Congestion Pricing and Roadspace Rationing: An Application to the San Francisco Bay Bridge Corridor

by

Katsuhiko Nakamura
Toll Road Planning Division
Japan Highway Public Corporation
nak@v007.vaio.ne.jp

and

Kara Maria Kockelman
(corresponding author)
Assistant Professor of Civil Engineering
The University of Texas at Austin
6.9 E. Cockrell Jr. Hall
Austin, TX 78712-1076
kkockelm@mail.utexas.edu
Phone: 512-471-0210
FAX: 512-475-8744

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ABSTRACT:

This paper presents an empirical application of a congestion-alleviation strategy that Daganzo (1995) proposed as a "hybrid between rationing and pricing." This strategy is applied to the San Francisco Bay Bridge corridor, in search of a practical and Pareto-improving solution to the Bridge's congestion. This work relies on a mode-split model for work trips across four different income groups residing in 459 origin zones; it applies an equilibrium analysis based on Bridge performance. Results indicate that modal utilities (and thus choices) are sensitive to the specific combination of toll and rationing rate, as well as to the Bridge's travel-time (or performance) function, and the length of the congested section. Though no combination of tolls plus rationing rates was found to benefit all groups of travelers studies, further investigations may improve upon these results by refining some of the assumptions made here.

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KEY WORDS

congestion pricing, rationing, Pareto-improving policies, San Francisco Bay Bridge

INTRODUCTION

This paper presents an empirical application of a congestion alleviation strategy that Daganzo proposed, a "hybrid between and rationing and pricing" (1995, p. 139). This strategy designates a certain fraction of the traveling population to pay a toll on certain days. In this way, these rotating fractions of drivers are "rationed," though they still may use the link upon payment of a toll. On all other days, they may drive their vehicles without paying a toll.

Daganzo argued that this strategy has the potential to benefit everyone – i.e., be Pareto improving – *without* redistribution of collected tolls. In this paper, Daganzo's strategy is applied to the San Francisco Bay Bridge corridor in search of a practical and Pareto-improving solution to Bridge congestion. Here, monetarized modal disutilities of various traveler groups (as classified by four values of time, 459 origin zones, and 127 destination zones) before and after implementation of such pricing-plus-rationing policies are estimated; this is done by applying nested-logit models of travel demand and computing equilibria travel-time conditions.

The concept of congestion pricing has been studied for several decades. However, in practice, only a few locations have implemented such a policy (e.g., Singapore, State Route 91 in California, and Interstate Highway 15 in San Diego [Small and Gómez-Ibáñez 1998]). A major difficulty of implementing a congestion pricing policy is that, in many cases, travelers and the public are strongly opposed to the idea. If a policy were found which benefits everyone, the public is likely to accept it and a more efficient allocation of roadspace may result.

The basic idea of congestion pricing is that if drivers are charged correctly on overcrowded roads, congestion can be managed to the point at which social welfare is maximized, or at least improved (Hau 1998). From an economic standpoint, the solution is simple: operators must charge road users the difference between marginal cost and average cost. However, conditions allowing first-best solutions (e.g., prices equaling marginal costs in all markets) generally are far too severe for roadway networks (Button and Verhoef 1998). In addition, even if a first-best solution could be determined, the issue of pricing an entire highway network is physically – or at least politically – impractical. Thus, some relaxation of first-best assumptions has to be introduced, leading to "second best" strategies (e.g., imposing tolls on portions of a network and imposing discrete or flat-rate tolls). The strategy applied here is a second-best strategy. Moreover, the traffic-demand during the morning peak period is assumed to be constant. This simplification is due, in part, to a lack of information on the time-varying nature of Bridge traffic demands. (For applications of dynamic models, please see, e.g., Arnott et al. [1994], Bernstein and Sanhouri [1994], and Cetin [2000].)

Implementation of congestion pricing will cause some travelers to change routes, destinations and modes. Though it may increase the overall welfare of a community, there often are people who reluctantly change and end up worse off. An evaluation of specific congestion pricing policies, therefore, needs to recognize the variety of affected individuals. In terms of socioeconomic characteristics, data on income and worker status often are readily available (Litman 1996). And researchers generally find that people with higher incomes have higher values of time. In fact, most U.S. values of time are within the range of 20 to 50 percent of average wages (Small 1983, 1992a, Button 1993, Purvis 1997). The average value of time assumed here is \$9.65/hour (in 1990 dollars), or 46 percent to the wage rate; this is derived from mode-choice models estimated by the Metropolitan Transportation Commission (MTC), the metropolitan planning organization for the San Francisco Bay Area (Purvis 1997).

