Revenue Choice on a Serial Network

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Abstract

A model to examine the choice by jurisdiction whether to finance roads with taxes or tolls is developed. The idea of decentralised, local control and multiple jurisdictions distinguishes this analysis from one where a central authority maximises global welfare. Key factors posited to explain the choice include the length of trips using the roads, the size of the governing jurisdiction, the elasticity of demand to revenue instruments, and the transaction costs of collection. These factors dictate the size and scope of the free rider problem associated with financing. Spatial complexity in this problem ensues because jurisdiction residents use both local and non-local networks, and each jurisdiction’s network is used by both local and non-local residents. The central thesis argues that, since jurisdictions try to do well by their residents who are both voters and travellers, the effects of a revenue instrument on local residents is a key consideration in the choice of that revenue instrument. Decentralisation of control and lower toll collection costs are identified as conditions under which tolls would be more likely to become the preferred revenue instrument for highways.

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**Introduction**

Cordon tolls are becoming a popular method of restricting traffic in cities and financing new infrastructure. Singapore, Oslo, Trondheim, and Bergen are cities with such a mechanism in place. Imperfect cordon, such as a toll barrier on a major highway with toll-free entrance and exit ramps, have traditionally been used both in the early days of turnpikes and more recently on some limited access highway systems. In both cases local trips, which remain within the cordon, do not pay tolls, while through trips, which cross the cordon, do. On the other hand, tax financing has been common both historically (initially the tax was in terms of labour), and more recently for local roads, which are funded through general revenues. Taxes also rely on a cordon, the boundary of the relevant jurisdiction, within which they are assessed.

In this paper a model of network financing is developed that incorporates the basic features of the economic structure of transport networks. It includes the demand and supply interaction, the choices available to actors (consumers and producers), and the linkage between the two when local residents own the network within their jurisdiction. The idea of decentralised, local control and multiple jurisdictions distinguishes this analysis from one where a central authority maximises global welfare. The model's theoretical results should be consistent with what is empirically known about network financing. It should thus describe network financing choices made under various circumstances. Policies can then be drafted that alter circumstances to effect the desired choice of financing mechanism.

The main complication is the joint production and consumption of the key good (network services) by the jurisdiction and its residents. The network operator (jurisdiction) makes the network available while residents consume the network for travelling. Spatial complexity in this problem results from the fact that jurisdiction residents use both local and non-local networks, and each jurisdiction's network is used by both local and non-local residents. The network is not perfectly competitive and thus retains some monopoly power. The degree of locality in the use of the network directly shapes the local welfare resulting from a particular revenue mechanism, and itself is a function of jurisdiction size. The choice of financing instrument must trade off the number of spatial free riders, system users who do not pay their cost because of the location, and the costs of collection. The price charged for a given instrument is limited by the elasticity of demand on those who are charged.

The central thesis argues that, since jurisdictions try to do well by their residents who are both voters and travellers, the effects of a revenue instrument on local residents is a key consideration in the choice of that revenue instrument. It is assumed that jurisdictions responsible for network financing behave as if
they have the objective of local welfare maximisation. Local welfare here reflects the consumers' surplus of residents of the jurisdiction and the profits accruing to the locally controlled network authority that the jurisdiction owns and manages. Levinson (1997) considers the thesis from a historical perspective. This paper, drawing from Levinson (1998), approaches the questions analytically to develop a positive theory of the choice of revenue mechanism over space as a function of key factors.

It is posited that the choice of tax or toll (or the optimal combination of both), while being historically contingent, is a function of several ahistorical or economic factors. These include the length of trips, the size of the jurisdiction, the transaction costs of collecting revenue, demand, and the cost of providing infrastructure. These properties indicate the nature of the free rider problem under the two different regimes (tax, toll). In the case of tax-only financing, travellers from outside the taxing jurisdiction do not pay taxes to support the construction, operation, and maintenance of the road. In the case of cordon toll-only financing, travellers entering and exiting the network within the cordon pay nothing. A perfectly excludable toll cordon, which tracks everyone entering and exiting each link, is not costless, and cannot necessarily be implemented everywhere. The free rider problem will occur whenever there is an incomplete or uneven revenue instrument; that is, when financing does not capture every user in proportion to use. In realistic situations of highway transport, there are transaction costs involved in collecting revenue, which dictate that a complete and perfect revenue instrument is not available on every link.

It is an assumption of this work that jurisdictions would rather place the burden of financing on non-local travellers in order to maximise local welfare. Therefore, in the case of local control there is a preference to tax through trips and exempt trips that both originate in and are destined for the jurisdiction (locals), thereby allowing locals to be the free riders. At the extreme case, that of a single short road segment (a near perfect cordon), this approaches the efficient revenue instrument of tolling nearly all travellers in proportion to use, as there are very few, if any, “locals”. However, if those who make through trips also control the political process, or through trips are really “local” because the road authority has a broad geographical scope, then taxes may be preferred because of their lower transactions costs.

This hypothesis does not claim to be a total explanation under all circumstances; as a socio-political system, infrastructure financing has many influences. For instance, perfect excludability on roads coupled with the presence of “free” alternatives, reductions in toll collection costs, and private ownership, may all increase the willingness of a jurisdiction to tolerate tolls even on local residents. The socio-economic level of the jurisdiction may influence its willingness to adopt congestion pricing. Further, the influence of key players
in business and politics with specific preferences are unpredictable and may greatly shape the decisions made over time. Another factor is the prevailing ideology of government. In the 18th and 19th centuries, a philosophy of limited, decentralised government, or *laissez-faire*, was conducive to private enterprise at all levels, including roads. However, this philosophy declined in America in the 20th century, at least until the early 1970s. Finally, regional rivalry and the idea of progress certainly have their place, promoting one-upmanship and construction for the sake of construction.

The model presented in this paper provides a strategic framework for assessing the outcome of alternative revenue instruments. The paper examines the free rider problem in relation to transaction (toll collection) costs. The model explicitly compares the welfare associated with taxes and those associated with tolls on a simplified network with various jurisdiction sizes. The actions available to network operators and the posited objectives that the two main sets of actors, the network operator (owned by residents) and travellers, are presented. Then the network geometry of this model is illustrated. The model of flow as a function of trip length and tolls is explained, as is the resultant consumers’ surplus. Profit calculations, and their component cost and revenue equations are presented. The models are then evaluated using assumed parameters to understand better its implication. Finally, key points, some policy conclusions, and directions for future research are summarised.

