U.S. HIGHWAY PRIVATIZATION AND MOTORISTS' HETEROGENEOUS PREFERENCES

Clifford Winston
Brookings Institution

Jia Yan
Washington State University

November 2008

Introduction

U.S. highways are experiencing a "perfect storm:" traffic congestion and delays are imposing ever greater costs on motorists and shippers; poorly maintained roads and bridges continue to damage vehicles and pose threats to travelers' safety; and for the first time since the Highway Trust Fund was created in 1956, the portion that finances federal highway expenditures is running a deficit.[1]

Highways' poor service quality and financial problems can be attributed to inefficient public policies, including the failure to charge appropriate prices for congestion and pavement damage, suboptimal road design and maintenance practices, and regulations that increase production costs (Winston (2000)). Efficient policies that would improve highway performance seem politically intractable because they would threaten long-standing subsidies to road users, rents to suppliers of highway capital and labor, and demonstration projects that improve politicians' re-election prospects.

When federal regulators were unable to solve significant economic problems in the intercity transportation system, they turned to markets for help by deregulating intercity modes' economic operations. As it has become clear that the public sector needs a large infusion of money to maintain and expand the highway system, it has turned to the private sector for assistance by forming so-called public-private partnerships (PPPs). But these partnerships are business deals that are intended to yield an acceptable rate of return for the firms(s) that invest in infrastructure and to provide budgetary relief for the government.[2] PPPs are not motivated by

---

[1] Some money in the trust fund is allocated to public transit.

[2] Recent examples of PPPs include the Chicago Skyway, Indiana toll road, and the proposed Texas Trans-Corridor; high-occupancy-toll (HOT) lanes in California, Texas, and the

policymakers' desire to reform highway policy to improve highway performance. Thus, they are not necessarily the first step toward a market solution—namely, privatization—or even an accurate preview of privatization's economic effects because the contract between the private firm and the government may be poorly structured (Engel et al. (2007)).

In this paper, we present exploratory empirical evidence on the economic effects of highway privatization by developing a stylized model where responsibility for providing highway services is transferred from the public sector to a private firm(s). Given the intractability of reforming public provision, privatization—while representing dramatic institutional change—may be the only hope for operating and maintaining the nation's $2.5 trillion road system more efficiently. Privatization may also be timely because the public sector is not needed to finance vast expansions of the road network; any new capacity that is added in the foreseeable future will represent a tiny fraction of the current network.

We analyze the fundamental tradeoff that is typically associated with privatization—the efficiency gains from private provision versus the potential welfare loss from market power (Vickers and Yarrow (1991))—and explore various factors that may improve the tradeoff for road users and address the system's long-run problems. We find that highway privatization can benefit road users, although they are currently subsidized under public provision because they are not charged for contributing to congestion, and increase social welfare. The key to privatization's success is that road users have heterogeneous preferences for highway service—travel speed and reliability—and through negotiations a private operator(s) may respond to those preferences in ways that public highway authorities have not.

Washington, D.C. metropolitan area; and the Dulles-Greenway private toll road and a proposed private toll road in Pennsylvania.

Background Literature

Our assessment of privatization is based on travel on a major limited-access state highway in California used heavily by long-distance commuters, but it could also apply to a federal highway. The "price" of travel on most federal and state highways is the gasoline tax, which does not vary with traffic congestion.

Knight (1924) injected a constructive role for privatization by arguing that a private road would set an optimal congestion toll if it faced competition from an alternative free (public) road. Friedman and Boorstin (1951), early advocates of privatization, suggested that the government should account for unfair competition by rebating fuel tax revenues generated by motorists driving on the free road to the private road owner. Even if the rebate does not occur, Viton (1995) found that a private road would be financially viable when competing against a public road for most types of road users. Edelson (1971) qualified Knight's result by showing that it holds in the special case that all travelers—including those using a transit alternative to the private road—have the same value of time. If travelers differ in their value of time, the toll could result in too much or too little congestion. De Palma and Lindsey (2000, 2002) and Calcott and Yao (2005) conclude that private operators have incentives to introduce time varying tolls in alternative competitive settings. In sum, previous literature suggests that highway privatization could lead to the adoption of congestion pricing, but pricing's efficiency and distributional effects are likely to depend on competitive alternatives to the private road, the heterogeneity of travelers' preferences, and how the government allocates gas tax revenues.

Although the evidence is circumstantial, recent assessments broadly suggest that highway efficiency in the United States would improve if a private road operator replaced a public authority. Roth (2005) reports that officials in the U.S. Department of Transportation estimate federal regulations raise highway project costs 20-30 percent. Poole and Samuel (2008) find that the share of toll revenues consumed by operating and maintenance costs is 43 percent for U.S. public toll roads and 23 percent for U.S. private toll roads. There are examples of reasonably low-cost public toll roads with a high cost/revenue ratio because tolls have been too low (e.g., the West Virginia Turnpike has not increased its tolls since 1989); but there are also examples of private operators whose tolls have been kept down by government caps (e.g., the Indiana Toll Road).[3] Finally, evidence from emergency highway repairs following an earthquake in 1994 that destroyed a bridge on Interstate 10 in Santa Monica and a gasoline tanker crash in 2007 that severely damaged a freeway ramp in Oakland indicates that economic incentives substantially reduce the time it takes the private sector to complete highway projects.

It is debatable whether the public sector's cost of capital in highway services is higher or lower than the private sector's cost of capital. In any case, Congress has recently introduced two measures that could reduce a private highway firm's cost of capital. First, the Transportation Infrastructure Finance and Innovation Act of 1998 established a new federal credit program under which the U.S. Department of Transportation may provide a private firm with tax exempt debt. Second, as part of the 2005 Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, state agencies that work with private highway firms may issue tax exempt bonds on behalf of the project.

Model

We consider a multiple-lane highway that is transferred fully or in part to a private firm(s). The highway can be partitioned into two parallel routes, $r1$ and $r2$, connecting the same

---

[3] We are grateful to Peter Samuel for this point.

origin and destination. A common example of the network is a carpool lane(s) and general purpose lane(s) that comprise highways in many U.S. metropolitan areas. Privatization could arise, for example, if as is often the case in California, the carpool lanes do not meet minimum federal standards requiring average peak-period speeds of 45 miles per hour and the state decides to allow a private firm to purchase the lanes, set prices, and presumably improve highway speeds. Competitive options include allowing the private firm to also purchase the general purpose lanes (monopoly); allowing a different private firm to purchase the general purpose lanes (duopoly); and allowing the government to operate the general purpose lanes as a free road or a toll road (public-private competition).

In the case of monopoly or duopoly we do not impose any price regulations, but we draw on the experience from surface freight deregulation (Winston (1998)) and improve consumers' bargaining power (and welfare) by allowing a third party, such as the American Automobile Association, to negotiate contracts with a private highway operator to determine tolls for road users. Because a bilateral monopoly arises, we consider a range of toll outcomes.

Privatization therefore consists of the government selling, not leasing, one or both routes to a private firm(s) for a one time payment to the government with all risk transferred to the firm(s). A private highway owner(s) is assumed to set profit maximizing tolls or tolls that are determined through bargaining. We do not consider the contracting problems that have been identified in public-private partnerships, where private firms bid to operate a highway for a fixed period of time. Engel et al. (2001) have developed a "least present value auction," where the firm that proposes the lowest present value of revenues is given the highway franchise and allowed to collect toll revenues until that present value is reached. The franchise then ends and the roads revert to the public sector. Engel et al. (2003) point out that renegotiation of highway franchises reduced their benefits in Latin America, and Engel et al. (2006) argue that franchise contracts for private toll roads in the United States during the 1990s were flawed because they did not adapt to demand realizations.

Turning to road users, we capture their heterogeneous preferences for highway services by using a demand model that accounts for the variability in the value of travel time and travel time reliability. Motorists are assumed to make the discrete choice of whether to travel and conditional on traveling, to make the discrete choice of route ($r1$ or $r2$) and vehicle occupancy (solo driving or carpooling) that maximizes the utility of their trips. Finally, because a federal trust fund is not necessary to finance (private) roads, we consider the effects of suspending (or simply rebating) the state and federal gasoline tax that motorists pay when both routes are privatized. Apparently, Arizona's 1991 private tollways law was the first to offer motorists the opportunity to receive a refund of gasoline taxes paid for miles driven on a private tollway. In what follows, we develop our empirical specification of highway demand, costs, and equilibrium.

