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6 **THE FINANCING OF NEW HIGHWAYS:**  
7 **OPPORTUNITIES FOR WELFARE ANALYSIS AND CREDIT-BASED CONGESTION**  
8 **PRICING**

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24  
25 To be presented at the 88<sup>th</sup> Annual Meeting of the Transportation Research Board

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27 **Key Words:** highway investment, congestion pricing, welfare analysis, optimal tolls

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29 **ABSTRACT**

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31 Pricing of roadways opens doors for infrastructure financing, and congestion pricing seeks to  
32 address inefficiencies in roadway operations. This paper takes a cost-benefit approach to  
33 illuminate how the costs of infrastructure can be offset via pricing, while ascertaining the welfare  
34 impacts of flat-toll, standard congestion pricing, and credit-based congestion pricing policies.  
35 While most roadway investment decisions focus on travel time savings for existing trips, this  
36 work turns to logsum differences (which quantify changes in consumer surplus) for nested logit  
37 specifications across two traveler types, two destinations, three modes and three times of day, in  
38 order to arrive at welfare- and revenue-maximizing solutions. This behavioral specification is  
39 quite flexible, and facilitates benefit-cost calculations (as well as equity analysis), as  
40 demonstrated in this paper.

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42 The various cases examined suggest significant opportunities for financing new roadway  
43 investment while addressing congestion and equity issues, with net gains for both traveler types.  
44 Application results illustrate how, even after roadway construction and maintenance costs are  
45 covered, receipts may remain to distribute to eligible travelers so that typical travelers can be  
46 made better off than if a new, non-tolled road had been constructed. Moreover, tolling both  
47 routes (new and old) results in substantially shorter payback periods (5 vs. 20 years) and higher  
48 welfare outcomes (in the case of welfare-maximizing tolls with credit distributions to all  
49 travelers). The tools and techniques highlighted here illustrate practical methods for identifying

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3 welfare-enhancing and cost-recovering investment opportunities, while recognizing multiple user  
4 classes and appropriate demand elasticity across times of day, destinations, modes and routes.  
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## 6 **INTRODUCTION**

7 Reliable and efficient transport is an essential ingredient in the economic prosperity of regions  
8 and countries. Traffic congestion hinders the movement of people and goods, but is on the rise,  
9 due to increases in population, and overall travel demand regularly outstripping system additions.  
10 Funding for capacity expansion and roadway maintenance through traditional means is limited,  
11 resulting in a quest for relatively innovative methods to finance new roads. While the use of tolls  
12 to generate such funding is not a new idea, toll financing is becoming an increasingly important  
13 option (USDOT 2005, U.S. GAO 2006, Samuel 2007).  
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15 The basic theories behind policies of roadspace rationing, optimal taxation, and congestion  
16 pricing are nothing new either. (See, e.g., Pigou 1920, Knight 1924, and Vickrey 1963.) As with  
17 consumption of scarce resources, the congestion of capacity-constrained infrastructure leads  
18 naturally to higher prices, in the presence of private markets, guided by an invisible hand.  
19 Whether the infrastructure consists of hotel rooms, aircraft, telephone lines, movie theatres, or  
20 roadways, the marginal costs of facility expansion are optimally borne by those who most benefit  
21 from the marginal investment. In most cases, there are many potential customers with high  
22 values of time who are willing to pay a premium in order to moderate (and/or eliminate) travel  
23 delays.

24 Here, a policy of credit-based congestion pricing (CBCP) is featured, and compared to other, toll  
25 and no-toll options, in the context of roadway financing. As proposed by Kockelman and  
26 Kalmanje (2005), CBCP is a revenue-neutral strategy that seeks to overcome the negative equity  
27 impacts of congestion pricing (CP) by allocating toll budgets to eligible travelers periodically. In  
28 its most basic form, the “average” driver pays nothing, while frequent, long-distance, peak-  
29 period drivers subsidize others, in effect paying them to stay off congested roads (or switch to  
30 less congesting modes, such as the bus). However, in the context of financing new capacity,  
31 opportunities for CBCP credits may be exhausted by infrastructure costs. This work offers a  
32 closer look at policy options and implications in a small network example in which demand  
33 elasticity across destinations, modes, times of day, and routes are recognized in a behaviorally  
34 consistent and rigorous way, via a four-level nested logit model structure. Such specifications  
35 allow more realism and flexibility in the choice process than most existing road-pricing work,  
36 which neglects opportunities for substituting destinations, and/or routes, modes, and times of day  
37 for travel.  
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## 39 **RELATED LITERATURE**

40 As evident in the work of countless transport economists (see, e.g., Walters [1961], Vickrey  
41 [1969], Arnott et al. [1994], Verhoef [2000], and Small and Verhoef [2007]), marginal social  
42 cost (MSC) pricing should be very effective in reducing (recurrent) congestion. MSC toll levels  
43 ensure that each traveler pays a cost equal to the cost of the added delay that he/she imposes on  
44 other road users (i.e., the marginal *external* cost of congestion). When MSC tolls are applied on  
45 all network links and modes, the socially optimal, or “first-best”, solution is achieved (Small and  
46 Verhoef 2007). Moreover, there is typically a rather simple analytic solution for finding the  
47 socially optimal tolls on each network link if one is dealing with rather standard link cost  
48 functions such as the Bureau of Public Roads (BPR) link performance function. (See, e.g., Small  
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3 and Verhoef 2007.) Of course, there are numerous reasons that make the “first-best” solution  
4 infeasible from a practical sense (e.g., it may be infeasible to toll all links or it may be infeasible  
5 to differentiate tolls across users with differing values of travel time, to name a couple), and  
6 much literature has been devoted to the formulation of “second-best” pricing strategies (see e.g.,  
7 Levy-Lambert 1968, Marchand 1968, Verhoef et al. 1996, Arnott and Yan 2000, Verhoef 2002a  
8 and 2002b, among many others). As expected, a key result is that “second-best” tolls differ from  
9 “first-best” tolls (Verhoef 2002b).

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11 Several studies have investigated roadway financing through tolls. Mohring and Harwitz (1962)  
12 showed that under certain conditions, priced roads could be self-financing. Verhoef and  
13 Rouwendal (2004) extended this result for a small network example, illustrating that optimal  
14 capacity choices throughout a network (assuming equal capacity provision costs anywhere in the  
15 network) result in constant optimal toll rates (throughout the network). Verhoef (2007) showed  
16 that the socially optimal road could be built and managed through a bidding process involving  
17 private firms.

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19 Despite the evident merits of roadway pricing, public and political opposition to pricing policies  
20 can be intense, for a number of reasons. The public often perceives tolls as a new tax on  
21 something that has always been free or paid for at the pump (Kockelman et al. 2006). Further,  
22 issues of social (in)equity can be very important to the public (U.S. GAO 2006), since not all are  
23 willing or able to pay the tolls that would emerge under potential policies. In particularly  
24 congested corridors (e.g., heavily used bridges and other key bottlenecks), tolls could quickly  
25 rise to \$1 USD or more per mile of vehicle travel<sup>1</sup>. Equity considerations may take center-stage  
26 in related policy debates. The distributed burdens and benefits of congestion pricing make  
27 regressive outcomes a key drawback. Researchers have suggested different solutions to  
28 overcome this, including commuter credits (Small, 1992), income tax reduction (Parry and  
29 Bento, 2001), FAIR lanes (DeCorla-Souza, 1995), roadspace rationing (Daganzo, 1995,  
30 Nakamura and Kockelman 2002), and providing ‘mobility rights’ (Viegas, 2001) to name a few.  
31 As noted earlier, Kockelman and Kalmanje (2005) proposed a somewhat different solution,  
32 called credit-based congestion pricing (CBCP).

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34 Kalmanje and Kockelman (2004) examined the traffic and traveler-welfare impacts of an Austin,  
35 Texas application. And Gulipalli and Kockelman (2008) conducted a similar study for the  
36 Dallas-Fort Worth Metroplex, which also closely examined implementation costs and vehicular  
37 emissions. Their models of travel behavior segmented the typical workday into five times of  
38 day, using static traffic assignment during those periods. In both cases, two MSC tolling systems  
39 were examined: pricing of the entire network (by time of day, in accordance with marginal social  
40 costs, under a single assumed value of travel time), and pricing only of major highways  
41 (primarily freeways). Short- and long-term scenarios were examined, holding job locations  
42 (work trips) fixed at no-pricing levels and then allowing those to vary, along with destination  
43 choices of all other trip types. Measures of equivalent variation for welfare changes pre- and  
44 post-pricing were examined, in order to ascertain the spatial and demographic distribution of  
45 benefits. As expected, speed improvements were substantial, as travelers shifted destination,  
46 mode, route and time of day choices. The analyses resulted in positive estimates of net benefits

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49 <sup>1</sup> Marginal costs of \$1 per mile or more emerge when using standard BPR parameter values in instances where  
50 demand-to-capacity ratios lie above 1.0 and values of time are on the order of \$10 per vehicle-hour (or more).  
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3 (net of implementation costs) for the great majority of residents (95% of budget-eligible<sup>2</sup>  
4 travelers in the DFW study<sup>3</sup>). In order to estimate these net benefits, money-scaled differences  
5 in logsums were used. As per Small and Rosen (1981) and Ben-Akiva and Lerman (1985), these  
6 represent measures of equivalent variation (in other words, the equivalent income effect of a  
7 switch to marginal-cost roadway pricing). Such values are computed after a uniform credit  
8 distribution to all registered vehicle owners or all workers (both representing two-thirds of the  
9 population). And they apply to the “average” traveler (which spanned 6 household classes, on  
10 the basis of income and vehicle ownership, in the DFW case). However, pricing at marginal  
11 social cost is not optimal when other, related goods are not priced similarly. Thus, in the case of  
12 major-highway-only pricing, many substitute routes are non-tolled, so MSC pricing is sub-  
13 optimal. Lower toll levels would be more appropriate in such instances, and more benefits may  
14 emerge. (See, e.g., Dial [1999] and Penchina [2003].)

15  
16 While marginal-cost pricing should be effective in reducing congestion, its value for raising  
17 infrastructure funds in non-urban areas and addressing other issues (such as greenhouse gas  
18 emissions) is not so clear. Of course, using the same electronic toll collection (ETC) systems  
19 that would be required for such pricing, one may rather easily incentivize the use of more fuel  
20 efficient vehicles with lower emissions. Two key questions then emerge: What are the costs of  
21 tolling infrastructure in this way, and what toll rates and credit levels are appropriate?