**Actions and Objectives**

A jurisdiction is defined as the owner of the road authority responsible for maintaining the road. These jurisdictions, or network operators, have several classes of actions; this research focuses on selecting a revenue instrument (taxes or tolls) and price or rate (collectively called revenue mechanism). Broadly, the two available revenue instruments are taxes and tolls. As used here, a *toll* ($t$) is a fixed sum of money charged for a specific service or privilege (for instance, the right to travel on a link or subnetwork). Our toll is a fee levied by the road authority as travellers cross a cordon. In contrast, the term *tax* ($x$) is defined as a fixed sum of money charged for a general service or privilege, such as the support of government or roads in general, independent of use. Our tax is a periodic (for example, annual) fee levied by a jurisdiction on its residents in the form of a poll tax. The distinction between a tax and a toll is in how specific or general the service is that is being provided and how closely it aligns with the revenue mechanism. Thus, a petrol tax is more like a toll than a property, poll, or income tax is. Petrol taxes are not analysed in this model, as they require the additional
Figure 1
One-Way, Long Road and Classes of Trips

Long Road
-oo ← J_a, J_b → oo
S a ← b

Class G_∞ Trips
- oo ← J_a, J_b → oo
s.t. y > x for all trips

Class G_∞ Trips
- oo ← J_a, J_b → oo

Class G_a Trips
- oo ← J_a, J_b → oo

Class G_a Trips
- oo ← J_a, J_b → oo
complication of determining where, in relation to the home, a driver purchases petrol.

In general, it is assumed that jurisdictions have the objective of local welfare maximisation \((\text{Max } W_L)\), where welfare is defined narrowly as the sum of profit (loss) from administering the road and consumers’ surplus for its residents, excluding external costs.

\[
\text{Max } \prod_i W_L = \Pi_i + U_i
\]  

(1)

where: \(\Pi_i\) is producer’s surplus (profit) on the network owned by jurisdiction \(i\); \(U_i\) is consumers’ surplus (transport and non-transport) of residents of jurisdiction \(i\); and \(P_j\) is a vector describing the price of infrastructure, a function of location of trip origin, destination, location of toll-booths, revenue mechanism (including the rate of odometer tax, cordon toll, or perfect toll and the basis of that toll), and is detailed later in the text.

In our model the residents own the network through the jurisdiction. So the jurisdiction that owns the network is comprised of residents who (collectively through their government) can set the policies for the network (revenue mechanism) to achieve a maximisation of their own welfare. Because profits are (or can be) redistributed to local residents, revenue in excess of costs from local residents is returned to them. Therefore, treating a jurisdiction and its residents as a single block is not unreasonable. The objective of a jurisdiction managing a roadway to maximise welfare for its residents, in addition to its obligation to cover costs, follows a long tradition of research (Downs, 1957).

This model differs from one that treats the network and its users as independent. In that case, the network operator will maximise profit while users will maximise their own utility. Inevitably, the monopolist network operator would raise prices relative to the welfare maximising toll and this would then result in lower welfare overall. A comparison between various objectives is conducted in other work by the author (Levinson, 1999a).

**Network Geometry**

The network geometry analysed here consists of an infinitely long road, as illustrated in Figure 1. There are two types of cordons along the road: jurisdiction boundaries and toll booths. A jurisdiction covers an area that contains, owns, and operates a portion of the road and is located between jurisdiction boundaries. In our model, all jurisdictions are identical in their fundamental features.
(including size), so we select one for analysis, which is called the jurisdiction of interest \( J_0 \). The jurisdiction of interest covers the portion of the road between boundary points \( a \) and \( b \), so its size is represented by the distance \( |b-a| \). All other jurisdictions (to the east and west of \( J_0 \)) are collectively called the environment \( E \). Jurisdictions to the west of \( J_0 \) are denoted by \( J_{-n} \), where \( n \) denotes the number of jurisdictions \( J_{-n} \) is from \( J_0 \). Similarly, jurisdictions to the east of \( J_0 \) are denoted by \( J_{+n} \). In our analysis of cordon tolls, we will assume that all tollbooths are located on jurisdiction boundaries, but not that all jurisdiction boundaries necessarily have tollbooths. Each jurisdiction that has cordon tollbooths has them both at the entrance and at the exit of the jurisdiction.

In an inter-city context, the geometry represents one jurisdiction (among many) that has authority over its portion of the long road, such as along an interstate highway under the authority of multiple states. In a more general problem, different densities of trip origins and destinations along the road could represent the centre and periphery of an urban region.

In order to make the analysis more convenient, sections \( (S) \) will be defined as aggregations of jurisdictions. For simplicity in our analysis, three sections are defined: the area comprised of all jurisdictions west of the jurisdiction of interest \( J_0 \) \( \{J_{-1}, J_{-2} \ldots \in S_-\} \), the jurisdiction of interest \( \{J_0\} \), and the area comprised of all jurisdictions east of \( J_0 \) \( \{J_{+1}, J_{+2} \ldots \in S_+\} \).

\[
\begin{array}{c|ccc}
\text{Section of Origin (s)} & S_- & J_0 & S_+ \\
\hline
S_- & G_- & G_0 & G_+ \\
J_0 & G_{0-} & G_{00} & G_{0+} \\
S_+ & G_{+} & G_{+0} & G_{++} \\
\end{array}
\]

**Table 1**

*General Trip Classification*

<table>
<thead>
<tr>
<th>Section of Origin (s)</th>
<th>Section of Destination (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_- )</td>
<td>( G_- )</td>
</tr>
<tr>
<td>( J_0 )</td>
<td>( G_0 )</td>
</tr>
<tr>
<td>( S_+ )</td>
<td>( G_+ )</td>
</tr>
</tbody>
</table>

Bold type indicates trip classes of interest on a one-way road. 0 indicates jurisdiction \( J_0 \); --, + indicates jurisdiction in \( S_- \), \( S_+ \) respectively.

User classes \( (G) \) are defined as section-to-section (rather than jurisdiction-to-jurisdiction) interactions. In principle the number of section-to-section interactions (classes) is \( S^2 \), where \( S \) is the number of sections. This article analyses
a one-way road, but assumes underlying symmetric demand functions, and round trips. On a one-way road, the number of relevant section-to-section interactions is reduced from the number \( S^2 \), as trips cannot exit upstream of where they enter. Furthermore, trips that do not travel through \( J_0 \) can be eliminated from consideration. Therefore, on a one-way road the three sections define only four section-to-section interactions, our classes of interest. The user classes are shown in Table 1. For convenience we assume all jurisdictions are identically sized.

**Consumption**

**Demand**

Flow across any point on a road can be described by the function below, following and extending Newell (1980):

\[
f(z) = \int_{x < y < z} \int \rho[P_T(r, x, y)]dxdy,
\]

(2)

where: \( f(z) \) is the flow past point \( z \); \( \rho[P_T(r, x, y)]dxdy \) is the demand function representing the number of trips that enter the facility between \( x \) and \( (x + dx) \) and leave between \( y \) and \( (y + dy) \); \( P_T(r,x,y) \) is the generalised cost of travel to users (defined below); \( x, y \) is where the trip enters or exits the road — \( x < y \) (to account for the fact that it is a one-way road); \( Z \) is a point on the road; and \( r \) is the collective toll paid by a traveller.

A key assumption is that markets are non-substitutable. This means that there is no cross-elasticity of demand. For instance, trips remaining entirely within \( J_0 \) (class \( G_{00} \)) are unaffected by price changes by \( J_{+1} \). There remain supply-side effects, so that a change in price by \( J_0 \) affects the demand for trips using roads in both \( J_0 \) and \( J_{+1} \) (such as \( G_{01} \) trips). In turn, this may affect prices faced by travellers in \( J_0 \) (say \( G_{00} \) trips), even if they do not travel in \( J_{+1} \). The following chain of logic can explain this price-demand interdependence. First, the optimal tolls in any jurisdiction, including \( J_{00} \), depend on the demand function for the link. Second, the demand on the link in \( J_0 \) depends on the demand of all trip classes using that link. Third, those trip classes that use links in more than one jurisdiction depend on prices on the links in each jurisdiction.

