tempted to adopt the revenue maximizing toll, such a policy has a very high social cost.

COMPARING OBJECTIVES: TIME-VARYING TOLLS

Given the significant effects of the revenue maximizing toll, it is important to take a closer look at what causes those effects. To do so, we now consider an example with a single path (i.e., the highway from above) and explore the influence of the "timing" of the toll.

To remove any toll mechanisms from consideration that we think are socially, technically, or politically unacceptable, we place several restrictions on these tolls. First, we consider only a step toll (i.e., there is a peak toll and an off-peak toll), the value of which is τ within the toll period $[t^+, t^-]$ and zero outside. We further restrict our investigations to toll schemes for which some commuters exit the bottleneck before the toll period (in equilibrium). Finally, we will require that $t^+ < t^* < t^-$ (i.e., the period during which the step toll is levied) is the period when congestion is at its worst under the no-toll situation and that the bottleneck remains used at capacity throughout the "rush" period (i.e., during the interval $[t_q, t_{q'}]$. (Note that, in equilibrium, a large number of commuters arrive at the bottleneck some time before the step toll is lifted. We will refer to these commuters as the "bulk" group.)

Socially Optimal Step Toll

The socially optimal step toll has been discussed at length elsewhere (*35*). Hence, we will present only a summary of their results. In particular, the socially optimal step toll can be characterized as follows:

$$\tau_{sc} = \frac{\beta\gamma}{\beta + \gamma}\frac{N_h}{2s_h} \tag{20}$$

$$t_q = t^* - \frac{\gamma}{\beta + \gamma}\frac{N_h}{s_h} + \frac{\gamma - \alpha}{(\beta + \gamma)(\alpha + \gamma)}\tau_{sc} \tag{21}$$

$$t^+ = t_q + \tau_{sc}/\beta \tag{22}$$

$$t^- = t_q + \frac{N_h}{s_h} - \frac{2\tau_{sc}}{\alpha + \gamma} \tag{23}$$

so that $R_{sc} = \tau_{sc}s_h(t^- - t^+)$ and $C_{sc} = \beta(t^* - t_q) - R_{sc}/N_h$.

Revenue Maximizing Step Toll

We now turn to the derivation of the revenue maximizing step toll to gain some insight into why the "timing" of the toll is important. Any given toll can lead to one of two possible traffic patterns. In the first, drivers pass through the bottleneck before, during, and after the toll period, whereas in the second, drivers pass through the bottleneck before and during the toll period only. We will denote the set of tolls that result in the first pattern by $\mathcal{S}_1$ and those that result in the second pattern by $\mathcal{S}_2$ and consider each separately below.

Traffic Pattern 1

We begin our derivation of the revenue maximizing toll in $\mathcal{S}_1$ by observing that this toll will never result in departures after the bulk group. With this in mind, it is relatively easy to derive the revenue maximizing toll. In particular, recall that the size of the bulk departure in equilibrium must be $(2s\tau)/(\alpha + \gamma)$ (*35*). Hence, it must be the case that the number of people exiting the queue between t^- and t_q is given by

$$s(t^- - t_q) = N_h - \frac{2s\tau}{\alpha + \gamma} \tag{24}$$

and hence that

$$(t^* - t_q) + (t^- - t^*) + \frac{2\tau^s}{\alpha + \gamma} = \frac{N_h}{s_h} \tag{25}$$

which further implies that

$$C_h = F_h + \beta \underbrace{\left[\frac{N_h}{s_h} - (t^- - t^*) - \frac{2\tau^s}{\alpha + \gamma}\right]}_{t^* - t_q} \tag{26}$$

Also, observe that several conditions must be satisfied for the toll to be in $\mathcal{S}_1$. First, commuters should not be deterred from passing through the toll booth right after the toll period begins. This implies that

$$\frac{\beta}{\alpha}(t^+ - t_q) - \frac{\tau}{\alpha} > 0 \tag{27}$$

Second, commuters should keep passing through the bottleneck until the very end of the toll period. This implies that

$$\frac{\beta}{\alpha}(t^* - t_q) - \frac{\tau}{\alpha} - \frac{\gamma}{\alpha}(t^- - t^*) > 0 \tag{28}$$

