CONGESTION PRICING WITH LOSS-AVERSE DRIVERS

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1. Introduction

Nonrecurring traffic congestion accounts for half or more of travel delays in major urban areas. Using Advanced Traveler Information Systems and Electronic Toll Collection technology, congestion tolls can be varied to match traffic conditions. Dynamic, or responsive, pricing is now standard practice for selling airline seats and it has been selectively introduced for Internet, electricity and other services. But dynamic road pricing has only been implemented on a few High Occupancy Toll (HOT) lane facilities in the US. Indeed, most tolls do not even vary according to a schedule but are constant over time.[2]

One explanation for the dearth of dynamic road pricing is that the infrastructure and operating costs are too high for it to be cost-effective (Levinson and Odlyzko, 2008). Another is that drivers have difficulty understanding complex pricing schemes (Bonsall et al., 2007). A third is that people may not learn tolls far enough in advance for them to alter their travel decisions.

This paper examines a fourth possible explanation: drivers dislike uncertainty about how much they will pay. According to standard consumer theory people are approximately risk-neutral with respect to small monetary outlays. Yet there is now a large body of laboratory

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[2] See http://www.tollroadsnews.com/node/3975 [February 11, 2009].

and other evidence that people suffer monetary losses more than they value gains of an equal amount even for stakes of just a few dollars. People can also be antagonized by price hikes that seem unfair — especially if they are not clearly justified by increases in supplier costs (Kahneman et al., 1986; Frey and Pommerehne, 1993).[3]

To formalize these ideas the paper employs a model of reference-dependent preferences due to Kőszegi and Rabin (2006). Individuals are assumed to be loss averse with respect to changes in travel costs and the toll they pay. Section 2 describes the model and derives individual behaviour. Section 3 derives optimal tolls, and Section 4 presents a numerical example. Section 5 summarizes the main results and identifies directions for future research.[4]

2. The Model

Consider a road on which travel conditions vary due to weather, accidents, special events or other shocks. The user cost of a trip in state w is $c_w(N_w)$ where N_w is total usage. The full price or generalized cost of a trip is $p_w = c_w + \tau_w$ where τ_w is the toll in state w.[5] The gross utility from using the road, V, varies from person to person but is independent of w. Utility from not using the road is normalized to zero.

To fix ideas and facilitate analysis, it is assumed that the period of usage is a day and there are just two states: *Good* days (w=G) and *Bad* days (w=B) with respective probabilities $1-\pi$ and π. *Good* days are preferred to *Bad* days in the sense that $c_G < c_B$ and $p_G < p_B$ in

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[3] As Vickrey (1971, p.346) remarked, "[T]he main difficulty with responsive pricing is likely to be not mechanical or economic, but political. The medieval notion of the just price as an ethical norm, with its implication that the price of a commodity or service that is nominally in some sense the same should not vary according to the circumstances of the moment, has a strong appeal even today."

[4] This paper draws on a longer and more general study. Due to space constraints various aspects of the model and much of the analytical details are omitted.

[5] To simplify notation, the dependence of c_w on N_w will be suppressed.

equilibrium. Individuals learn whether a day is *Good* or *Bad* and then decide whether to use the road.

Following Kőszegi and Rabin (2006), individual utility in each state has two components. The first component is "intrinsic utility" of $V - p_w$. The second is "gain-loss utility" which is evaluated relative to a reference point. In Kőszegi and Rabin's model the reference point is the lottery of possible outcomes conditional on the individual's decisions. For someone who takes the road in both states, the reference point is a lottery that yields intrinsic utility $V - p_G$ on *Good* days and $V - p_B$ on *Bad* days. For someone who only uses the road on *Good* days, the lottery yields an intrinsic utility of $V - p_G$ on *Good* days and zero on *Bad* days. And for someone who never uses the road, the reference point has a utility of zero. An individual reaches a "personal equilibrium" if his/her decisions are optimal conditional on the reference point lottery that stems from his/her decisions.

A focal question of the paper is whether individuals perceive gains and losses with respect to the user cost they incur and the toll they pay separately or together. Kőszegi and Rabin (2006) assume that people perceive gains and losses separately for each commodity in their consumption bundle. In the model here, where c_w and τ_w are stochastic but *V* is deterministic, this is equivalent to assuming that gains and losses are felt separately for the benefit from a trip before paying the toll, $V - c_w$, and the (dis)utility from the toll, $-\tau_w$. If, instead, people "mentally integrate" the user cost and the toll, they perceive gains and losses only with respect to the overall surplus, $V - c_w - \tau_w = V - p_w$.

