ROAD PRICING AND INVESTMENT

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Introduction

Traffic congestion is a bane of modern city life. In its latest annual Urban Mobility Report (Schrank et al., 2011), the Texas Transportation Institute estimates that in 2010, congestion in the 439 major urban areas of the US caused approximately 4.8 billion hours of travel delay and 1.9 billion gallons of extra fuel consumption with an estimated total cost of $101 billion. The average cost per automobile commuter was $713, and in six of the largest urban areas it exceeded $1,000. Broadly similar estimates are found in other developed countries (VTPI, 2011).

The traditional approach to controlling congestion was to forecast traffic growth, and then build enough road capacity to accommodate it. This "Predict and provide" strategy was abandoned in the 1990s in the face of evidence that new capacity soon fills up with new traffic. Other policies to combat congestion are also common: land-use planning, improvements in traffic management, vehicle priority lanes, odd-even license plate restrictions on car use and so on. But these policies can be expensive to implement. They are also blunt instruments for targeting congestion, and to the extent that they make driving more attractive they encourage driving just as road building does.

Cities face other road-transport challenges as well: accidents, air pollution, and other externalities; rising costs of road construction and maintenance; and shortage of funds for public transit as an alternative to driving. Economists have long argued that road pricing is the best single tool to address these problems because it can serve three functions. First, it can manage demand by influencing all dimensions of travel behavior without actually banning any particular trips. Second, it generates revenues to fund road investment, maintenance, and operations. And third, toll revenues provide a signal whether capacity expansion is warranted.

Road pricing and road construction are both controversial and raise a number of questions. Two are addressed in this review. First, how are road pricing and investment decisions related? Expanding road capacity relieves congestion, but it also costs money for construction and subsequent maintenance. Investment decisions thus affect tolling decisions for demand management and cost recovery. Reciprocally, tolling decisions affect investment needs because tolls affect traffic volumes. A question of obvious importance for long-run investment planning and funding requirements is whether more or less road capacity is needed if road pricing is implemented.

The second question is: what role should the private sector play in building new roads and tolling them? Many intercity highways and some urban roads have been designed, financed, built, operated, maintained and/or tolled by the private sector. Private entities can be more cost efficient than public ones, and they can accelerate construction of new roads or lanes by providing financing to cash-strapped governments. But the private sector has an incentive to exercise market power by setting high tolls and underinvesting (or possibly overinvesting) in road capacity. How serious are these distortions, and how do they depend on the topology of the road network and the way in which control over road links is assigned?

System-optimal toll and capacity decisions

This section briefly reviews the theory of optimal toll and capacity decisions on a road network that is controlled by a welfare-maximizing public operator. The theory directly addresses the first question on how toll and capacity decisions are related, and it provides a benchmark against which to evaluate the efficiency of private toll roads.[2] The road network is represented by a set of nodes and a set of links that join the nodes. There is a set of origin-destination (O-D) pairs or "markets" between some of the pairs of nodes. Let N_m be the number of trips made in market *m*, and $d_m\left(N_m\right)$ be the inverse demand curve for trips in market *m*. Market *m* is connected by a set of routes. The correspondence between links and routes is described by indicator variables δ_{lr}, where $\delta_{lr}=1$ if route *r* uses link *l*, and $\delta_{lr}=0$ otherwise. Similarly, the correspondence between routes and markets is described by indicator variables δ_{rm}, where $\delta_{rm}=1$ if route *r* serves market *m*, and $\delta_{rm}=0$ otherwise.

Let v_l denote traffic flow on link *l*, and V_r traffic flow on route *r*. The v_l, V_r, and N_m variables are related by the accounting identities

(1) $v_l=\sum_r \delta_{lr}V_r$, and $N_m=\sum_r \delta_{rm}V_r$.