Without redistribution of tolls and assuming homogeneous users, Richardson *et al.* (1998) argued that everyone loses under congestion pricing. Those remaining on the tolled road have to pay additional costs, and those who shift to non-tolled roads or other facilities will suffer from longer travel times and/or costs. Heterogeneity of individuals changes this scenario. With traveler heterogeneity (via, e.g., varying values of time), many researchers assert that winners are the toll-collecting entity and people with higher values of time (and usually incomes), who enjoy the benefits of reduced travel times on tolled roads (e. g., Hau 1998, Richardson *et al.* 1998, Rietveld and Verhoef 1998, Anderson and Mohring 1997, and Gómez-Ibáñez 1992). Some researchers have concluded that congestion pricing can benefit all groups of people if toll revenue is carefully distributed (e.g., Gillen 1994, Small 1983, and Litman 1996). However, redistribution is fraught with complexities; a Pareto-improving solution that does not require redistribution is very desirable.

RELATED LITERATURE

There are several pieces of existing work that consider the impact of congestion pricing (without rationing) on travelers across a region, and there are a few that discuss congestion on the Bay Bridge. Small (1983, 1992b) estimated effects of congestion pricing in the San Francisco Bay Area and Los Angeles region for various income groups. Without toll redistributions, both cases yielded both winners and losers. In his Bay Area study (Small 1983), travel time reductions were given first, and then corresponding optimal tolls were calculated. On the demand side, a logit model, which incorporated three travel modes (drive alone, bus with walk access, and bus with auto access), was used. Data came from a survey performed before the Bay Area Rapid Transit (BART) system began operation in 1972. On the supply side, a simple, linear formula that related time delay to volume was used. For the Bay Area, Small concluded that low- and medium-income groups emerged as losers in all three cases. When the travel time reductions were small even the high-income group suffered reductions in welfare.

In Small's Los Angeles study (1992b), a charge of 15 cents per vehicle-mile was applied. Winners under this policy were carpool users and transit users who did not change modes under the new toll. All those who kept driving, or changed from driving alone to carpooling, lost some benefits. In both the San Francisco and Los Angeles cases, Small estimated that tolls exceeded disbenefits, so all groups could benefit if tolls were somehow appropriately redistributed.

Frick *et al.* (1996) examined the effects of raising tolls on the San Francisco Bay Bridge. They concluded that, if the toll were raised from $1 to $3 during the three-hour peak period (6 to 9 a.m.), volumes would decrease by 7 percent; this corresponded to an estimated eight-minute reduction in travel times. However, no welfare impacts were assessed in this work.

Mohring (1999) predicted the effects of congestion pricing during the morning peak period by income category in the Twin Cities area (Minneapolis and St. Paul, Minnesota). He calculated marginal costs for each roadway link in the area (20,336 links total), and assumed that the difference of marginal cost and average cost was charged on every link. The result was that only people with incomes above $80,000 enjoyed welfare increases, when the roads were severely congested; this range rose to more than $100,000 when congestion was not too severe.

In Daganzo's work (1995), a fraction of travelers are rationed in their free use of a roadway on particular days; on these days they can use the roadway only if they pay higher tolls than non-rationed people. The rationing fractions are determined systematically so that everyone is equally rationed in a given period. In theory, Daganzo concludes that, under some rather restricted scenarios, *every* group of users can increase its welfare *without* toll redistribution. This is a Pareto-improving solution. According to Daganzo's logic, the conditions for everyone benefiting from such a scheme are determined by rationing rate, tolls charged, travel-time savings on the roadway, and value of time of the *lowest* income group.

Daganzo's strategy is the basis for this work, and his approach is described in more detail under the following section. This work builds on Daganzo's contributions by applying a non-deterministic model of mode choice, incorporating a more elaborate performance (supply) function, and perusing an empirical application to an actual corridor used by a great variety of traveling socioeconomic groups.

THEORY AND METHODOLOGY

Daganzo's (1995) strategy places an extra toll on a group of people; this essentially is quasi-rationing of roadspace. This group changes day by day such that everyone is equally (quasi-) rationed. His strategy also recognizes many socioeconomic classes with different values of time. Daganzo concludes that *under certain value-of-time distributions* and flow-travel time scenarios, an appropriate combination of pricing and rationing could improve everyone's utility.

Daganzo's computations rely on some rather restrictive assumptions. For example, there is only one bottleneck on the route. And, there must be one or more *alternative* mode(s) for bottleneck users whose costs (in time and money) are fixed (independent of demand). Both of these assumptions are maintained here.