Empirical evidence is mixed on whether gains and losses for goods and money are perceived separately or together, and the matter remains unsettled (Bateman *et al.*, 2005). The question has received little attention in the transportation literature[6] and it is reasonable to

[6] See De Borger and Fosgerau (2008) for a recent study in the context of valuing travel time. Econometric studies of HOT lane usage (e.g., Brownstone et al., 2003; Small et

entertain both possibilities. In both cases gain/loss utility is captured by a function $\mu(\ )$. Kőszegi and Rabin (2006) consider a piecewise linear function (their Assumption A3) that is adopted here:

(1) $$\mu(x)=\begin{cases}\eta x & for\ \ x\geq 0\\ \eta\lambda x & for\ \ x\leq 0\end{cases},\quad \eta>0,\ \lambda>1.$$

The assumption $\lambda>1$ embodies loss aversion in the sense that losses are weighted more heavily than gains. The possibility that gains and losses are mentally integrated or "bundled" is analyzed first.

Individual choices with bundled preferences

To begin, consider someone who uses the road in both states. Utility on a *Good* day from deciding to use the road (denoted *Y*, for yes) given a decision to use it in both states (*YY*) is given by

(2) $$\begin{aligned}U_G(Y\mid YY)&=\underbrace{V-p_G}_{(a)}+(1-\pi)\underbrace{\mu\left(V-p_G-(V-p_G)\right)}_{(b)=0}\\&+\pi\underbrace{\mu\left(V-p_G-(V-p_B)\right)}_{(c)>0}\end{aligned}.$$

Term (a) in Eq. (2) is the intrinsic utility from taking the road. Term (b) is gain/loss utility from taking the road relative to taking it on a *Good* day. Since $\mu(0)=0$, term (b) is zero. Term (c) is gain/loss utility from taking the road on a *Good* day compared to taking it on a *Bad* day. Since $p_G<p_B$, term (c) is positive. It reflects "elation" from using the road on a *Good* day rather than a *Bad* one. Term (c) is weighted by the proportion, π, of days that are *Bad*. Using Eq. (1), Eq. (2) simplifies to

(3a) $$U_G(Y\mid YY)=V-p_G+\pi\eta(p_B-p_G).$$

Utility from using the road on a *Bad* day is derived in the same way; it works out to

(3b) $$U_B(Y\mid YY)=V-p_B-(1-\pi)\eta(p_B-p_G).$$

Gain/loss utility in Eq. (3b) is negative. It reflects "disappointment" from using the road on a *Bad* day rather than a *Good* one.

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al., 2005) have assumed that utility is a linear function of the toll, and therefore do not provide evidence on attitudes towards toll variation.

Using the road in both states is a "personal equilibrium" if and only if utility would be lower from deciding not to use it given the reference point *YY*. This utility is the same in each state and equal to

$$U_G(N \mid YY) = U_B(N \mid YY) = \underbrace{0}_{(a)} + (1-\pi)\underbrace{\mu\left(0-(V-p_G)\right)}_{(b)} \tag{4}$$
$$+\pi \underbrace{\mu\left(0-(V-p_B)\right)}_{(c)} = -(1-\pi)(V-p_G) - \pi(V-p_B)\ .$$

Term (a) in Eq. (4) is intrinsic utility from not taking the road, term (b) is regret from not taking it on a *Good* day, and term (c) is regret from not taking it on a *Bad* day. Since $U_B(Y \mid YY) < U_G(Y \mid YY)$, using the road in both states is a personal equilibrium if and only if $U_B(Y \mid YY) \geq U_B(N \mid YY)$, a condition which simplifies to

$$V \geq c_B + \tau_B \equiv V_B\ . \tag{5}$$

By similar reasoning, a decision to use the road only on *Good* days (denoted *YN*) yields a utility on *Good* days of