The argument of the demand function is assumed to be a weighted sum of the time and money costs of travel. A negative exponential form is used. Therefore we may rewrite the density function as dependent on the total price users pay \( (P_T) \), a decay coefficient \((\alpha)\), as well as a multiplier \((\delta)\) representing the number of trips generated per unit length.
\[ p[P_T(r, x, y)] = \delta e^{\alpha P_T(r, x, y)} \]  

The total price users pay for travel \((P_T)\), is the sum of several components. Direct infrastructure charges \((P_I)\) transferred to the network operators depend on the revenue policy selected by each jurisdiction (cordon tolls or general taxes). In general, the price of infrastructure is a function of the rate of cordon toll \(r_s\) and the quantity over which each unit rate is applied (number of tolls crossed). The price of infrastructure can be decomposed into the price inside \(J_0\) and the price outside \(J_0\), which are summed to attain the price paid by users. This decomposition enables a clear analysis of situations where a jurisdiction employs one policy while the environment imposes another. Under a general tax policy, user payment for infrastructure is independent of the amount or location of travel. The rate of toll paid to a jurisdiction that imposes taxes is 0 for all user groups. A toll policy is more complicated than a general tax policy, as tolls affect demand while taxes do not. In the case of cordon tolls, direct infrastructure charges transferred to the network operators depend on the location of the origin and destination, that is, an incidence matrix \([I(x,y,n)]\), which represents whether toll booth \(n\) is crossed for trips between \(x\) and \(y\). Infrastructure charges also depend on the toll per crossing \((r_{\text{toll}})\), which is a policy variable available to the various jurisdictions. This is illustrated in Figure 2.

**Figure 2**  
*Tolls by Location of Origin and Destination*
Private vehicle costs \((P_V)\) depend on the distance travelled \((y-x)\), the cost per unit distance \((v)\), as well as a number of fixed components \((\xi)\) depending on the age and type of vehicle used.

Free-flow travel time costs \((P_F)\) depend on trip length \((y-x)\) and free-flow speed \((S_F)\), as well as the value of time \((V_T)\). Congested travel time is not dealt with here. Implicit in this model is that jurisdictions have the obligation of maintaining a level of service with a resulting free-flow speed consistent with congested speeds. Thus “congestion effects” are ascribed to infrastructure costs, which are proportional to traffic flow (described in the cost section).

To simplify the analysis we assume no (dis)economies of scale and we assume smoothly and continuously increasing infrastructure costs. External costs are also excluded, since by definition they do not figure into the calculations of the network operator.

\[
P_T = P_I + P_V + P_F
\]

\[
= \sum_{n=1}^{\infty} r_{tn} [I(x, y, n)] + (\xi + v|y-x|) + V_T \left( \frac{|y-x|}{S_F} \right)
\]

where: \(I(x, y, n)\) is the toll incidence matrix, and \(I(x, y, n) = 1\) if \(x < L(n) < y\), \(I(x, y, n) = 0\) otherwise, and \(L(n)\) is the location of toll booth \(n\); \(n\) is the index of toll-booths along the road; \(r_{tn}\) is the rate of toll at toll crossing \(n\); \(S_F\) is the free-flow speed; \(V_T\) is the value of time; \(x, y\) are points where the trip enters and exits the road; \(v\) is the private variable cost (per unit length); and \(\xi\) is the private fixed vehicle cost.

**Consumers’ Surplus**
The sum of transport consumers’ surplus for all trips originating in jurisdiction \(J_0\) for the two relevant user classes is given by the following equation:

\[
U_0 = U_{00} + U_{0+}
\]

\[
= \int_{a}^{b} \int_{x}^{y} \int_{r}^{\infty} \rho[P_T(p, x, y)] dp dy dx
\]

\[
+ \sum_{n=1}^{\infty} \int_{a}^{b} \int_{n(b-a)}^{(n+1)(b-a)} \int_{r}^{\infty} \rho[P_T(p, x, y)] dp dy dx
\]
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where: $U_0$ is the consumer’s surplus of trips originating in $J_0$; $U_{00}$, $U_{0a}$ are consumer’s surplus for trips of $G_{00}$ and $G_{0a}$; $\rho(P_T(p,x,y))dx\,dy$ is the demand function; $P_T(p,x,y)$ is the generalised cost of travel to users at price $p$; $n$ is the index for the number of toll booths on the road; $a$, $b$ are jurisdiction $J_0$ cordon locations; and $p$ is the user monetary cost (integrated from $r$ to infinity).

Price paid ($P_T$) for a group is the product of the rate of cordon toll assessed by jurisdiction multiplied by the basis over which the rate is collected. Local trips ($G_{00}$) do not pay cordon tolls because they do not cross the toll cordon. Cordon tolls on locally originating, non-locally destined trips ($G_{0a}$) are assessed both by the home jurisdiction ($J_0$ assesses a toll rate $r_T$) and by other jurisdictions (which assess a toll rate $r_T$). Because jurisdictions are identical, the effective price under identical policies (and toll-setting behaviour) is identical across jurisdictions.

Technically speaking, we define each $x$–$y$ pair as a distinct market (rather than defining each section-to-section pair as a distinct market). When we do so, then the $x$–$y$ pair has its consumers’ surplus measured before it is aggregated with other $x$–$y$ pairs. This requires integrating over the range of tolls for each flow, and then integrating all the resulting consumers’ surpluses over the relevant spaces. Fortunately, by Fubini’s Theorem, as long as a function is continuous over real space, the order of integration of a double (or triple, and so on) integral does not matter. So the results would be the same, independent of how the markets are defined.

Production

Profit
Profit or producers’ surplus ($\Pi_T$) is defined below as total revenue from transport ($R_T$) minus total (fixed and variable) costs ($C_T$):

$$\Pi_T = R_T - C_T.$$  \hspace{1cm} (6)

In our model any loss is, by definition, made up from general taxes, and any profit is used to reduce them. Therefore the impact of general taxes to support roads on welfare can be measured in terms of the profit or loss of the network operator. Because general taxes and transport demand are assumed to be independent, taxes do not need to be measured explicitly.

Cost
We take as a network cost model a function where total costs to the network operator ($C_T$) are an increasing function of jurisdiction size ($C_J$), traffic flow ($C_P$),
and variable and fixed toll collections \( C_{CV}, C_{CF} \). We assume a linear model, so there are no (dis)economies of scale or scope. The assumption of approximately no economies of scale is consistent with the literature (Small, 1989), though future research may relax this assumption.

