

**U.S. HIGHWAY PRIVATIZATION AND
MOTORISTS' HETEROGENEOUS PREFERENCES**

**Clifford Winston
Brookings Institution**

**Jia Yan
Washington State University**

March 2009

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

The road system’s poor service quality and growing financial problems can be attributed to inefficient government 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 the system’s 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.

After policymakers accepted the fact that their policies were responsible for creating significant inefficiencies in intercity transportation, they turned to markets for help by deregulating the 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, policymakers have turned to the private sector for assistance by forming so-called public-private partnerships (PPPs), where the government leases a road to a private investor(s) for a specified period.² These partnerships are business deals that are intended to provide budgetary relief to

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

² Examples of PPPs include the Chicago Skyway, Indiana toll road, and the proposed Trans-Texas Corridor; high-occupancy-toll (HOT) lanes in California and Texas and that are currently

the government and yield an acceptable rate of return for the firms that invest in infrastructure subject to government regulations. At the same time, highway travel conditions may not necessarily improve, especially because the contract between the private firm and the government may be poorly structured and prevent efficient pricing (Engel et al. (2007)). A pure market solution—namely, highway privatization—would not be encumbered by the government and could result in less delay and greater travel reliability, but it could also produce a welfare loss from market power (Vickers and Yarrow (1991)).

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 and the limitations of PPPs, 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 U.S. road network is largely complete and vast, enormously expensive investments in new capacity, which arguably justified public ownership and management of the roads in the past, are not necessary.

We analyze our model using data from motorists’ travel on a major highway in California and find that under certain conditions highway privatization can benefit road users 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 be forced to respond to those preferences in ways that public highway authorities have not. The importance of preference heterogeneity in generating benefits suggests

being constructed in the Washington, D.C. metropolitan area; and the Dulles-Greenway private toll road.

that it would be inadvisable to subject private operators to price regulation because regulatory authorities typically enact policies that treat consumers as homogeneous.

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 significantly with the level of 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 production 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.

³ We are grateful to Peter Samuel for this point.

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, r_1 and r_2 , connecting the same 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 an analogy from certain shippers who were organized into bargaining units following 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 (r_1 or r_2) 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 $\Omega = \{0, 1, \dots, J\}$ 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:

$$U_{i0} = \delta_0 + \varepsilon_{i0} \quad (1)$$

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:

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

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,

$$\Theta_i \equiv (\alpha_i, \eta_i, \phi_i, B_i)' \sim N(Z_i \gamma, \Sigma), \quad (3)$$

where Σ is a diagonal variance matrix, and γ is a vector of parameters to be estimated.

We specify the joint distribution of $\varepsilon_i \equiv (\varepsilon_{i0}, \varepsilon_{i1}, \dots, \varepsilon_{iJ})$ 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. Our mixed-logit specification for travel choices

allows for various potential error correlation patterns among travel alternatives, which could arise from individual-specific preferences for travel features that are shared by particular alternatives.⁴

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

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

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

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

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

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

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

$$S_{i0} = \frac{e^{\delta_0}}{e^{\delta_0} + e^{\lambda D_i}}. \quad (7)$$

The volume of traffic that is generated by individuals who choose a travel alternative j with

vehicle occupancy O_j is $V_j \equiv \frac{N \cdot S_j}{O_j}$.

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—a stable period of highway travel—to analyze motorists' behavior on California State Route 91, a major limited-access expressway used

⁴ The mixed-logit model is a multinomial logit model with random parameters.

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. The cost of electronic toll collection is small. Carpools of three or 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). The three choices are assumed conditional on mode choice (car versus public transport), residential location, and time of day of travel. We discuss the possible effects of this assumption on our findings later.

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 normally distributed, for travel time, travel time uncertainty, and the HOV2 and HOV3 dummies.⁶

The value of travel time (VOT) and value of reliability (VOR) are 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

$$VOT = \frac{\eta_i}{\alpha_i} \quad (8)$$

$$VOR = \frac{\phi_i}{\alpha_i} \quad (9)$$

Small and Verhoef (2007) report from a survey of mode choice models that a reasonable average VOT is 50 percent of the gross wage, while Miller (1989) finds an average value from a survey of route choice models that is closer to 60 percent of the gross wage. Small and Verhoef

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.