22 Kockelman et al. (2005) concluded that RFID toll tags are the best toll technology for the near  
23 term, allowing local pricing of road use<sup>4</sup>. As summarized in Gulipalli and Kockelman (2008),  
24 the present cost of RFID transponder stickers lies at and/or below \$1 per user. When  
25 permanently attached to one’s vehicle, stickers of this type allow operators to identify vehicles,  
26 enabling pricing of emissions and other negative externalities. Though offering fewer anonymity  
27 protections, such permanent tags are popular for toll administration, serving as the standard  
28 option for residents of the Austin, DFW, and Houston regions. Of course, roadside readers and  
29 gantry systems (to hang video cameras and readers), vehicle-classification curtains, and other  
30 system components are not inexpensive. Nevertheless, they represent a one-time cost. Over a  
31 system’s lifetime, Gulipalli and Kockelman (2008) predicted these to be small in comparison to  
32 observed system administration costs, which average \$100,000 USD per lane-mile in current  
33 U.S. systems. Such costs are likely to fall over time, thanks to growing experience and  
34 technological innovations (e.g., paperless billing and more robust reader systems).

## 35 36 **METHODOLOGY**

37 While urban-system analyses, such as the Austin and DFW case studies described above, are  
38 very useful – and complex, they can obscure salient features of the policy under question, and  
39 they require second-best solutions: finding optimal toll levels in such system-level analyses is  
40 not feasible if some roads or modes are not tolled or otherwise imperfectly priced and multiple  
41 user classes exist. To illuminate key features of a CBCP policy in the context of road financing,  
42 an example of multiple alternatives for travel between a single origin and two destinations is  
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44 <sup>2</sup> In Gulipalli and Kockelman’s (2008) analysis, budget eligibility was based on vehicle registrations, so 70% of the  
45 region’s 3 million residents were assigned credits.

46 <sup>3</sup> Implementation costs were not examined in the earlier, Austin study, and so were not applied. With a zero-  
47 implementation-cost assumption, virtually all “average” travelers in the Austin study were predicted to benefit under  
48 such a policy. In reality, implementation costs would reduce credit levels, and great heterogeneity exists in any  
49 regional population, resulting in significant benefits for some, and no doubt significant costs for others.

50 <sup>4</sup> In the longer term, global positioning system (GPS) technology may be best.  
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used here. The alternatives include the choice of destination, mode (auto, bus, or walk), time-of-day (AM peak, PM peak, and off-peak), and route. Figure 1 details the layout of this idealized network. Such choice flexibility is a key difference between the methods used here and those applied in most prior pricing research (both first- and second-best related pricing). While some prior work considers elasticity in demand functions between given zone pairs (e.g., Maruyama and Sumalee 2007), most studies consider only route choice (e.g., Braid 1996, Dial 1999, Liu and McDonald 1999, and Penchina 2003). Recognition of destination choice is a major piece of the behavioral puzzle, and it allows for very natural (in that it fits into the framework of random utility maximization) elasticity effects in trip generation, avoiding a presumption of fixed trip tables. Of course, there are examples where such choice flexibility has been used in welfare analyses (see, e.g., Kalmanje and Kockelman 2004 and de Jong et al. 2007), but these studies focus on the welfare analysis rather than optimal toll levels.

Using a nested logit specification (see, e.g., Ben-Akiva and Lerman 1985), so that clusters of similar options exhibit correlated error terms, and making some assumptions about cost and time sensitivity, as well as scale parameters, one can compute flows for each alternative. There are four distinct choice dimensions being modeled here, so the nesting structure exhibits three embedded nests. At the lowest level is route choice, above that is time-of-day choice, mode, and destination at the highest level. Reasonable behavioral parameter values were selected to characterize preferences. Figure 2 shows the overall nesting structure of the model, and the associated scale parameters (the  $\mu$  values).

Two destination options (A and B) are available for each user. Destination A represents a location close in proximity to the origin (1 mile), while destination B is much farther away (8 miles). However, the attractiveness of destination A is much less than that of B (10 versus 200 – much like a local versus regional activity center). Further, the free-flow speed to A via automobile is only 10 mph as compared to 60 mph to B. The two routes to destination B (existing and new)<sup>5</sup> are assumed to be identical in their physical characteristics, and the Bureau of Public Roads (BPR) link performance function (Equation 1) was used to compute travel times as a function of free-flow times, capacities, and volumes, with alpha ( $\alpha$ ) and beta ( $\beta$ ) parameters of 0.85 and 5.5, respectively (as suggested by Martin and McGuckin (1998)):

$$t_l = t_{free,l} \left( 1 + \alpha \left( v_l / c_l \right)^\beta \right) \quad (1)$$

where  $t_l$  is travel time on link  $l$ ,  $t_{free,l}$  is free-flow travel time on link  $l$ ,  $v_l$  is demand for link  $l$ , and  $c_l$  is link  $l$ 's capacity flow volume.

For destination A, capacity is assumed to be unlimited, which is reasonable when assuming that these trips use the local street network with multiple paths (and relatively low demand, as compared to supply).

In the second level of the nest, three mode alternatives are available, though the walk mode is only available to destination A (since a distance of 8 miles to B is assumed too far for someone to reasonably consider walking). Walk speed is assumed to be 4.47 mph, and bus speed is assumed to be the same as the auto mode<sup>6</sup>. However, a flat 15 min penalty is added to bus times

<sup>5</sup> Note that in the base scenario, it is assumed that only one of these two routes to destination B exists (it does not matter which one since they are identical in their characteristics). In all other scenarios, both routes exist.

<sup>6</sup> In the case of travel to destination B, buses are assumed to travel on route 2, which is the route selected for tolling in the model applications. However, bus users do *not* pay tolls.

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3 to represent its added wait, access, and egress times. Further, the bus fare is set at \$0.50 per trip  
4 (the case of Austin's CapMetro system), and buses on the network are assumed to be equivalent  
5 to 2.0 passenger cars (as suggested by the *Highway Capacity Manual* [TRB 2001]), and buses  
6 are assumed to ride "full", at 20 persons of capacity. For the auto mode, a fixed operating cost of  
7 \$0.20/mile is assumed (which is less than the American Automobile Association [AAA 2006]  
8 recognizes for full-cost accounting of vehicle ownership and use but about 35% more than  
9 current gas costs, assuming a 20 mi/gallon vehicle). Last, in calculation of utilities for each  
10 alternative, alternative specific constants (ASCs) are assumed for each mode: 0.0 for auto, -1.1  
11 for bus, and -1.3 for walk.<sup>7</sup>  
12

13 The last two levels of the nesting structure are for time-of-day (TOD) and route choices (though  
14 choice of route is only available to those driving to destination B). Three TOD alternatives are  
15 available and link capacities to destination B are assumed to vary by the number of hours in each  
16 time period (which assumes uniform assessment of all traffic within each period). AM peak is  
17 assumed to last 3 hours (6-9 am) and PM peak is assumed to last 4 hours (3-7 pm). Instead of  
18 giving the off-peak (OP) period the remaining 17 hours of the day, it is assumed that most OP  
19 travel will occur between the AM and PM peaks; thus, the OP period lasts 6 hrs. If 2,000  
20 passenger cars per hour per lane (pcphpl) is assumed for freeway capacity, and each route to B  
21 has two lanes, then capacities on both routes are the same for each TOD: 12,000 passenger cars  
22 equivalents in the AM, 24,000 in the OP, and 16,000 in the PM. In computing utilities, ASCs for  
23 each TOD alternative are assumed to be 0.0, -0.3, and 0.2 for the AM peak, OP, and PM peak, to  
24 reflect relative preference for travel during the PM and then AM periods, respectively.  
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26 Several other assumptions are needed here as well. The total number of system users is assumed  
27 to be 125,000, segmented into two groups. Low value of travel time (VOTT) users make up half  
28 of the population (with a \$6/hour VOTT), and high VOTT users make up the other half (with a  
29 \$12/hour VOTT). Finally, it is important to discuss the scale parameters (which are the inverse  
30 of the inclusive value coefficients) in each level of the nested model. While scaling parameters  
31 need not be the same for two different nests at the same level in the nesting structure, all were  
32 assumed to be the same here for simplicity. For example, the scale parameters across TODs for  
33 walk mode to A are assumed to be the same as the scaling parameter across TODs for bus mode  
34 to B. Consistent with McFadden's random-utility theory the scale parameters for the route  
35 choice, TOD, mode and destination choice nests were assumed to be 1.8, 1.6, 1.4, and 1.2,  
36 respectively. In contrast to most nested logit specifications (where the top level nest enjoys a 1.0  
37 scale factor), the top level scaling parameter is assumed here to be 1.2. The reason for this is that  
38 the coefficient on cost in the utility equations is set equal to -1 (as will be shown below). In this  
39 way all top-level utility values are in terms of dollars already.<sup>8</sup>  
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41 As shown in Figure 2, scale parameters ( $\mu_1$ ) of 1.8 in the lowest nest (driving to destination B via  
42 route 1 or route 2), 1.6 ( $\mu_2$ ) in the next lowest nest (AM versus PM versus OP TOD), 1.4 ( $\mu_3$ ) in  
43 the second highest level nest (walk versus bus versus auto), and 1.2 ( $\mu_4$ ) in the upper level nest  
44 (destination A versus destination B) were assumed. These are the inverse of inclusive value  
45 coefficients, essentially, and they reflect the degree of substitution that occurs between nested  
46 alternatives versus alternatives outside the nest. The greater the scale parameter, the greater the

47 <sup>7</sup> Values were selected to represent reasonable preference structures and are simply for illustrative purposes.