The first cost category, cost as a function of jurisdiction size, can be considered analogous to a fixed cost. It depends only on the size of the jurisdiction \( |b-a| \) and the cost per unit distance \( (\gamma) \) of constructing and operating infrastructure. The second cost category, cost as a function of traffic flow, depends on the vehicle distance travelled in the jurisdiction, which is multiplied by a cost per vehicle distance travelled \( (\phi) \). Because we are assuming that the network is sized to ensure a given (uncongested) level of service, the cost as a function of traffic flow is a composite of infrastructure capital and operating and maintenance costs. While the first cost category is determined by the length of the road, the second is determined in part by the width of the road necessary to ensure a particular level of service. The third and fourth cost categories are the variable and fixed costs of collecting tolls. The variable cost depends on the number of toll booths \( (K_i) \) maintained by jurisdiction \( i \) and flow at each toll booth \( k, f(k) \), as well as the cost per collection transaction \( (\Theta) \). The fixed portion simply multiplies a fixed cost per toll booth \( (\kappa) \) by the number of toll booths in the jurisdiction (which is 0 in the case of general taxes and 2 in the case of cordon tolls). The model can be expressed as follows:

\[
C_T = C_S + C_p + C_{CV} + C_{CF} \\
= \gamma |b - a| + \phi \int_{a}^{b} f(z) dz + \Theta \sum_{k=1}^{K_i} f(k) + \kappa K_i
\]

where: \( C_T \) is the total cost; \( C_S \) is the fixed cost of jurisdiction size; \( C_p \) is the variable cost of traffic flow; \( C_{CV} \) is the variable cost of toll collection; \( C_{CF} \) is the index for the number of toll booths on the road; \( a, b \) are cordon boundary locations; \( \gamma, \phi, \Theta, \kappa \) are cost coefficients; \( z \) is a point on the road; \( f(z) \) is the traffic flow across point \( z \); \( k \) is the index of toll booths in jurisdiction \( i \); \( f(k) \) is the traffic flow across tollbooth \( k \); and \( K_i \) is the total number of toll booths in jurisdiction \( i \).

**Revenue**

Revenue depends on the specific instrument chosen, the rate, and the quantity. Table 2 gives the equations for revenue. For instance, the revenue from tolls collected at toll booths in jurisdiction \( i \) \( (K_i) \) \( (k = 1, \ldots, K_i) \) on the road is given below. In the case of jurisdiction-based cordon tolls, \( K_i = 2 \) \( (a \) and \( b) \).
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\[ R_T = r_T \sum_{k=1}^{K_i} f(k) \] (8)

where: \( R_T \) is the total revenue (\$); \( r_T \) is the rate of toll (\$/crossing); \( k \) is the index of tollbooths in jurisdiction \( i \); \( f(k) \) is the traffic flow across tollbooth \( k \); and \( K_i \) is the number of toll booths in jurisdiction \( i \).

Mathematical Solution

The discussion to date still leaves some latitude for solving the tactical problem of determining the rate of toll. The issue, in solving for the \( J_0 \)'s toll \( (r_T) \), is what does \( J_0 \) assume the other jurisdiction use as a toll \( (r_T) \) when it is known what policy they choose. For convenience, we assume that all other jurisdictions are imposing identical policies (either all tax or all toll), though not necessarily the same policy as \( J_0 \). We are seeking a non-cooperative Nash equilibrium for toll setting, which assumes no collusion (implicit or otherwise) between jurisdictions. This means that \( J_0 \) can do no better by changing its toll, given what all other jurisdictions do, while each other jurisdiction can also do no better. This does not necessarily result in the best satisfaction of the objective function, but is sustainable.

We use an iterative approach to solve for this equilibrium, (employing a macro and the solver algorithm of a standard spreadsheet software package). For each iteration, we assume \( J_0 \) sets its payoff-maximising toll as if the tolls in other jurisdictions are fixed. Under that constraint, the best assumption \( J_0 \) can make is that the other jurisdictions are using their last posted toll. Their last posted toll happens to be the toll previously solved for by \( J_0 \), since all jurisdictions are identical, and simultaneously performing these calculations.

To translate this into an algorithm: during solution round \( (i) \), \( J_0 \) assumes that \( r_T \) is equal to \( J_0 \)'s toll in solution round \( i - 1 \): \( r_T^i = r_T^{i-1} \). The algorithm says: given \( r_T \) and all the other pertinent variables, \( J_0 \) finds the welfare maximising \( r_T \), updates \( r_T \), and solves until equilibrium \( (r_T^* = r_T^*) \).

The reduced form solutions of the model components are given in Table 2. Table 3 shows the underlying assumptions about the rate of toll in \( J_0 \) (\( r_T \)) and in the other jurisdictions (the environment) (\( r_T \)) under the various \( J_0 \) policy and environment conditions.
<table>
<thead>
<tr>
<th>Group</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Collection Costs ($C_{CV}$)</td>
<td>$G_{00}$: $0$</td>
</tr>
<tr>
<td></td>
<td>$G_{0+}, G_{-0}$: $\theta \delta w^2 v^2 \mu e^{\alpha(r_1 + r_1)(1-t)^2} / [1 - te^{\alpha 2r_1}]$</td>
</tr>
<tr>
<td></td>
<td>$G_{-+}$: $\theta \delta w^2 v^2 \mu e^{\alpha 2(r_1 + r_1)(-1-t)^2} / [1 - te^{\alpha 2r_1}]^2$</td>
</tr>
<tr>
<td>Fixed Collection Costs ($C_{CF}$)</td>
<td>All: $\kappa K_i$</td>
</tr>
<tr>
<td>Variable Network Costs ($C_{\nu}$)</td>
<td>$G_{00}$: $\phi \delta w^3 v^3 [\ln(t) + \ln(t) - 2t + 2]$</td>
</tr>
<tr>
<td></td>
<td>$G_{-0}, G_{0+}$: $-\phi \delta w^3 v^3 (1 + t)[-1 + \ln(1+t)] e^{\alpha(r_1 + r_1)(1-t)} / (1 - te^{\alpha 2r_1})$</td>
</tr>
<tr>
<td></td>
<td>$G_{-+}$: $\phi \delta (b - a) w^2 v^2 \mu e^{\alpha 2(r_1 + r_1)(-1-t)^2} / [1 - te^{\alpha 2r_1}]^2$</td>
</tr>
<tr>
<td>Fixed Network Costs ($C_{\nu}$)</td>
<td>All: $\gamma \nu \ln(t)$</td>
</tr>
<tr>
<td>Toll Revenue ($R$)</td>
<td>$G_{00}$: $0$</td>
</tr>
<tr>
<td></td>
<td>$G_{0}, G_{0+}$: $r_1 \delta w^2 v^2 \mu e^{\alpha(r_1 + r_1)(1-t)^2} / (1 - te^{\alpha 2r_1})$</td>
</tr>
<tr>
<td></td>
<td>$G_{-+}$: $2r_1 \delta w^2 v^2 \mu e^{\alpha 2(r_1 + r_1)(-1-t)^2} / [1 - te^{\alpha 2r_1}]^2$</td>
</tr>
<tr>
<td>Consumers' Surplus ($U$)</td>
<td>$G_{00}$: $\phi w^3 v^3 [1 - t + \ln(t)]$</td>
</tr>
<tr>
<td></td>
<td>$G_{0+}$: $-\delta w^2 v^2 \mu e^{\alpha(r_1 + r_1)(1-t)^2} / (1 - te^{\alpha 2r_1})$</td>
</tr>
<tr>
<td></td>
<td>$G_{-0}, G_{-+}$: $0$</td>
</tr>
</tbody>
</table>

where: $\nu = 1/\psi, w = 1/\alpha, t = e^{\alpha \psi |b - a|}, \mu = e^{\alpha \xi}, \psi = \nu + (V_i f_i S_j), f(k) =$ traffic flow across tollbooth $k, \text{ and } K_i =$ total number of tollbooths in jurisdiction $i$. 