$$U_G(Y \mid YN) = (1+\pi\eta)(V-p_G)\ , \tag{6a}$$

and a utility on *Bad* days of

$$U_B(N \mid YN) = -(1-\pi)\eta\lambda(V-p_G)\ . \tag{6b}$$

It is easy to show that *YN* is a personal equilibrium if and only if

$$V < V_B\ , \text{ and } V \geq c_G + \tau_G \equiv V_G\ . \tag{7}$$

Finally, never using the road (denoted *NN*) yields a utility of zero. It is a personal equilibrium if and only if

$$V < V_G\ . \tag{8}$$

Conditions (5), (7) and (8) are mutually exclusive and collectively exhaustive so that each individual has a unique personal equilibrium. Since conditions (5), (7) and (8) do not depend on parameters η and λ, the personal equilibrium is the same as without reference-dependent preferences. However, as shown in Section 3 reference-dependent preferences do affect optimal tolling policy.

Individual choices with unbundled preferences
Analysis of unbundled preferences is more tedious than for bundled preferences. Utility from taking the road in both states is still given by Eq. (3a,b) but the other expressions are more complicated. Necessary and sufficient conditions for personal equilibrium work out as follows:

— for using the road in both states (*YY*):

$$V \geq c_B + \frac{1+\eta\left(\pi+(1-\pi)\lambda\right)}{1+\eta\lambda}\tau_B - \frac{(1-\pi)\eta(\lambda-1)}{1+\eta\lambda}\tau_G \equiv V_B^{YY}, \tag{9}$$

— for using the road only on *Good* days (*YN*):

$$\begin{aligned} V &< c_B + \frac{1+\eta\lambda}{1+\eta\left(\pi+(1-\pi)\lambda\right)}\tau_B - \frac{(1-\pi)\eta(\lambda-1)}{1+\eta\left(\pi+(1-\pi)\lambda\right)}\tau_G \equiv V_B^{YN}, \\ V &\geq c_G + \frac{1+\eta\left(1+\pi(\lambda-1)\right)}{1+\eta\left(\pi+(1-\pi)\lambda\right)}\tau_G \equiv V_G^{YN} \end{aligned} \tag{10}$$

— for never using the road (*NN*):

$$V < c_G + \frac{1+\eta\lambda}{1+\eta}\tau_G \equiv V_G^{NN}. \tag{11}$$

Condition (9) is less stringent than condition (5) since $V_B^{YY} < V_B$, and condition (11) is less stringent than condition (8) since $\lambda > 1$. Moreover, $V_B^{YY} < V_B^{YN}$ and $V_G^{YN} < V_G^{NN}$. This implies that for certain values of *V* there are multiple personal equilibria. As Kőszegi and Rabin (2006) point out, multiple equilibria are a generic characteristic of their model. In the model here this is because when people are loss averse separately with respect to user costs and the toll, they are resistant to change (i.e., biased towards the status quo), and candidate equilibria are more robust to deviations.

To keep the analysis manageable it is assumed that a personal equilibrium of type *NN* prevails over equilibria of types *YN* and *YY*, and a personal equilibrium of type *YN* prevails over one of type *YY*.

Attention is thus restricted to unique personal equilibria that result in lower aggregate usage than alternative equilibria.[7]

3. Optimal Tolls

Optimal tolls for *Good* and *Bad* days are now derived for bundled and unbundled preferences. The objective function is taken to be expected welfare: the sum of aggregate expected utility and expected toll revenue. The distribution of V in the population of potential road users is described by a finite density function $h(V)$.

Tolls with bundled preferences

Aggregate expected utility with bundled preferences is derived by dividing individuals into three groups defined by the threshold values V_B in Eq. (5) and V_G in Eq. (7):

- those with $V < V_G$ who never use the road and get zero utility,
- those with $V \in [V_G, V_B)$ who use the road only on *Good* days and get utilities on *Good* and *Bad* days specified in Eq. (6a,b), and
- those with $V \geq V_B$ who use the road regularly and get utilities on *Good* and *Bad* days specified in Eq. (3a,b).