48 <sup>8</sup> An equivalent formulation emerges when setting the top level scaling parameter to 1.0 (as is customary) and  
49 adjusting other parameters accordingly. Such a formulation will require subsequent conversion of utility values to  
50 dollars, however.  
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substitution between nested alternatives, versus other alternatives. These are falling (from the lowest to the highest level nest) and the inverse of each lies between 0 and 1, consistent with random utility maximization (BenAkiva & Lerman 1985). With all these assumptions in place, equilibrium shares of destination, mode, TOD, and route choices, and equilibrium travel times were estimated for a variety of pricing scenarios. The associated equations, for generalized trip costs, systematic utilities, inclusive values (scaled logsums) of the nested choices and choice probabilities are as follows:

$$GC_{i,dmpr} = VOTT_i \cdot t_{dmpr} + \tau_{dmpr} + OC_{dmpr} \quad (2)$$

$$V_{i,dmpr} = [\ln(Attr_d) - \ln(Attr_B)] + ASC_m + ASC_p - GC_{i,dmpr} \quad (3)$$

$$\Gamma_{i,dmp} = \frac{1}{\mu_1} \ln[\exp(\mu_1 V_{i,dmp,route1}) + \exp(\mu_1 V_{i,dmp,route2})] \quad (4)$$

$$\Gamma_{i,dm} = \frac{1}{\mu_2} \ln[\exp(\mu_2 \Gamma_{i,dm,AM}) + \exp(\mu_2 \Gamma_{i,dm,OP}) + \exp(\mu_2 \Gamma_{i,dm,PM})] \quad (5)$$

$$\Gamma_{i,d} = \frac{1}{\mu_3} \ln[\exp(\mu_3 \Gamma_{i,d,Walk}) + \exp(\mu_3 \Gamma_{i,d,Bus}) + \exp(\mu_3 \Gamma_{i,d,Auto})] \quad (6)$$

$$Pr_{i,d} = \frac{\exp(\mu_4 \Gamma_{i,d})}{\sum_{l \in D} \exp(\mu_4 \Gamma_{i,l})} \quad (7)$$

$$Pr_{i,dm} = Pr_{i,d} \frac{\exp(\mu_3 \Gamma_{i,dm})}{\sum_{l \in M} \exp(\mu_3 \Gamma_{i,dl})} \quad (8)$$

$$Pr_{i,dmp} = Pr_{i,dm} \frac{\exp(\mu_2 \Gamma_{i,dmp})}{\sum_{l \in P} \exp(\mu_2 \Gamma_{i,dml})} \quad (9)$$

$$Pr_{i,dmpr} = Pr_{i,dmp} \frac{\exp(\mu_1 \Gamma_{i,dmpr})}{\sum_{l \in R} \exp(\mu_1 \Gamma_{i,dmpl})} \quad (10)$$

Here  $GC$  is the generalized cost,  $V$  stands for systematic utility of the alternative (as measured in dollars),  $\Gamma$  denotes the inclusive value or expected maximum utility for an upper level alternative,  $Pr(\cdot)$  represents the probability of a particular choice,  $i$  denotes user group (either low or high VOTT),  $d$  stands for the destination of interest (either A or B),  $m$  represents the mode of interest (walk, bus, or auto),  $p$  denotes the TOD (AM, OP, or PM),  $r$  is the route (either 1 or 2)<sup>9</sup>,  $D$  is the set of destination alternatives,  $M$  is the set of mode alternatives,  $P$  is the set of TOD alternatives, and  $R$  is the set of route alternatives. Here,  $VOTT$  denotes the value of travel time for the associated traveler group,  $\mu_1$ ,  $\mu_2$ ,  $\mu_3$ , and  $\mu_4$  serve as the scaling parameters for the route, TOD, mode, and destination nests, respectively,  $\tau$  represents out-of-pocket charges (for toll or bus fare)

<sup>9</sup> Two routes exist only if auto mode and destination B are chosen. In the other cases, route 2 can simply be assumed to have some arbitrarily large disutility (or travel cost) associated with it such that route 2 is not chosen.

and has no coefficient (so that utilities are in dollars<sup>10</sup>),  $OC$  is the out-of-pocket operating expenses (set to zero for bus and walk modes),  $t$  denotes the travel time,  $ASC$  represents the alternative specific constants for mode and TOD alternatives, and  $Attr$  is the attractiveness value of each destination.

Estimates of the change in consumer surplus ( $\Delta CS$ ) of each tolled scenario were computed as well. For a model such as the one formulated here, normalized logsums of systematic utilities provide the basis for consumer surplus calculations. When divided by the marginal utility of money (which in this case is 1 [as explained in footnote 11]), the welfare change from one scenario to another can be computed simply as logsum differences between any two scenarios (see, e.g., Small and Rosen 1981, Ben-Akiva and Lerman 1985, de Jong et al. 2007, and Zhao et al. 2008). The CS computation is as follows:

$$\Delta CS_i = \frac{1}{\mu_4} \left( \ln \left[ \sum_{k \in D} \exp(\mu_4 \Gamma_{i,k}^1) \right] - \ln \left[ \sum_{k \in D} \exp(\mu_4 \Gamma_{i,k}^0) \right] \right) \quad (11)$$

This is the difference in expected net benefits per traveler type  $i$  for scenario 1 relative to the base scenario 0. In general, the  $\Delta CS$  can be measured between any two scenarios, but we will look primarily at the change in consumer surplus as measured in reference to the base scenario – where only one of the two routes to destination B is available. In other words, the base scenario is a “do nothing”, scenario where no new roadway is built to destination B. Equations 2 through 11 were applied for both traveler types, recognizing the distinctive values of time scenarios examined.

## APPLICATION RESULTS

An assortment of tolled and non-tolled scenarios were investigated. The base scenario is such that only one of the two routes to destination B exists, and this route is not tolled. In addition, another non-tolled scenario is constructed such that both routes to destination B exist, but neither is tolled (i.e., build a new road without tolls). Six distinctive tolled scenarios were also considered, for a total of eight scenarios<sup>11</sup>. The simplest of these involve the building of a new road with a flat toll assessed (both \$0.05 per mile and \$0.10 per mile tolls are considered here). Optimal toll levels were sought, to maximize expected net benefits, across all 125,000 travelers (relative to the non-tolled scenario). Moreover, this scenario was extended to the case where optimal toll levels are assessed on both routes to destination B. Finally, revenue maximizing tolls were considered on the new route as well as on both routes to destination B. The results of these applications emerge from relatively straightforward (at least in this relatively simple, idealized setting) network equilibration and optimization procedures. And for each scenario, equilibrium was reached between traveler choices and network travel times and costs.

### Traveler Choices and Network Effects

<sup>10</sup> Since utility is unobserved, forcing the cost coefficient to equal one necessitates the use of two (non-unitary) scale factors (one for each nest). This offers greater transparency in dimensioning, but is in some contrast to most NL specifications (where  $\mu$  is set equal to 1 in the upper [or lower] nest).

<sup>11</sup> These scenarios are in no way exhaustive and simply serve to illustrate key policy cases. In reality, an infinite number of scenarios could be run, with different new-route capacities, parameter and future traffic growth assumptions, and so forth. As mentioned earlier in the paper, other costs and benefits could also be considered, such as emissions, crashes, bus expenditures, and so forth, for a truly comprehensive approach to transportation investment decision-making.

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3 Under the above assumptions, base conditions (where only one route to destination B exists)  
4 result in volume-to-capacity (V/C) ratios for peak and off-peak periods of 1.08 (for both AM and  
5 PM peaks) and 0.98, respectively, to destination B. This results in 19 minute and 15 minute peak  
6 and off-peak travel times to destination B, which are quite high relative to its 8-minute free-flow  
7 travel time.  
8

9 Of course, what is of interest is how this compares to scenarios in which a second route (to  
10 destination B) is added (essentially doubling corridor capacity). In each case of an **added route**  
11 **to destination B**, substantial delay reductions emerge. When the new route is not tolled, V/C  
12 ratios, and thus travel times, to B are lower. Travel times are just under 14 minutes in the peak  
13 periods and 10 minutes in the off-peak period (Table 1), saving travelers about 5 minutes per trip  
14 in all TODs. If a **flat toll** of \$0.40 (equivalent to 5¢ per mile) is assessed **on the new route** to  
15 destination B, lower V/C ratios are experienced on the tolled route (in comparison to the non-  
16 tolled case); and V/C ratios are higher on the non-tolled route (as compared to the non-tolled  
17 case), but lower than the base (no-build) scenario. If a flat toll of \$0.80 (equivalent to 10¢ per  
18 mile) is assessed on the new route to B, similar results emerge, but with more significant  
19 differences. Thus, in comparison to the non-tolled scenario, travel times to destination B in these  
20 two tolled scenarios fall by about 2 and 3.5 minutes per trip in peak periods (for the 5¢ and 10¢  
21 per mile settings, respectively, as shown in Table 1). However, traffic shifts to the non-tolled  
22 route, where travel times rise.

23 In the case of **welfare maximizing tolls**<sup>12</sup>, two scenarios were investigated: one where only the  
24 **new route** to destination B is tolled and one where both the new and old routes to destination B  
25 are tolled. In the case of one tolled route, the welfare maximizing toll on that route is found to be  
26 \$0.89 in the AM peak, \$0.91 in the PM peak, and \$0.26 in the off-peak period (Table 1). Both  
27 peak periods' optimal tolls are higher than the flat tolls considered above, while the off-peak  
28 period toll is somewhat less, since it is less attractive to travelers (and thus was assigned a  
29 negative ASC). These tolls result in travel times on the new route that are almost the same for  
30 peak and off-peak periods (just 9 minutes during the off-peak and about 9.5 minutes during the  
31 two peaks), in clear contrast to the flat tolls discussed above. If welfare maximizing tolls are  
32 charged on **both routes** to destination B, tolls rise (to about \$1.10 to \$1.20 in the peak periods  
33 and about \$0.60 in the off-peak period, as shown in Table 1). The reason tolls rise in this  
34 scenario (as compared to welfare maximizing tolls on a single route) is that MSC tolls are  
35 required, since this is a first-best solution. When only a single route is tolled, MSC tolls are  
36 inefficient in a welfare-maximizing sense, and toll levels will be lower (since an unpriced  
37 alternative is available). While tolls may be high, travelers enjoy significant travel time benefits  
38 when driving to destination B. No travelers destined for B experience more than a 9.5 minute  
39 travel time.  
40

41 If road managers instead wish to **maximize revenue** on the **new route**, optimal tolls will be  
42 \$1.33 in the AM peak, \$0.99 in the off-peak, and \$1.35 in the PM peak (Table 1). If one  
43 maximizes revenues by tolling **both routes** to destination B, the lowest travel times emerge,  
44 since fewer travelers choose destination B, due to tolls on the order of \$1.60 to \$1.70 in the peak  
45 periods and \$1.35 in the off-peak period (as shown in Table 1), much higher than in any of the  
46 other scenarios. High tolls, such as these, result in a substantial reduction in VMT. In fact,  
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49 <sup>12</sup> Here, welfare maximizing tolls refer to toll levels that result in the maximum social welfare, which includes  
50 traveler-perceived costs and benefits, along with revenues generated.  
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3 maximizing revenue on both routes is the only scenario in which VMT drops relative to the base  
4 scenario (5.4% less). All other scenarios see a substantial increase in VMT relative to the base,  
5 ranging from a 24.6% increase in the case of welfare maximizing tolls on both routes to a 53.4%  
6 increase when neither route to destination B is tolled.  
7

8 Figures 3 and 4 show the shares of low- and high-VOTT travelers, respectively, choosing  
9 destination-mode alternatives under each of the eight scenarios. In the base scenario, 90% of  
10 low-VOTT travelers drive (34% to destination A and 56% to destination B) and 96% of high-  
11 VOTT travelers drive (67% to destination A and 30% to destination B). Outside of the case of  
12 welfare maximizing tolls on both routes, no other scenario comes close to the percentage of  
13 travelers choosing the drive option to destination A for either low- or high-VOTT travelers. Of  
14 course, this is due to the fact that destination B is more attractive and adding capacity results in  
15 more travelers choosing their preferred destination.