⁶ Brownstone and Train (1999) show how such a structure mimics a generalized extreme value model that is analogous to a generalized nested logit model with error terms for groups of alternatives with different car occupancies (solo, HOV2, HOV3) that are correlated with each other.

point out that VOT estimates vary from roughly 20 to 100 percent of the gross wage. Table 2 presents VOT and VOR estimates and shows that motorists' median values can be interpreted as being close to the high end of previous estimates of VOT, 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: the 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:

$$\delta_0 = \bar{\delta} + \hat{\delta} \cdot C . \quad (10)$$

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.⁷ 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 -0.3.⁸

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:

$$T_r = t_f L_r \left(1 + 0.15 \left(\frac{V_r}{K_r} \right)^4 \right), \quad (11)$$

where T_r is the travel time on route r ; t_f is the travel time per-mile 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.⁹ As in SWY, we

⁷ We set $\lambda = 0.2$ and found in sensitivity tests that alternate values did not have much effect on the main findings.

⁸ 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 our central findings are not particularly sensitive to the assumed values of the elasticities.

⁹ Our findings were not particularly sensitive to assuming powers of the volume-capacity ratio that were somewhat higher or lower than four.

specify travel time uncertainty on route r as a constant fraction of travel time delay (travel time minus free-flow travel time):

$$R_r = 0.3785 \cdot T_r, \quad (12)$$

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 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 damage 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 damage 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:

$$PC_r = 0.0008 \cdot V_r \cdot L_r. \quad (13)$$

Because the road is already built and the private operator is assumed to own and operate the highway forever, we can ignore the initial cost paid by the private operator to the government to acquire the highway. Accordingly, we do not make any particular assumptions about how the private operator finances the purchase of the road or the interest rate that is paid. The initial cost affects the decision of a private firm to buy the highway; it is especially important when a private firm can own and operate the highway only for a finite period—as is the case for recent public-private partnerships—because the firm may not be able to raise sufficient revenues 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.¹⁰ 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 Equilibria* of games as the number of players goes to infinity (Haurie and Marcotte (1985)). Denote p_j as the price of alternative j and $p \equiv (p_1, \dots, p_J)$ as the price vector; the market share vector $S^*(p) \equiv (S_1^*(p), \dots, S_J^*(p))$ 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.

¹⁰ It is possible that current pricing decisions may affect future ones through reputation effects. For example, operators might develop reputations for “price gouging” and motorists would develop habits to avoid those roads. But reputation effects are not likely to arise in the cases that we analyze here that involve some form of competition, such as private duopoly, because the two routes are perfectly substitutable and there are no costs for motorists to switch from one route to the other. Reputation effects could develop in the monopoly case, but we also consider bilateral long-run price negotiations between users and the monopolist to limit monopoly power.

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:

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

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

We state the profit maximization problem as

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

$$K_{r1} + K_{r2} = K,$$

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:

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

where $CS(K_{r1}, K_{r2}, p_{r1}, p_{r2})$ 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

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

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

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

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

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

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

The operator of route $r2$ solves:

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

The solution to the problem, denoted by $p_{r_2} = f_{r_2}(p_{r_1})$, is the toll schedule with respect to p_{r_1} .

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 r_2 is the leader), the operator of r_1 still solves the problem given in equation (19), and the operator of route r_2 solves the problem in equation (20) but with an additional constraint of $p_{r_1} = f_{r_1}(p_{r_2})$. (In our setting, one firm is able to commit to a decision before the other if the government privatizes highway capacity sequentially.) 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. The final scenario we consider allows the government to compete with a private provider. We assume the government's objective is to maximize net benefits that are composed of consumer surplus and its budget balance. The government does not explicitly concern itself with the private operator's profits; it assumes that the private operator makes profit-maximizing decisions.