Demand. Let Ω={0,1,…,J} denote the choice set facing a potential road user, where alternative 0 is the outside choice of not traveling and alternatives 1–J represent the different combinations of routes and vehicle occupancy.

The utility of individual *i* choosing alternative 0 is:

$$U_{i0} = \delta_0 + \varepsilon_{i0} \quad , \tag{1}$$

where the traveler's utility from not traveling is divided into a mean δ_0, which is constant for all motorists, and a random deviation ε_{i0}. The utility of individual *i* choosing alternative *j* is:

$$U_{ij} = \alpha_i P_j + \eta_i T_j + \phi_i R_j + X_j B_i + \varepsilon_{ij} \, , j>0 \; , \tag{2}$$

where P_j is the price of the alternative and α_i is the individual's preference for price; T_j is the travel time of the alternative and η_i is the individual's preference for travel time; R_j is the travel time uncertainty of the alternative and ϕ_i is the individual's preference for time uncertainty; X_j is a vector of observed exogenous attributes of alternative j and B_i are the individual's preferences for those attributes; and ε_{ij} is a random deviation which is independent of the observed attributes.

We assume N potential travelers consider using the highway. Each individual i in the sample is drawn from this population. To account for the heterogeneity in travel preferences, we assume the coefficients of equation (2) are normally distributed, conditional on an individual's observed profile denoted by Z_i; hence,

$$\Theta_i \equiv (\alpha_i, \eta_i, \phi_i, B_i)' \sim N(Z_i \boldsymbol{\gamma}, \Sigma), \tag{3}$$

where Σ is a diagonal variance matrix, and $\boldsymbol{\gamma}$ is a vector of parameters to be estimated.

We specify the joint distribution of $\varepsilon_i \equiv (\varepsilon_{i0}, \varepsilon_{i1}, ..., \varepsilon_{iJ})$ by the Generalized Extreme Value distribution; thus, the market share of an alternative has the nested-logit form where all the travel choices (route and vehicle occupancy) are in one nest with a similarity parameter λ and the choice of whether to travel is in another nest. This specification captures the idea that the substitution pattern between any two travel choices is likely to be different from the substitution pattern between traveling and not traveling.

The preceding assumptions imply that the share of choice alternative j is given by:

$$S_j = \int_{\Theta_i} S_{ij}(\Theta_i) \cdot f(\Theta_i | Z_i) d\Theta_i, \tag{4}$$

where $f(\Theta_i | Z_i)$ is the normal density function of Θ_i;

$$S_{ij}(\Theta_i)=\frac{e^{\left(\alpha_i P_j+\eta_i T_j+\phi_i R_j+X_j B_i\right)/\lambda}}{e^{\lambda D_i}}\cdot\frac{e^{\lambda D_i}}{e^{\delta_0}+e^{\lambda D_i}} \tag{5}$$

is the share conditional on the values of the normal random variates, and

$$D_i=\ln\sum_j e^{\left(\alpha_i P_j+\beta_i T_j+\phi_i R_j+X_j B_i\right)/\lambda} \tag{6}$$

is the inclusive value of the travel choices. The conditional share of individuals who do not travel is

$$S_{i0}=\frac{e^{\delta_0}}{e^{\delta_0}+e^{\lambda D_i}}\,. \tag{7}$$

The volume of traffic that is generated by individuals who choose a travel alternative j with vehicle occupancy O_j is $V_j\equiv\dfrac{N\cdot S_j}{O_j}$.

Demand model parameters. The values of the parameters of the route-vehicle occupancy choice model (equation (2)) are obtained from Small, Winston, and Yan (2006), hereafter SWY. SWY conducted surveys in 1999 and 2000 to analyze motorists' behavior on California State Route 91, a major limited-access expressway used heavily by long distance commuters. A ten-mile stretch in Orange Country includes four free lanes and two express lanes in each direction. Travel times were obtained from field measurements at many different times of day, corresponding to the travel periods covered by the surveys.

Motorists who wish to use the express lanes must set up a financial account and carry an electronic transponder to pay a toll, which varies hourly according to a preset schedule. Carpools or three of more people could use the express lanes during the period of the surveys at a 50 percent discount. Unlike the regular lanes, the express lanes have no entrances or exits between their end points. SWY analyzed the determinants of three simultaneous decisions by motorists: 1) whether to acquire a transponder, which gives them the flexibility to use the express lanes whenever they desire; 2) whether to travel on the express toll or free lanes for their trip; and 3) how many people to travel with in their vehicle: solo, carpool with another person (HOV2), or carpool with at least two other people (HOV3).[4]

We modify the SWY choice model for our purposes by setting the preference parameter for a transponder to zero because all travelers are assumed to have a transponder to travel on the tolled highway. We also set the preference parameter associated with lane choice to zero because the two routes under consideration are assumed to be homogeneous; travelers choose between them based on the toll, travel times, and travel time uncertainties.

The coefficients of the utility function based on motorists' choices among six alternative combinations of route (free or tolled) and vehicle occupancy (solo, HOV2, or HOV3) are shown in table 1.[5] The toll (price) coefficient enters the specification separately and is interacted with household income; travel time, measured at the median value, is interacted with a cubic function of trip distance; and travel time uncertainty, measured as the difference between the 80th and 50th percentiles of the distribution of travel times, enters separately. The interactions for the toll and travel time variables capture observed heterogeneity among travelers. The HOV2 and HOV3 dummies indicate (negative) preferences for carpooling, and additional observed heterogeneity is indicated by interactions among certain socioeconomic characteristics and a carpool dummy. Finally, the model captures unobserved heterogeneity with random coefficients, assumed to be

---

[4] The three choices are assumed conditional on mode choice (car versus public transport), residential location, and time of day of travel.

[5] The coefficients are from table 3 of SWY but rescaled using the scale parameter of the Brookings RP (revealed preference) sample, which is used in our simulations.

normally distributed, for travel time, travel time uncertainty, and the HOV2 and HOV3 dummies.

We define the value of travel time (VOT) and value of reliability (VOR) as the ratios of the marginal utilities of travel time and travel time uncertainty to the marginal utility of money cost. Given our specification of utility in equation (2), the values are expressed as

$$VOT = \frac{\eta_i}{\alpha_i} \tag{8}$$

$$VOR = \frac{\phi_i}{\alpha_i} \ . \tag{9}$$

Table 2 presents these values and shows that motorists, on average, have a high value of travel time and reliability, indicating that highway service quality is important to them. At the same time, motorists exhibit a wide range of preferences for speedy and reliable travel, as the total heterogeneity in the value of time and the value of reliability (uncertainty) is roughly aligned with or exceeds the corresponding median value.

We also need to calibrate the three parameters that relate to the outside choice of whether to travel—population size of potential travelers (N), the mean utility of the outside choice (δ_0), and the similarity of the travel choices (λ). A further consideration is that private highways are assumed to be funded solely by toll revenues. Currently, U.S. highways are mainly funded by federal and state gasoline taxes, averaging \$0.49 per gallon. We assume that motorists do not have to pay these taxes when the highway is privatized, which is equivalent to assuming a 10%-15% decrease in gasoline prices at current prices. In the context of our nested-logit model where travelers first decide whether to travel and then choose a route-vehicle occupancy alternative, lower gasoline prices mainly affect the decision of whether to travel and can therefore be captured by expanding the specification of the parameter δ_0 in the choice model.

We specify δ_0 as a linear function of the operating cost of driving (C), which includes fuel costs as the main component:

$$\delta_0 = \bar{\delta} + \hat{\delta} \cdot C . \tag{10}$$

The average operating cost of driving in the U.S. is about \$0.40 per mile (Langer and Winston (2008)). Given the average gas mileage for new and used vehicles in the United States is about 15 to 17 miles per gallon (www.nhtsa.gov), elimination of the gasoline tax implies that operating costs would decline \$0.03 to \$0.04 (per mile) or roughly 10%.