Let K_l denote the capacity of link *l*. Users are assumed to be homogeneous in their costs of travel. The user cost function on link *l*, $c_l\left(v_l,K_l\right)$, is assumed to be an increasing function of v_l, and a decreasing function of K_l. It is also assumed that $\partial^2 c_l \big/ \partial v_l \partial K_l \le 0$ which implies that the marginal benefit from expanding capacity in reducing user cost is greater at higher traffic volumes. Given a toll (if any) of τ_l on link *l*, the generalized cost of using link *l* is $c_l\left(v_l,K_l\right)+\tau_l$.

The generalized cost of taking a route is the sum of the generalized costs of using the constituent links. In equilibrium the generalized cost of taking any route that is used must equal the willingness to pay for travel in the corresponding market:

(2) $$\sum_l \delta_{lr}\left(c_l\left(v_l,K_l\right)+\tau_l\right)=d_m\left(N_m\right).$$

The final element of the model is the annualized infrastructure cost for link *l* which is assumed to be a strictly increasing function of its capacity: $F_l\left(K_l\right)$.

The social optimum is derived by choosing τ_l and K_l on each link to maximize the sum of net consumers' surplus in all markets minus infrastructure costs:

(3) $$B = \sum_m \int_{n=0}^{N_m} d_m(n)\,dn - \sum_l c_l(v_l, K_l)v_l - \sum_l F_l(K_l)$$

subject to accounting identities (1), equilibrium conditions (2), and non-negativity constraints on link flows and route flows. Toll collection costs are ignored, and toll revenues do not enter expression (3) because they are a transfer from users to the government.

For a "first-best" setting in which tolls on all links can be set freely the optimum is easy to derive. The optimal toll on link *l* is given by the formula:

(4) $$\tau_l = \frac{\partial c_l(v_l, K_l)}{\partial v_l} v_l .$$

Given $\partial^2 c_l / \partial v_l \partial K_l \leq 0$, τ_l is a decreasing function of K_l for any given level of usage. Thus, the optimal toll falls if capacity is expanded. Although changing the toll on one link affects flows on other links, the first-best toll is imposed as if other links do not exist. The reason is that if all links are efficiently priced, marginal changes in flows on other links are welfare-neutral and can be ignored.

Optimal capacity for link *l* is determined by the first-order condition:

(5) $$\underbrace{-\frac{\partial c_l(v_l, K_l)}{\partial K_l} v_l}_{\text{(a) User benefit}} - \underbrace{\frac{\partial F_l(K_l)}{\partial K_l}}_{\text{(b) Capacity cost}} = 0.$$

Term (a) in eqn. (5) is the reduction in user costs due to a marginal increase in capacity. Term (b) is the marginal increase in capacity cost. Since v_l depends on τ_l (and tolls on other links as well) optimal capacity depends on the tolling policy. Thus, eqns. (4) and (5) together reveal how toll and capacity choices are interdependent.

For various reasons first-best conditions do not hold in practice. Some links on the road network cannot be tolled freely, if at all. Substitute or complementary modes of transport may be mispriced, labor and other markets linked to road transport can be distorted by taxes and regulations, and so on. A substantial literature has developed on second-best pricing of road transport.[3] Attention here is focused instead on second-best optimal capacity decisions when tolls are non set optimally.

Most roads in Canada and elsewhere are not tolled. However, fuel taxes effectively serve as a crude sort of toll so that positive values of τ_l can be considered descriptive of the status quo. In addition, some toll roads have rather high tolls. To encompass the various possibilities, suppose that the toll on link *l* is fixed at a level τ_l which could be below or above the first-best toll in eqn. (4). In place of eqn. (5) the first-order condition for K_l works out to be:

$$(6) \qquad \underbrace{-\frac{\partial c_l(\nu_l, K_l)}{\partial K_l}\nu_l}_{\text{(a) User benefit}} - \underbrace{\frac{\partial F_l(K_l)}{\partial K_l}}_{\text{(b) Capacity cost}} + \underbrace{\left(\tau_l - \frac{\partial c_l(\nu_l, K_l)}{\partial \nu_l}\nu_l\right)\frac{d\nu_l}{dK_l}}_{\text{(c) Induced demand}} = 0.$$