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 r_1 is privatized). The government first determines the capacity to privatize (K_{r_1}); 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 r_2 first. Both cases correspond to those in private duopoly competition with the only difference that the objective function of the public operator is assumed to maximize net benefits, as defined above. 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 account for some but not all of the ways that the government's budget will be affected by highway privatization. The government receives 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 those 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.¹¹ 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

¹¹ 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. Verhoef and Small (2004) also find that a private monopoly operator differentiates tolls very little.

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.¹²

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 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 23 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

¹² 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.

motorists from privatization are likely to be broadly shared.¹³ 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 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;¹⁴ 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

¹³ Descriptive data summaries indicate that many motorists pay to use the express toll lanes on California SR 91 one or two days a week. This behavior makes it difficult to calculate an accurate distribution of driver benefits by, for example, income level.

¹⁴ The other equilibrium is obtained by switching the tolls of the two routes.

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 \$3.00 per person (potential traveler).¹⁵ 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

¹⁵ 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.

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).

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.¹⁶ 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

¹⁶ 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.

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.

Discussion

It is useful to assess our findings in light of the assumptions and features of our model and our sample. First, we assume that motorists' route and vehicle occupancy decisions are conditional on their choice of mode, residence and workplace location, and time of trip. Mode choice is not a particularly relevant consideration because of the small use of public transit in our sample of Orange County households. But by taking motorists' location and trip timing choices as exogenous, we may be understating the benefits of privatization because households could reduce the cost of higher tolls by moving closer to their workplace (assuming the reduction in transport costs exceeds the increase in housing costs) as well as by traveling at different times of day, or increase the benefits from faster and more reliable trip times by living further from their workplace in lower cost housing as well as by traveling at more convenient times of day.¹⁷

Our model accounts for motorists' heterogeneous preferences and we conclude that privatization is a potentially attractive policy if the private operator's pricing and capacity decisions is responsive to those preferences. In table 6, we show how our findings are affected

¹⁷ Langer and Winston (2008) find that the social benefits of congestion pricing are much greater when households' residential location decisions are taken into account.

when we ignore preference heterogeneity and assume that road users have homogeneous preferences. Generally, monopoly tolls are lower than they are for heterogeneous users because when users are heterogeneous, the monopolist sets high tolls to serve users with the highest value of time and reliability. With homogenous users, we obtain corner solutions that maximize consumer surplus through bargaining—that is, the monopoly sets the lowest tolls that enable it to break even. And with homogeneous users, different market structures—monopoly, Bertrand duopoly, and Bertrand public-private competition—yield similar positive overall welfare gains; but private roads are less feasible politically because consumer surplus is always negative. In contrast, when users are heterogeneous, it is possible to obtain outcomes that generate a gain in consumer surplus and enable the operator(s) to be profitable.

As noted, our sample consists of Southern California motorists, who have a high value of time and reliability and who commute long distances, in part on a limited access highway. Thus, it would be incautious to suggest that our findings generalize to every metropolitan area in the United States. At the same time, there are major metropolitan areas, such as San Francisco, Seattle, New York, and Washington, DC, with motorists and travel conditions that are similar to those in Southern California—and there are several other cities with a notable share of drivers who are probably less than a decade away from willing to pay large sums to improve travel conditions.

From a policy perspective, we have suggested that consumers could gain from privatization if tolls were negotiated between the private provider and a private entity that represents motorists. Alternatively, Armstrong and Sappington (2006), among others, point out that even if an industry is privatized, it may be appropriate to regulate it; thus, it could be argued that the government could represent consumers' interests by implementing regulations, which set

consumer welfare maximizing tolls. But government regulation is notoriously poor at facilitating an environment that is responsive to preference heterogeneity. Indeed, one of the major benefits of economic deregulation is that private firms have introduced price-service packages, which were prohibited under regulation, that cater to different types of consumers (Winston (1998)). Accordingly, it would be unlikely that the government would be effective at regulating differentiated tolls that come close to optimizing consumer welfare.

Conclusions

We have developed an equilibrium model of highway supply and motorists' demand to investigate the economic effects of privatizing a public highway. 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 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 are particularly important when the effects of truck traffic on pavement

costs are considered, and to spur innovation in highway services, which will benefit all road users.