16 Another interesting result evident in Figures 3 and 4 is transit usage across the tolled scenarios,  
17 especially for low-VOTT travelers. In these scenarios, one sees greater transit usage to  
18 destination B, reaching a maximum at about 25% of low-VOTT travelers (in the welfare-  
19 maximizing toll-both-routes scenario). The reason for this is two-fold: tolls on one or both  
20 routes to B cause users to switch modes while reducing bus travel times, thus enhancing the bus  
21 mode's appeal.  
22

23 Another set of meaningful results emerge from trip-timing choices as summarized in Table 2.  
24 Pricing incentives help shift traffic to less congested TODs, in order to better balance demand  
25 and supply. Table 2 shows the percentages of travelers choosing destination B in each scenario  
26 for each TOD, reductions in these percentages (versus the no-toll added-capacity scenario), the  
27 percent of travelers choosing the new route to destination B in each TOD, and the reductions in  
28 these percentages (versus the no-toll added-capacity scenario). Such results provide a good idea  
29 of the differences one might expect for each tolling scenario in comparison to the no-toll case.  
30 Restricting the discussion to the four tolling scenarios where only the new road is tolled, one  
31 finds that the only scenario that in fact shifts traffic to the off-peak is the one in which tolls are  
32 set to maximize welfare. In the other cases, only minor shifts away from destination B are found  
33 in the peak periods (less than 1% change for both flat toll scenarios and about 5% change for the  
34 revenue-maximizing-toll-scenario), but reductions in travel to B in the off-peak are about 6%,  
35 16%, and 18% for 5¢/mile toll, 10¢/mile toll, and maximum-revenue toll, respectively. If tolls  
36 are set to maximize welfare, however, one finds 4% reductions in peak-period travel to  
37 destination B and only 1.5% reduction in off-peak travel. By definition, the net social benefit or  
38 welfare maximizing toll works to better utilize corridor capacity across TODs.  
39

40 The preceding discussion highlights traveler choices and network effects for each of the  
41 scenarios investigated. While such comparisons highlight some of the key consequences of each  
42 scenario, they do not yet address the question of how to finance new highway infrastructure. The  
43 following section deals with the welfare impacts of each scenario, relative to the costs and  
44 payback periods associated with building and operating the new road.  
45

## 46 **Welfare Results**

47 Equation 11 specifies equivalent variation or average traveler welfare change as measured  
48 relative to the one-route (to destination B) base scenario, in units of dollars per traveler. A  
49 positive welfare change means that users benefit (on average) from the policy, whereas a  
50 negative welfare change indicates user losses. In addition to traveler welfare impacts, revenues  
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3 resulting from each tolling scenario are considered here. If those revenues are distributed  
4 equally to each traveler, as is the case with standard CBCP, such travel credits add to changes in  
5 traveler welfare. (Of course, if revenues are not distributed to travelers, then they are retained by  
6 the toll collector.) Table 3 presents the predicted revenue streams and traveler welfare before  
7 and after credits are distributed for each of the scenarios previously discussed. It is important to  
8 note here that since capacity to destination A is assumed to be unlimited (representing a network  
9 of local roads), there are *no* changes in travel times or traveler welfare for those traveling to  
10 destination A.

11  
12 As shown in Table 3, generated revenues range from \$0 in the Build, No Toll route scenario to  
13 \$81,000 per day in the Revenue Maximizing, Both Routes Tolled scenario.<sup>13</sup> In discussing  
14 traveler welfare, it is not so surprising that in all of the scenarios with the new route to B, welfare  
15 change estimates are positive (even for the Revenue Maximizing, Both Routes Tolled scenario  
16 where VMT falls), meaning net benefits exist for all travelers even before credits are distributed.  
17 This is due to the highly congested conditions of the one-route base scenario, and the simple  
18 result that doubling capacity to destination B allows for great congestion relief.

19 The greatest welfare improvements without a CBCP policy emerge in the no-toll scenario (\$0.63  
20 and \$0.69 per traveler per day for low- and high-VOTT travelers, respectively). However, in  
21 comparison to a CBCP policy where credits are distributed evenly, this no-toll (no-credits)  
22 scenario offers the lowest *net* benefits for both low- and high-VOTT travelers alike. Even when  
23 tolls are set to maximize revenues, low-VOTT travelers fare better than in a no-toll scenario (as  
24 long as credits are returned to travelers). These welfare benefits are useful to highlight for all  
25 stakeholders. Not only do they suggest that there are benefits for both camps of travelers, but  
26 they indicate that low-VOTT travelers may fare best under a CBCP scenario, making good use of  
27 the credits afforded them and taking advantage of the higher-speed roadway when needed, while  
28 opting for bus when warranted.

29  
30 Of course, the greatest benefits under a CBCP policy emerge when all “goods” are priced  
31 optimally – so that tolls are set to maximize welfare on *both* routes (EV equals \$0.77 and \$1.01  
32 per traveler per day for low- and high-VOTT travelers, respectively). If a no-toll route to  
33 destination B must be provided, the best option emerges from the welfare maximizing scenario  
34 with a single route tolled (EV equals \$0.70 and \$0.81 per traveler per day for low- and high-  
35 VOTT travelers, respectively). Clearly, there are benefits for both low- and high-VOTT travelers  
36 and high-VOTT travelers benefit more, but the disparity between the two traveler types is larger  
37 when both routes are tolled (differences of \$0.11 with one route tolled and \$0.24 with both  
38 tolled). A similar result is found when tolls are set to maximize revenues. The difference  
39 between low- and high-VOTT travelers when one route is tolled is \$0.06 per traveler per day  
40 (\$0.64 versus \$0.70) while the difference when both routes are tolled is \$0.24 per traveler per  
41 day (\$0.65 versus \$0.89), again supporting the notion that the impacts are more evenly  
42 distributed when one route is left non-tolled. The availability of substitute travel options may be  
43 essential in maximizing user benefits under tolling (and other) policies while wooing supporters  
44 across all demographic classes. Of course, such welfare calculations do not account for the costs  
45 of construction of the new facility nor do they account for the operation of tolling technology  
46 needed for scenarios with tolling implemented.

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49 <sup>13</sup> Of course, in a symmetric travel and network-capacity situation, where travelers return from destinations A and B,  
50 such revenues will double.  
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## Accounting for Highway Costs

In order to more fully appreciate the scenarios as investment alternatives, it is necessary to recognize the costs associated with building and operating a new roadway. Litman's (2002) review of the literature suggests that freeways in urban areas cost on the order of \$5 to 10 million per lane-mile, which includes land acquisition, pavement, and intersection reconstruction<sup>14</sup>. Assuming the cost is \$5 million per lane-mile, an 8-mile, 2-lane freeway will cost \$80 million. If one also assumes that routine annual maintenance costs of highways are \$14,000 per lane-mile<sup>15</sup> and toll road management costs are \$50,000 per lane-mile per year<sup>16</sup>, a single toll facility will cost \$1.02 million per year, and two toll facilities will cost \$1.82 million per year<sup>17</sup>. Finally, if it is assumed that calculated revenues are for weekdays only and weekend days generate only half that of weekdays, daily revenues can be multiplied by 313 to find yearly revenue streams in each scenario. Given these assumptions, it is possible to perform a cost-benefit analysis of traveler welfare, system expenditures and toll revenues.<sup>18</sup>

The analysis of financing the new road is performed in two ways. First, we assume that all toll revenues go toward the construction and management costs of the new road, after discounting future revenues at 5% per year<sup>19</sup>. In the scenario where the new road is built without tolls, there are no revenues, but one can still compute costs and traveler benefits, which results in a net benefit of about \$0.52 per traveler per day (one-way), or \$20.4 million per year (if costs are financed via a 5-percent 30-year loan. Table 4 presents the results of the analysis, including total and net annual revenues (after covering construction loan costs and toll road management), net annual revenues, and time period it takes to fully recover construction and management costs (assuming an annualized payback). In the case of a flat 5¢/mile toll, toll revenues are not enough to cover all costs when future revenues are discounted at 5%. In each of the other scenarios, the repayment period is rather modest (about 20 years or less), with the minimum payback duration (less than 4 years) resulting from tolling of both routes. If the corridor were located in a rural area, construction costs would be much lower (on the order of \$2 million per lane mile instead of \$5 million), which would result in repayment periods ranging from 1.4 years (in the case of revenue maximizing tolls on both routes) to 10.6 years (in the case of 5¢/mile tolls – which will

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<sup>14</sup> The costs of building a new road in a non-urban area would be substantially lower. However, the demand associated with a non-urban corridor would likely be lower as well. Thus, in non-urban areas, both costs and revenues would likely be lower than the results presented in this paper. In such cases, welfare benefits generally accrue through the addition of new, faster routes. The methods used here would be directly applicable, and may demonstrate very similar results, in terms of the presence of benefits for both investors and travelers.

<sup>15</sup> Routine annual maintenance costs were based on estimates taken from FDOT (Florida Department of Transportation) in 2003, which range from \$13,100 to \$14,600 per lane mile in urban areas. Estimates for rural highways generally are lower (on the order of \$10,200 to \$10,800 per lane mile, according to FDOT [2003]).

<sup>16</sup> Total operating expenses and number of toll road lane-miles for NHTA (NHTA, 2003), New Jersey Turnpike Authority (NJTA, 2003), and San Joaquin Hills Transportation Corridor Agency (SJHTCA, 2003) were used to find average management costs for toll roads. All three were on the order of \$100,000 per lane-mile, but these systems are mature, and rely on past technology. With new, paperless systems, management costs of \$50,000 per lane-mile were assumed to be reasonable here.

<sup>17</sup> To ensure comparability, highway maintenance costs are accounted for only on the new facility, in these numbers.

<sup>18</sup> For purposes of policymaking, more comprehensive analysis may also be pursued, including computation of bus service subsidies, emissions effects, and crash costs.

<sup>19</sup> While private investors traditionally discount at higher rates, private-public partnerships help reduce risk and facilitate access to lower-interest capital via publicly backed bonds and other financial instruments. Nevertheless, a discount rate of 5% may be too low for publicly financed tolled roads. Gilroy (2007) suggests that a rate of 7 to 9% may be more appropriate for such facilities.