Expected welfare is therefore

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\begin{aligned}
E \bullet W = {} & \int_{V=V_G}^{V_B} \left[\begin{array}{l} (1-\pi)(V - c_G - \tau_G) \\ -\pi(1-\pi)\eta(\lambda-1)\left(\underbrace{V - c_G - \tau_G}_{(*)} \right) \end{array} \right] h(V)\, dV \\
& + \int_{V=V_B}^{\infty} \left[\begin{array}{l} (1-\pi)(V - c_G - \tau_G) + \pi(V - c_B - \tau_B) \\ -\pi(1-\pi)\eta(\lambda-1)(c_B + \tau_B - c_G - \tau_G) \end{array} \right] h(V)\, dV \\
& + (1-\pi)\tau_G N_G + \pi \tau_B N_B
\end{aligned}
\qquad (12)
$$

The first line of Eq. (12) denotes aggregate expected utility for those who use the road only on *Good* days; it is written in a way that

[7] This assumption can be defended on the grounds that not using the road is the status quo before the toll road is built.

facilitates later comparison with unbundled preferences. The second line denotes aggregate expected utility of those who use the road in both states. And the third line specifies expected toll revenues. Optimal tolls are derived by differentiating $E \bullet W$ with respect to τ_G and τ_B; they work out to:

(13a) $$\tau_G = \underbrace{\frac{\partial C_G(N_G)}{\partial N_G} N_G}_{(a)} + \underbrace{\frac{\pi\eta(\lambda-1)N_G}{h(V_G)}}_{(b)},$$

(13b) $$\tau_B = \underbrace{\frac{\partial C_B(N_B)}{\partial N_B} N_B}_{(c)} - \underbrace{\frac{(1-\pi)\eta(\lambda-1)N_B}{h(V_B)}}_{(d)}.$$

Terms (a) and (c) are the standard Pigovian tolls. Terms (b) and (d) make adjustments for reference-dependent preferences. Term (b) is positive, and term (d) is negative. The toll on *Good* days is therefore raised above the Pigouvian toll, and the toll on *Bad* days is set below it. The size of each adjustment is proportional to the strength of reference-dependent preferences (measured by η), and the degree of loss aversion (measured by $\lambda-1$). Adjusting tolls in this way brings generalized costs on *Good* days and *Bad* days closer together, and therefore reduces the degree of disappointment experienced on *Bad* days. This provides a sort of insurance against especially bad travel conditions.[8] If $\eta(\lambda-1)$ is large enough it is possible to have $\tau_G > \tau_B$.

Tolls with unbundled preferences

Expected welfare with unbundled preferences is derived in the same way as for bundled preferences. The expression differs from Eq. (12) in two respects. First, V_G and V_B in the limits of the integrals are replaced by V_G^{NN} and V_B^{YN}. Second, for individuals who only use the

[8] As a possible example, Mayor Boris Johnson suspended the £8 London congestion charge during a bad snow storm in early February, 2009 (http://edition.cnn.com/2009/WORLD/europe/02/02/europe.snow/index.html). However, in the model p_G cannot exceed p_B since the direction of losses would then be reversed.

road on *Good* days the term $V - c_G - \tau_G$ identified by the (*) is replaced by $V - c_G + \tau_G$. To see why, note that on *Good* days these individuals perceive a gain of $V - c_G$, and a loss of τ_G. On *Bad* days they perceive a loss of $V - c_G$, and a gain of τ_G.[9] Because losses weigh more heavily than gains, they experience a net loss proportional to the sum of $V - c_G$ and τ_G. (By contrast, with bundled preferences the net loss is perceived on overall surplus, $V - c_G - \tau_G$, which is a decreasing function of τ_G.) This creates an incentive to reduce τ_G which pulls in the opposite direction to the incentive — noted with respect to bundled preferences — to reduce the spread in generalized costs between *Good* and *Bad* days by increasing τ_G. As a consequence, formulae for the optimal tolls are more complicated than Eqs. (13a,b) and it is not possible to rank the tolls relative to their Pigouvian counterparts without further assumptions. To explore a little further, a numerical example is examined in the next section.

4. A numerical example

To facilitate calculation and interpretation a linear example is adopted with values measured in dollars. User cost is a linear function of aggregate usage with a higher slope on *Bad* days: $c_G = 8 + N_G / 3000$ and $c_B = 8 + N_B / 1500$. The probability of a *Bad* day is set to $\pi = 0.2$. And $h(V)$ is uniformly distributed over the interval $[0, 36]$ with a density of 500.

There is little evidence to draw on in choosing values of η and λ. The importance of reference-dependent preferences will depend on whether travel conditions are affected by demand or supply shocks, on how much experience people have in using the road and so on. In a theoretical paper, Laciana and Weber (2008) make the "somewhat arbitrary assumption" (p.10) that gain-loss utility does not exceed 10% of intrinsic utility. This is equivalent to assuming $\eta \le 0.1$ here.