Privatization is likely to be attractive in the current economic environment because all levels of government are interested in strategies—such as selling public assets like highways, transit systems, and office buildings—that could reduce their budget deficits and provide fiscal stimulus. To be sure, the United States has not had any recent experience with a fully privatized highway market; moreover, important uncertainties surround the conclusions reached here, especially whether negotiations could lead to consumer gains or whether regulations may be desirable and effective.

Recently, the federal government has begun to explore the issue of airport privatization by calling for privatization experiments.¹⁸ Accordingly, it would be useful for the government to carefully design some highway 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.

¹⁸ Chicago Midway Airport is committed to such an experiment and several other cities have expressed interest in privatizing their airports.

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 $V_j^g \equiv \frac{N \cdot S_j^g}{O_j}$, 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

$$V_{r1}^g = \sum_{j \in \Omega_{r1}} V_j^g \text{ and } V_{r2}^g = \sum_{j \in \Omega_{r2}} V_j^g .$$

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

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

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

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

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 $j, k \in \Omega_r$,

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

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.¹⁹

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,

$$U_{ig(i)} = \max \{U_{i0}, U_{i1}, \dots, U_{ij} \mid V_{r1}^g, V_{r2}^g, p\} \text{ for all } i. \text{ Konishi (2004) proves the uniqueness of the}$$

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 Konishi'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 Schmeidler (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, Schmeidler'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

¹⁹ 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 $V_{r_1}^g = V_{r_1}^{g'}$ and $V_{r_2}^g = V_{r_2}^{g'}$.

We prove this by contradiction. Suppose allocations g and g' are both Wardrop equilibria and traffic volumes on the two routes are different for g and g' . Without loss of generality, we can assume that $V_{r_1}^g < V_{r_1}^{g'}$. This implies that there exists a traveler i and an alternative $j \in \Omega_{r_1}$ 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, $U_{i0} \geq U_{ij}(V_{r_1}^g)$, $U_{i0} \leq U_{ij}(V_{r_1}^{g'})$, and $U_{ij}(V_{r_1}^{g'}) \geq U_{ij}(V_{r_1}^g)$; from property (A.2), the last inequality means that $V_{r_1}^g \geq V_{r_1}^{g'}$. Thus, we obtain a contradiction.

Case 2: $g(i) \in \Omega_{r_1}$. 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 $U_{ig(i)}(V_{r_1}^g) \geq U_{ij}(V_{r_1}^g)$ and $U_{ij}(V_{r_1}^{g'}) \geq U_{ig(i)}(V_{r_1}^{g'})$.

Case 3: $g(i) \in \Omega_{r_2}$. This case indicates that traveler i chooses alternative j under allocation g' but switches to an alternative that is associated with route r_2 under allocation g . By (A.2), we have $U_{ij}(V_{r_1}^{g'}) > U_{ij}(V_{r_1}^g)$. Since g and g' are both equilibrium allocations, we can have the other two inequalities, $U_{ig(i)}(V_{r_2}^g) \geq U_{ij}(V_{r_1}^g)$ and $U_{ij}(V_{r_1}^{g'}) \geq U_{ig(i)}(V_{r_2}^{g'})$. Combining the

three inequalities, we have $U_{ig(i)}(V_{r2}^g) > U_{ig(i)}(V_{r2}^{g'})$ 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 $U_{nm_2}(V_{r2}^g) > U_{nm_1}(V_{r1}^g)$ with m_1 denoting the alternative on route $r1$ with the same vehicle occupancy as m_2 ; from (b) we have $U_{hk_1}(V_{r1}^g) > U_{hk_2}(V_{r2}^g)$ 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.²⁰ 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

²⁰ 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).

As shown in the figure, when the two firms engage in Bertrand competition, tolls are strategic substitutes when a rival's toll is low and strategic complements when a rival's toll is high. The main explanation for V-shape toll reaction functions is motorists' preference heterogeneity. Users with low VOT and VOR take the route with the lower toll. So, if the toll on route 2 is low, operator 1 prefers to cater to high VOT users (analogous to the long side of the market in a Hotelling line model) and sets a high value for the toll on route 1. As the toll on route 2 rises, the mix of travelers on route 1 shifts toward a lower VOT and operator 1 finds it profitable to cut the toll on route 1 even though usage increases. This explains why the reaction function of operator 1 is downward-sloping for low values of the toll on route 2.

