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Publication Date

1998-04-01

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On Whom the Toll Falls: A Model of Network Financing

by

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B. (Georgia Institute of Technology) 1988

M. (University of Maryland) 1992

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Civil Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

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Spring 1998

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University of California, Berkeley

Spring 1998

On Whom the Toll Falls: A Model of Network Financing

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by

David Matthew Levinson

Abstract

On Whom the Toll Falls: A Model of Network Financing

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David Matthew Levinson

Doctor of Philosophy in Civil Engineering

University of California, Berkeley

Professor Mark M. Hansen, Chair

This dissertation examines why and how jurisdictions choose to finance their roads. The systematic causes of revenue choice are explored qualitatively by examining the history of turnpikes. The question is approached analytically by employing game theory to model revenue choice on a long road. The road is covered by a series of jurisdictions seeking to maximize local welfare. Jurisdictions are responsible for building and maintaining the local network. Complexity arises because local network users may not be local residents, and local residents may use non-local networks. Key factors posited to explain the choice of revenue mechanism include the length of trips using the road, the size of the governing jurisdiction, the degree of excludability, and the transaction costs of toll collection. These factors dictate the size and scope of the free rider problem. It is hypothesized that smaller jurisdictions and lower collection costs favor tolling policies over taxes.

The analytical model is operationalized by assuming jurisdictions have two decisions: the strategic decision to tax or toll, and the tactical decision of setting the rate of tax or toll. Models of user demand as a function of trip distance and monetary cost and of network costs as a function of traffic flow and the number of toll collections are specified. The values of the constants and coefficients of the model are developed from recent cost literature and the estimation of a model of collection costs from California Toll Bridge data.

The model is applied to evaluate the dissertation's hypotheses. The application evaluates the welfare implications of a jurisdiction and its neighbors imposing general tax, cordon toll, odometer tax, or perfect toll policies. Sensitivity tests of the model under alternative behavioral assumptions, and with varying model coefficients are conducted. Finally, policy implications from the analysis are drawn. The general trends which bode well for road pricing (electronic toll collection (ETC), decentralization, advanced infrastructure, privatization, and federal rules) are established. Possible scenarios for three cases are presented: deploying ETC and building new toll roads, and converting free roads.

_____

Mark Hansen, Chair

Dedication

To Trinh and Roslyn,

whose blind faith have seen me through.

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1. CHAPTER ONE: INTRODUCTION

Man in Bowler Hat: "To improve the British economy, I'd tax all foreigners living abroad" (Chapman et al. 1989)

1.1 Introduction

Policy makers face the problems of roadway congestion, air pollution from cars, and the dearth of resources to finance new infrastructure. Transportation economists often suggest road pricing, charging users a monetary toll for the use of a specific part of the roadway network, as a solution to these problems. While tolls are common for certain expensive facilities such as tunnels and bridges, they are less common on streets and highways, which are more typically funded from user taxes or general revenue. This research identifies critical technological, economic, geographic, and political factors associated with a government jurisdiction's choice of revenue mechanism (for instance taxes or tolls) for its network. In contrast to the large thread of research which focuses on optimal congestion prices, this research analyzes the political and economic implications of alternative revenue mechanisms and organizational structures for the road network.

Several factors can be identified as affecting the choice of revenue mechanism. The size of jurisdictions and the length of trips on the network dictate the proportion of trips which pass through each jurisdiction and the proportion which remain entirely within that jurisdiction. Depending on the nature of the financing system, either through trips or local trips can be free riders. Free riding distorts equity and efficiency and produces potential political problems. Federal, state, and governments may each choose to finance the same link differently as the definition of free rider changes. The fixed and variable cost of collecting tolls and taxes may favor one method over the other and influence the spacing of tolls and thus the number of free riders. Clearly, recent technological advances in electronic toll collection are reducing the associated transaction costs, and thus the viability of tolls

relative to taxes. The elasticity of demand to tolls and taxes of various kinds also influences the choice of financing mechanism.

There are a number of frameworks for evaluating the effects of financing decisions which will be considered in this study. Efficiency, loosely speaking, says that no one can be made better off without worsening the condition of another. Technically, an economically efficient solution may or may not be a stable or unique equilibrium. A small shock may move the system to a new equilibrium. Furthermore there are equity considerations: while it may be theoretically possible to compensate individuals for losses from changes designed to make the system more efficient, unless that compensation is undertaken, winners and losers emerge.