Everyone who is a potential user of the bottleneck decides whether he or she will use it, based on its benefits of utility relative to the alternative mode(s). The mode-choice model in Daganzo's approach is deterministic; in other words, the utilities of the travel alternatives have no random components. And it relies on just travel time and travel cost. In contrast, MTC's random-utility nested-logit model of mode choice is used here, and more explanatory variables are incorporated. For existence of a Pareto-improving solution, the difference in these utilities – after implementing a roadway policy – must be positive for all traveler classes.

Another distinction between this work and that of Daganzo (1995) is the performance model used; here they are non-linear, whereas Daganzo's was linear. The following section describes the specific assumptions of the application in detail.

CASE STUDY OF THE SAN FRANCISCO BAY BRIDGE

The San Francisco-Oakland Bay Bridge was chosen for this case study because its transportation situation is highly appropriate for an application of Daganzo's strategy. It links the East Bay Area to San Francisco's very dense central business district. Many people living in the East Bay work in San Francisco and commute via the Bay Bridge and/or transit systems. The Bay Area's bridges are heavily congested during peak hours, and the San Francisco Bay Bridge is the most commonly used bridge for East Bay to San Francisco trips. In parallel, the Bay Area Rapid Transit (BART) rail line connects the East Bay and San Francisco counties, providing an alternative mode that, hypothetically, is not nearly as congestible as the Bridge. (Presently, however, BART does in fact run out of passenger space on many morning trains, due to technical and budget limitations.)

Travel Modes

In 1995, about 240,000 people made trips west-bound on the Bay Bridge every weekday. Nearly a quarter of the trips, 59,000, were concentrated during the morning peak period, between 7 and 9 am (MTC 1995). This same number held in 1990. Of the peak-period person-trips, 52 percent were by private vehicles (either drive alone, shared ride, vanpool, or commercial vehicles), and 48 percent were by transit (either BART, bus, or ferry).

The Bay Bridge is an 8.4 mile-long double-decked toll bridge. Its upper level, with five 11.5-feet-wide lanes, is for westbound trips (Caltrans 2000). A toll is charged only in this westbound direction. In 1990, the toll was one dollar, for all personal vehicles carrying two or fewer persons; this toll was raised to $2 in 1998. The models estimated here are based on 1990 data for the Bay Area Traffic Analysis Zones and transportation network under consideration. The 1990 tolls of $1 are recognized and maintained here; these act as minimum, fixed tolls and are applied to all Bridge users. The peak traffic loads on the Bridge in 1990 (10,339 vph) are used as the reference demand, before implementing a toll-plus-rationing strategy. Capacity for the five lanes is taken to be 10,000 vph.

The alternatives to driving across the Bay Bridge (and paying a toll on one's rationing day) are carpooling, bus, and BART modes. In 1990, BART connected far-away cities such as Fremont (in Alameda County), Concord, and Richmond (both in Contra Costa County) to downtown San Francisco (BART 1991b). That same year BART carried more than 240,000 person-trips per weekday (BART 1991a). Its frequency on the Bay Bridge corridor in 1999 was 24 trains per hour (a headway of 2.5 minutes) during the peak period; it's capacity is about 1,120 passengers per train or 27,000 passengers per hour. BART's maximum and average speeds are 80 mph and 36 mph, respectively (BART 2000). In many corridors and for many commute trips, BART is very competitive with driving. Thus, it may be the most attractive alternative to car commuters when tolls are applied along competing roadways. Unlike carpooling, it (and other forms of transit use) are assumed to be noncongestible here.

Traveling Populations

The only trips considered in this application are home-based work trips from Alameda, Contra Costa, and Solano Counties to San Francisco County. Those who live in these three counties are situated geographically so that it is very likely they will use the Bay Bridge to access downtown San Francisco. Though parts of these counties are far from the bridge and thus have alternative highway routes, the number of people who do not use the Bay Bridge is expected to be low, because the distances of the Bay Bridge route are shorter.

459 traffic analysis zones make up the three counties generating the trips, and 127 San Francisco County zones are used as destinations. Together these zone make up over half of the 1099-zone system used by MTC in its nine-county travel demand models.

Across the origin zones, four different socioeconomic groups are defined by income quartile. The total number of workers making this type of work trip from these three counties is about 95,000, or roughly 17 percent of San Francisco's total workers. The number of such workers in the first income quartile is relatively few (less than 12% of the total).

Demographic and travel data used here come from the 1990 Census of Population and MTC's 1990 Bay Area Travel Survey.