Terms (a) and (b) in eqn. (6) match the two corresponding terms of eqn. (5). Term (c) reflects the effects of *induced* demand. Suppose the toll is set below the first-best toll while capacity is held fixed at its first-best level. Term (b) does not change. But usage increases so that term (a) is larger than in the first-best solution. This *usage effect* underlies the conventional wisdom that optimal capacity is larger when usage is underpriced or not tolled at all. However, eqn. (6) also includes term (c) which is negative when usage is underpriced because $d\nu_l/dK_l > 0$. Term (c) is an *induced demand effect* that arises because expanding capacity attracts additional flow that has a private benefit less than its social cost. The additional flow can be caused by traffic diversion from other routes as well as by an increase in the number of trips taken in some of the markets.

Arnott and Yan (2000) show that if usage is underpriced, the volume-capacity ratio ν_l/K_l is always greater in the second-best optimum than the first-best optimum. Thus, if first-best congestion pricing were introduced, and capacity were adjusted from the second-best level given in eqn. (6) to the first-best level given in eqn. (5), travel would become less congested even if it is optimal to reduce capacity.

Without specific assumptions about the user cost and demand functions, the topology of the network, and the level of τ_l, it is not possible to determine whether the usage effect or the induced demand effect dominates. Consequently, it is not possible to say generally whether second-best capacity is larger or smaller than first-best capacity. A number of empirical studies have examined the strength of induced demand. Assessments vary widely. One view is that it is not significant enough to undermine the benefits of highway capacity additions. Duranton and Turner (2011) ascribe this view to the American Road and Transport Builders Association (ARTBA).[4] The opposing view derives from a belief in the *Fundamental law of road congestion*, conceived by Downs (1962), according to which "you can't pave your way out of traffic congestion".[5]

One measure of the strength of induced demand is the elasticity of traffic volume with respect to road capacity. This elasticity has been estimated for individual highway projects as well as for regions. If *v* denotes aggregate flow, and *K* denotes capacity measured in lane-km, the elasticity is defined as $\varepsilon \equiv (dv/dK)\cdot(K/v)$. A value of $\varepsilon = 0$ corresponds to no induced demand, whereas $\varepsilon = 1$ implies that capacity expansion attracts an equiproportional increase in traffic so that travel speeds do not improve at all. Small and Verhoef (2007, §5.1.3) review empirical studies that obtained estimates of ε ranging from 0.2 to 0.8.

Elasticities tend to increase over time as residential and other land-use developments respond to improved mobility. Elasticities also tend to be larger for individual road projects because traffic diversion from alternative routes, or modal shifts from transit, are ready sources of induced demand. Elasticities are generally smaller at a regional level because there is less scope for traffic diversion. Two recent studies have estimated elasticities at a regional level using US data. Duranton and Turner (2011) use data on interstate highway kilometers and highway vehicle kilometers travelled (vkt) for cities. Consistent with the *Fundamental law* they obtain estimates of ε close to one. They attribute the high level of induced demand mainly to increases in driving by current residents and increases in transportation-intensive production activity (e.g., trucking and warehousing). Migration and traffic diversion are of secondary importance. They also find that public transportation capacity has no statistically significant effect on vkt. Overall, they conclude that neither road capacity expansion nor public transit investment is effective in addressing traffic congestion which "leaves congestion pricing as the main candidate tool to curb traffic congestion". (p.2646).

The second study by Hymel et al. (2010) uses vehicle miles travelled (VMT) at the state, rather than city, level as a dependent variable, and total length of state roads as a measure of capacity. They obtain elasticity estimates of 0.037 in the short run and 0.186 in the long run. Insofar as migration and traffic diversion are less important at the state than the city level, the fact that their estimates are smaller than those obtained by Duranton and Turner (2011) is understandable. Nevertheless, the differences in estimates are so large that other factors are almost certainly at work that deserve investigation.