This dissertation analyzes roadway network financing, constructing a model that includes the basic features of the economic structure of transportation networks. It includes the demand and supply interaction, the choices available to actors (consumers and producers), and the linkage between the two when the residents of a jurisdiction own the local network. The idea of decentralized, local control and multiple jurisdictions distinguishes this analysis from one where a central authority maximizes global welfare. The model's theoretical results should be consistent with what is empirically known about network financing. It should thus explain what network financing choices are made under various circumstances. Policies that alter circumstances to affect the desired choice of revenue mechanism can then be drafted.

This research reveals many of the underlying reasons that jurisdictions choose to use taxes or tolls of various kinds. In brief, the main hypothesis is formulated and tested that small jurisdictions have a greater motive to impose tolls than large ones. First, the smaller the jurisdiction, the greater the percentage of toll revenue that comes from non-local residents. Second, in large jurisdictions cordon tolls provide insufficient revenue to recover

costs. In a sense, toll policies enable a jurisdiction to achieve the locally ideal policy of "taxing foreigners living abroad" as suggested in the opening quote.

The application of this knowledge to several problems presents itself, including: determining the exit spacing and number of toll gates, the use of cordon tolls, the network wide deployment of road pricing, the deployment of infrastructure such as automated highway systems, and the assignment of links to the appropriate jurisdictional level (local, state, federal) for management or regulation. These problems are all inter-related and require a thorough understanding of financing on a spatially situated network. An understanding of the issues will inform decision makers now facing choices about how best to finance infrastructure, manage congestion, and reduce environmental impacts.

To motivate this research, we begin by considering four main rationales for road pricing: financing infrastructure and relieving congestion through capacity expansion, social costs, changes in the vehicle fleet and tax base for highways, and allocating exisiting infrastructure more efficiently. Then the plan of the dissertation is outlined in some depth.

1.2 Rationales for Road Pricing

1.2.1 Financing Infrastructure

The first main rationale for road pricing is to finance infrastructure, particularly the capital costs of infrastructure, though also the operating costs. Highway infrastructure here can be divided into two basic types: conventional and advanced, though the logic for the two is largely the same. Advanced highway infrastructure can be distinguished from more conventional infrastructure by its use of intelligent transportation systems (advanced highway systems (AHS) particularly).

While it is unclear at this early date what shape advanced highway systems will take, certain forms of AHS may require complete separation of traffic into groups equipped with the appropriate technology to take advantage of AHS and groups which aren't equipped.

3

Without the appropriate financing mechanism such as road pricing, constructing this infrastructure would entail cross-subsidies from the existing (non-equipped) fleet users to those with the new technology, likely to also be a transfer from poor to rich.

Similarly, construction of new conventional highways can result in spatial cross-subsidies when financed out of general revenue, or even non-spatially specific gas taxes. A new highway only serves a subset of the population , those using the origin-destination pairs that it connects. The political impact of the cross-subsidies can be reduced if a large "package deal" is assembled (for instance, with new highways in every political district). This was the case with the interstate highway program of the 1950s - 1980s. However the ability to form package deals of new roads becomes more difficult as the conventional highway system reaches maturity and market saturation.

There are strong arguments on both equity and efficiency grounds that the users (those who benefit directly) should pay for its use. Road pricing, unlike more general financing mechanisms like the gas tax, much less property or income taxes, ties revenue for the use of roads to the users of that specific facility.

On a simple balance sheet analysis, the revenue and costs of highways and streets are nearly equal (as shown in Table 1.1). The vast majority of highway revenue comes from user fees in the form of gas taxes, licensing fees, and related vehicle taxes. Furthermore, general revenues have been limited since the early 1980s. There has been a move away from taxes and toward user fees as government resources are (and more importantly, are perceived to be) constrained. However, the expenditures may be more or less than what would be socially optimal. In the absence of road pricing, expenditures clearly are insufficient to eliminate congestion.

The Texas Transportation Institute (1997) reports that congestion levels have risen an average of more than 22 percent between 1982 and 1994 in America's fifty largest cities (just under two percent per year). This despite roughly stable journey to work times

(Levinson 1998). At some point, rising congestion costs outweigh construction costs, (after accounting for other social and private costs) indicating a net social benefit for the construction of new roads. Road pricing has effects which bear on this issue, including reduced demand (and increased allocative efficiency) in the absence of additional infrastructure and increased revenue for constructing new infrastructure.