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3 not even cover construction costs in an urban setting). Of course, once the costs of building,  
4 maintaining, and managing the new road have been recovered, future revenues can go toward  
5 any number of things, including credits to travelers, other infrastructure improvements, or the  
6 improvement of transit services.  
7

8 The second analysis assumes that the construction of the new road will be paid for by a 30-year  
9 loan with 5% interest rate and fixed yearly payments. This amounts to annual payments of  
10 approximately \$5.2 million (not including maintenance and management costs<sup>20</sup>). (In a rural  
11 setting with construction costs of \$2 million per lane mile, annual payments would be just \$2.1  
12 million.) The last two rows of Table 4 offer the results of this investment analysis. This includes  
13 the additional yearly revenues left over after all payments are made, which is negative in two  
14 scenarios, where revenues cannot cover costs. However, a cost-benefit analysis of each scenario  
15 yields benefit over cost (B/C) ratios ranging from a low of 4.20 (in the case of revenue-  
16 maximizing tolls on a single route) to a high of 4.96 (in the case of welfare maximizing tolls on  
17 both routes). In fact, the no-toll scenario has a higher B/C ratio (of 4.76) than the welfare  
18 maximizing toll on a single route (4.74), which is due to the fact that the no-toll scenario has the  
19 lowest associated costs.

20 If welfare maximizing tolls are assessed on just the new road, a total of about \$1.0 million per  
21 year is available for implementing other transportation policies and/or building new roads. If  
22 welfare maximizing tolls are assessed on both routes, almost \$14 million per year is expected to  
23 become available. Of course, this money could be used to credit travelers. Also shown in Table  
24 4 is the amount of available credits per traveler per day. In all of the tolled scenarios, except the  
25 5¢/mile scenario, additional revenues are left over after this loan is paid off. Moreover, in  
26 comparison to the welfare gain of building the new road without tolls (which is about \$0.66 per  
27 traveler per day if construction costs are ignored), the relative cost per traveler of a welfare  
28 maximizing toll on the new road is only about 6¢ per day (or about \$20 per year) after the road is  
29 fully financed. In contrast, building the new road without tolls will require about \$44 per  
30 traveler per year. If welfare maximizing tolls were enforced on both routes to destination B,  
31 credits of about \$0.35 per traveler per day could be distributed, resulting in a welfare gain of  
32 over 5¢ per traveler per day in comparison to the non-financed, no-toll scenario. In other words,  
33 after fully financing a new road through welfare maximizing tolls on both the new and existing  
34 roads and distributing remaining revenues as credits, the average traveler will be better off than if  
35 a new, no-toll road could be built for zero dollars (which, of course, is not possible). In other  
36 words, there are toll rates for existing roads that may benefit all stakeholders (on average [see  
37 Zhao et al. 2008]), thanks to the distribution of credits, net of costs.  
38

### 39 **IN SUMMARY**

40 Much work already exists on the topic of CBCP, in terms of public opinion, implementation  
41 costs, and system-level effects in reasonably congested U.S. regions. As shown in eight  
42 numerical examples, with two distinctive (and latently heterogeneous) traveler types, congestion  
43 levels can be largely reduced in the presence of pricing (even with flat tolls), and welfare effects  
44 can be significant, and largely positive, thanks to the provision of credits. And while disparities  
45 exist between the welfare benefits of low- and high-VOTT travelers, these are lessened when a  
46 no-toll or low-tolled option is preserved. Moreover, low-VOTT travelers may fare best under a  
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48 <sup>20</sup> Here, yearly maintenance and management costs are subtracted from total yearly revenues to find net revenues,  
49 which can then be applied to loan payments.  
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3 CBCP policy that allows them to choose faster, more reliable routes, as needed while offering  
4 other alternatives such as bus and walking modes.  
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6 Results also indicate that congestion pricing can provide a valuable means to finance new  
7 highways along previously congested corridors, though these results may be dampened in the  
8 case of a typical rural corridor with moderate demand. In the congested-corridor context  
9 examined here, it was found that all but one pricing policy led to revenues that could fully  
10 finance the infrastructure costs within 30 years, with excess revenues. Such excess revenues can  
11 be used for any number of things. A CBCP policy puts these back in traveler pockets, thereby  
12 lessening the negative impact of tolls. Moreover, it was found that it may be possible to fully  
13 finance new roads by toll revenues with enough left over to distribute as credits that the average  
14 traveler would actually be better off than if a new road was built at no cost and no tolls were  
15 charged. While this may be an idealistic scenario, it illustrates an important point that  
16 congestion pricing can have quite positive impacts for everyone, especially if toll revenues are  
17 used wisely. Such calculations are feasible in software packages as common as MS Excel, as  
18 long as the route and mode alternatives are relatively compact.

19 Of course, the analysis provided here illustrates only key concepts in an idealized set of  
20 scenarios. Many potential extensions exist, to further highlight key issues involved. For  
21 instance, one can imagine no tolls during off-peak periods, thereby allowing for more “free”  
22 substitutes. Such a policy may dampen any disparities between low- and high-VOTT user  
23 benefits. In addition, one may be interested in the optimal capacity addition to the corridor, and  
24 this was done, for the case of welfare maximizing tolls on the new route, resulting in an optimal  
25 capacity addition of 3.6 lanes (or 3 lanes if only integer values are allowed). One also may be  
26 interested in how results change when external costs (and benefits) of travel are recognized,  
27 when uncertainty exists in behavioral parameters (as it invariably does) and/or when more  
28 destinations, modes, routes, TODs and traveler types are permitted; such questions will require  
29 more and/or more complicated analysis, but such questions merit investigation when millions –  
30 and often billions – of dollars are at stake. The simplified region discussed here assumed that the  
31 new roadway capacity would not affect overall traveler demand, but in reality, it likely would  
32 (via future land development impacts and pent-up or latent demand from other, congested areas  
33 of the network). Moreover, scenario analysis always involves the forecasting of future demand  
34 conditions, which are inherently uncertain. A more comprehensive analysis of optimal toll levels  
35 that allows for uncertainty in some or all model parameters and inputs would be possible if  
36 certain assumptions are made regarding that uncertainty.  
37

38 In summary, a variety of pricing policy options exist for those willing to invest in new  
39 transportation infrastructure that offers travel time savings. The tools and techniques highlighted  
40 here illustrate practical methods for identifying welfare-enhancing and cost-recovering  
41 investment opportunities. These techniques recognize demand elasticity across times of day,  
42 destinations, modes and routes, which are standard features of most travelers’ choice sets but too  
43 often neglected in most analysts’ toolkits.  
44

## 45 **ACKNOWLEDGEMENTS**

46 Graduate student researcher Rui Gao assisted in performing numerous scenarios for this paper’s  
47 example application, and Drs. Charles Raux and Martin Lee-Gosselin were indefatigable in  
48 organizing the valuable 2007 Lyon colloquium on transport, energy and climate change, which  
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3 initiated this investigation. We appreciate the comments of several anonymous reviewers and the  
4 administrative contributions of Ms. Annette Perrone.  
5

## 6 7 **REFERENCES** 8

9 AAA (2006) *Your Driving Costs, 2006*. American Automobile Association Public Affairs,  
10 Accessed September 2006 from <http://www.aaapublicaffairs.com/Main/>.  
11

12 Arnott, R., A. de Palma, and R. Lindsey (1994) "The Welfare Effects of Congestion Tolls with  
13 Heterogeneous Commuters," *Journal of Transport Economics and Policy*, 28 (2), 139-161.  
14

15 Arnott, R. and A. Yan (2000) "The Two-Mode Problem: Second-Best Pricing and Capacity,"  
16 *Review of Urban and Regional Development Studies*, 12 (3), 170-199.  
17

18 Ben-Akiva, M., and Lerman, S. R. (1985) *Discrete Choice Analysis: Theory and Application to*  
19 *Travel Demand*. Cambridge, Massachusetts: MIT Press.  
20

21 Braid, R.M. (1996) Peak-Load Pricing of a Transport Facility with an Unpriced Substitute.  
22 *Journal of Urban Economics*, 40, 179-197.  
23

24 Cao, X., Mokhtarian, P. (2005) How do individuals adapt their personal travel? A conceptual  
25 exploration of the consideration of travel-related strategies, *Transport Policy* 12: 199-206.  
26

27 Daganzo, C. (1995). "A Pareto Optimum Congestion Reduction Scheme." *Transportation*  
28 *Research*. 29B:139-154.  
29

30 Davies, John, M. Grant, J. Nenezia, J. Aamidor (2007) US Transportation Sector Greenhouse Gas  
31 Emissions: Trends, Uncertainties and Methodological Improvements. Proceedings of the 86<sup>th</sup>  
32 Annual Meeting of the Transportation Research Board, Washington D.C.  
33

34 de Jong, G., A. Daly, M. Pieters, and T. van der Hoorn (2007) The Logsum as an Evaluation  
35 Measure: Review of the Literature and New Results. *Transportation Research Part A*, 41, 874-  
36 889.  
37

38 DeCorla-Souza, P. (1995). "Applying the Cashing Out Approach to Congestion Pricing."  
39 *Transportation Research Record*, 1450, 34-37.  
40

41 Dial, R.B. (1999) "Minimal Revenue Congestion Pricing Part I: A Fast Algorithm for the  
42 Single-Origin Case," *Transportation Research Part B*, 33: 189-202.  
43

44 EPA (2006) Inventory of US Greenhouse Gas Emissions and Sinks (Accessed at  
45 [http://www.epa.gov/climatechange/emissions/downloads06/06\\_Complete\\_Report.pdf](http://www.epa.gov/climatechange/emissions/downloads06/06_Complete_Report.pdf), on April  
46 30, 2007.)  
47

48 FDOT (2003) *2002 Transportation Costs*. Office of Policy Planning, Florida Department of  
49 Transportation.  
50  
51  
52

1  
2  
3  
4 Geller, H., P. Harrington, A.H. Rosenfeld, S. Tanishimad and F. Unander (2006) Policies for  
5 Increasing Energy Efficiency: Thirty years of Experience in OECD Countries. *Energy Policy* 34  
6 (5): 556-573  
7

8 Gilroy, L.C. (2007) NTTA's Proposal for SH-121, Is it Better than Cintra's? Commentary  
9 provided by the Reason Foundation. Accessed April 2008 from  
10 [http://www.reason.org/commentaries/gilroy\\_20070511.shtml](http://www.reason.org/commentaries/gilroy_20070511.shtml).  
11

12 Gulipalli, Pradeep and Kockelman, K. (2008) "Credit-Based Congestion Pricing: A Dallas-Fort  
13 Worth Application." *Transport Policy* 15 (1): 23-32.  
14

15 TRB (2001) *Highway Capacity Manual* 2000. Transportation Research Board, Washington, D.C.  
16

17 Knight, F. (1924). "Some Fallacies in the Interpretation of Social Costs." *Quarterly Journal of*  
18 *Economics*. 38(4): 582-606.  
19