To calibrate the four parameters $(N, \lambda, \bar{\delta}, \hat{\delta})$, we follow SWY and choose λ as small as possible without causing numerical instability because we expect the travel alternatives to be much closer alternatives to each other than to not traveling.[6] We calibrate the other parameters to generate travel conditions that are consistent with previous evidence on travel conditions on SR 91: namely, travel times on the free (untolled) lanes are 20 minutes; the elasticity of travel with respect to the full cost of travel (including the toll and the value of travel time and unreliability) is -0.36; and the elasticity of travel with respect to the operating cost of driving is -0.3.[7]

Costs. The cost side of our model consists of travelers' time costs and the firm's production costs. Travel time on route $r \in (r1, r2)$ is determined by the Bureau of Public Roads formula used by many researchers:

---

[6] We set λ =0.2 and found in sensitivity tests that alternate values did not have much effect on the main findings.

[7] The operating cost elasticity of -0.3 is consistent with long-run estimates reported in Mannering and Winston (1985); the short-run operating cost elasticity estimate is roughly -0.2. Sensitivity analyses indicated that are our central findings are not particularly sensitive to the assumed values of the elasticities.

$$T_r = t_f \cdot \left(L_r + 0.15 \cdot \left(\frac{V_r}{K_r} \right)^4 \right), \tag{11}$$

where T_r is the travel time on route r; t_f is the travel time under free-flow conditions; L_r is the length of the route r; $V_r \equiv \sum_{j \in \Omega_r} V_j$ is the traffic volume on route r and Ω_r is the subset of travel choices involving travel on route r; and K_r is the capacity of the route. As in SWY, we specify travel time uncertainty on route r as a constant fraction of travel time delay (travel time minus free-flow travel time):

$$R_r = 0.3785 \cdot T_r, \tag{12}$$

where the fraction is based on travel on the free lanes averaged over 5:00a.m. to 9:00a.m.

When a highway is privatized, a firm purchases it from the government. The firm's production cost includes the initial fixed cost to acquire the infrastructure and the variable costs to maintain the facility's pavement. According to the U.S. Federal Highway Administration (2000), marginal pavement costs for automobile traffic on an urban interstate highway are \$0.001 per vehicle mile. We do not include heavy trucks in this analysis, but it is useful to note that their marginal pavement costs range from \$0.01 per vehicle mile to \$0.40 per vehicle mile, depending on the truck's weight and axle configuration. Based on the evidence summarized earlier, we assume that pavement maintenance costs are reduced 20% under privatization and specify them as:

$$PC_r = 0.0008 \cdot V_r \cdot L_r. \tag{13}$$

Because the road is already built and the private operator is assumed to own and operate the highway forever, we can ignore the initial fixed cost paid by the private operator to the government to acquire the highway. The fixed cost is important when the private firm owns and operates the highway for a finite period—as is the case for recent public-private partnerships—because the firm may not be able to raise enough money to recover this cost.

Equilibrium. The objective of a private highway operator is to charge prices (tolls) that maximize the present value of its future profits. Because current pricing decisions are not likely to affect future decisions, we can express the dynamic problem as a series of identical static problems. The analysis of the static problem can be formulated as a two-stage game: in the first stage, the operator sets prices to maximize its objective; in the second stage, travelers choose alternatives to maximize their utilities given road prices and those choices determine highway travel times and travel time uncertainties. Equilibrium of the game is then a *subgame perfect equilibrium* (SPE) and we characterize it by backward induction.

Because the number of travelers is large, each traveler behaves as both a price taker and a traffic flow taker. Thus, the equilibrium of the subgame at the second stage is a *Wardrop Equilibrium* (Wardrop (1952)), which can be obtained as the limit of a sequence of *Nash Equilibira* of games as the number of players goes to infinity (Haurie and Marcotte (1985)). Denote p_j as the price of alternative *j* and $p \equiv (p_1, ..., p_J)$ as the price vector; the market share vector $S^*(p) \equiv (S_1^*(p), ..., S_J^*(p))$ denotes the Wardrop Equilibrium given $p \geq 0$. In the appendix, we show that a unique Wardrop Equilibrium exists for a price vector $p \geq 0$.

Policy Scenarios

We consider alternative highway privatization policies that generate different competitive situations in the first stage of the game.

Monopoly provision. Both routes are sold to a private firm that determines how road capacity is allocated (K_{r1}, K_{r2}) and charges prices (p_{r1}, p_{r2}) to maximize profits:

$$\pi(p_{r1}, p_{r2}, K_{r1}, K_{r2}) = \sum_{m\in(r1,r2)} V_m(p_{r1}, p_{r2}, K_{r1}, K_{r2}) \cdot p_m - \sum_{m\in(r1,r2)} PC_m(p_{r1}, p_{r2}, K_{r1}, K_{r2}) \ , \quad (14)$$

where $V_m(p_{r1}, p_{r2}, K_{r1}, K_{r2})$ is the traffic volume and $PC_m(p_{r1}, p_{r2}, K_{r1}, K_{r2})$ is the pavement cost on route m at the Wardrop equilibrium given the tolls and capacity allocation.

We state the profit maximization problem as

$$\begin{aligned} &\underset{(K_{r1}, K_{r2}, p_{r1}, p_{r2})}{Max} \quad \pi(p_{r1}, p_{r2}, K_{r1}, K_{r2}) \\ &s.t. \ \ p_{r1}, p_{r2} \geq 0 \\ &\qquad K_{r1} + K_{r2} = K \ , \end{aligned} \quad (15)$$

where p_{r1} and p_{r2} are the tolls charged on the two routes; the price of alternative j is obtained by dividing the toll by vehicle occupancy; and K is total capacity of the highway. The solution $(K^*_{r1}, K^*_{r2}, p^*_{r1}, p^*_{r2})$ along with the Wardrop Equilibrium $S^*(K^*_{r1}, K^*_{r2}, p^*_{r1}, p^*_{r2})$ is the equilibrium of the overall game.

The problem in equation (15) assumes that travelers have no negotiating power in setting tolls; thus, solutions of the problem represent an upper bound for tolls under monopoly provision. A more general formulation recognizes that tolls could be set through negotiations between travelers, represented by a third party such as the American Automobile Association, and the firm. The problem then becomes

$$\begin{aligned} &\underset{(p_{r1}, p_{r2}, K_{r1}, K_{r2})}{Max} \quad \omega \cdot CS(p_{r1}, p_{r2}, K_{r1}, K_{r2}) + (1-\omega) \cdot \pi(p_{r1}, p_{r2}, K_{r1}, K_{r2}) \\ &s.t. \ p_{r1}, p_{r2} \geq 0 \\ &\quad \pi(p_{r1}, p_{r2}, K_{r1}, K_{r2}) \geq 0 \\ &\quad K_{r1} + K_{r2} = K \end{aligned} \quad (16)$$

where $CS(p_{r1}, p_{r2})$ indicates consumer surplus and $\omega \in [0,1]$ represents the bargaining power of the travelers; $\omega = 0$ yields the pure monopoly solution given above and $\omega = 1$ yields the "consumers' " solution, which is the other extreme outcome in the bilateral negotiation—namely, tolls maximize travelers' consumer surplus subject to the firm earning non-negative profits.

Following Choi and Moon (1997), consumer surplus for the nested logit model of demand is expressed as

$$CS\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right) = \sum_i \frac{1}{\tau_i} \ln\left[e^{\delta_0} + e^{\lambda D_i}\right], \qquad (17)$$

where τ_i is the individual's marginal utility of income determined from the coefficient of the price variable in equation (2) using Roy's identity, and D_i is the inclusive value given in equation (6) with travel times and travel time uncertainties at the Wardrop Equilibrium given the tolls and allocation of highway capacity.

Duopoly provision. In this scenario, the highway is partitioned into two routes with equal capacities that are operated by competing private firms. The profit function of the operator on route $r \in (r1, r2)$ is

$$\pi_r\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right) = V_r\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right) \cdot p_r - PC_r\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right). \qquad (18)$$

When the firms engage in Bertrand competition and set tolls simultaneously, the operator of route $r1$ solves:

$$\begin{aligned} &\underset{p_{r1}}{Max} \quad \pi_{r1}\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right) \\ &s.t.\, p_{r1} \geq 0 \end{aligned} \qquad (19)$$

The solution of the problem, denoted by $p_{r1} = f_{r1}\left(p_{r2}\right)$, is the toll schedule with respect to p_{r2}.

The operator of route $r2$ solves:

$$\begin{aligned} &\underset{p_{r2}}{Max} \quad \pi_{r2}\left(p_{r1}, p_{r2}, K_{r1}, K_{r2}\right) \\ &s.t.\, p_{r2} \geq 0 \end{aligned} \qquad (20)$$

The solution of the problem, denoted by $p_{r2} = f_{r2}\left(p_{r1}\right)$, is the toll schedule with respect to p_{r1}.