Table 1.1 U.S. Highway & Local Street Revenues & Expenditures: 1995

HIGHWAY USER REVENUES	$ Millions
Net Collections [4]	$84,143
Investment Income and Other Receipts	$6,742
Bond Issue Proceeds [8]	$7,619
Funds Drawn from or Placed in Reserves [9]	($2,809)
Total Revenues	$95,695
HIGHWAY EXPENDITURES	
Capital Outlay:	$43,097
Maintenance and Traffic Services:	$24,455
Administration and Research [10]	$8,332
Highway Law Enforcement and Safety	$7,977
Interest on Debt	$3,982
Bond Retirements [8]	$4,661
Total Expenditures	$92,504
REVENUES COMPARED TO EXPENDITURES	
Revenues over Expenditures	$3,194
Ratio of Revenues to Expenditures	1.034
NON-HIGHWAY REVENUES & EXPENDITURES	
Less: Amount for Non-highway Purposes [5]	($15,841)
Less: Amount for Mass Transportation	($5,634)
Less: Amount for Collection Expenses [6]	($2,969)
Less: Amount for Territories [7]	($138)
Property Taxes and Assessments	$5,150
General Fund Appropriations	$12,142
Other Taxes and Fees	$4,098
Net Non-Highway	($3,192)
BALANCE	
Net Non-Highway + Revenues	$92,504
Total Expenditures	$92,504
Balance	($0)

Source: Highway Statistics 1995 Table HF-10, available at
<http://www.publicpurpose.com/>

Notes on next page.

Table 1.1 Notes:

1   This table summarizes data reported in greater detail in the FA, FE, SF, and LGF table series. Some data are preliminary. Table HF-10A contains final data for all units of government for 1994.

2   Includes the Mass Transit Account of the Highway Trust Fund. Also includes Federal Highway Administration activities funded by general funds and all other agencies and funds that make appropriations for highways or that receive highway-user revenues. See Table FA-5 for additional information.

3   Data for local governments are estimated.

4   Represents gross receipts less refunds and loss allowances.

5   Federal column amount represents net collections less transfers to the Highway and Mass Transit accounts of the Highway Trust Fund. Due to timing differences between collections and transfers to the Highway Trust Fund, the amount will not correspond exactly to distributions for deficit reduction and for the Leaking Underground Storage Tank (LUST) Fund.

6   Includes only those collection and administrative costs paid from motor-fuel and motor-vehicle tax receipts. Operational costs of toll facilities are reported as traffic services. Federal collection expenses are excluded since they are paid for by the General Fund. Local expenses are excluded, because local motor-fuel and motor-vehicle tax data are reported net of collection expenses.

7   Amounts shown represent Federal payments to territories, and Federal expenditures in territories for highways and mass transit. Territories' funding for highways are excluded from the highway finance table series. See Table TER-1 for details on territories.

8   Proceeds and redemptions of short-term notes and refunding issues are excluded.

9   Negative numbers indicate that funds were placed in reserves.

10 Includes small amounts of engineering and equipment costs not charged to capital outlay and maintenance.

1.2.2 Social Costs

There has been a great deal of interest in the issue of the social or external costs of transportation (Keeler et al. 1974, Fuller et al. 1983, Quinet 1990, Mackenzie et al. 1992, INRETS 1993, Miller and Moffet 1993, Works 1993, IWW/INFRAS 1995, IBI 1995, Litman 1995, Delucchi 1996, Levinson et al. 1996). At the center of this debate is the question of whether various modes of transportation are implicitly subsidized because they generate unpriced externalities, and to what extent this biases investment and usage decisions. On the one hand, claims of environmental damages as well as environmental standards formulated without consideration of costs and benefits often result in slowing or stopping investment in new infrastructure. On the other hand, the real social costs are typically not recovered when financing projects and are rarely used in charging for their use.

A proposed solution is to price travel based on the amount of externalities generated. To the extent that externalities vary in space, it may be appropriate to charge for them with road tolls rather than more general sources such as gas taxes. The main externalities include congestion, air pollution, carbon emissions, noise pollution, and increased accident damage. Congestion pricing will be considered in the next section, this section briefly examines the costs of noise and air pollution.

The costs of accidents and noise and air pollution vary with traffic speed and density, as well as with nearby land use activity, and thus a good case can be made for imposing charges for these externalities in a spatially differentiated manner. The following paragraphs discuss the costs of accidents, noise, and air pollution.