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Table 3
Rate of Toll Under Various Policies

<table>
<thead>
<tr>
<th>Environment Policy</th>
<th>Tax</th>
<th>Toll</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_0$</td>
<td>$r_{TX}^X = 0$</td>
<td>$r_{TX}^X = 0$</td>
</tr>
<tr>
<td>Policy</td>
<td>$r_{T}^X = 0$</td>
<td>$r_{2}^X = r_{2}^T$</td>
</tr>
<tr>
<td>Toll</td>
<td>$r_{T}^X = r_{T}^T$</td>
<td>$r_{2}^T = r_{2}^T$</td>
</tr>
</tbody>
</table>

$r_{T}$ = toll set by $J_0$, $r_{2}$ = toll set by all other jurisdictions.

Assuming the demand functions described, and keeping toll rates fixed, we draw some basic conclusions in the case of cordon tolls. As the size of jurisdiction $J_0$ increases, the total number of trips crossing cordon $a$ remains the same or increases and the ratio of non-through to through trips increases. As $b$ gets farther from $a$, the number of trips crossing both $a$ and $b$ decreases, and the negative effect (finance externality) of a toll at $b$ on traffic crossing $a$ declines. Any trip going the distance $|y-x|$ is more likely to take place if it crosses one tollbooth rather than two. Similarly, as jurisdiction size increases, the number of trips originating in or destined for jurisdiction $J_0$ increases. However, the number of non-local trips approaches a limit (the maximum flow past the cordon) while local trips increase with jurisdiction size.

Table 4
Baseline Scenario: Empirical Values of Model Coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\zeta$</td>
<td>Fixed cost of vehicle ownership ($/vehicle-trip)</td>
<td>1.23</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$V + V_pS_p$ variable cost of travel ($/vkt$)</td>
<td>0.15</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Coefficient relating demand to price</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Total demand multiplier (trips)</td>
<td>180</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Fixed collection cost ($/toll-booth/hour$)</td>
<td>90</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fixed network cost ($$/km$)</td>
<td>0</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Variable collection cost ($$/vehicle$)</td>
<td>0.08</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Variable network cost ($$/vkt$)</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Source: Levinson (1998)
Evaluation

The toll that maximises welfare can be found by solving the welfare maximisation problem; that is, by setting the first derivative of the welfare expression to zero and solving for the toll. As can be seen from the slew of equations described above, this is a rather long expression in its full (expanded) form.

Perhaps a more comprehensible way to understand what is going on is by examining some illustrations of how welfare changes as certain factors are altered. The underlying assumptions are given in Table 4, developed from empirical studies of travel cost and demand (Levinson, 1998). Any changes to those assumptions are discussed in the text. Briefly, the cost of vehicle ownership was estimated directly from the economic value that cars lose as they age and are driven. A value of time of $10 per hour, consistent with other studies, and a free-flow speed of 100kph, typical of highway travel was assumed. The variable \( \alpha \) was estimated from a gravity model for the Washington DC region. Toll collection costs were estimated using data from bridges in California. Network costs were estimated based on highway expenditure data collected from the states by the federal highway administration.

Figure 3
Welfare in \( J_0 \) as a Function of \( J_0 \) Toll

![Graph showing welfare in terms of toll](image-url)
Revenue Choice on a Serial Network  

Levinson

Figure 3 shows how welfare changes in \( J_0 \) as it varies its toll, keeping fixed jurisdiction size (at 10 km) and all other factors, assuming first that all other jurisdictions employ a tax, and second that they all employ a toll. Tolls of zero are computed both with and without collection costs for comparison. Higher welfare is found without collection costs; a toll of value zero is equivalent to a tax policy in the absence of collection costs. Here (with $0.05 increments on the graph) the welfare maximising toll can be read as $0.70, lower than the profit maximising toll ($1.10). This reflects the inclusion of consumers' surplus and profit in the welfare objective function. The serial (complementary) nature of the network creates interactions that do not necessarily exist in a strictly competitive market analysis. Welfare can remain positive despite the lack of cost-recovery, suggesting that, under certain circumstances, welfare maximisation may result from a combination of cordon tolls and tax financing used to subsidise roads. At low tolls, costs exceed revenues (at very high tolls, costs exceed revenues as well). Here, however, the optimum toll rate generates a positive profit, which, as explained above, is returned to the jurisdiction's residents through reduced taxes or a direct payout.

In the all-toll environment, the welfare and welfare-maximising toll of a given jurisdiction depend upon the tolls of other jurisdictions. We solve the tactical, toll-setting problem by assuming jurisdictions do not cooperate. This gives the Nash equilibrium toll, which is necessary to find the Nash equilibrium policy. At the Nash equilibrium toll, the tolls set by all jurisdictions will be the same. To find the Nash equilibrium value, we assume that all jurisdictions other than \( J_0 \) charge the same toll, and find the value for that toll such that \( J_0 \)'s welfare maximising toll takes the same value. Observe (by comparing the tax and toll environments) that for any toll level, the welfare attained by \( J_0 \) is less when other jurisdictions are charging tolls. At low toll values, the welfare difference is dominated by consumers' surplus, reflecting the payments that \( J_0 \)'s residents are making to other jurisdictions. At high toll levels, profit disparities predominate, since the tolls in other jurisdictions are suppressing lucrative toll crossings at \( J_0 \). However, the welfare-maximising toll in the all-tax environment is approximately the same ($0.70) as that in the all-toll environment. This implies that the system is fairly stable; tolls in one jurisdiction will not fluctuate significantly as a result of road finance mechanism changes in other jurisdictions.

Under the tax regime, it is fairly clear that to achieve a maximum of local (transport and non-transport) welfare while still recovering costs, the rate of taxes must be set so that total revenue equals total costs. The total welfare associated with a tax policy in an all-tax environment thus rises linearly with jurisdiction size. Because the environment and \( J_0 \) have identical policies, neither of which affects travel demand, there is no per capita variation in welfare, cost, or

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consumers' surplus. The horizontal line in Figure 4 (denoted by “W-Tax/km”) illustrates this, displaying the welfare resulting from both tax and toll policies in an all-tax environment.