The Bertrand-Nash equilibrium of duopoly price competition is determined by the intersection of the two response functions.

When the two firms engage in Stackelberg competition and set tolls sequentially (without loss of generality, we assume that the operator of route $r2$ is the leader), the operator of $r1$ still solves the problem given in equation (19), and the operator of route $r2$ solves the problem in equation (20) but with an additional constraint of $p_{r1} = f_{r1}(p_{r2})$. We can also account for bargaining in the duopoly context, in which case the objective function of the firms is the weighted sum of consumer surplus and each firm's (non-negative) profits, with the weights indicating motorists' bargaining power.

Public-private provision. In this case, the private firm purchases one of the routes and the government continues to operate the other route (without loss of generality, we assume that route $r1$ is privatized). The government first determines the capacity to privatize (K_{r1}); price competition then evolves in two alternative ways: 1) the private and public operators set tolls simultaneously; 2) the government sets the toll on route $r2$ first. Both cases correspond to those in private duopoly competition with the only difference that the objective function of the public operator is to maximize net benefits, given by consumer surplus and its operating "profit." We assume in this case that the government eliminates the gas tax. Finally, the government could continue to charge a gasoline tax and not charge a toll on its portion of the highway.

Findings

In the simulations, we make the standard assumption that road capacity is 2,000 vehicles per lane per hour, which yields 12,000 vehicles per hour for the six-lane freeway under consideration. In the base case scenario, we assume no tolls are charged and that travel time on the highway is 20 minutes implying a speed of 30 miles per hour, which is approximately the travel speed on the SR91 free lanes during the afternoon rush hour. Based on our equilibrium model of supply and demand, we simulate the economic effects of alternative privatization scenarios. For each, we calculate tolls, travel times, choice shares, revenue, and the change in maintenance costs, consumer surplus, and social welfare.

We generally do not focus on how the government's welfare—that is, its budget—is affected by privatization. The government does receive less revenue when the gasoline tax is eliminated; but this revenue contributed to the highway trust fund, which the government no longer uses to finance highway expenditures. As discussed in Winston and Langer (2006), the allocation of expenditures among states from this fund is inefficient because, among other things, it is based on a formula that places an insufficient weight on traffic congestion in a state. In our case, the gas tax revenues paid by motorists exceed the maintenance expenditures attributable to motorists' use of the road, and we perform a sensitivity analysis to show how our findings are affected when we assume the government's budget only consists of these items. But this ignores the typical case where both cars and trucks use the highway; as noted, the pavement damage caused by trucks is much greater than the damage caused by cars. And the gas taxes paid by trucks do not cover the pavement costs incurred by truck traffic (Small, Winston, and Evans (1989)). Thus, by not including trucks in the analysis, we are likely to understate the improvement in the government's budget from privatization. Finally, we do not account for the admittedly uncertain lump sum payment that the government receives from a private firm that purchases the highway.

Monopoly. As shown in table 3, we find that transferring the highway from the public sector to a private firm reduces social welfare because the highway operator maximizes profits by setting a very high toll that significantly reduces travel times, but significantly increases the share of motorists who do not travel on the road. The large volume of toll revenues fails to offset the loss in consumer surplus and the monopolist has little incentive to differentiate highway services, which would benefit users given their heterogeneous preferences, because the traffic is substantially reduced.[8] In fact, most motorists who continue to use the highway form carpools.

Privatization raises social welfare when motorists are no longer charged a gasoline tax. As noted, eliminating the gas tax affects the decision to travel and in equilibrium results in more travel and greater highway revenues that offset the loss in consumer surplus. The gain in social welfare is only modestly reduced when we account for the change in the government's budget, assuming that it only consists of tax revenues and maintenance costs attributable to motorists.

As we have learned from the public sector's reluctance to adopt congestion pricing, any proposed change in highway policy is unlikely to gain widespread political support if, on average, it harms motorists. Privatization can potentially gain public support by benefiting motorists, on average, if policymakers draw on U.S. experience with surface freight deregulation and encourage transportation users and suppliers to negotiate prices. For example, certain railroad shippers have been able to obtain lower prices by organizing into a bargaining unit and allowing a third-party logistics firm to negotiate prices for them (Winston (1998)). A similar practice could develop in a private highway market, where motorists are represented by a firm or association that negotiates tolls with the private operator.[9]

We have already considered one polar case, monopoly profit maximization, which could arise with bilateral monopoly; we now consider the other polar case where tolls and the allocation of highway capacity are set to maximize consumer surplus subject to the private

---

[8] When the capacity of the two routes is allocated equally, the monopolist maximizes its profits and the difference between the profit maximizing tolls on the two routes is only about $0.002.

[9] The framework could be expanded to allow all road users, including truckers, government services, and motorists, to be represented by an agent who negotiates tolls on their behalf.

operator earning non-negative profits. As noted, travelers' welfare is likely to increase if the operator is responsive to motorists' varying preferences for travel speed and reliability. As shown in column 5 of the table, product differentiation contributes to maximizing motorists' welfare as one third of capacity is allocated to express lanes with a toll of $7.14 and a travel time of 13 minutes and the other 4 lanes have no toll and travel times of 22 minutes. Consumer surplus is now positive because travelers with higher values of travel time and reliability can pay a toll to use the fast lanes and travelers with lower values can continue to use the free lanes, while not paying a gas tax, and experience only a small increase in travel time over the current situation. Moreover, because many of the motorists who use the free lanes may want to use the express lanes on particular days when they are anxious to reach their destination, the benefits to motorists from privatization are likely to be broadly shared.[10] Interestingly, the monopoly operator still earns positive profits because reducing tolls (and toll revenues) to generate zero profits would result in slower travel speeds that make motorists worse off.

Of course, by the time a privatization policy is implemented, traffic delays will be even greater than they are today. The last three columns of the table indicate that privatization's social benefits and benefits to motorists are even larger if we assume the population of potential travelers grows 20 percent, which generates additional traffic and congestion. Under such conditions, tolls are more essential for allocating scarce highway capacity and negotiations between motorists and the highway operator can produce tolls that are more efficient than those set by a profit maximizing monopoly operator.

Duopoly. Policymakers may be concerned about allowing a monopolist to provide highway services and may be willing to support privatization only if duopoly highway

---

[10] Evidence from California SR 91 indicates that many motorists pay to use the express toll lanes one or two days a week.

competition can be created. We assume that the highway consists of two equal capacity routes each operated by a private operator and that the gas tax is rebated. As shown in table 4, duopoly competition sharply reduces tolls from monopoly provision and improves welfare. Under Bertrand competition, the two operators set tolls simultaneously and generate two equilibria with the same welfare effects;[11] under the equilibria each route offers similar tolls and travel times. Under Stackelberg competition, the two operators set tolls sequentially; namely, the leader (route r2) sets a toll to force the follower to set a higher toll that enables the price leader to earn greater toll revenues. By differentiating highway services more sharply, Stackelberg competition reduces the loss to motorists and increases the welfare gains from privatization. In the appendix, we present graphical solutions that show that each form of competition produces a unique equilibrium.

Although duopoly competition improves on monopoly provision, it does not enable motorists to gain directly from highway privatization; thus, we explore the effects of allowing motorists and the duopolists to negotiate tolls (graphical solutions of duopoly equilibria under bargaining are shown in the appendix). We present the extreme case in the last two columns of the table where the two operators set tolls that maximize consumer surplus subject to earning non-negative profits. We find that Bertrand and Stackelberg competition generate very similar results: travelers prefer product differentiation where one route is essentially free and the other charges a toll of roughly $5.00; travel time is ten minutes less on the tolled route; consumer surplus is positive because highways offer differentiated service that is more responsive to motorists' preferences than when each operator maximizes profits; and overall welfare improves

[11] The other equilibrium is obtained by switching the tolls of the two routes.

$3.00 per person (potential traveler).[12] An interesting feature of the results is that travel on the faster route still moves considerably more slowly than a free-flow speed. This is consistent with findings obtained by Small and Yan (2001), which indicate that when one route is essentially free, the other is best priced to allow some congestion. This contrasts with current pricing on most high-occupancy-toll (HOT) lanes that set prices to approximately generate free-flow speeds.