At some point, the toll on route 2 is close to \$10 according to the figure; operator 1 finds it profitable to switch from a high-toll high-quality strategy to a lower toll and lower quality. The figure shows that the reaction function takes a small downward jump, and this is reflected in the small downward jump in operator 2's profit in the lower panel of Figure A1. As the toll on route 2 rises further, the mix of travelers on route 1 shifts toward a higher VOT and operator 1

responds by raising the toll on route 1; the response function of operator 1 is therefore upward-sloping for higher values of the toll on route 2.

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). In Bertrand competition, tolls are strategic complements when a rival's toll is very low; but in order to satisfy the break-even condition, they are unresponsive to a rival's toll once it exceeds a threshold. When a rival's toll is very low, an operator can improve consumer surplus by increasing its toll to maintain toll differences that benefit high VOT users. When a rival's toll exceeds a certain level, \$0.60 according to Figure A2, the operator cuts its toll to the break-even level to benefit low VOT users.

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). The reaction function for the private operator in Figure A3 is qualitatively similar to the reaction functions in Figure A1 except for a much bigger discontinuity at the transition point. In contrast, the public operator's reaction curve is nearly flat. This may be because the public operator takes into account not only the VOT for the marginal user but also the VOT for the inframarginal users. The public operator is therefore reluctant to cut the toll because this would exacerbate congestion for users with the highest VOT.

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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 (80 th 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 per hour	19.63
As a percent of the wage ^b	85
Value of Reliability	
Dollars per hour	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 tolls are set 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.

Table 6. Simulation Results with Homogeneous Road Users^a

	Base: current situation	Monopoly with the gas tax rebate	Monopoly bargaining without the gas tax rebate ^b	Bertrand Duopoly Competition with the gas tax rebate	Free Public Route without the gas tax rebate ^c	Bertrand Private- Public Competition with the gas tax rebate ^c
Capacity (vehicles/hour)^a						
Route r1	6000	6000	6000	6000	2000	2000
Route r2	6000	6000	6000	6000	10000	10000
Toll (\$)						
Route r1	\$0.00	\$7.26	\$0.01	\$6.91	\$9.72	\$7.51
Route r2	\$0.00	\$7.26	\$0.01	\$6.91	\$0.00	\$6.67
Travel times (min.):						
Route r1	20.00	11.24	19.92	11.63	10.64	11.19
Route r2	20.00	11.24	19.92	11.63	21.11	11.85
Aggregated choice shares (%):						
No travel on the corridor	2	16	2	14	4	13
Travel on the corridor	98	84	98	86	96	87
For those who travel on the corridor						
Solo driving	81	42	80	45	76	46
HOV2	16	42	17	40	18	39
HOV3	3	16	3	15	6	15
Toll revenue (\$/person)^b						
Route r1	0.00	2.10	0.004	2.09	0.86	0.72
Route r2	0.00	2.10	0.004	2.09	0.00	3.43
Maintenance cost change (\$/person)^b						
Route r1	0.000	-0.002	-0.001	-0.002	-0.001	-0.001
Route r2	0.000	-0.002	-0.001	-0.002	-0.003	-0.004
Consumer surplus change (\$/person)^b	0.00	-0.74	-0.01	-0.69	-0.43	-0.69
Welfare change (\$/person)^b	0.00	3.46	0.00	3.49	0.43	3.46

^a We modify the demand model in Table 1 in the following ways to eliminate the heterogeneity in the value of time and value of time uncertainty: 1. set the random components of travel time and travel time uncertainty coefficients to zero; 2. assume that all travelers have the same trip distance (mean travel distance in the sample) and same income (the dummy of high income is replaced by the ratio of high income in the sample). We recalibrate the parameters $(N, \lambda, \bar{\delta}, \hat{\delta})$ after those modifications following the same procedures described in the text.

^b The bargaining solution here is the extreme case in which tolls are set to maximize consumer surplus.