Figure 4 also shows how welfare ($W-Toll$), profit ($\Pi$), and consumers' surplus ($U$) vary with jurisdiction size under a cordon toll policy in $J_0$ and an all-tax environment. Total welfare increases simply because the number of trips (and thus consumers' surplus) increases. Per capita transport consumers' surplus surplus increases with size as the effective price falls (more and more trips are local and thus pay no toll). This happens because the proportion of non-toll paying local trips increases relative to the toll paying boundary crossing trips. However, this increase in consumers' surplus with jurisdiction size does not offset the loss due to a levelling off of revenue and a steady increase in cost. Thus per capita welfare declines despite the increase in total welfare. This graph indicates that small jurisdictions have a higher per capita payoff from tolls than larger jurisdictions, and thus a greater incentive to toll. This policy is profitable for jurisdictions of up to almost 50 km in length, similar in size to a metropolitan area.
A key point to note is that welfare remains positive despite the fact that costs exceed revenue. This indicates that a mixed financing system of taxes and tolls maximises welfare even when cordon tolls cannot be relied on to finance the roads alone. Total costs increase non-linearly with jurisdiction size, because travel demand increases when the share of trips paying tolls decreases. It should be further noted that a toll policy always results in greater per capita welfare than a tax policy in the all-tax environment. To see this, compare the curve denoted “W-Toll/km” with “W-Tax/km”. However, the differences reduce as jurisdiction size increases.

It might be noted that the choice of toll does not affect welfare very much in the neighbourhood of the optimum value. This suggests a certain robustness of the results, and the importance of getting near the right answer rather than on it. The robustness follows from the offsetting factors (local welfare and total demand decline with increases in tolls, especially in a toll environment, but revenue per toll-payer rises). Still, being far from the optimal value will result in significant welfare loss.

**Figure 5**

*Welfare in $J_0$ at Welfare Maximising Tolls vs Jurisdiction Size in an All-Toll Environment*
Figure 5 illustrates the welfare over a range of jurisdiction sizes in a toll environment. The curve denoted "W-Tax/km" illustrates the case when jurisdiction $J_0$ imposes taxes. While welfare rises with jurisdiction size, it does so at a decreasing rate. This is because as jurisdictions get larger, the impact of other jurisdictions on local welfare diminishes, so non-local policies affect a smaller proportion of locally originating trips. The curves in very large jurisdictions therefore approach those of a tax-policy in an all-tax environment. It should be noted that welfare is negative at very small jurisdiction sizes, indicating the cost of the road outweighs its benefits.

The curves representing the welfare (W-Toll), consumers' surplus (U), and profit (π) from a cordon toll policy in an all-cordon toll environment are also shown in Figure 5. Welfare is maximised at the largest jurisdictions here, rising continuously at a decreasing rate. The cordon toll policy tracks closely (though is always slightly greater than) the welfare resulting from a tax policy in this environment. Again, welfare is negative at very small jurisdiction sizes, though higher than the tax policy case, suggesting a very high finance externality. This scenario is profitable for jurisdictions over a limited range of jurisdiction sizes (from about 2 km to above 20 km). This peaked shape is due to the interaction of jurisdictions. Closely spaced toll booths (found in small jurisdictions) have a much greater finance externality than a wider spacing, so demand for longer trips increases with the spacing of toll booths. However, profit declines for larger jurisdictions because revenue reaches a maximum while costs increase steadily. The welfare increase indicates that the rise in consumers' surplus outweighs the decrease in profit.

We can compare welfare over the range of jurisdiction sizes under the assumptions outlined above for the four strategies. The highest welfare is attained by imposing tolls when others impose taxes (all-tax environment), followed by imposing taxes in the all-tax environment, imposing tolls in the all-cordon toll environment, and imposing taxes in the all-cordon toll environment. In the larger jurisdictions (above 100 km in length) the welfare measurements are very close and almost independent of policy. However, imposing tolls always beats imposing taxes in either environment.

Policy Selection

We can define four cases that describe a jurisdiction's possible strategic decision with regard to tax or toll policy:
(1) Always Tax;
(2) Always Toll;
Revenue Choice on a Serial Network

(3) Mixed (do the opposite): Toll when everyone else is taxing, and Tax when everyone else is tolling; and
(4) Mixed (do the same): Tax when everyone else is taxing, and Toll when everyone else is tolling.

Three of the four cases appear in the range of data examined below. Clearly the mixed solution "do the opposite" is not, in and of itself, stable. If every jurisdiction is supposed to toll when others tax and tax when others toll, they will flail about in their policy selection. A certain fraction of jurisdictions invoking one policy and the rest the other is more likely to be stable. The solution "do the same" has at least two stable points, everyone taxing and everyone tolling, though which will be achieved depends on the evolution of the system, or perhaps on which gives higher welfare, depending on the behaviour ascribed to the decision makers and the process they employ.

We compute the fixed collection costs \( C_{CF'} \) necessary to equate tax and toll policies under each environment. We need to find the fixed collection cost where welfare from tolling equals the welfare from taxing under the all-tax environment \( W_{\tau\lambda} = W_{\lambda\lambda} \), and the all-cordon toll environment \( W_{\tau\tau} = W_{\lambda\lambda} \). The equations in the case of the all-tax environment are given below (the equations in the all-cordon environment are similar):

\[
W_{\tau\lambda} + C_{CF} - C'_{CF} - W_{\lambda\lambda} = 0; \\
C'_{CF} = W_{\tau\lambda} + C_{CF} - W_{\lambda\lambda}.
\]

(9)

Figure 6

Policy Choice as a Function of Fixed Collection Costs and Jurisdiction Size
Figure 6 illustrates policy selection as fixed collection costs (per jurisdiction) and jurisdiction sizes vary. The figure shows that when fixed collection costs (from both the entry and exit toll booths) are high, jurisdictions should (in the interest of maximising local welfare as defined here) always tax (regardless of what other jurisdictions do); when they are low, jurisdictions should always toll. Small jurisdictions, basically below 20 km in length, also have a large mixed solution for collection costs between $100 and $700 of tax when other jurisdictions toll and toll when other jurisdictions tax. The exact threshold where a policy shifts from being “always tax” to “tax when other jurisdictions toll and toll when other jurisdictions tax” varies with jurisdiction size. Two factors influence the location of this threshold. First, large jurisdictions spread fixed collection costs over a larger number of users. Second, small jurisdictions suffer a finance externality from other jurisdictions’ tolls. There is a large range of values where the policy choice depends on the behaviour of neighbouring jurisdictions. Because tolling when everyone else taxes is not a stable equilibrium among identical jurisdictions, the mixed region suggests a mixed set of policies. Thus we have a situation where some proportion of jurisdictions tax and others toll in order to arrive at a stable equilibrium. We might also consider the shape of those areas. As jurisdiction size increases, the always tax area increases.
(takes effect at a lower fixed collection cost). The always toll region is relatively flat with jurisdiction size.