Because the duopoly operators are allocated the same highway capacity, motorists and the highway providers negotiate only over tolls. In contrast, motorists and the monopoly provider negotiate over tolls and the allocation of highway capacity, which enables motorists to determine the combination of tolls and capacity that maximizes consumer surplus. The difference between the negotiations is important because in the extreme case that we consider here we find that overall welfare actually falls when negotiations are introduced in duopoly competition and motorists' welfare is *lower* than it is under monopoly with negotiations. In a privatized highway market, motorists may therefore be potentially better off negotiating with a monopoly than with duopoly operators.

Public-private provision. Finally, the government may be willing to privatize only part of the highway and keep one route in the public sector. We assume the government privatizes the amount of capacity (part of or the entire second route) that maximizes consumer surplus and its toll revenues. Given the government's allocation of capacity, the public and private operators set prices—either simultaneously or sequentially with the public operator as the price leader—to maximize their own objectives (graphical solutions of public-private duopoly equilibria are shown in the appendix).

---

[12] Again, there are two equilibria with the same welfare effects under Bertrand competition; the other equilibrium is obtained by switching the tolls of the two routes.

As indicated in table 5, the optimal capacity allocation for the government is to privatize only one lane (denoted route r1). Given this allocation, we find two equilibria exist under Bertrand competition, although the one with the higher toll on the public lanes generates the largest welfare gains.[13] When the public operator is the first mover in Stackelberg competition, it charges a toll that is between the tolls it charges under Bertrand competition and it causes the private operator to charge lower tolls than it does under Bertrand competition. However, motorists' welfare is reduced under either form of public-private duopoly competition. When the government does not charge a toll on its route (5 lanes) while the private operator charges a high toll for express service on its lane, motorists who are willing to pay for significant improvements in travel time and reliability have the option to do so. But because a large part of highway is unpriced, the gain in social welfare in this scenario is less than the gain generated by monopoly and duopoly competition under negotiations that maximize consumer surplus. Motorists realize a welfare gain if the government eliminates the gas tax, but they incur a small welfare loss if the government keeps it. Some reduction of the tax would be in order because a private operator is financing part of the highway.

Conclusions

We have developed an equilibrium model of highway supply and motorists' demand to investigate the potential for privatization of a public highway to improve motorists' and social welfare. Because motorists' values of travel time and reliability vary widely, we find that privatization can raise motorists' and social welfare if it causes the highway operator(s) to allocate capacity and charge tolls that result in differentiated service that is aligned as closely as

[13] The welfare generated by the public operator, including consumer surplus and public toll revenue, under the two equilibria exceeds the welfare generated by the public operator under alternative allocations of capacity.

possible with motorists' varying preferences. This outcome can be achieved even if the highway is owned and operated by a monopolist, provided motorists are able to negotiate aggressively with the private highway operator to allocate capacity and determine tolls. In fact, motorists' may gain more from privatization if they negotiate with a monopoly highway provider than with duopoly providers or if the government owns part of the road and competes with the monopoly provider.

We stress that our findings are conservative in the sense that we have focused on inefficiencies associated with current road pricing and capacity allocation, and to a certain extent, with current road maintenance policies. Privatization is also likely to reduce highway production costs, which is particularly important when the effects of truckers on pavement costs are considered, and spur innovation in highway services, which will benefit all road users.

To be sure, the United States has not had any recent experience with how a completely privatized highway market would function. Hence, it would be useful for the government to carefully design some privatization experiments that go beyond the restrictive framework of public-private partnerships. We have identified some features of a private highway market that should be heeded if such experiments are to be successful. Hopefully, future work will provide additional motivation and guidance for policymakers who realize that the time has come to assess whether the private sector can improve on the public sector's provision of highway services.

Appendix

This appendix demonstrates the existence and uniqueness of the Wardrop equilibrium in our analysis and presents graphical solutions to private and public-private duopoly competition.

Wardrop Equilibrium

We show that a unique Wardrop equilibrium for the second stage of the overall game exists for a price vector $p \geq 0$. Define *allocation* $g : N \rightarrow \Omega$, which maps potential travelers to the choice set, to represent travelers' choices. Traveler $i's$ choice is denoted $g(i)$. The market share of alternative j under allocation g is denoted by S_j^g, and the corresponding traffic volume is $V_j^g \equiv \dfrac{N \cdot S_j^g}{O_j}$, where O_j is vehicle occupancy. The transportation network is a simple two-route network and traffic volumes on the two routes $(r1, r2)$ under allocation g are $V_{r1}^g = \sum_{j \in \Omega_{r1}} V_j^g$ and $V_{r2}^g = \sum_{j \in \Omega_{r2}} V_j^g$.

The utility of choosing not to travel in equation (1) of the text is not a function of traffic volume. Given a price, the utility function of a traveler choosing a travel alternative that is associated with a route in our choice set is a function of the traffic volume on the route because both travel time and travel time unreliability are increasing functions of the route's traffic volume. Formally, traveler $i's$ utility for choosing a travel alternative under allocation g can be expressed as

$$U_{ig(i)} = U_{ig(i)}\left(V_r^g\right) \text{ for } g(i) \neq 0, \qquad \text{(A.1)}$$

where the choice $g(i)$ is associated with route r and subscript i indicates that the utility function is individual specific. The utility function has two properties. The first is

$$U_{ig(i)}\left(V_r^g\right) < U_{ig(i)}\left(V_r^{g'}\right) \Leftrightarrow V_r^g > V_r^{g'}, \qquad \text{(A.2)}$$

which says that a traveler's utility of choosing a travel alternative decreases as the volume on the chosen route *i* increases. The second property is for $j, k \in \Omega_r$

$$U_{ik}\left(V_r^g\right) < U_{ij}\left(V_r^g\right) \Leftrightarrow U_{ik}\left(V_r^{g'}\right) < U_{ij}\left(V_r^{g'}\right). \qquad \text{(A.3)}$$

Since j and k are two travel alternatives on the same route, they must have different car occupancies. The property in (A.3) says that a traveler's preference for two alternatives on the same route, but with different car occupancies, is invariant to the traffic volume on the route.[14]

Allocation g is a Wardrop equilibrium if and only if under the allocation each traveler maximizes her utility given the traffic volumes and price; that is,

$U_{ig(i)} = \max\left\{U_{i0}, U_{i1}, \ldots, U_{iJ} \middle| V_{r1}^g, V_{r2}^g, p\right\}$ for all i. Konishi (2004) proves the uniqueness of the Wardrop equilibrium in transportation networks with heterogeneous commuters for a model with only route choice. We consider travelers' route and vehicle occupancy choices, but the proof of the uniqueness of the Wardrop equilibrium follows Konish's idea.

We first show the existence of the Wardrop equilibrium. The second stage game of the paper is an example of the atomless game considered by Schmeildler (1973). The game is anonymous in the sense that travelers care only about the number of travelers for each alternative but do not care about who they are. Under anonymity, Schmeildler's result is that the Wardrop equilibrium exists.

The uniqueness of the Wardrop equilibrium depends on whether traffic volumes of the alternatives are the same for any equilibria g and g'. If the traffic volumes are the same, then the pricing decisions at the first stage and the welfare effects of the overall game are also the same

[14] For example, if a traveler prefers driving alone to using a carpool on a route when the route is not congested, the traveler still prefers driving alone to using a carpool on the route when the route is congested.

for any Wardrop equilibria g and g'. To prove uniqueness, we first show that traffic volumes on the two routes are the same for any two equilibria; that is, if g and g' are two Wardrop equilibria, we have $V_{r1}^{g} = V_{r1}^{g'}$ and $V_{r2}^{g} = V_{r2}^{g'}$.

We prove this by contradiction. Suppose allocations g and g' are both Wardrop equilibrium and traffic volumes on the two routes are different for g and g'. Without loss of generality, we can assume that $V_{r1}^{g} < V_{r1}^{g'}$. This implies that there exists a traveler i and an alternative $j \in \Omega_{r1}$ such that $g'(i) = j$ and $g(i) \neq j$. We can divide this possibility into the following cases:

Case 1: $g(i) = 0$. This case indicates that traveler i chooses alternative j under allocation g' but switches to the no-travel option under allocation g. We are able to construct the following inequalities, $U_{i0} \geq U_{ij}\left(V_{r1}^{g}\right)$, $U_{i0} \leq U_{ij}\left(V_{r1}^{g'}\right)$, and $U_{ij}\left(V_{r1}^{g'}\right) \geq U_{ij}\left(V_{r1}^{g}\right)$; from property (A.2), the last inequality means that $V_{r1}^{g} \geq V_{r1}^{g'}$. Thus, we obtain a contradiction.