^c We fix the capacity of the private road (route r1) as 2000 (1 lane) to compare with the results in Table 5.

Figure A1. Solutions to Private Duopoly Competition

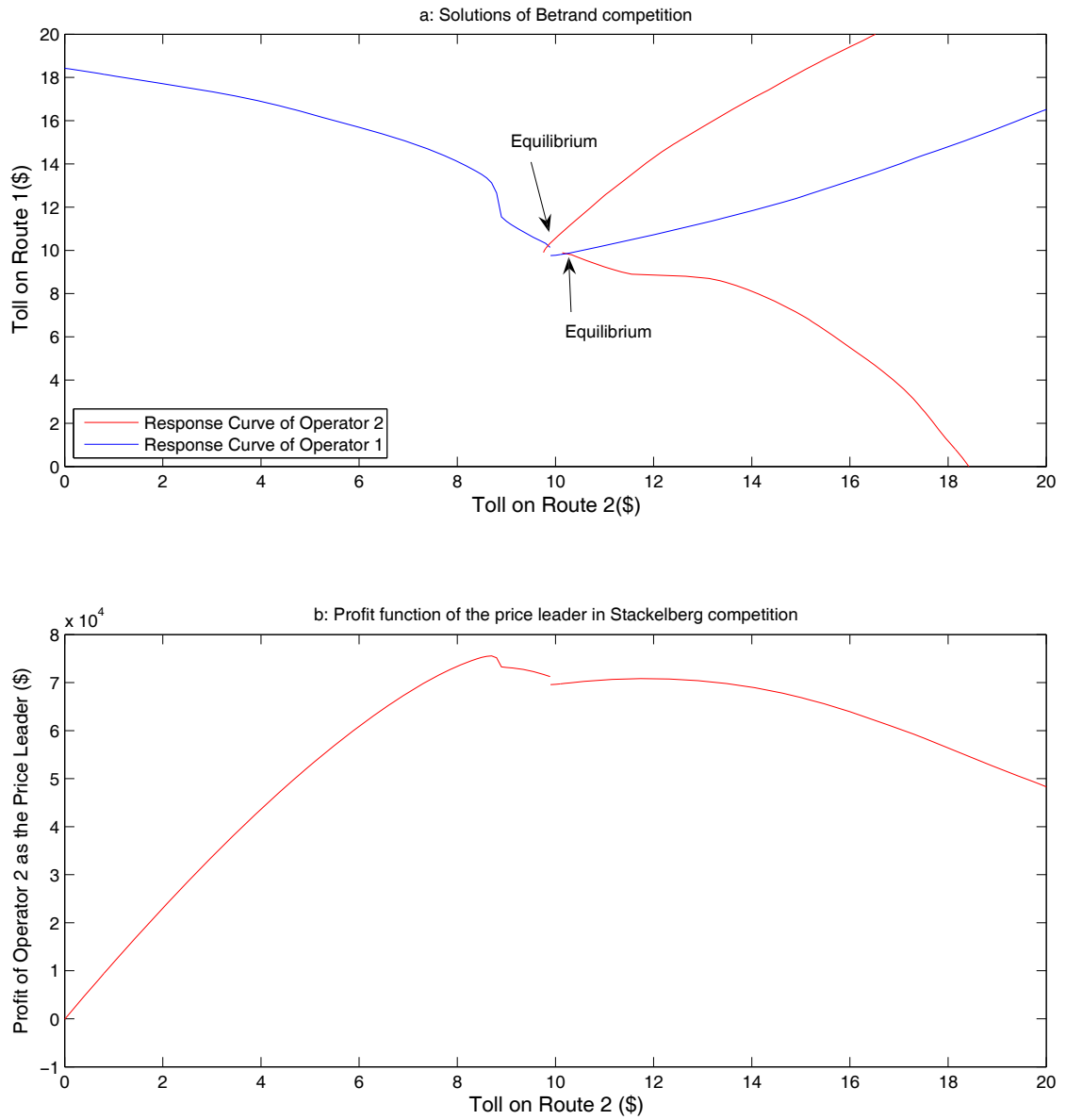