In summary, it is fair to say that the strength of induced demand is highly context specific. It depends on the geographical scale over which capacity investment is undertaken, on the time period considered, on the type of roads that are built or expanded (e.g., limited-access highways versus city streets), on the quality of public transit in the affected region, and so on. The consequences of implementing road pricing are therefore likely to be varied. Construction or expansion may be warranted for some links. Other links should be abandoned when they require major rehabilitation of reconstruction. Still other links should be built years later than they would be without road pricing.

Private roads

Private toll roads have been gaining favour as a supplement or alternative to public, toll-free roads. In part, support derives from the same concerns that motivate road pricing generally: shortages of public funds, dwindling revenues from fuel taxes, and growing acceptance of the user-pay principle.[6] Private firms may be more cost efficient than public operators due to stronger financial incentives, greater freedom from procurement rules and political interference, and so on. The public may also accept innovative pricing mechanisms such as peak-period tolls more readily from a private firm because innovative pricing is common in airline, hotel and other private markets.

Views differ widely on private roads. Proponents emphasis the potential advantages just mentioned. Opponents worry about the exercise of monopoly power, and lack of coordination in toll and investment decisions if control of road networks is devolved to multiple private firms. To assess the pros and cons of private toll roads we first examine the analytics of toll and capacity choice decisions, and then briefly address some practical concerns.

One firm

Consider an unregulated profit-maximizing firm that controls link *l*. The firm's goal is to maximize its revenue, $\tau_l v_l$, given an inverse link-demand curve $d_l\left(v_l\right) = p_l$ and the constraint $p_l = c_l\left(v_l, K_l\right) + \tau_l$ where p_l is the generalized cost on link *l*. Function $d_l\left(v_l\right)$ is determined by the pattern of O-D demands on the network and any tolls set on other links which are assumed to be outside the firm's control. The profit-maximizing toll works out to:

(7) $$\tau_l = \frac{\partial c_l\left(v_l, K_l\right)}{\partial v_l} v_l - \frac{\partial d_l\left(v_l\right)}{\partial v_l} v_l = \left(\frac{\partial c_l\left(v_l, K_l\right)}{\partial v_l} - \frac{\partial d_l\left(v_l\right)}{\partial v_l}\right) v_l .$$

The toll equals the first-best congestion toll in eqn. (4) plus a markup due to the firm's market power. The functional form of eqn. (7) reflects that the link-demand function net of user cost facing the firm is $d_l(v_l) - c_l(v_l, K_l)$. The slopes of $d_l(v_l)$ and $c_l(v_l, K_l)$ with respect to v_l therefore affect willingness to pay in the same way. In effect, the firm incurs two costs to attract an additional user. One is the marginal external congestion cost the user imposes on other users which reduces their willingness to pay. The firm accounts for this cost in the same way as does a public operator. The second cost is that the firm has to decrease the toll in order to attract the new user. This causes a loss of revenue from existing users equal to the markup. The markup creates a deadweight loss since the lost revenue is a transfer to users with no social cost.

If demand is perfectly elastic, perhaps because there is a congestion-free alternative route, the markup is zero and the firm sets the first-best toll. Otherwise the toll is too high. If demand is relatively inelastic, and congestion is not severe, the benefits from tolling in congestion relief are outweighed by the loss from tolling off too many users, and welfare is lower than if the link remained untolled.

The firm's capacity choice rule turns out to be identical to eqn. (5) for a public operator. This is an example of Spence's (1975) general result that if users value product quality equally, and quantities are the same, profit-maximizing and socially-optimal quality choices coincide. Given the toll rule in eqn. (7), the firm sets a toll above the first-best optimum so that output (i.e., link volume) is too low, and therefore capacity is less than the first-best capacity as well. However, if $c_l(v_l, K_l)$ exhibits constant returns to scale[7], the firm chooses the same volume-capacity ratio, v_l / K_l, as in the first-best optimum. The firm provides optimal quality, but too little quantity.