Case 2: $g(i) \in \Omega_{r1}$. This case indicates that traveler i stays on the same route but switches to another alternative with larger vehicle occupancy. This case contradicts property (A.3) because it implies that $U_{ig(i)}\left(V_{r1}^{g}\right) \geq U_{ij}\left(V_{r1}^{g}\right)$ and $U_{ij}\left(V_{r1}^{g'}\right) \geq U_{ig(i)}\left(V_{r1}^{g'}\right)$.

Case 3: $g(i) \in \Omega_{r2}$. This case indicates that traveler i chooses alternative j under allocation g' but switches to an alternative that is associated with route *r2* under allocation g. By (A.2), we have $U_{ij}\left(V_{r1}^{g}\right) > U_{ij}\left(V_{r1}^{g'}\right)$. Since g and g' are both equilibrium allocations, we can have the other two inequalities, $U_{ig(i)}\left(V_{r2}^{g}\right) \geq U_{ij}\left(V_{r1}^{g}\right)$ and $U_{ij}\left(V_{r1}^{g'}\right) \geq U_{ig(i)}\left(V_{r2}^{g'}\right)$. Combining the three inequalities, we have $U_{ig(i)}\left(V_{r2}^{g}\right) > U_{ig(i)}\left(V_{r2}^{g'}\right)$ which implies $V_{r2}^{g} < V_{r2}^{g'}$. Given the total number of travelers on the routes is fixed (from case 1), both routes can be less congested under the allocation g only when some travelers on the routes switch to alternatives with larger vehicle occupancy. Case 2 indicates that it is impossible for travelers to make such changes on the same route, so we can conclude that: (a) there exists one traveler (denoted by n) who switches from an alternative on route $r1$ to an alternative (denoted by m_2) with larger vehicle occupancy on route $r2$; (b) there exists one traveler (denoted by h) who switches from an alternative on route $r2$ to an alternative (denoted by k_1) with larger vehicle occupancy on route $r1$. From (a) we have $U_{nm_2}\left(V_{r2}^{g}\right) > U_{nm_1}\left(V_{r1}^{g}\right)$ with m_1 denoting the alternative on route $r1$ with the same vehicle occupancy as m_2; from (b) we have $U_{hk1}\left(V_{r1}^{g}\right) > U_{hk_2}\left(V_{r2}^{g}\right)$ with k_2 denoting the alternative on route $r2$ with the same vehicle occupancy as k_1. The first inequality requires $V_{r1}^{g} > V_{r2}^{g}$ and the second inequality requires $V_{r1}^{g} < V_{r2}^{g}$, which again results in a contradiction.

Summarizing the three cases, we can conclude that if g and g' are two equilibrium allocations, $V_{r1}^{g} = V_{r1}^{g'}$ and $V_{r2}^{g} = V_{r2}^{g'}$. But although traffic volumes are the same, the composition of vehicles with different occupancies can be different for g and g'. If this is true, pricing decisions at the first stage and the welfare effects of the overall game can be different for the two equilibria.[15] It is also the case that we can find an alternative j such that $V_{j}^{g} \neq V_{j}^{g'}$; that is, there exists one traveler with different choices for these two equilibria. However, since $V_{r1}^{g} = V_{r1}^{g'}$ and

[15] For example, operators charge different prices for carpoolers and solo drivers under a policy of high-occupancy-tolls (HOT).

$V_{r2}^{g} = V_{r2}^{g'}$, a traveler obtains the same utility under the two equilibria from choosing an alternative; accordingly, her ranking of the alternatives should be the same for g and g'. Thus, given prices, we obtain a unique Wardrop equilibrium.

Solutions to Duopoly Equilibrium

We present graphical solutions to private and public-private duopoly competition. Figure A1 pertains to private duopoly competition. In the first panel, we show that there are two symmetric equilibria for Bertrand competition; the second panel plots the profit function of the price leader in Stackelberg competition (operator 2) given the response by the follower (operator 1).

Figure A2 presents duopoly equilibria when the operators negotiate tolls with motorists. The first panel shows there are two symmetric equilibria for Bertrand competition; the second panel plots consumer surplus as a function of the toll of the price leader under Stackelberg competition (operator 2) given the response by the follower (operator 1).

Finally, figure A3 presents duopoly equilibria under public-private competition. The first panel shows that there are two symmetric equilibria for Bertrand competition; the second panel plots the welfare function of the price leader under Stackelberg competition (operator 2) given the response by the follower (operator 1).

References

Calcott, Paul and Shuntian Yao (2005), "Competition Between Highway Operators: Can We Expect Toll Differentiation?," *Papers in Regional Science*, volume 84, pp. 615-626.

Choi, Ki-Hong and Choon-Geol Moon (1997), "Generalized Extreme Value Model and Additively Separable Generator Function," *Journal of Econometrics*, volume 76, pp. 129-140.

de Palma, Andre and Robin Lindsey (2002), "Private Roads, Competition, and Incentives to Adopt Time-Based Congestion Tolling," *Journal of Urban Economics*, volume 52, pp. 217-241.

de Palma, Andre and Robin Lindsey (2000), "Private Toll Roads: Competition Under Various Ownership Regimes," *Annals of Regional Science*, volume 34, pp. 13-35.

Edelson, Noel M. (1971), "Congestion Tolls Under Monopoly," *American Economic Review*, volume 61, pp. 873-882.

Engel, Eduardo M., Ronald Fischer, and Alexander Galetovic (2007), "The Basic Public Finance of Public-Private Partnerships," NBER working paper 13284, October.

Engel, Eduardo M., Ronald Fischer, and Alexander Galetovic (2006), "Privatizing Highways in the United States," *Review of Industrial Organization*, volume 29, pp. 27-53.

Engel, Eduardo M., Ronald Fischer, and Alexander Galetovic (2003), "Privatizing Highways in Latin America: Fixing What Went Wrong," *Economia*, volume 4, pp. 129-158.

Engel, Eduardo M., Ronald Fischer, and Alexander Galetovic (2001), "Least-Present-Value-of-Revenue Auctions and Highway Franchising," *Journal of Political Economy*, volume 109, pp. 993-1020.

Friedman, Milton and Daniel Boorstin (1951), "How to Plan and Pay for the Safe and Adequate Highways We Need." Epilogue in Gabriel J. Roth (1996), *Roads in a Market Economy,* Aldershot, Hants: Avebury Technical, pp. 223-245.

Haurie, Alain and Patrice Marcotte (1985), "On the Relationship between Nash-Cournot and Wardrop Equilibria," *Networks*, volume 15, pp. 295-308.

Knight, Frank H. (1924), "Some Fallacies in the Interpretation of Social Costs," *Quarterly Journal of Economics*, volume 38, pp. 582-606.

Konishi, Hideo (2004), "Uniqueness of User Equilibrium in Transportation Networks with Heterogeneous Commuters," *Transportation Science*, volume 38, pp. 315-330.

Langer, Ashley and Clifford Winston (2008), "Toward a Comprehensive Assessment of Road Pricing Accounting for Land Use, *Brookings-Wharton Papers on Urban Affairs*, pp. 127-175.

Mannering, Fred and Clifford Winston (1985), "A Dynamic Empirical Analysis of Household Vehicle Ownership and Utilization," *Rand Journal of Economics*, volume 16, pp. 215-236.

Poole, Robert W., Jr. and Peter Samuel (2008), "Pennsylvania Turnpike Alternatives," Reason Foundation Policy Brief No. 70, April.

Roth, Gabriel (2005), "Liberating the Roads: Reforming U.S. Highway Policy," CATO Institute Policy Analysis 538, March.

Schmeilder, David (1973), "Equilibrium Points of Nonatomic Games," *Journal of Statistical Physics*, volume 7, pp. 295-300.

Small, Kenneth A., Clifford Winston, and Jia Yan (2006), "Differentiated Road Pricing, Express Lanes, and Carpools: Exploiting Heterogeneous Preferences in Policy Design," *Brookings-Wharton Papers on Urban Affairs*, pp. 53- 96.