Finally, commuters should have no incentive to pass through the bottleneck after the bulk group. This implies that

$$\beta(t^* - t_q) < \gamma(t_{q'} - t^*) \tag{29}$$

Now, using Equation 25 and Equations 27 through 29 and letting $q = \beta(\gamma - \alpha)/[(\gamma + \alpha)(\gamma + \beta)]$, it can be shown that the revenue maximizing toll in $\mathcal{S}_1$ must satisfy the following conditions:

$$\frac{N_h}{s_h} > (t^- - t^+) + \frac{\tau}{\beta}\left(1 + \frac{2\beta}{\alpha + \gamma}\right) \tag{30}$$

$$\frac{\beta}{\beta + \gamma}\frac{N_h}{s_h} > (t^- - t^*) + \frac{\tau}{\gamma}(1 + q) \tag{31}$$

With these results, it is now relatively easy to show that the revenue maximizing toll within $\mathcal{S}_1$ must satisfy Equations 30 and 31 as equalities.

First, observe that C_h is independent of t^+. Thus N_h is independent of t^+. As a result, toll revenues are maximized when t^+ is set at the lower bound given in Equation 30.

Now, observe that, in general, $R = \tau s_h(t^- - t^+)$. Hence, for this subset of toll schemes we have

$$R = N_h\tau - \frac{s_h}{\beta}\left(1 + \frac{2\beta}{\alpha + \gamma}\right)\tau^2 \tag{32}$$

Further, it follows from Equation 26 and the equilibrium condition that N_h is an increasing function of t^-. Hence, for any given toll scheme with t^+ defined by Equation 30, toll revenues are maximized by setting t^- at its upper bound in Equation 31.

It thus follows that

$$(t^- - t^*) = \frac{\beta}{\beta + \gamma}\frac{N_h}{s_h} - \frac{\tau}{\beta}(1 + q) \tag{33}$$

and since $(t^* - t^+) = \gamma/\beta(t^- - t^*)$ in equilibrium, it must be the case that

$$t^* - t^+ = \frac{\gamma}{\beta + \gamma}\frac{N_h}{s_h} - \frac{\tau}{\beta}(1 + q) \tag{34}$$

To maximize toll revenues, we simply set

$$\tau_{\text{tr}}^{(1)} = \frac{1}{1 + q}\frac{\beta\gamma}{\beta + \gamma}\frac{N}{2s_h} \tag{35}$$

and

$$(t^* - t^+)_{\text{tr}} = \frac{\gamma}{\beta}(t^- - t^*)_{\text{tr}} = \frac{\gamma}{\gamma + \beta}\frac{N}{2s_h} \tag{36}$$

which means that

$$C_{\text{tr}}^{(1)} = F_h + \left(1 - \frac{q}{2(1 + q)}\right)\frac{\beta\gamma}{\beta + \gamma}\frac{N}{s_h} \tag{37}$$

and

$$R_{\text{tr}}^{(1)} = \frac{1}{1 + q}\frac{\beta\gamma}{\beta + \gamma}\frac{N^2}{4s_h} \tag{38}$$

Traffic Pattern 2

We now turn our attention to finding optimal toll schemes within the subset $\mathcal{S}_2$. In this case (i.e., when drivers exit the bottleneck before and during the toll period only), it is relatively easy to show that the equilibrium conditions imply that

$$t^* - t_q = \frac{\gamma}{\beta + \gamma}\frac{N_h}{s_h} + \frac{\tau}{\beta + \gamma} \tag{39}$$

$$t_{q'} - t^* = \frac{\beta}{\beta + \gamma}\frac{N_h}{s_h} - \frac{\tau}{\beta + \gamma} \tag{40}$$

$$C_h = F_h + \frac{\beta\gamma}{\beta + \gamma}\frac{N_h}{s_h} + \frac{\beta\tau}{\beta + \gamma} \tag{41}$$

In addition, several conditions must be satisfied by tolls in $\mathcal{S}_2$. First, commuters should not be deterred from passing through the toll booth right after the toll period begins. This implies that

$$t^* - t^+ < \frac{\gamma}{\beta + \gamma}\frac{N_h}{s_h} - \frac{\gamma}{\beta}\frac{\tau}{\beta + \gamma} \tag{42}$$

Second, no commuter should pass through the bottleneck after t^-. This implies that

$$t^- - t^* > t_{q'} - t^* \tag{43}$$

Hence, given that $t^* - t^+$, $t^+ - t_q$, and $t_{q'} - t^*$ must be positive, it follows that $\tau < \beta\ (N_h/s_h)$.