Assumptions

Several important assumptions are implicit in the methods used here. Changes to these may affect the results in significant ways. The most influential assumptions are expected to be the following: (1) Congestion reduction occurs only on the Bay Bridge; (2) All Bridge travel times decrease by the same amount during the morning peak hours (7 am to 9 am); (3) There is no latent demand; (4) The Bridge's time-speed relationship (performance curve) follows either the a

Modified-Updated-BPR formula, Akçelik's formula, or an Updated-BPR formula; (5) The mode choice model used is applicable to all travelers of interest (though the predictive model used was developed from home-based work-trip mode choices for the entire region).

Other, less influential assumptions are the following: (1) Non-Bridge modes are not congestible (i.e., their travel times are fixed); (2)The total number of vehicles on the bridge per hour during the morning commute equals the ratio of vehicle trips predicted before and after (using the MTC mode-choice model) multiplied by the traffic level observed during peak morning hours in 1995 (which is believed to be the same as in 1990)[1]; (3) All commuters from the three East Bay counties to San Francisco County use the Bay Bridge corridor; (4) Only the welfare effects for these workers are computed and presented here (whereas congestion reductions for other populations should add benefits – and tolls will add costs); and (5) Traveler welfare depends only on travel time and cost.

A final assumption has to do with the value of time for each of the traveling populations. This value was taken to be 48% of each quartile's estimated wage, because this corresponds to the rate estimated by MTC, using its 1990 data sets (Purvis 1997). Wages were estimated using Census data on total hours worked and household income earned by each of the quartiles. Note that the average wages for Alameda, Contra Costa, and Solano Counties were estimated to be \$19.07, \$22.65, and \$16.82, respectively, before taxes in 1990.

Models Used

In order to predict modal shifts under various combinations of tolls and rationing, two MTC models were applied (Purvis 1997) and several Bridge performance (or travel time) functions were examined. The first of the MTC models is a nested logit model to predict the number workers and vehicles in a household (across a total of 36 classes). The second was a Home-Based-Work Mode Choice (HBWMC) nested logit model, used to predict mode shares based on income quartile, access times, in-vehicle travel time, travel costs, household size and number of vehicles owned. The five modes considered are drive alone (DA), two-person shared ride (SR2), shared ride with three or more people (SR3+), transit with auto access (TA), and transit with walk access (TW).

For the expression of relationship between travel-flow and travel time, the Bureau of Public Road (BPR) (FHWA 1979) is often used:

BPR formula:

$$t = t_f \times \left[1 + 0.15 \left(\frac{Q}{C} \right)^4 \right]$$

where t = travel time,
t_f = free-flow travel time,
Q = traffic demand, and
C = "capacity".

Singh (1999) argues that this formula is not sufficiently sensitive to demands exceeding capacity. He compares the BPR performance model to an Updated-BPR formula (Skabardonis & Dowling 1997) and Akçelik's formula (Akçelik 1991). These two are the following:

Updated-BPR formula (U-BPR):

$$t = t_f \times \left[1 + 0.05\left(\frac{Q}{C}\right)^{10}\right]$$

Akçelik's formula:

$$t' = t_0 + \left\{0.25T\left[\left(\frac{Q}{C} - 1\right) + \left\{\left(\frac{Q}{C} - 1\right)^2 + \left(8J_a \frac{Q}{C} \Big/ QT\right)\right\}^{0.5}\right]\right\},$$

where t' = average travel time per unit distance (hours/mile),
t_0= free-flow travel time per unit distance (hours/mile),
T = flow period, or the time interval in hours, during which an average arrival rate persists, and
J_a = a delay parameter (0.1 for freeways).

For another, perhaps better model of travel time versus flow, a formula with a slope somewhere between Akçelik's and the Updated-BPR formulae is introduced here, by changing the coefficient of 0.05 in the Updated-BPR formula to 0.02. This formula is referred to here as the "Modified-Updated BPR" formula, and its profile is illustrated in Figure 1.

Modified Updated BPR formula (MU-BPR):

$$t = t_f \times \left[1 + 0.02\left(\frac{Q}{C}\right)^{10}\right]$$

As in the case of BPR and Updated-BPR formulae, the capacity of the Modified-Updated-BPR formula is set to 6,600 vph. Here, the Modified-Updated-BPR, Updated-BPR, and Akcelik's formulae are used for comparison of scenario outcomes. To use these, the Bay Bridge's distance and free-flow speed are set to 8.4 miles and 65 mph. Base "demand" is assumed to be 10,339 vph (the flow observed during the average peak period on the Bay Bridge in 1995). And the base (west-bound) capacity of the bridge is assumed to be 10,000 vehicles per hour (vph), across its five lanes (based on Dittmar *et al.* [1994]).