Policy choice as a function of variable collection costs is more complicated than as a function of fixed collection costs. Though tolls are independent of fixed collection costs, they depend on variable collection costs (and thus the variable θ). Similar to the case of fixed allocation costs, we need to find the variable cost coefficient (θ') where welfare from tolling equals the welfare from taxing under both the all-tax and the all-cordon toll environment. For the all-tax environment, we have the following equations (the equations in the all-cordon toll environment are similar):

\[ W_{τX} + C_{CV} - C'_{CV} \theta' - W_{X} = 0, \]

\[ θ' = \frac{W_{τX} + C_{CV} - W_{X}}{C'_{CV}}. \]  

Figure 7 shows the results where the welfare is calculated using the collection costs (θ') that are consistent with the welfare maximising tolls resulting from those collection costs. This calculation uses a recursion procedure to solve for both the welfare-maximising toll and the collection cost necessary to equalise the welfare from toll and from tax policies. It was not possible to obtain solutions in all cases; for instance, the points not shown on the figure. Examining the variable collection costs, we see that both curves are downward sloping. The lower the collection cost, the more likely it is that a jurisdiction will toll, but the larger the jurisdiction size, the more likely it is that it will tax. Our estimate of collection costs using conventional technology (estimated from California data) falls below the two results for all values of jurisdiction size. This indicates that with the baseline scenario we expect the always toll solution, consistent with the one-shot game described in a previous section and consistent with the results for fixed collection costs. We find in practice that given equal collection costs, large states are less likely to toll than small states. This model result confirms our expectation that the two curves be downward sloping (the always toll area becomes smaller and the always tax area becomes larger as jurisdiction size increases) for both fixed and variable costs. The figure also shows the tolls consistent with the collection costs necessary to equate the welfare from tax and toll policies. It is interesting that the tolls are decreasing with jurisdiction size. This is at odds with the previous cases, where the coefficient for variable collection costs was not varied.
Government Hierarchy

We can use the information we have generated to examine the consequences of larger or smaller governments. This is analogous to the serial monopolist problem, where the toll paid by a traveller using two serial monopolists over an area is more than if the area were under the control of a single monopolist.

Table 5 summarises the welfare maximising tolls from the analysis above of a toll policy in an all-cordon toll environment as jurisdiction size varies. For instance, travelling 20 km through two 10 km jurisdictions, our analysis finds that a traveller pays four tolls of $0.65 ($2.60). However, travelling 20 km through one 20 km jurisdiction, the traveller only pays two tolls of $0.68 ($1.36).

<table>
<thead>
<tr>
<th>Jurisdiction Size (km)</th>
<th>Tolls</th>
<th>Welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$0.65</td>
<td>2367</td>
</tr>
<tr>
<td>2 x 10</td>
<td>$1.30</td>
<td>4734</td>
</tr>
<tr>
<td>20</td>
<td>$0.68</td>
<td>5451</td>
</tr>
</tbody>
</table>

Source: Author's analysis of toll policy to $J_0$ and all-cordon toll environment.

Table 5 also summarises the welfare for the case of a toll policy in an all-cordon toll environment. Here, more total welfare is generated for one government of 20 km than the sum of two 10 km governments. For this case, the consolidation of jurisdictions eliminates a finance externality, and thus increases welfare. However, under a different scenario (for instance, lower collection costs), the welfare gains from a reduction in the finance externality may be outweighed by the efficiency gains from a reduction in free riders associated with closer toll booths.

Here we assumed no diseconomies of scale associated with higher levels of government. However, two particular issues should be kept in mind. First, higher government levels have a broader span of control, so for the same number of managers, each area receives less attention, or more levels of management must be appointed. This can be more costly than local governance. Second, logrolling in a political environment can be a problem when resources need to be allocated centrally to numerous constituencies. Logrolling can lead to inefficient investments as the incentives for efficiently managing other peo-
ple’s money are less than for managing one’s own. If economies of scale in the provision of networks do exist for a particular facility type, the lower costs with a higher level of government may offset these administrative inefficiencies. The presence of scale economies would thus make it harder to implement tolls.

**Stability and Uniqueness of Tolls**

We now consider how a jurisdiction’s payoff maximising toll depends upon its neighbours’ tolls. Figure 8 constructs reaction curves for four cases: two objectives, profit maximising ($\Pi^*$) and welfare maximising ($W^*$), each solved at two different jurisdiction sizes (1km and 10km). The profit maximisation objective is introduced for comparison purposes. These two sizes were chosen as they are the most likely to show differences. As jurisdiction sizes increase, the interaction between the tolls at one cordon and the next reduces. All other conditions are identical to those assumed in the previous sections. Under welfare maximisation, the tolls in jurisdiction $J_0$ are almost (but not entirely) independent of the tolls in other jurisdictions. To the extent that they interact, welfare maximising tolls are negatively correlated (a rise in one begets a fall in another). Under profit maximisation, the tolling policies are more dependent and positively correlated (a rise in one begets a rise in another). Furthermore, profits are more sensitive in small jurisdictions than large. The profit-maximising toll is higher than the welfare-maximising toll, all else being equal.

**Figure 8**

*Reaction Curves: Best $J_0$ Toll as Tolls Vary in Toll Environment*
The increased sensitivity to other jurisdictions' tolls of the profit-maximising objective in comparison with welfare maximising objective should not be surprising. The welfare-maximising objective depends on the consumers' surplus of local residents, while the profit maximising objective does not. Rises in the price level will increase profits to a point, but will always reduce consumers' surplus, so welfare maximisation is subject to more offsetting factors than profit maximisation.

The diagonal (45°) line intersects each curve at the Nash equilibrium point when all jurisdictions are identical in all aspects, including the use of a toll policy. Thus in the case of welfare maximisation, the Nash equilibrium toll is $0.59 for jurisdiction sizes of 1 km, while it is about $0.65 for jurisdictions of 10 km in length. Similarly, for profit maximisation, Nash equilibrium tolls are $0.98 and $1.12.

The welfare maximising tolls presented in earlier sections under an all-cordon toll environment were computed with an algorithm that began by assuming that other jurisdictions had a given "seed" toll \( r^i_0 \), computing the toll for \( J_0 \), and then updating the tolls assessed by other jurisdictions. This process was iterated to convergence. We want to confirm that the initial seed toll does not affect the result. Figure 9 illustrates this for one set of assumptions (jurisdiction size = 1 km, welfare maximising, non-cooperative toll-setting, empirical coefficients). It shows that for four different seeds (−$1, $0, $1, and $10), they all converge after three iterations to the same value (within six decimal places here). This result has been repeated for numerous other cases (not shown). We have thus corroborated experimentally that a unique solution is independent of initial conditions.

**Figure 9**

*Uniqueness, Non-Cooperative Welfare Maximising \( J_0 \) Toll as Initial Toll for Other Jurisdiction Varies in Toll Environment*
Sensitivity to Model Coefficients

This section examines the sensitivity of the basic welfare measures to model coefficients, under standardised assumptions of a local welfare maximisation objective, a 10km jurisdiction size, a toll policy, and an all-cordon toll environment where jurisdictions employ non-cooperative toll-setting. Each of the variables is examined over a range of coefficient values approximately centered upon the default values developed in Table 4. Table 6 summarises the elasticity about the mean for each of the key variables. The elasticity is calculated by dividing the change in welfare (revenue, cost, consumers’ surplus, and profit) by the difference between two values of the variable in question, where one value is the mean, and the other is a 1 per cent increment on the mean.