It is now easy to show that the revenue maximizing toll must satisfy Equation 42 as an equality. In particular, observe that toll revenues are given by

$$R = s_h\left[\underbrace{\left(\frac{\beta}{\beta + \gamma}\frac{N_h}{s_h} - \frac{\tau}{\beta + \gamma}\right)}_{t_{q'} - t^*} + (t^* - t^+)\right]\tau \tag{44}$$

Also, observe once again that C_h does not depend on t^+ and hence that N_h is independent of t^+. As a result, toll revenues are maximized only when t^+ is set at its lower bound (as given by Equation 42).

It then follows that

$$R = \tau\left(N - \frac{s_h}{\beta}\tau\right) \tag{45}$$

To maximize this expression, we set

$$\tau_{\text{tr}}^{(2)} = \beta\frac{N}{2s_h} \tag{46}$$

and

$$(t^* - t^+)_{\text{tr}} = \frac{\gamma}{\beta + \gamma}\frac{N_h}{2s_h} \tag{47}$$

where $(t^- - t^*)$ must be chosen in such a way that $(t^- - t^*)_{\text{tr}} > \beta/\beta + \gamma\ N_h/2s_h$. Hence, for this toll mechanism, we have

$$C_{\text{tr}}^{(2)} = F_h + \left(1 + \frac{\beta}{2\gamma}\right) \frac{\beta\gamma}{\beta + \gamma} \frac{N_h}{s_h} \tag{48}$$

and

$$R_{\text{tr}}^{(2)} = \beta \frac{N^2}{4s_h} \tag{49}$$

Comparison

When the toll must be set in such a way that commuters choose to exit the bottleneck before, during, and after the toll period we find that (using the same values of the parameters as above) switching to the revenue maximizing scheme leads to a 0.7 percent increase in toll revenues, an 8 percent drop in the level of the step toll, and an increase in the length of the toll period (as compared with the socially optimal toll). On the other hand, when the toll can be set in such a way that nobody departs after the end of the toll period, we find that switching to the revenue maximizing scheme leads to a 37 percent increase in toll revenues, a 25 percent increase in the level of the step toll, and an increase in the length of the toll period.

Hence, it seems that the additional revenues (and additional costs) generated by the revenue maximizing permanent toll (as compared with the socially optimal permanent toll) are, in large part, a result of the fact that commuters cannot depart after the end of the toll period. In situations in which commuters must be allowed to depart after the toll ends, there is much less difference between the revenue maximizing and socially optimal tolls.

CONCLUSION

Although these results are in no way intended to be conclusive, we believe they yield some interesting insights. Most important, they provide evidence that the different objectives of peak period pricing do "compete" in some situations.

In general, it appears that toll revenues can be increased substantially by changing toll policies. In fact, by experimenting with various values of the above parameters, we have found that the revenue maximizing toll results in an increase in toll revenues of between 20 and 50 percent over the socially optimal toll. However, this increase in revenues comes at great cost to commuters—each additional dollar of toll revenue costs society between $2.00 and $4.00.

The most substantial revenue gains can be realized by imposing a toll that cannot be avoided (i.e., either a toll that lasts throughout the entire day or a toll that ends so late in the day that nobody is inclined to depart after the toll period ends). Unfortunately, this is exactly the type of toll that most increases the cost to society. On the other hand, when the toll is set in such a way that commuters will choose to depart after the toll period ends, society does not suffer much if the revenue maximizing toll is imposed. Not surprisingly, however, very little additional revenue is generated in such situations.

In short, these models seem to provide some evidence that the length and end of the toll period, and not the value of the toll, has the biggest impact on both revenues and social costs. Hence, it is the length and end of the toll period that policy makers may find most tempting to change. Yet it is probably the value of the toll that the public will react to most strongly, at least in the short run. In practice this could result in a very interesting political dynamic.

Of course, much more work needs to be done before we can have any real confidence in these results. Most important, these results need to be extended to more general networks. We are hopeful that recent advances in dynamic network equilibrium modeling [see, for example, previously published works (*33,34*)] will make this possible. In addition, longer-run decisions, such as the decision to travel and the choice of destination, should also be included, as should nonwork trips. The results of these extensions will be reported in subsequent papers.

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