Small, Kenneth A., Clifford Winston, and Jia Yan (2005), "Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability," *Econometrica,* volume 73, pp. 1367−82.

Small, Kenneth A., Clifford Winston, and Carol A. Evans (1989), *Road Work*: *A New Highway Pricing and Investment Policy*, Brookings Institution, Washington, D.C.

Small, Kenneth A. and Jia Yan (2001), "The Value of "Value Pricing" of Roads: Second-Best Pricing and Product Differentiation," *Journal of Urban Economics*, volume 49, pp. 310-336.

U.S. Federal Highway Administration (2000), "Addendum to the 1997 Federal Highway Cost Allocation Study: Final Report," U.S Department of Transportation, Washington, D.C., May.

Vickers, John and George Yarrow (1991), "Economic Perspectives on Privatization," *Journal of Economic Perspectives*, volume 5, pp. 111-132.

Viton, Philip A. (1995), "Private Roads," *Journal of Urban Economics*, volume 37, pp. 260-289.

Wardrop, John G. (1952), "Some Theoretical Aspects of Road Traffic Research," *Proceedings of the Institute of Civil Engineers*, Pt. II, vol. 1, pp. 325-378.

Winston, Clifford (2000), "Government Failure in Urban Transportation," *Fiscal Studies*, volume 21, pp. 403-425.

Winston, Clifford (1998), "U.S. Industry Adjustment to Economic Deregulation," *Journal of Economic Perspectives*, volume 12, pp. 89-110.

Winston, Clifford and Ashley Langer (2006), "The Effect of Government Highway Expenditures on Road Users' Congestion Costs," *Journal of Urban Economics*, volume 60, pp. 463-483.

Table 1. Estimated Coefficients for the Route-Vehicle Occupancy Choice Model

Variable	Coefficient[a]
Toll ($)	-1.4580
Toll × dummy for high household annual income (> $60K)	0.8411
Median travel time (minutes) × trip distance (units of 10 miles)	-0.3489
Median travel time × trip distance squared	0.0684
Median travel time × trip distance cubed	-0.0030
Travel-time uncertainty (80th percentile minus the median) (minutes)	-0.4541
HOV2 dummy	-6.9854
HOV3 dummy	-12.580
Female × age 30−50 × household size × carpool dummy[b]	0.8735
Random components of coefficients	
Standard deviation of travel-time coefficient	0.3866
Standard deviation of travel-time uncertainty coefficient	0.6009
Common standard deviation of HOV2 and HOV3 dummies	6.2597

Source: Small, Winston, and Yan (2006).

[a] All coefficients are statistically significant at the five percent level.
[b] The carpool dummy is set to one if the route-vehicle occupancy choice includes HOV2 or HOV3.

Table 2. Value and Heterogeneity of Travel Time and Reliability [a]

Item	Median estimate
Value of Median Travel Time	
Dollars	19.63
As a percent of the wage [b]	85
Value of Reliability	
Dollars	20.76
As a percent of the wage [b]	90
Heterogeneity [c]	
Median travel time	19.02
Reliability	35.51

[a] Source: Small, Winston, and Yan (2006).
[b] The wage rate, estimated in Small, Winston, and Yan (2005), is about $23 per hour.
[c] Heterogeneity is expressed here as the interquartile range of the quantity in question across individuals.

Table 3. Welfare Effects under Monopoly Provision

	Base case: current situation	Monopoly without the gas tax rebate	Monopoly with the gas tax rebate	Monopoly with gas tax rebate & change in government budget [c]	Monopoly bargaining with the gas tax rebate [d]	Base case: with traffic growth [e]	Monopoly with gas tax rebate and traffic growth[e]	Monopoly bargaining with the gas tax rebate and traffic growth[d,e]
Capacity (vehicles/hour) [a]								
Route r1	6000	6000	6000	6000	4000	6000	6000	4000
Route r2	6000	6000	6000	6000	8000	6000	6000	8000
Toll ($)								
Route r1	0.00	20.32	22.14	22.14	7.14	0.00	22.77	9.28
Route r2	0.00	20.32	22.14	22.14	0.00	0.00	22.77	0.00
Travel times (min.):								
Route r1	20.00	9.48	9.50	9.50	13.08	24.40	9.69	14.61
Route r2	20.00	9.48	9.50	9.50	22.83	24.40	9.69	28.00
Aggregated choice shares (%):								
No travel on the corridor	8	34	31	31	5	16	32	11
Travel on the corridor	92	66	69	69	95	84	68	89
For those who travel on the corridor								
Solo driving	80	10	8	8	70	80	8	65
HOV2	17	51	50	50	23	17	50	26
HOV3	3	39	42	42	7	3	42	9
Toll revenue ($/person) [b]								
Route r1	0.00	3.26	3.62	3.62	1.52	0.00	3.56	1.79
Route r2	0.00	3.26	3.62	3.62	0.00	0.00	3.56	0.00
Maintenance cost change ($/person)[b]								
Route r1	0.00	-0.0028	-0.0028	-0.0028	-0.0005	0.0037	-0.0028	-0.0024
Route r2	0.00	-0.0028	-0.0028	-0.0028	0.0003	0.0037	-0.0028	0.0005
Consumer surplus change ($/person)[b]	0.00	-6.94	-6.33	-6.33	1.43	0.00	-4.91	1.54
Change in government budget ($/person)[c]	0.00	0.00	0.00	-0.22	0.00	0.00	0.00	0.00
Welfare change ($/person)[b]	0.00	-0.41	0.91	0.69	2.95	0.00	2.21	3.32

[a] The monopolist's profit is maximized when the capacity of the two routes is equal. When the objective is to maximize consumer surplus, the optimal capacity allocation is the one presented in the table (4000, 8000).
[b] Maintenance cost, consumer surplus, and social welfare are measured relative to the no-toll scenario. These three items and toll revenue are each divided by the total number of potential users N. Social welfare is the sum of consumer surplus plus toll revenue minus maintenance cost.
[c] In this scenario, we subtract the government's gas tax revenues and maintenance costs attributable to travel by motorists. Gas tax revenues are calculated assuming average gas mileage of 16 miles per gallon.
[d] The bargaining solution here is the extreme case in which travelers set the tolls to maximize consumer surplus, that is, is the solution to the problem in equation (16) when $\omega = 1$.
[e] Population size (N) is increased by 20% in the scenarios with traffic growth.

Table 4. Welfare Effects under Duopoly Provision (with the gas tax rebate)

	Base case: current situation	Bertrand Competition [c]	Stackelberg Competition [d]	Bargaining Bertrand Competition [c]	Bargaining Stackelberg Competition [d]
Capacity (vehicles/hour) [a]					
Route r1	6000	6000	6000	6000	6000
Route r2	6000	6000	6000	6000	6000
Toll ($)					
Route r1	0.00	10.25	12.65	4.92	0.01
Route r2	0.00	9.84	8.81	0.01	5.13
Travel times (min.):					
Route r1	20.00	11.61	10.16	14.83	24.39
Route r2	20.00	12.26	14.94	24.39	14.68
Aggregated choice shares (%):					
No travel on the corridor	8	8	8	5	6
Travel on the corridor	92	92	92	95	94
For those who travel on the corridor					
Solo driving	80	33	34	70	69
HOV2	17	45	44	23	24
HOV3	3	22	22	7	7
Toll revenue ($/person) [b]					
Route r1	0.00	2.90	2.83	1.72	0.00
Route r2	0.00	2.95	3.10	0.00	1.78
Maintenance cost change (cents/person) [b]					
Route r1	0.00	-0.0018	-0.0023	-0.0013	-0.0005
Route r2	0.00	-0.0017	-0.0013	-0.0005	-0.0013
Consumer surplus change ($/person) [b]	0.00	-2.14	-2.01	1.28	1.21
Welfare change ($/person) [b]	0.00	3.71	3.92	3.00	2.99

[a] The routes are set to have equal capacity under duopoly provision.
[b] Maintenance cost, consumer surplus, and social welfare are measured relative to no-toll scenario. These three items and toll revenue are each divided by total number of potential users N. Social welfare is the sum of consumer surplus plus toll revenue minus maintenance cost.
[c] There are two symmetric equilibria for Bertrand competition. Welfare effects under the two equilibria are the same.
[d] Without loss of generality, we assume that operator 2 is the price leader of the Stackelberg competition.