The BPR and Updated-BPR formulae require that the capacity be set at a level-of-service C limiting flow, or 6,600 vph, which is 66 percent of the base (TRB 1997). A comparison of these models for the Bay Bridge's conditions is shown in Figure 1. Akçelik's formula creates a relatively steep time-vs.-flow dependence, while the BPR formula is more gentle. The slopes of the Updated-BPR and Akcelik's formulae are very close, when demand exceeds 10,000 vph.

After assuming the base demand and performance characteristics, equilibria travel times and traffic flows are estimated via iteration of the model-choice model results and the Bridge's travel time function. Welfare changes are estimated for each traveler based on travel times and costs before and after strategy implementation; these welfare changes are simply weighted by mode-choice probabilities and the travel times are monetarized by a quartile's estimated value of time.[2] These welfare changes of workers living in the three East Bay counties and working in San Francisco are the focus of the results presented here.

RESULTS

A variety of toll-plus-rationing rate scenarios are considered here. The toll levels used are the following: \$0, \$5, \$10, \$15, and \$∞[3]; the extreme case of an infinite toll essentially means no way for one to avoid being rationed off driving the Bridge on his/her rationing day.

The rationing rates examined are the following: 0.1, 0.2, 0.3, and 1.0. The extreme case of 1.0 (100%) rationing is the commonly treated case of pure tolls (everyone must pay, every day). A rate of 0.1 means rationing every fifth workday (i.e., once a week).

When these scenarios are applied, the resulting changes in equilibria travel times (i.e., the resulting travel-time savings on the Bridge) can be significant. Estimates of these (illustrated in Nakamura 2000) suggest that Akçelik's formula produces the highest travel-time savings, while the U-BPR formula produces slightly lower time savings, and the MU-BPR formula yields about half of these savings. As expected, higher tolls and higher rationing rates results in shorter travel times in all scenarios.

Applying Daganzo's condition for a Pareto-improving solution to these scenarios and recognizing the many different traveler classes involved here is estimated to require more than *double* (and sometimes quadruple) the travel-time savings found here. These calculations suggest that it will be very difficult to provide a Pareto-improving policy for this corridor via pricing and rationing, and without redistribution of toll revenues.

Table 1 shows estimated changes in aggregate welfare levels (over workers using the corridor) by income quartile. These accrue under the three distinct performance formulae and across the various toll and rationing scenarios. It is quite interesting that the seemingly Draconian policy of pure rationing is estimated to dominate, improving welfare for all four income quartiles in the aggregate. No tolls are generated under this assumption of pure rationing, but the total monetarized benefits accruing are high. One issue may be the assumption of zero latent demand; such demands may not permit such travel-time savings to actually accrue.

In comparing the three performance functions, the assumption of Akçelik's performs best, in terms of delivering significantly more benefits to workers using this corridor for their commutes. If the Bridge operates according to a MU-BPR performance function, the only group posting any aggregate benefits are those workers in the highest income quartile. Benefits under the U-BPR assumption lie somewhere in between these two.

One might expect lower rationing rates to be associated with higher benefits. And, in comparing the various rationing rates, increased rates appear to have highly negative consequences for the two lowest income groups, across all toll levels and performance functions examine. Workers in the highest income-quartile (i.e., those with the highest value-of-time) do better under most cases of increased rationing, and those in the third quartile sometimes see benefits following a hike in the rationing rate. This general result is quite consistent with the results of congestion-pricing investigations reviewed here, under the section on related literature.

Under all scenarios examined using the U-BPR and Akçelik formulae and having rationing rates less than 100%, estimated net benefits accruing to workers on this corridor are positive. This is rarely the case when the Bridge's performance exhibits the MU-BPR performance characteristics. Yet when toll revenues are included in the computation of net benefits, the results are substantially positive for *all* scenarios examined. This implies that though the utility changes shown here are not Pareto-improving (because aggregate utility changes of the first quartile are all negative, except under pure rationing), there is a potential for everyone benefiting if toll revenues are somehow redistributed to the "losers" under these scenarios.

Table 2 provides a look at *average* gains and losses, reported in 1990 dollars per day per worker. These are largely negative (assuming no redistribution of tolls), except for the pure rationing cases and the overall averages across all four quartiles. These values range from -$4.10 per worker per day (under 100% rationing with a pure toll of $15 for the second income quartile and using a MU-BPR formula for travel times) to +\$6.56 (under pure rationing [toll = $\$\infty$] at 30% for the highest income quartile and using the U-BPR formula).