Competition

Competition between toll-road firms is difficult to analyze on general networks, and most studies have focused on simple settings with links in parallel or series. To begin, assume that capacities are fixed and consider toll competition. With parallel links, competitive equilibrium is most efficient in the symmetric case when firms control links with equal capacities and free-flow travel times. The efficiency of equilibrium improves with the number of firms, and in the limit attains the first-best optimum because firms lose all their market power (Engel et al., 2004).

By contrast, when firms control links in series, increasing the number of firms has the opposite effect because links are perfect complements and each firm effectively has monopoly control over total usage. Each firm adds a monopoly markup, and the end result is an equilibrium generalized trip cost that is far higher than in the first-best outcome. This suggests that the most efficient market structure is one with multiple competing routes with a single firm in control of the links that comprise each route.

Suppose now that firms compete in both tolls and capacity. As true of market competition in general, equilibrium depends on the timing of decisions. Three settings have been studied for the case of links in parallel. In the simplest setting all firms choose their capacities and tolls simultaneously. The solution to this game is the same as for the one-firm case considered above. Each firm therefore chooses the socially optimal volume-capacity ratio independently of other firms' choices. However, firms still impose a markup on their tolls so that volumes and capacities are inefficiently low.

A second, and arguably more realistic, setting is a two-stage game. In stage 1, firms simultaneously and independently choose their capacities, and in stage 2 they simultaneously and independently choose their tolls. Consistent with general results in the industrial organization literature (Fudenberg and Tirole, 1984) in this game firms behave strategically and hold back on capacity in stage 1 in order to soften toll competition in stage 2. As a result, firms choose a higher volume-capacity ratio, and a correspondingly lower service quality, than in the first-best optimum.

The third setting, studied recently by Van den Berg and Verhoef (2011), is a Stackelberg game in which firms choose their capacities in sequence and then choose their tolls simultaneously once all roads have been built.[8] Firms face conflicting incentives in this game: they gain from restricting capacity to limit toll competition (as in the two-stage game), but they also gain from building a high capacity to induce subsequent firms to build less capacity. Van den Berg and Verhoef show that the first firm to move chooses a capacity that is larger than in the corresponding two-stage game, whereas the last firm chooses a capacity that is smaller. They find that welfare can be higher or lower in the Stackelberg game than in the two-stage game.

To sum up: analytical studies of private toll roads have yielded several conclusions. If users are homogeneous, firms internalize congestion externalities efficiently in their choices of both toll and capacity, but they add a markup to the toll. Decentralization of control over the road network to independent private firms is efficiency-enhancing when substitute links are controlled by different firms, but counterproductive if the links are complements. If firms act strategically, and limit capacity to soften toll competition, efficiency is harmed, whereas if they increase capacity to deter other firms from investing, the effect on efficiency is ambiguous a priori.

Practical considerations

While private toll roads are experiencing a resurgence in popularity, resistance continues to be strong in some countries. Traditional arguments for public provision of roads and other transportation infrastructure still carry some weight (Vickerman, 2005). To a degree, roads are natural monopolies and have the scope to set high tolls. Road capacity is also rigid and lumpy. During the "ramp-up" period when demand is growing on a new facility, a firm may run a large deficit unless it sets an inefficiently high toll. Links in low-density regions may never be profitable because of low traffic volumes. Moreover, profitability is neither a necessary nor a sufficient condition for construction of a new link to be welfare-improving (Mills, 1995). There are two opposing biases: new links create social surplus that a firm cannot fully expropriate, but some of their profits may come at the expense of profits on other links. These same biases apply generally to entry decisions in differentiated-products markets (Mankiw and Winston, 1986).

A further difficulty is that toll roads are immobile, and have few if any alternative uses. Asset specificity creates significant risks, especially in underdeveloped areas where demand depends on future development decisions, land-use regulations, and so on. All this suggests that some form of public-sector involvement is inevitable. There is a growing literature on regulation, contract design, and public private partnerships that is beyond the scope of this review.

Conclusions

Traffic congestion in major cities has persisted in the face of many policies to combat it including large-scale investments in road capacity. Many transportation economists and a growing number of other transportation professionals support road pricing as the most promising demand-side approach to curbing congestion.