Table 5. Welfare Effects under Public-Private Provision (with gas tax rebate)

	Base case: current situation	Bertrand Competition (two equilibria)		Stackelberg Competition [c]	Free Public Route	Free Public Route without the gas tax rebate
Capacity (vehicles/hour) [a]						
Route r1 (1 lane)	6000	2000		2000	2000	2000
Route r2 (5 lanes)	6000	10000		10000	10000	10000
Toll ($)						
Route r1	0.00	12.64	8.80	8.07	16.57	15.27
Route r2	0.00	8.60	10.22	9.20	0.00	0.00
Travel times (min.):						
Route r1	20.00	10.68	18.74	18.84	10.30	10.32
Route r2	20.00	13.24	11.28	11.94	22.42	21.67
Aggregated choice shares (%):						
No travel on the corridor	8	7	7	6	7	7
Travel on the corridor	92	93	93	94	93	93
For those who travel on the corridor						
Solo driving	80	40	34	38	74	74
HOV2	17	41	44	43	20	20
HOV3	3	19	22	19	6	6
Toll revenue ($/person) [b]						
Route r1	0.00	1.04	1.17	1.08	1.28	1.18
Route r2	0.00	4.56	4.64	4.47	0.00	0.00
Maintenance cost change (cents/person) [b]						
Route r1	0.00	-0.0005	0.0002	-0.0001	-0.0005	-0.0004
Route r2	0.00	-0.0012	-0.0010	-0.0016	0.0003	0.0001
Consumer surplus change ($/person) [b]	0.00	-1.79	-1.72	-1.50	1.01	-0.21
Welfare change ($/person) [b]	0.00	3.81	4.09	4.05	2.29	0.97

[a] Capacity allocation between the two routes is determined by the government to maximize consumer surplus plus its toll revenue.
[b] Maintenance cost, consumer surplus, and social welfare are measured relative to the no-toll scenario. These three items and toll revenue are each divided by total number of potential users N. Social welfare is the sum of consumer surplus plus toll revenue minus maintenance cost.
[c] Public operator (operator 2) is the price-leader of Stackelberg competition.

Figure A1. Solutions to Private Duopoly Competition

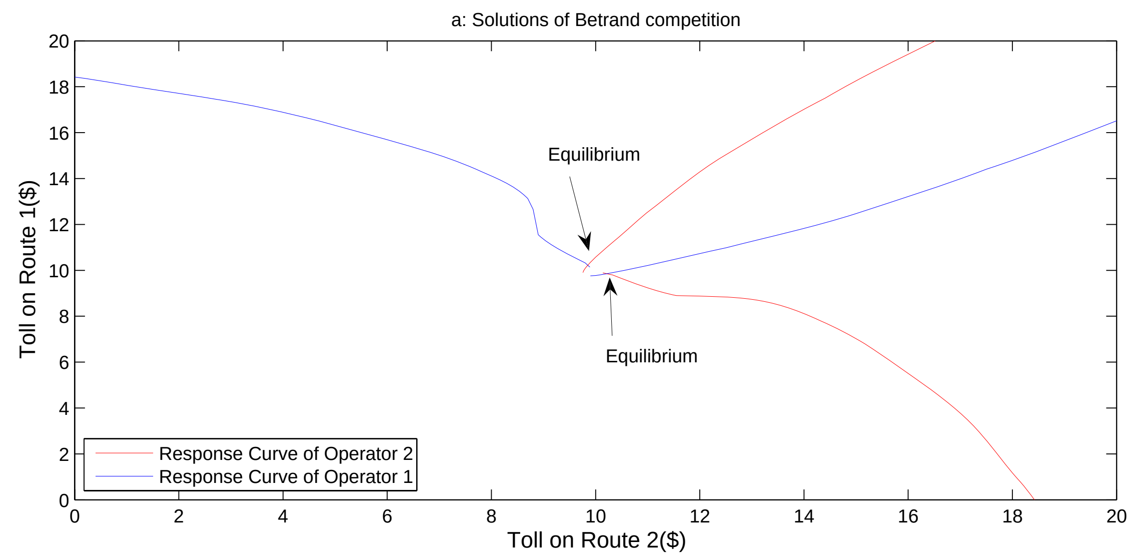
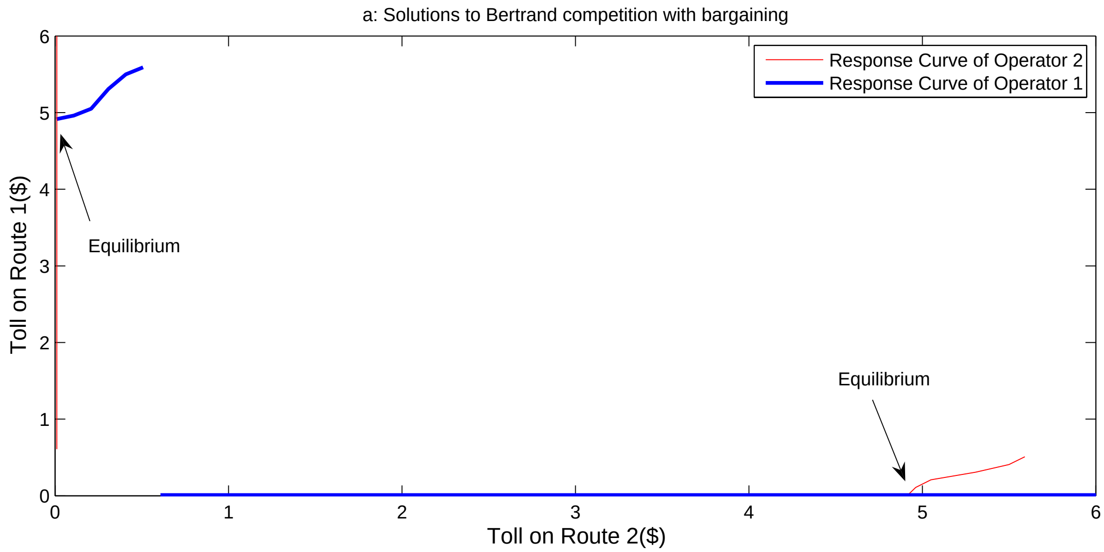


Figure A2. Solutions to Private Duopoly Competition with Bargaining



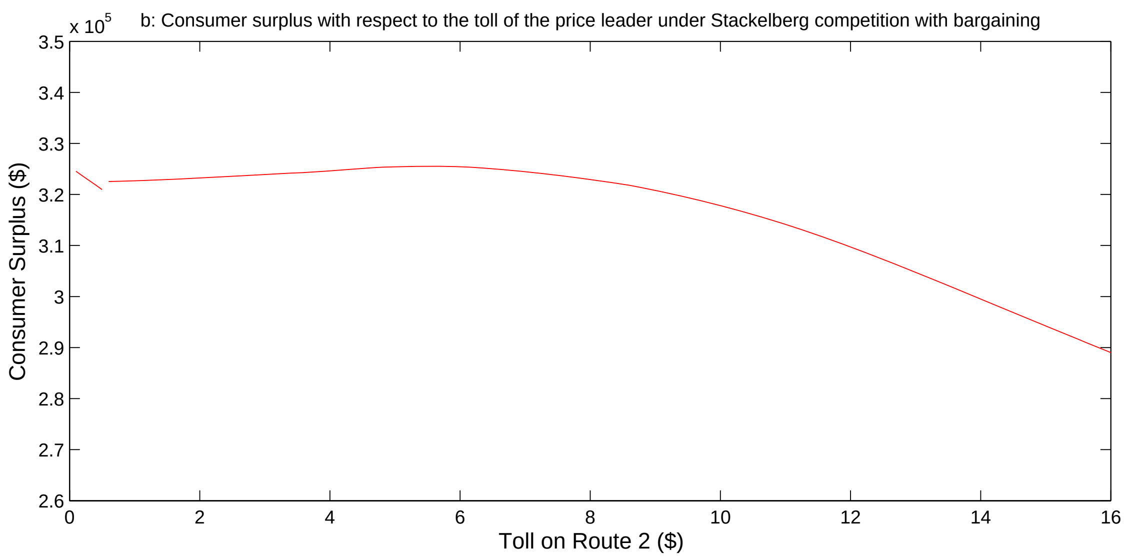


Figure A3. Solutions to Public-Private Duopoly Competition