Another way to assess the results is to consider how many commuters lose a large amount of welfare each workday. As an illustration of this, the fraction of commuters who were expected to endure a loss in welfare of \$1.50 or more each day was significant for almost all of the first three quartiles of commuters under all nine of the 100% rationing (pure toll) scenarios. For the first income quartile, those fractions ranged from 21.7% (in the case of a \$5 toll, using Akçelik's formula) to 55.6% (in the case of a \$15 toll, using the U-BPR formula). The percentage went as high as 67.6%, in the case of the third quartile of commuters, under a \$15 toll and using Akçelik's formula. Figure 2 provides an illustration of the levels of loss and gain sustained by different commuters across each of the four income quartiles. The shading of the horizontal bars suggests the degree of loss/gain. It appears on these three that higher tolls can bring more gain to those in higher income quartiles (i.e., those in higher income quartiles), but also more severe losses to those in lower quartiles.

Finally, it is of interest to what degree congestion benefits elsewhere on the roadway network, particularly, for example, on links leading to and from the Bay Bridge accrue. Nakamura (2000) has approximated such an examination by simply assuming the Bridge to be 50 percent longer. His results suggest even greater benefits and fewer losses, across the subset of four scenarios that he examines.

CONCLUSION

A policy of combining tolls and roadspace rationing has the potential to increase the utility of every group of travelers – without requiring redistribution of toll revenues. An attempt to find such a solution for the San Francisco-Oakland Bay Bridge was performed here, based on actual data and practical formulae. The only Pareto-improving solution estimated under the assumptions used here was that of pure rationing, where the tolls were effectively set at infinity on the days that a commuter was rationed off of driving across the Bridge. The results reveal that welfare estimates are highly sensitive to the assumption of the corridor's travel time or performance function.

Further study may result in more accurate solutions. For example, more realistic performance functions may exist for the Bridge than those used here. And mode-choice models which permit distinct values of time across commuter classes could be used for demand estimation and welfare estimates. Also important are the issues of latent demand and dynamic demand effects, as well as network response and the behaviors of non-Bridge-using travelers. For example, time-varying pricing may diminish negative impacts during the non-peak periods, and may induce large shifts in demand by time of day (Acka-Daza 1998). Behavioral changes under this form of pricing will be difficult to predict, but they may be critical.

The effects of pricing and rationing on the non-peak period are likely to be negative under a fixed toll rate (as used in this study), but these are not considered here. The impacts of such policies on the evening-peak period may be highly positive for many traveler groups, but these are not included either. In total, these impacts might be positive or negative. When combined with time-varying tolls, negative impacts may diminish.

Finally, the need for congestion pricing has increased not only from the perspective of vehicle users, but also from environmental and energy-saving perspectives. It is hoped this study and its extensions will contribute improvements in transportation policy and optimization of transportation systems.

FOOTNOTES

[1] Estimates of the peak-period demand *curve* for the Bay Bridge are not available. And the published counts of "demand" being used here probably represent counts of capacity flows across the Bridge, rather than flows arriving at the back of toll plaza queues. Thus, this application neglects latent demand and may substantially underestimate actual demand levels.

[2] The HBWMC model was not used for a random-utility-consistent logsum measure of expected utilities since it did not distinguish travelers by value of time (its single, implicit value of time was $9.65/hour).

[3] Note that the 1990 base toll of $1 was maintained on all scenarios examined, so the *added* tolls essentially were $0, $4, $9, $14, and $∞. The base toll was kept since it is felt that this influenced the assumed base demand (of 10,339 vph) to a certain extent.