This paper has focused on two questions related to road pricing. First, how are road pricing and investment decisions related? Tolls are often seen as a substitute for investment since, by reducing traffic flows, they reduce the number of trips that can benefit from capacity-induced congestion relief. What this argument overlooks is that when usage is underpriced, adding capacity creates induced demand with a private value less than its social costs. Empirical evidence at both the individual facility and larger regional level indicates that induced demand can be a potent force. Depending on the time span considered, the type of road investment, and other factors such as quality of public transit service, induced demand may be quite strong. If so, road investment is actually more beneficial if road pricing is introduced.

Road pricing and investment are also complementary from a public acceptability perspective. Three common objections to road pricing are: paying for something that was previously free, double taxation, and inequity. Each of these objections applies with less force to tolls that are imposed on new roads — particularly if toll revenues are used to fund capacity expansion, operations and maintenance.

A second goal of the paper is to review some of the economics of private toll roads. When users are homogeneous, and value trip quality equally, a private firm is cost efficient. It correctly accounts for the congestion costs borne by users, and chooses a road capacity that minimizes the sum of road construction and user costs. But a private firm is allocatively inefficient because it exploits its market power by adding a markup to the toll. The markup is inversely proportional to the elasticity of demand. If firms operate competing parallel roads, the market power of each firm is limited and decreases with the number of competitors. By contrast, if firms operate road links that are in series, the outcome can be grossly inefficient because each firm adds a monopoly markup to the price of a trip. This suggests that the most efficient market structure is one with multiple competing routes, with a single firm in control of the links that comprise each route.

Competition "in the market" (as opposed to "for the market") between private road operators is still rare, and there is little experience to judge how it will play out. But as support increases for road pricing as a way to deal with traffic congestion, pollution and declining fuel tax revenues, organizational and regulatory issues with private toll road markets are likely to become more urgent. Similar issues may also arise if control over toll-road networks ends up in public-sector hands as municipal, regional, state/provincial and national governments compete for business and residents while also trying to generate revenues for their respective budgets.

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Endnotes

[1] This is an abridged version of a longer paper that addresses a wider range of topics including investment in public transportation, dedicated rights of way, and future developments in travel demand and technology.
[2] The theory is covered in more detail in Small and Verhoef (2007, Chaps. 4 and 5).
[3] See Small and Verhoef (2007, §4.2) for a review.
[4] Recent statements by ARTBA bear this out. For example, on 27 September 2011, ARTBA President & CEO Pete Ruane remarked: “Everyone who drives already knows congestion robs parents of time with their children and unnecessarily drives up the cost of everything Americans buy .... Robust new investments aimed at creating additional transportation infrastructure capacity are the key to getting motorists, businesses and the economy moving forward again.” (http://www.artba.org/article/delaydelaydelayon-highwaysand-on-capitol-hill-when-it-comes-to-passing-a-long-term-transportation-investment-bill/). In addition, the FAQ link on the ARTBA website asks the question "Does building new roads cause more driving, more traffic, and, therefore, more air pollution?." Its response is: "No. Just as building new schools does not "cause" more students or studying, building roads does not "cause" more drivers or traffic." (http://www.artba.org/about/faqs-transportation-general-public/faqs/#28)
[5] This view was starkly expressed by David Begg, then chairman of the UK Commission for Integrated Transport, who is quoted by The Economist (2002) as saying: "A big road-building programme without pricing is as ludicrous as giving a heroin addict a last fix."
[6] This view is supported by Poole (2012) who describes developments with privately-funded and operated roads in the US.
[7] That is, increasing v_l and K_l by the same proportion leaves user costs unchanged.
[8] This setting is plausible for a toll-road industry. Entry is costly and protracted because of the time required to get environmental approval and to build each road. In contrast, tolls are easily changed, and long-term toll contracts may be difficult to write or enforce. The first firms to enter therefore cannot commit themselves to set a particular toll that might influence the decisions of subsequent firms in a strategically advantageous way.