20 Kalmanje, S. and Kockelman, K. (2004) Credit-Based Congestion Pricing: Travel, Land Value  
21 and Welfare Impacts," *Transportation Research Record* 1864: 45-53.  
22

23 Kockelman, K. (2004) Traffic Congestion. In *Transportation Engineer's Handbook* (Chapter  
24 22). McGraw-Hill.  
25

26 Kockelman, K. and S. Kalmanje (2005). "Credit-based congestion pricing: A policy proposal  
27 and the public's response." *Transportation Research Part A*, 39(7): 671-690.  
28

29 Kockelman, Kara, Kaethe Podgorski, Michelle Bina, Shashank Gadda (2006) Public Perceptions  
30 of Pricing Existing Roads and Other Transportation Policies: The Texas Perspective.  
31 Proceedings of the 85th Annual Meeting of the Transportation Research Board, Washington,  
32 D.C.  
33

34 Lemp, Jason, and Kara Kockelman (2008) Quantifying the External Costs of Vehicle Use:  
35 Evidence from America's Top-Selling Light-Duty Models. Proc'gs of the 87<sup>th</sup> Annual Meeting of  
36 the Transportation Research Board, Washington, D.C.  
37

38 Lévy-Lambert, H. (1968) "Tarification des Services à Qualité Variable – Application aux Péages  
39 de Circulation," *Econometrica*, 36 (3-4), 564-574.  
40

41 Litman, T. (2002) *Transportation Cost Analysis: Techniques, Estimates and Implications*.  
42 Victoria Transport Policy Institute. Victoria, BC, Canada.  
43

44 Liu, L.N. and J.F. McDonald (1999) Economic Efficiency of Second-Best Congestion Pricing  
45 Schemes in Urban Highway Systems. *Transportation Research Part B*, 33, 157-188.  
46

47 Marchand, M. (1968) "A Note on Optimal Tolls in an Imperfect Environment," *Econometrica*,  
48 36 (3-4), 575-581.  
49  
50  
51  
52

1  
2  
3  
4 Martin, W.A. and N.A. McGuckin (1998) Travel Estimation Techniques for Urban Planning.  
5 National Cooperative Highway Research Program (NCHRP) Report 365. National Research  
6 Council, Washington, D.C.

7  
8 Maruyama, T. and Sumalee, A. (2007) Efficiency and equity comparison of cordon- and area-  
9 based road pricing schemes using a trip-chain equilibrium model. *Transportation Research* 41A  
10 (7): 655-671.

11  
12 Mohring, H. and M. Harwitz (1962) *Highway Benefits: An Analytical Framework*.  
13 Northwestern University Press, Evanston, IL.

14  
15 Nakamura, Katsuhiko and Kara Kockelman (2002) Congestion Pricing and Roadspace  
16 Rationing: An Application to the San Francisco Bay Bridge Corridor. *Transportation Research*  
17 36A (5): 403-417.

18  
19 NJTA (2003) *Statement of Revenues and Expenses for the Year Ended December 31, 2003*, First  
20 Consolidated Toll Road Annual Report 2003, New Jersey Turnpike Authority.

21  
22 NTTA (2003) *Financial Statements and Supplementary Data 2003*, North Texas Tollway  
23 Authority, Dallas North Tollway System.

24  
25 Parry, I. W. H. and Bento, Q. (2001) "Revenue Recycling and the Welfare Effects of Road  
26 Pricing," *Scandinavian Journal of Economics*, 103(4): 645-671.

27  
28 Penchina, C.M. (2003) "Stability of Minimal Revenue Pricing." Paper presented at the 82<sup>nd</sup>  
29 Annual Meeting of the Transportation Research Board, Washington, D.C.

30  
31 Pigou, A.C. (1920). *Wealth and Welfare*. Macmillan, London.

32  
33 Raux C., and Marlot G. (2005) A System of Tradable CO2 Permits Applied to Fuel Consumption  
34 by Motorists, *Transport Policy* 12 (3): 255-265.

35  
36 Samuel, P. (2007) The Role of Tolls in Financing 21<sup>st</sup> Century Highways. Reason Foundation  
37 Policy Study 359.

38  
39 SJHTCA (2003) *Statement of Revenues, Expenses and Changes in Fund Net Assets (Deficit) for*  
40 *the Year Ended June 30, 2003*, Annual Financial Report 2003, San Joaquin Hill Transportation  
41 Corridor Agency.

42  
43 Small, K.A. and H.S. Rosen (1981) "Applied Welfare Economics with Discrete Choice Models,"  
44 *Econometrica*, 49 (1): 105-130.

45  
46 Small, K. (1992) "Using the Revenues from Congestion Pricing," *Transportation*, 19: 359-381.  
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1  
2  
3 Small, K.A. and E.T. Verhoef (2007) *The Economics of Urban Transportation*. Routledge,  
4 London and New York.  
5

6 Smith, Adam (1976) *An Inquiry into the Nature and Causes of the Wealth of Nations*. London.  
7

8 United States Department of Transportation (USDOT) (2006) *Expert Forum on Road Pricing  
9 and Travel Demand Modeling Proceedings*. Report No. DOT-OST/P-001-06.  
10

11 United States Government Accountability Office (U.S. GAO) (2006) *Highway Finance: States'  
12 Expanding Use of Tolling Illustrates Diverse Challenges and Strategies*, GAO Report to  
13 Congressional Requesters, June 2006.  
14

15 Verhoef, E.T., P. Nijkamp, and P. Rietveld (1996) "Second-Best Congestion Pricing: The Case  
16 of an Untolled Alternative," *Journal of Urban Economics*, 40, 279-302.  
17

18 Verhoef, E.T. (2000) "The Implementation of Marginal External Cost Pricing in Road Transport:  
19 Long Run vs. Short Run and First-Best vs. Second-Best," *Papers in Regional Science*, 79, 307-  
20 332.  
21

22 Verhoef, E.T. (2002a) "Second-Best Congestion Pricing in General Static Transportation  
23 Networks with Elastic Demands," *Regional Science and Urban Economics*, 32, 281-310.  
24

25 Verhoef, E.T. (2002b) "Second-Best Congestion Pricing in General Networks: Heuristic  
26 Algorithms for Finding Second-Best Optimal Toll Levels and Toll Points," *Transportation  
27 Research Part B*, 36, 707-729.  
28

29 Verhoef, E.T. and J. Rouwendal (2004) "Pricing, Capacity Choice, and Financing in  
30 Transportation Networks," *Journal of Regional Science*, 44 (3), 405-435.  
31

32 Verhoef, E.T. (2007) "Second-Best Road Pricing through Highway Franchising," *Journal of  
33 Urban Economics*, 62, 337-361.  
34

35 Vickrey, W.S. (1963) "Pricing in Urban and Suburban Transport," *American Economic Review;  
36 Papers and Proceedings*, 53: 452- 465.  
37

38 Vickrey, W.S. (1969) "Congestion Theory and Transport Investment," *American Economic  
39 Review; Papers and Proceedings*, 59 (2), 251-260.  
40

41 Viegas J. M. (2001). "Making Urban Road Pricing Acceptable and Effective: Searching for  
42 Quality and Equity in Urban Mobility." *Transport Policy*. 8(4): 289-294.  
43

44 Walters, A.A. (1961) "The Theory and Measurement of Private and Social Cost of Highway  
45 Congestion," *Econometrica*, 29 (4), 676-699.  
46  
47  
48  
49  
50  
51  
52

1  
2  
3 Zhao, Y., K.M. Kockelman, and A. Karlstrom (2008) Welfare Calculations in Discrete Choice  
4 Settings: The Role of the Error Term Correlation. Proc'gs of the 87<sup>th</sup> Annual Meeting of the  
5 Transportation Research Board, Washington, D.C.  
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3 **FIGURES AND TABLES**  
4

5 Figure 1: Network Layout

6 Figure 2: Nested Logit Model Structure with Associated Scale Parameters

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8 Figure 3: Distribution of Low-VOTT Travelers Choosing Destination/Mode Combinations  
9 across Scenarios

10 Figure 4: Distribution of High-VOTT Travelers Choosing Destination/Mode Combinations  
11 across Scenarios

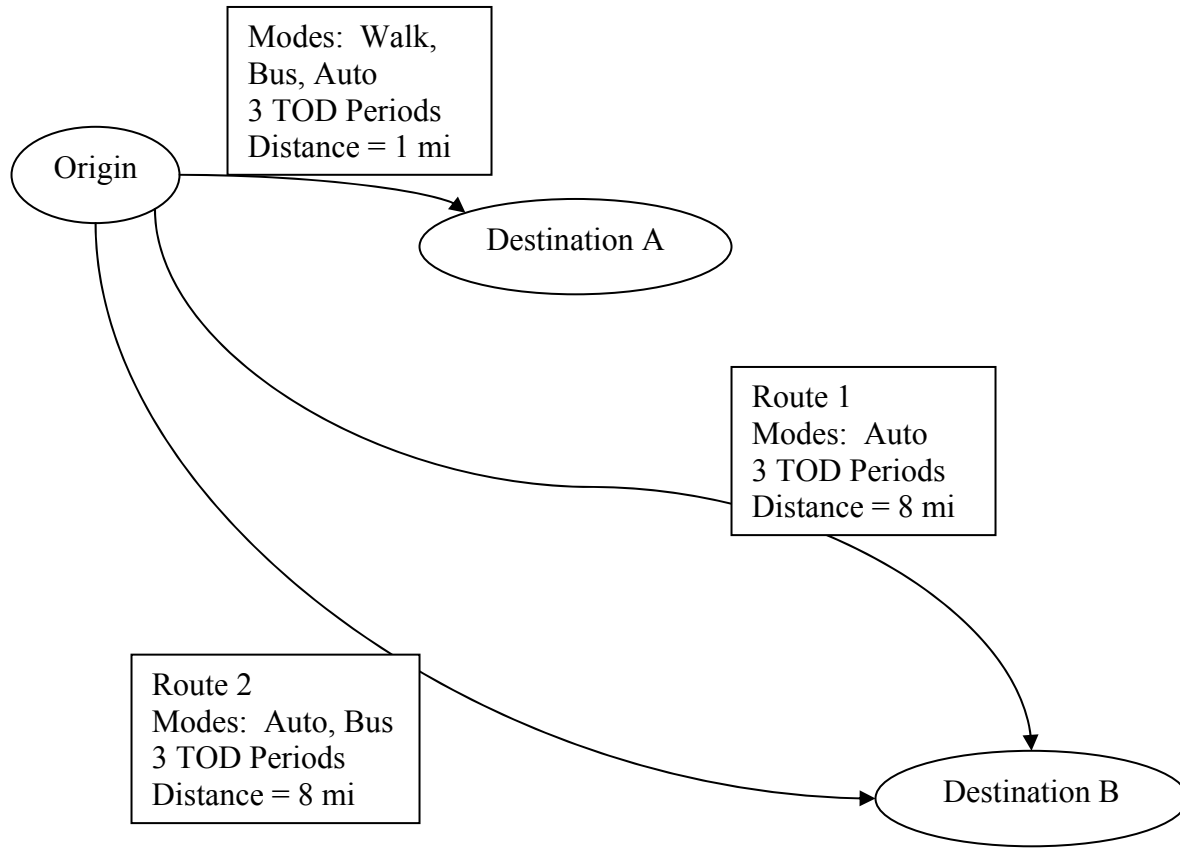
12 Table 1: Travel Times, Tolls, V/C Ratios, and VMT across Scenarios