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[9] τ_G is perceived as a gain because the toll is not paid on *Bad* days.

By contrast, Rotemberg (2008) uses an example with parameters equivalent to $\eta = 1$. As far as the loss aversion parameter, values for λ of 2 and up have been estimated, or assumed, in various studies. To be conservative, λ is set equal to 2 here and solutions are calculated for a range of values of η starting at zero.

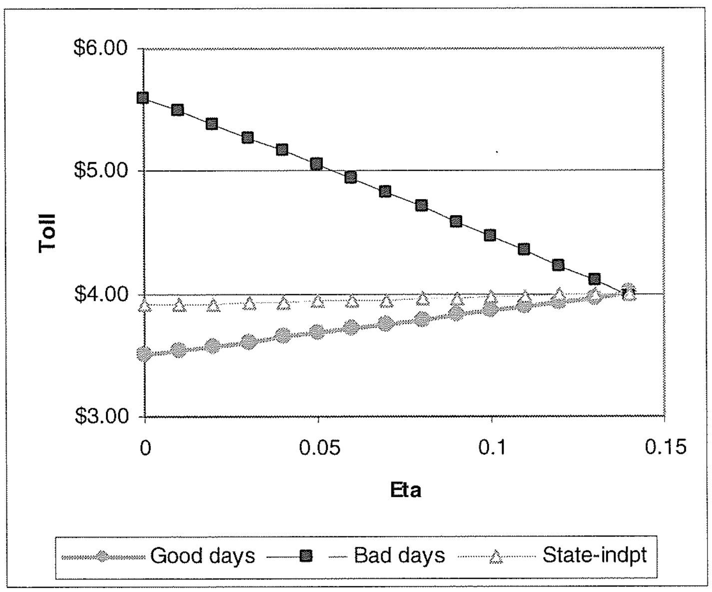

Figure 1: Optimal tolls with bundled preferences

Optimal tolls for bundled preferences are shown in Figure 1. With $\eta = 0$, the tolls are τ_G =\$3.50 and τ_B =\$5.60. Consistent with Eqs. (13a,b), the gap between the tolls narrows as η rises, and with $\eta \cong 0.14$ the tolls converge at about \$4.00. Thus, when gain-loss utility amounts to just one seventh of intrinsic utility it is optimal to set the same toll in each state and the tolls are no longer responsive. This is confirmed by plotting the optimal state-independent toll in

Figure 1. The toll is a weighted average of τ_G and τ_B, and thus coincides with the two tolls at the point where they converge.

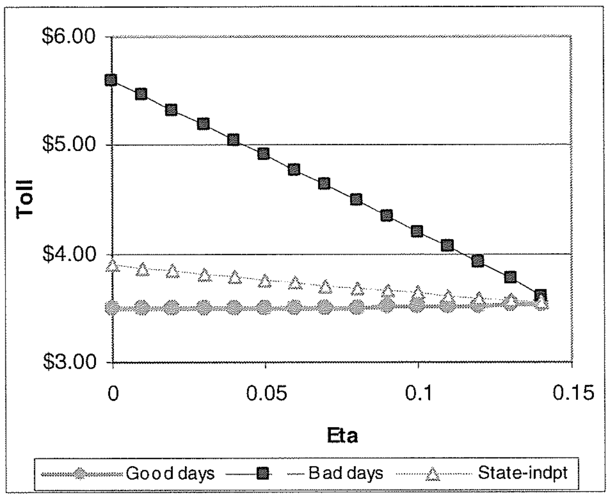

Figure 2: Optimal tolls with unbundled preferences

Optimal tolls for unbundled preferences are shown in Figure 2. The tolls again move towards each other as η increases, and they converge at about the same value of η as with bundled preferences. However, τ_G declines more steeply and the common toll ends up at \$3.55 rather than \$4.00. As explained in Section 3, this is due to the greater loss aversion with respect to τ_G that users perceive when preferences are unbundled.