Table 6
Elasticity About Mean

<table>
<thead>
<tr>
<th>Variable</th>
<th>Welfare</th>
<th>Revenue</th>
<th>Cost</th>
<th>Consumer’s Surplus</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\alpha</td>
<td></td>
<td>sensitivity of demand to cost</td>
<td>$-3.070$</td>
<td>$-3.437$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>density of trip origins</td>
<td>$1.038$</td>
<td>$1.000$</td>
<td>$0.699$</td>
<td>$1.000$</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>private fixed costs</td>
<td>$-0.424$</td>
<td>$-1.150$</td>
<td>$-0.498$</td>
<td>$-0.239$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>sensitivity of demand to trip length</td>
<td>$-0.094$</td>
<td>$-0.143$</td>
<td>$-0.119$</td>
<td>$-0.065$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>fixed costs associated with network length</td>
<td>$-0.044$</td>
<td>$-0.000$</td>
<td>$0.250$</td>
<td>$0.000$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>variable cost associated with network use</td>
<td>$-0.049$</td>
<td>$-0.028$</td>
<td>$0.277$</td>
<td>$-0.017$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>variable collection costs</td>
<td>$-0.016$</td>
<td>$-0.013$</td>
<td>$0.053$</td>
<td>$-0.009$</td>
</tr>
</tbody>
</table>

Note: Elasticity of Welfare (Revenue, Cost, Consumer’s Surplus, Profit) About Mean of $\alpha$ ($\delta$, $\zeta$, $\psi$, $\gamma$, $\phi$, $\theta$).

First, the sensitivity of demand to cost in general, the variable $\alpha$, is evaluated over a range of values (recall the default value of $-1.00$). Clearly, as expected from inspection of the model as $\alpha$ increases in absolute value, welfare, revenue, cost, and consumers’ surplus drop.
Second, the density of trip origins, the variable $\delta$, is evaluated with a default value of 180. As the density of trips increases, total welfare, consumers' surplus, revenue, and cost rise. Under the model, the more trips, the higher the welfare, because there is no offsetting congestion factor.

Third, the private fixed costs per trip, the elasticity for the variable $\xi$, is computed with a default value of 1.23. As might be expected, as this cost rises, welfare, costs, revenue, and consumers' surplus drop.

The fourth variable $\psi$, which is the sensitivity of demand to trip length $|y-x|$, has a default value of 0.018. As sensitivity increases, welfare, revenue, cost, and consumers' surplus decrease.

The fifth variable, $\gamma$, is the coefficient on jurisdiction size (in $/km$) in the cost equation. Recall that we have set fixed costs equal to zero in the analyses in previous sections. As $\gamma$ rises, costs rise (by definition) and welfare falls continuously. However, only as costs approach $100 per linear kilometer per hour do they noticeably influence the welfare indicators. Revenue and consumers' surplus remain unchanged, because this variable does not affect tolls.

The sixth variable, $\phi$, reflects the variable cost to the jurisdiction as a function of vehicle flow, with a default value of $0.018/vkt$. As the variable cost increases, per capita cost increases (again, by definition), and welfare, consumers' surplus, and profit fall. Interestingly, revenue peaks at a value of about $0.10/vkt$; as costs rise, so do tolls, but above a certain point, the tolls are sufficiently high to drive away the significant amount of toll-paying (inter-jurisdictional) traffic.

Finally, we consider $\theta$, the variable cost of toll collection as a function of flow past the toll booth, with a default value of $0.08/trip$. As this coefficient increases, welfare and consumers' surplus fall. Costs rise up to $0.20$, and then fall, as the increase in welfare-maximising tolls drives away more traffic (and thus reduces costs) than the increase in variable collection costs increases costs.

Conclusions

While many jurisdictions do not actually consider their choice of revenue mechanism, they probably should. Changes in technology and funding sources warrant a reconsideration of the standard financing mechanisms. The purpose of this research was to develop a model to explain whether jurisdictions choose to tax or to toll as a function of the length of trips, the size of the jurisdiction, the transaction costs of collecting revenue, demand, and the cost of providing infrastructure. In short, the intent was to help frame the analysis of how juris-
dictions have historically considered, albeit in a more complex and less mathematical environment, and may in the future consider, the choice of revenue mechanism.

Large jurisdictions are more likely to impose taxes or a mixed financing policy than cordon tolls alone, because cordon tolls raise insufficient revenues to cover costs, as revenue levels off above a certain point. Similarly, the higher the cost of collecting tolls, the less likely it is that tolls will be the preferred revenue mechanism. The welfare-maximising toll may not fully recover costs, and still require subsidy. The maximum welfare from taxes may exceed those of tolls under certain circumstances, depending on model parameters. However, if jurisdictions are sufficiently small, demand sufficiently high, and collection costs relatively low, then tolls will be preferred. Levinson (1999b), examining the financing behaviour of US States, has corroborated the result that small states are more likely to toll. In that work, it was found that states that import proportionately more workers (typically the smaller east coast states) tend to have a higher share of the state’s highway revenue from tolls than other states.

The gains to a jurisdiction of imposing tolls exceed the gains from taxes under certain circumstances. The gains come primarily from residents of other jurisdictions. This problem, a finance externality, is well known in certain cases: for instance, the reliance by local governments on some mix of sales, income, and property taxes, each of which is borne by a different set of people, not all of whom are local.

Congestion pricing has long been a goal of transport economists, who argue that it will result in more efficient use of resources. The path for implementing such a system has been strewn with political potholes: pricing inevitably creates winners and losers. An alternative approach, one that would create the local winners necessary to implement road pricing, is required before congestion pricing can be expected to become widespread. This research suggests one approach, one that would decentralise the decision about whether to tax or toll before attempting to impose road pricing. Road pricing is a necessary prerequisite to congestion pricing. Imposing congestion pricing on already tolled roads is not nearly as difficult a problem as placing tolls on untolled roads in the first place. And tolls are a rational financing mechanism for a sufficiently small jurisdiction, particularly with the advent of electronic toll collection systems.

The prospects for the future success of toll roads depend on several factors, including the relative centralisation of control of the highway sector, and the transaction costs of collecting revenue. Factors that would be conducive to a return to turnpikes are a reduction in collection costs and a decentralisation of authority. Should the governance become more decentralised, and collection costs continue to drop, tolls could return to prominence as the preferred means of financing roads for both local and intercity travel.
The analysis presented here is a simplified representation of reality. The network geometry, while representative of certain stylised cases without parallel competitive roads, certainly does not reflect all conditions. However, it does represent, in a way, cases such as the northeast corridor of the United States where parallel roads are controlled by the same government. Future research should be directed towards a more general network formulation of the model, where links or sets of links within the network are governed collectively.

The analysis also excludes the effect of tolls on land value. Economic theory dictates that higher tolls will lead to lower property value. Because of the structure this paper imposes, a jurisdiction's toll falls on residents and non-residents alike. So if a jurisdiction tolls, its immediate neighbors on the network cannot gain a competitive advantage regarding commercial location by not tolling. Tolls will lead to a greater share of local (non-boundary crossing) trips, and higher tolls lower consumers' surplus. Still, model extensions should endogenise the changes in property value as an aspect in the toll-setting problem.

Other future specific extensions include: congestion and travel times as a function of use, public versus private ownership, multiple owners and different numbers of owners of alternative routes, degrees of vertical and horizontal integration, scale, scope, and sequence economies, and heterogeneous users with different values of time, which might lead to a differentiated network.

References