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15 No Toll, Build Scenario Share

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Figure 1: Network Layout



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Figure 2: Nested Logit Model Structure with Associated Scale Parameters

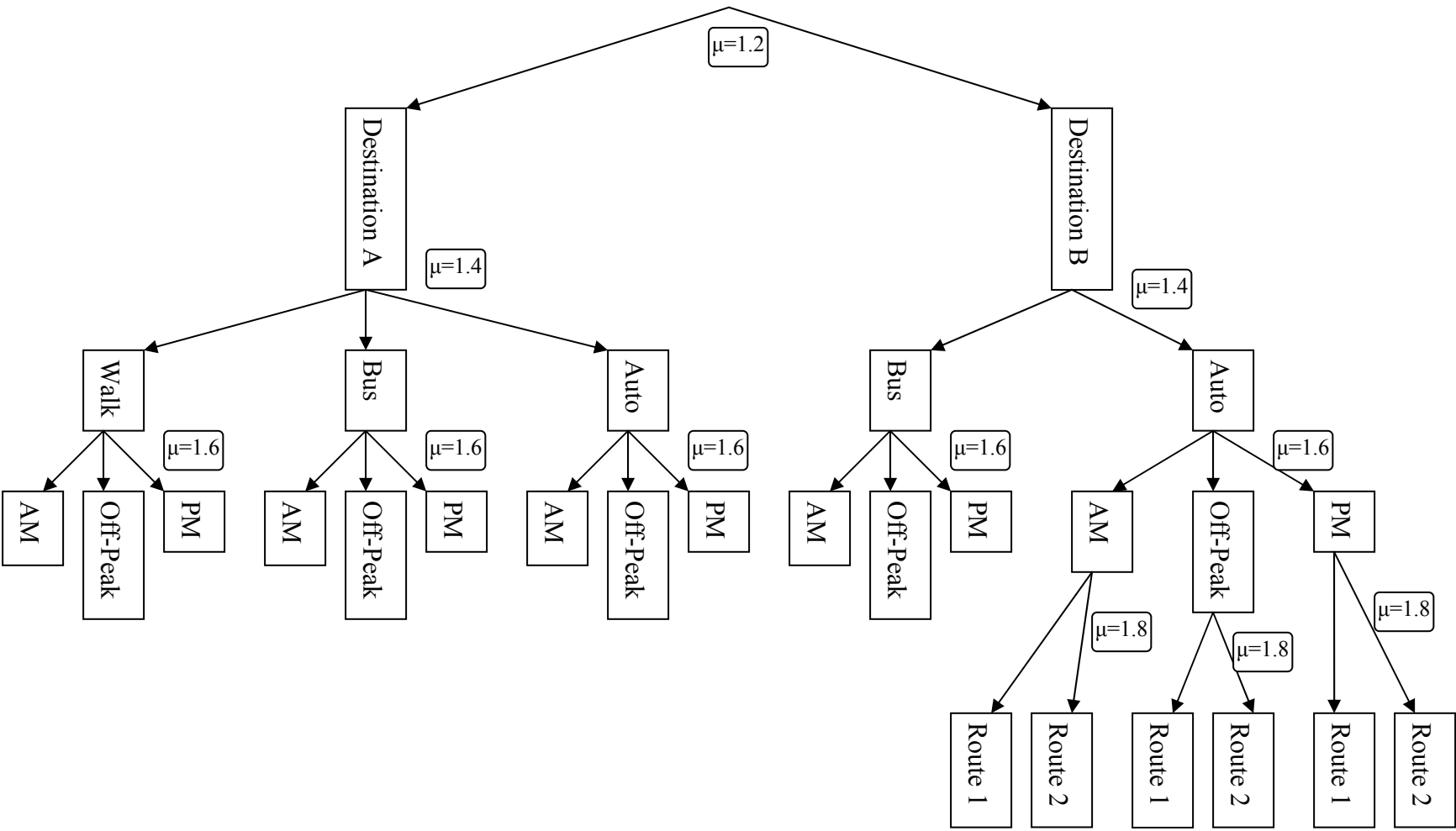


Figure 3: Distribution of Low-VOTT Travelers Choosing Destination/Mode Combinations across Scenarios

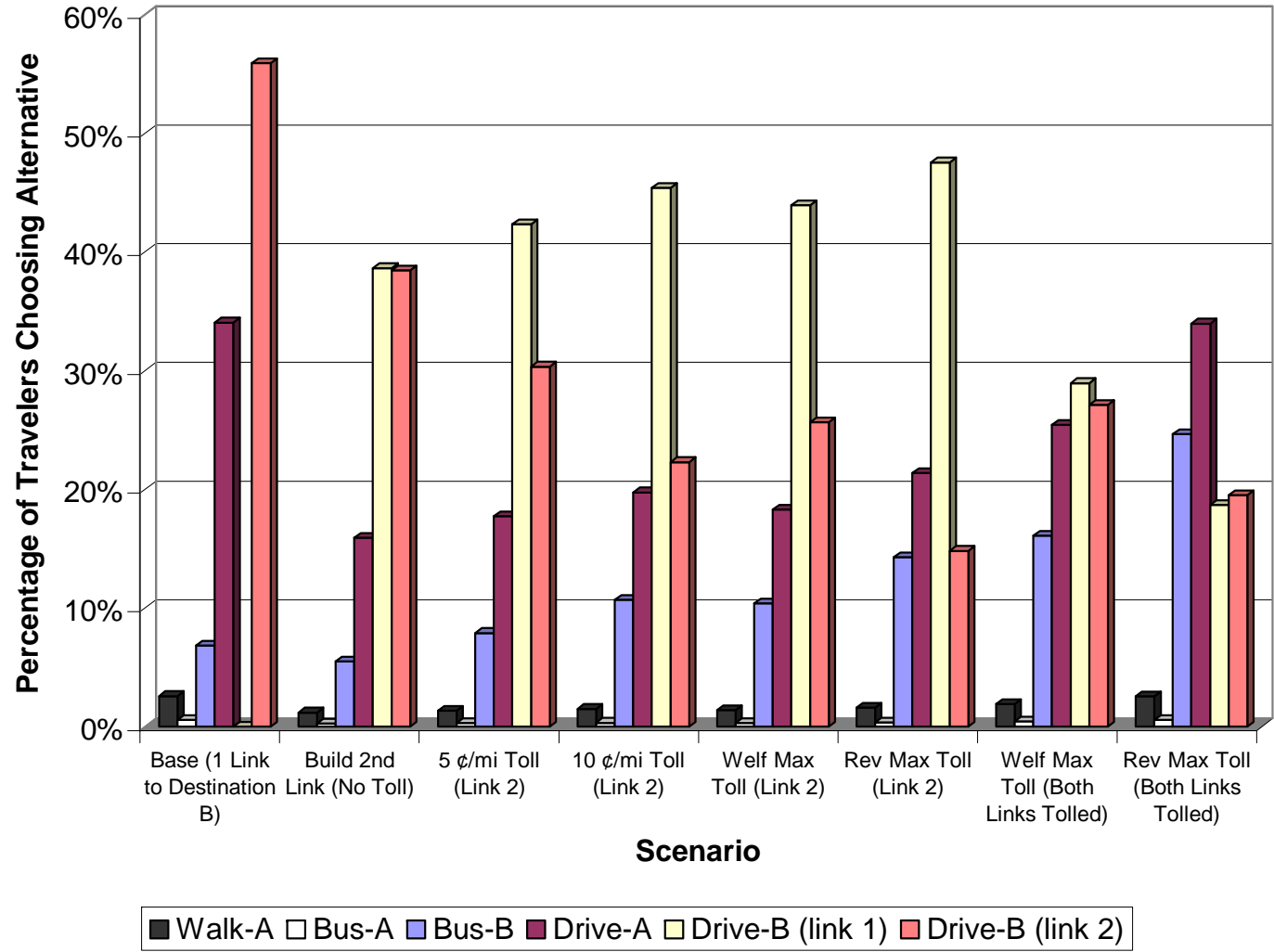
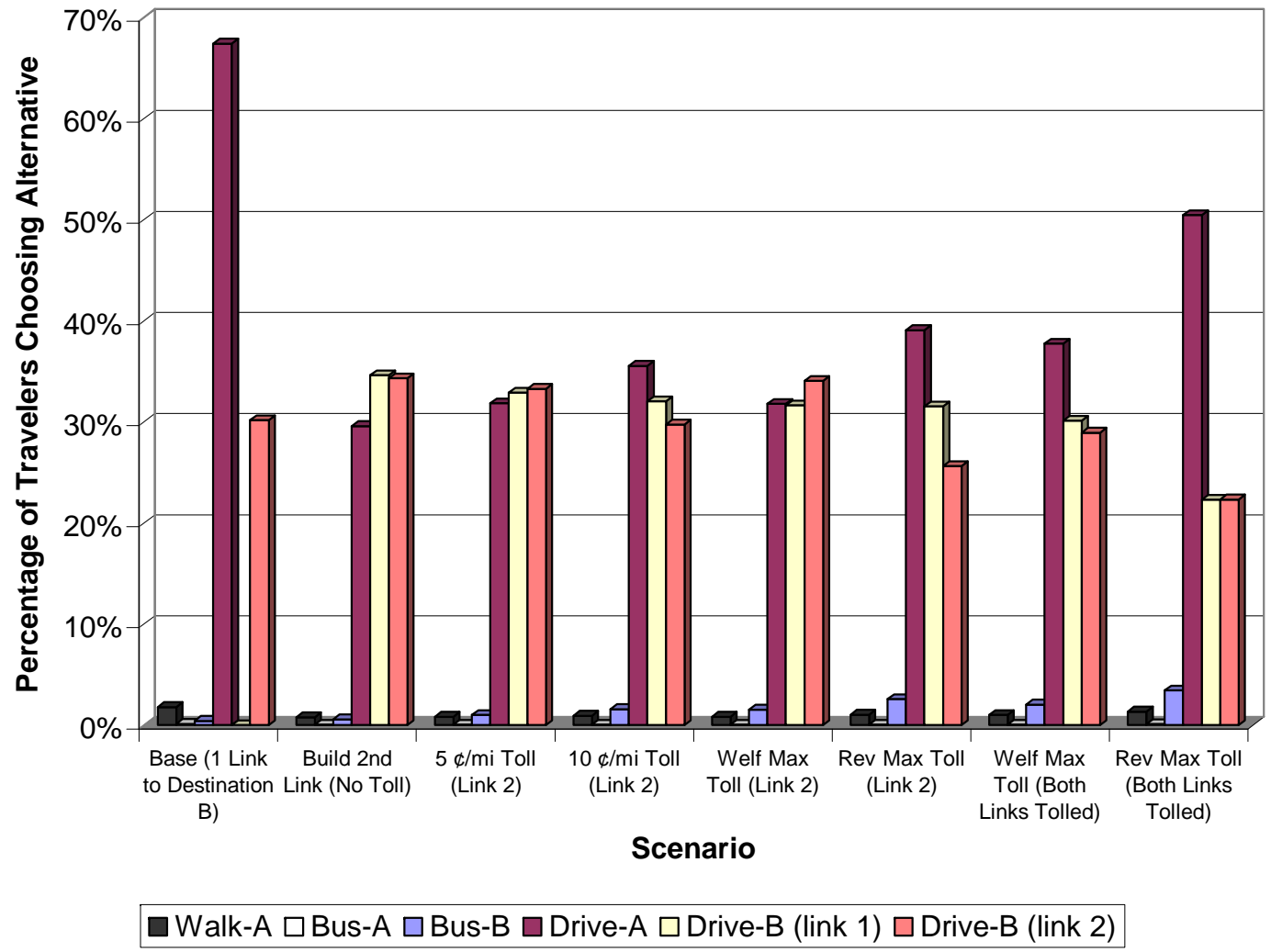