5. Conclusions and directions for future research

The principles of social marginal cost pricing suggest that road tolls should be based on current driving conditions. Yet to date, responsive pricing has only been implemented on a few High Occupancy Toll (HOT) lanes in the US. Tolls are adjusted to maintain free-flow conditions on the HOT lanes and are posted at the entrance. Motorists can decide at the last minute whether to use the HOT lanes or take the toll-free lanes that run in parallel a few meters away. HOT lanes receive high public approval ratings. Responsive pricing may be less readily accepted for other types of road-pricing schemes such as cordons where it is difficult, or impossible, for motorists to avoid paying tolls when they are high.

To analyze aversion to responsive pricing this paper adopts a model of reference-dependent preferences. The benefit from taking a trip has two components: an "intrinsic" utility and a "gain-loss" utility measured relative to the probability distribution over states of utility outcomes. Individuals decide whether or not to drive in each state. Two types of reference-dependent preferences are analyzed: *bundled* preferences in which drivers perceive gain/loss with respect to generalized trip costs, and *unbundled* preferences in which they perceive gains and losses for user costs and tolls separately.

Individual choices and optimal tolls are derived for a simple setting with two states called *Good* days and *Bad* days. With bundled preferences the toll pattern is clear-cut: on *Good* days the toll is set above the benchmark Pigouvian toll, and on *Bad* days the toll is set below it. Adjusting tolls in this way reduces variability in generalized costs and hence the magnitude of gains and losses. With unbundled preferences the pattern is less transparent. A numerical example suggests that with both types of preferences the difference between *Good*-day and *Bad*-day tolls decreases with the strength of reference-dependent preferences. Indeed, when the weight on "gain-loss" utility reaches a modest fraction of the weight on intrinsic utility, *Good*-day and *Bad*-day tolls converge and state-independent tolling is optimal.

The analysis in this paper is preliminary and could be extended in several directions. A limiting feature of the model is the assumption that individuals are perfectly informed about travel conditions when they make their trip decisions.[10] Responsive pricing is ineffective, of

[10] An advantage of this assumption is that the model is applicable not only to stochastic fluctuations in travel conditions, but also to predictable, recurring

course, if users know nothing more than the unconditional probability distribution of states. But users may have access to imperfect information such as regional weather reports or news bulletins about accidents. An interesting aspect of HOT lane facilities is that drivers do not know the extent of congestion on the toll-free lanes when they have to make a lane choice. On facilities with dynamically set tolls drivers appear to use tolls as an indicator of congestion, and increase usage when tolls are higher than normal (Brownstone *et al.*, 2003). This illustrates a general point that responsive pricing can convey information. Nevertheless, in many choice situations there will be a many-to-one correspondence between states and tolls so that the state cannot be perfectly inferred from the toll.

In Kőszegi and Rabin's (2006) model the reference point is the complete lottery of possible outcomes that an individual may experience. This is plausible for the variant of the model studied here with just two states, but it sits less easily if there are many states. Alternative specifications of the reference point have been proposed in the literature. Gul (1991) uses the certainty equivalent of a lottery. Grant and Kajii (1998) use the best outcome. And Sugden (2003) assumes that outcomes are compared with the reference lottery state by state rather than with the whole lottery.

One important empirical observation is that the intensity of gain-loss preferences tends to decline with experience (e.g. List, 2003). Indeed, as noted at the beginning of the paper dynamic pricing is now accepted practice for commodities such as airline seats. Still, adaptation is likely to take time and infrequent users may never become fully acclimatized. Adaptation can be added to the model by classifying users as experienced or inexperienced, and assigning experienced users a smaller η than inexperienced ones.

The fact that people adapt to experience reflects one of the lessons of behavioral economics that preferences are not immutable. This has

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fluctuations in travel conditions such as morning and evening rush hours or seasonal peaks in tourist traffic. The model applies to deterministic peak-load pricing if π is interpreted to be the fraction of time that peak-period conditions apply.

raised the question whether gain-loss utility should be included in the welfare function at all. The question is under debate.[11] One could argue that tolls should be set responsively at their Pigouvian levels (i.e., based only on intrinsic preferences) since once people have adapted, the tolls will be optimal given their actual preferences. The need to periodically adjust tolls as people gradually adapt would be avoided. However, tolls may not be implemented at all unless people accept them. Models with reference-dependent preferences may help in designing responsive tolling schemes that can clear this initial acceptability hurdle.

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[11] See, for example, Kahneman and Sugden (2005) and Bernheim and Rangel (2007).

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