Figure A2. Solutions to Private Duopoly Competition with Bargaining

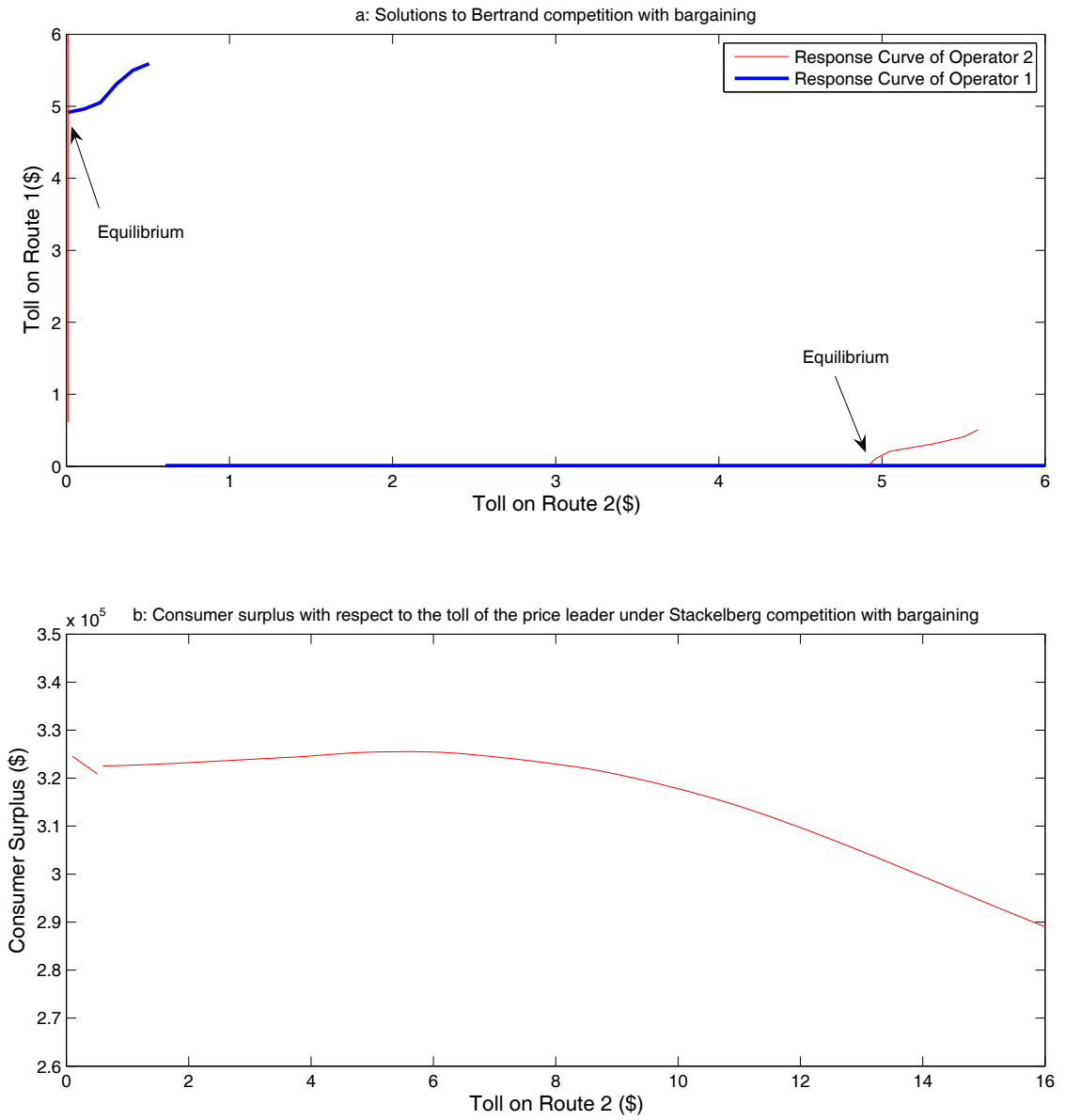


Figure A3. Solutions to Public-Private Duopoly Competition