Figure 4: Distribution of High-VOTT Travelers Choosing Destination/Mode Combinations across Scenarios



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Table 1: Travel Times, Tolls, V/C Ratios, and VMT across Scenarios

	Link	TOD	Base (1 Link to Destination B)	Build 2nd Link (No Toll)	Link 2 Tolled			Both Links Tolled		
					5 cent/mi Toll	10 cent/mi Toll	Welfare Maximizing Toll	Revenue Maximizing Toll	Welfare Maximizing Toll	Revenue Maximizing Toll
Travel Time (min)	Link 1	AM	19.12	13.69	14.26	14.94	14.43	15.55	9.40	8.44
		MID	14.20	9.69	10.11	10.67	10.16	11.14	8.70	8.02
		PM	19.26	13.81	14.39	15.07	14.56	15.68	9.43	8.45
	Link 2	AM	N/A	13.72	11.85	10.28	9.44	8.52	9.20	8.77
		MID	N/A	9.71	8.51	8.06	9.00	8.03	8.67	8.03
		PM	N/A	13.84	11.97	10.38	9.45	8.54	9.21	8.81
Toll (\$)	Link 1	AM	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$1.13	\$1.70
		MID	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.58	\$1.36
		PM	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$1.14	\$1.71
	Link 2	AM	N/A	\$0.00	\$0.40	\$0.80	\$0.89	\$1.33	\$1.20	\$1.63
		MID	N/A	\$0.00	\$0.40	\$0.80	\$0.26	\$0.99	\$0.60	\$1.36
		PM	N/A	\$0.00	\$0.40	\$0.80	\$0.91	\$1.35	\$1.21	\$1.64
V/C Ratio	Link 1	AM	N/A	0.97	0.99	1.00	0.99	1.02	0.75	0.61
		MID	N/A	0.78	0.81	0.84	0.81	0.87	0.66	0.36
		PM	N/A	0.97	0.99	1.01	0.99	1.02	0.75	0.61
	Link 2	AM	1.08	0.96	0.89	0.80	0.73	0.60	0.70	0.62
		MID	0.98	0.77	0.62	0.42	0.70	0.35	0.65	0.36
		PM	1.09	0.96	0.89	0.81	0.73	0.60	0.70	0.63
VMT (veh-mi/day)	All Auto Links	AM	125,179	194,603	190,194	184,694	175,915	167,845	152,235	135,864
		MID	200,548	303,155	280,188	249,487	296,518	242,451	259,171	148,089
		PM	168,159	260,863	255,118	248,005	235,481	225,281	204,024	183,109
		Total	493,886	758,622	725,500	682,186	707,914	635,577	615,429	467,062

Table 2: Shares of Travelers Choosing Destination B by TOD and Percentage Difference from No Toll, Build Scenario Shares

Destination & Route	TOD	Percent	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
				5 cent/mi Toll	10 cent/mi Toll	Welfare Maximizing Toll	Revenue Maximizing Toll	Welfare Maximizing Toll	Revenue Maximizing Toll
Destination B, Both Routes Combined	AM Peak	% of Travelers <sup>1</sup>	19.36	19.27	19.19	18.51	18.29	16.88	16.39
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-0.46	-0.84	-4.39	-5.51	-12.79	-15.30
	Off-Peak	% of Travelers <sup>1</sup>	30.79	28.82	25.97	30.32	25.34	27.12	16.95
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-6.39	-15.65	-1.54	-17.70	-11.91	-44.96
	PM Peak	% of Travelers <sup>1</sup>	25.92	25.82	25.75	24.80	24.59	22.67	22.13
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-0.39	-0.64	-4.29	-5.14	-12.53	-14.61
Destination B, via New Road	AM Peak	% of Travelers <sup>1</sup>	9.22	8.53	7.68	7.04	5.74	6.70	6.00
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-7.48	-16.69	-23.58	-37.73	-27.29	-34.94
	Off-Peak	% of Travelers <sup>1</sup>	14.83	11.86	8.03	13.42	6.78	12.39	6.87
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-20.00	-45.81	-9.47	-54.25	-16.44	-53.68
	PM Peak	% of Travelers <sup>1</sup>	12.34	11.43	10.32	9.39	7.70	8.95	8.06
		% Decrease vs. No-Toll Build Scenario <sup>2</sup>	0.00	-7.35	-16.36	-23.88	-37.56	-27.47	-34.66

<sup>1</sup>This is the total percentage of travelers choosing destination B and the given route and TOD.

<sup>2</sup>This is the percentage difference of the number of travelers choosing destination B and the given route and TOD as measured from the non-tolled new road scenario where all roads are non-tolled.

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Table 3: Revenues and Welfare Results by Scenario

		Base (1 Link to Destination B)	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
				5 cent/mi Toll	10 cent/mi Toll	Welfare Maximizing Toll	Revenue Maximizing Toll	Welfare Maximizing Toll	Revenue Maximizing Toll
Net Revenue (\$/day)	Total	0	0	\$15,910	\$26,033	\$22,952	\$30,931	\$65,888	\$81,102
Welfare Change from Base (\$/traveler/day)	Low VOTT	\$0.000	\$0.634	\$0.543	\$0.454	\$0.517	\$0.388	\$0.243	\$0.002
	High VOTT	\$0.000	\$0.686	\$0.625	\$0.533	\$0.626	\$0.455	\$0.483	\$0.242
	Average	\$0.000	\$0.660	\$0.584	\$0.494	\$0.572	\$0.422	\$0.363	\$0.122
Welfare Change under CBCP (\$/traveler/day)	Low VOTT	\$0.000	\$0.634	\$0.670	\$0.663	\$0.701	\$0.636	\$0.770	\$0.651
	High VOTT	\$0.000	\$0.686	\$0.752	\$0.742	\$0.810	\$0.702	\$1.011	\$0.891
	Average	\$0.000	\$0.660	\$0.711	\$0.702	\$0.755	\$0.669	\$0.890	\$0.771

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Table 4: Overall Financial Results, for New Road Investment across Scenarios

	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
		5 cent/mi Toll	10 cent/mi Toll	Welfare Maximizing Toll	Revenue Maximizing Toll	Welfare Maximizing Toll	Revenue Maximizing Toll
Toll Revenues (Millions of \$/year) <sup>1</sup>	\$0	\$4.98M	\$8.15M	\$7.18M	\$9.68M	\$20.62M	\$25.38M
Roadway Maintenance Cost for New Highway (Millions of \$/year)	\$0.224M	\$0.224 M	\$0.224 M	\$0.224 M	\$0.224 M	\$0.224 M	\$0.224 M
Toll Management Cost (Millions of \$/year)	\$0	\$0.8M	\$0.8M	\$0.8M	\$0.8M	\$1.6M	\$1.6M
Net Revenue (Millions of \$/year) <sup>2</sup>	\$0	\$3.96M	\$7.12M	\$6.16M	\$8.66M	\$18.80M	\$23.56M
Repayment Time with 5% Discount Rate (years) <sup>3</sup>	N/A	N/A	16.9 yrs	21.5 yrs	12.7 yrs	4.9 yrs	3.8 yrs
Additional Revenues with 30-year Loan at 5% (Millions of \$/year) <sup>4</sup>	-\$5.43M	-\$1.25M	\$1.92M	\$0.96M	\$3.45M	\$13.59M	\$18.36M
Credits Available (\$/traveler/weekday) <sup>5</sup>	-\$0.139	-\$0.032	\$0.049	\$0.024	\$0.088	\$0.347	\$0.469
Net Traveler Welfare (\$/average traveler/weekday) <sup>6</sup>	\$0.521	\$0.552	\$0.543	\$0.596	\$0.510	\$0.711	\$0.591

<sup>1</sup>Revenue generated for a year assumes 261 weekdays and 104 weekend days per year, where weekend-day revenues are one half those of regular weekdays.

<sup>2</sup>Net revenue is the difference between total revenue and the sum of maintenance and toll management costs.

<sup>3</sup>Repayment time is the time it takes to pay off an \$80 million loan using all of the net revenues generated by the scenario. Here, a discount rate for future revenues is assumed to be 5%.

<sup>4</sup>Additional revenues are calculated as the difference between the net revenues and the annual (\$5.2 million) payment on an \$80 million, 30-year loan with 5% interest.

<sup>5</sup>Credits available are the amount of credits available to be distributed to travelers per (effective) weekday. This calculation is based on the additional revenues, which is divided by the number of travelers (125,000) and divided by the effective total number of weekdays per year (313).

<sup>6</sup>Net traveler welfare is simply the average welfare effect per traveler, before credits are distributed (as shown in Table 2), plus the credits available per person.

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