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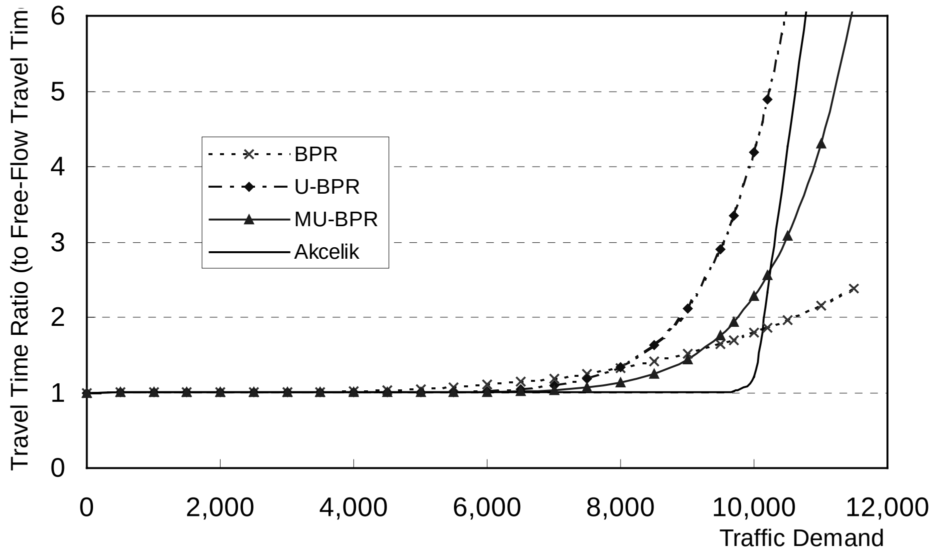
Figure 1. Comparison of Performance Functions: BPR, Updated-BPR, Modified-Upgraded-BPR, & Akçelik's Formulae



Traffic-Travel Time Relationship

Notes: Capacity in BPR, U-BPR, & MU-BPR foumulae is set at 6,600
Capacity in Akcelik's formula is set at 10,000.

Table 1. Aggregate Welfare Changes & Toll Revenues, by Income Quartile & Scenario ($/day)

Modified-Updated-BPR

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	7.3	11.4	13.1	1.3	2.5	3.3	8.6	2.5	4.6	6.4	12.8	3.6	6.5	8.7	13.6
Quartile 1	$4,168	6,621	7,669	-$1,014	-2,112	-3,446	-13,456	-$1,777	-3,892	-6,270	-27,695	-$1,894	-4,410	-7,481	-35,970
Quartile 2	$15,622	25,238	30,063	-$2,237	-4,738	-8,030	-33,156	-$4,003	-9,063	-14,944	-71,364	-$4,174	-10,289	-18,172	-96,430
Quartile 3	$28,232	45,682	54,613	-$2,551	-5,552	-9,954	-44,095	-$4,464	-10,739	-18,419	-98,578	-$4,090	-11,497	-21,954	-135,650
Quartile 4	$38,432	61,051	71,277	$848	1,094	-669	-16,944	$2,023	1,609	-692	-53,331	$4,752	5,074	1,211	-83,410
Total	$86,454	138,592	163,622	-$4,954	-11,309	-22,099	-107,651	-$8,221	-22,085	-40,325	-250,968	-$5,405	-21,122	-46,396	-351,460
Toll Revenue	NA			$18,064	36,344	54,733	187,180	$31,999	64,784	98,186	339,390	$37,486	76,437	116,319	400,090

Akçelik

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	16.5	17.2	17.2	2.4	4.4	6.4	17.0	4.9	9.4	13.9	17.2	7.2	14.1	17.1	17.2
Quartile 1	$9,721	10,165	10,163	-$429	-1,115	-1,843	-9,774	-$518	-1,447	-2,573	-26,508	-$24	-627	-3,606	-35,580
Quartile 2	$34,298	37,063	38,346	-$212	-1,266	-2,420	-19,220	$376	-469	-1,794	-66,124	$2,351	3,104	-4,139	-93,710
Quartile 3	$61,259	66,528	69,184	$1,067	662	110	-18,591	$3,374	4,709	5,332	-88,448	$7,608	12,664	3,579	-129,860
Quartile 4	$86,246	91,129	92,231	$6,128	10,206	14,156	21,928	$13,523	24,504	34,868	-36,529	$21,992	41,201	40,010	-72,530
Total	$191,524	204,885	209,924	$6,555	8,487	10,003	-25,657	$16,754	27,297	35,834	-217,609	$31,928	56,343	35,844	-331,680
Toll Revenue	NA			$18,163	36,686	55,567	194,500	$32,448	66,575	102,370	347,300	$38,395	80,270	122,670	409,150

Updated-BPR

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	13.6	24.7	31.3	2.1	4.4	6.4	15.8	4.2	7.8	11.3	28.7	6.1	11.5	16.4	33.5
Quartile 1	$7,912	15,070	19,590	-$589	-1,115	-1,843	-10,340	-$889	-2,278	-3,894	-22,845	-$603	-1,961	-3,945	-32,903
Quartile 2	$28,250	53,320	69,070	-$766	-1,266	-2,420	-21,293	-$912	-3,380	-6,467	-50,654	$333	-1,592	-5,355	-78,383
Quartile 3	$50,582	94,910	122,960	$76	662	110	-22,375	$1,069	-518	-3,095	-58,865	$3,992	4,207	1,372	-98,290
Quartile 4	$70,791	132,070	169,580	$4,683	10,206	14,156	16,172	$10,142	16,759	22,260	11,918	$16,664	28,564	36,662	-15,321
Total	$157,535	295,370	381,200	$3,404	8,487	10,003	-37,836	$9,410	10,583	8,804	-120,446	$20,385	29,219	28,734	-224,897
Toll Revenue	NA			$18,136	36,686	55,567	193,472	$32,317	65,979	100,920	368,110	$38,118	78,960	122,140	449,780

Table 2. Average Per-Traveler Welfare Changes, by Income Quartile and Scenario ($/day)

Modified-Updated-BPR

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	7.3	11.4	13.1	1.3	2.5	3.3	8.6	2.5	4.6	6.4	12.8	3.6	6.5	8.7	13.6
Quartile 1	$0.37	0.59	0.69	-$0.09	-0.19	-0.31	-1.20	-$0.16	-0.35	-0.56	-2.48	-$0.17	-0.39	-0.67	-3.22
Quartile 2	$0.66	1.07	1.28	-$0.10	-0.20	-0.34	-1.41	-$0.17	-0.39	-0.64	-3.04	-$0.18	-0.44	-0.77	-4.10
Quartile 3	$0.84	1.37	1.63	-$0.08	-0.17	-0.30	-1.32	-$0.13	-0.32	-0.55	-2.95	-$0.12	-0.34	-0.66	-4.06
Quartile 4	$1.44	2.29	2.67	$0.03	0.04	-0.03	-0.64	$0.08	0.06	-0.03	-2.00	$0.18	0.19	0.05	-3.13
Average	$0.91	1.46	1.73	-$0.05	-0.12	-0.23	-1.14	-$0.09	-0.23	-0.43	-2.65	-$0.06	-0.22	-0.49	-3.71

Akçelik

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	16.5	17.2	17.2	2.4	4.4	6.4	17.0	4.9	9.4	13.9	17.2	7.2	14.1	17.1	17.2
Quartile 1	$0.87	0.91	0.91	-$0.04	-0.10	-0.17	-0.88	-$0.05	-0.13	-0.23	-2.37	-$0.00	-0.06	-0.32	-3.19
Quartile 2	$1.46	1.58	1.63	-$0.01	-0.05	-0.10	-0.82	$0.02	-0.02	-0.08	-2.81	$0.10	0.13	-0.18	-3.99
Quartile 3	$1.83	1.99	2.07	$0.03	0.02	0.00	-0.56	$0.10	0.14	0.16	-2.65	$0.23	0.38	0.11	-3.89
Quartile 4	$3.23	3.42	3.46	$0.23	0.38	0.53	0.82	$0.51	0.92	1.31	-1.37	$0.82	1.54	1.50	-2.72
Average	$2.02	2.16	2.22	$0.07	0.09	0.11	-0.27	$0.18	0.29	0.38	-2.30	$0.34	0.59	0.38	-3.50

Updated-BPR

Total Toll	$∞ (Rationing Only)			$5				$10				$15			
Rationing Rate	0.1	0.2	0.3	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0	0.1	0.2	0.3	1.0
Travel Time Savings (min.)	13.6	24.7	31.3	2.1	4.4	6.4	15.8	4.2	7.8	11.3	28.7	6.1	11.5	16.4	33.5
Quartile 1	$0.71	1.35	1.75	-$0.05	-0.10	-0.17	-0.93	-$0.08	-0.20	-0.35	-2.05	-$0.05	-0.18	-0.35	-2.95
Quartile 2	$1.20	2.27	2.94	-$0.03	-0.05	-0.10	-0.91	-$0.04	-0.14	-0.28	-2.16	$0.01	-0.07	-0.23	-3.33
Quartile 3	$1.51	2.84	3.68	$0.00	0.02	0.00	-0.67	$0.03	-0.02	-0.09	-1.76	$0.12	0.13	0.04	-2.94
Quartile 4	$2.65	4.95	6.36	$0.18	0.38	0.53	0.61	$0.38	0.63	0.83	0.45	$0.62	1.07	1.37	-0.57
Average	$1.66	3.12	4.02	$0.04	0.09	0.11	-0.40	$0.10	0.11	0.09	-1.27	$0.22	0.31	0.30	-2.37

Figure 2. Share of Zones by Average Changes in Individual Welfare