Accidents

Combining accident rate data from models developed by Sullivan and Hsu (1988) and accident cost data from Miller (1993), Levinson et al. (1996) estimate accident costs at approximately $0.040/vkt ($0.026/pkt) for rural travel or $0.023/vkt ($0.015/pkt) for urban

travel. To compare, the average amount paid per year in insurance for collision, property damage, and liability, given by AAA (1993) was $617 per year. This ranges between $0.025/pkt at 24,000 km/yr. and $0.038/pkt at 16,000 km/year. The full cost of accidents exceeds the private cost in general, though the transfer of costs to the insurance company generally results in some rate of profit to the companies, as well as additional overhead associated with managing risks. While accident costs do involve an element of externality, and the risk is not uniform over space, it is an open question whether road pricing is the best way to recover that externality.

Noise

The damages caused by noise include the loss of sleep, lower productivity, psychological discomfort and annoyance. These are hard to quantify, but because they are associated with a place, the quantity of damage is often viewed as resulting in lower property values. A number of studies have been performed over the years to measure the decline in residential property value due to noise and its associated vibration. Hedonic models of housing collected by Modra and Bennett (1985), Nelson (1982), and others are summarized in Levinson et al. (1996). Applying the loss of economic value of homes due to noise from hedonic studies with a model of noise production, Levinson et al. (1996) estimate a wide range for the economic damage due to noise, but at typical values, the cost is on the order of $0.0045/pkt. To compare, INFRAS/IWW (1995) gives noise estimates from Europe of $0.0058/pkt for automobiles, about the same for buses ($0.0054/pkt) and $0.0163/tkt (tonne km traveled) by truck. Miller and Moffet (1993) report a range from $0.0008/pkt to $0.0013/pkt urban based on various studies, in 1990 U.S. dollars. The internalization of noise costs would ideally (in the absence of transaction costs) be a function of the noise produced by specific vehicles as well as the location that the noise is produced. Road pricing is a viable mechanism for capturing the location-specific effects (noise in a

residential area should be more costly than in an industrial area for instance), other pricing strategies would be required to capture vehicle specific effects.

Air Pollution and Global Climate Change

Recent work on the costs of air pollution from cars comes from Small and Kazimi (1995) analyzing the Los Angeles region. They update air pollution emission factors from the EMFAC, (California Air Resources Board 1991) model to correct for reported underestimation of pollution. They then review recent evidence on mortality and morbidity and its association with pollutants (VOC, PM10, SOx, NOx). They combine various exposure models of the Los Angeles region with health costs Their findings suggest that particulate matter is a primary cause of mortality and morbidity, followed by morbidity due to ozone. Of course, costs in densely populated areas, such as the Los Angeles basin, should be higher than in rural areas as the exposure rate is far higher. While they also assume a value of life of $4.87 million in their baseline assumptions, Levinson et al. (1996) report their estimate using a $2.7 million value of life (V_L) for consistent comparison with other studies and our accident costs. A review of the literature on material and vegetation damages suggests that those cost components are small compared with the costs of health damages.

Nordhaus (1994) uses a macro-economic/global climate model to estimate a "carbon tax" which would be the price of damages from pollution. His model estimates the appropriate tax (per ton of Carbon equivalent) at a given point of time to optimize the amount of pollution, trading off economic costs of damages due to greenhouse gases and the damages due to imposing the tax. For 1995, his model estimates an appropriate tax of $5.29/ton C.

Performing the calculations combining emission rates and damages per unit of emission with the data reported in Table 1.2, Levinson et al. estimate the local air pollution

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cost as $0.0053/vkt ($0035/pkt), and the global environmental impact cost as $0.0003/vkt ($0.0002/pkt). To compare, these costs tend to be on the low end of pollution and climate change cost estimates. Miller and Moffett (1993) calculate car and light truck pollution costs to be about $0.024/pkt - $0.042/pkt. A summary of estimates of air pollution costs by IBI (1995), ranges from $0.0015/pkt - $0.026/pkt.

Table 1.2 Air Pollution and Global Change Costs of Highway Travel

Pollutant	Health Damage $/kg	Auto Emissions gm/vkt	Cost $/vkt
PM10	$12.85	0.0066	$0.000085
SOx	$13.82	0.0228	$0.000315
HC	$ 1.71	2.254	$0.003850
CO	$0.0063	7.8	$0.000049
NOx	$ 1.33	0.756	$0.001000
Carbon	$0.0058	46	$0.000260
TOTAL			**$0.0056**

Source: Emissions: Small & Kazimi 1995 Energy Information Administration (1994); Damage Costs:

Small and Kazimi (1995), Nordhaus (1994). Value of Life = $2.7 Million

The uncertainties around the cost of air pollution and global warming are clearly large, but even a ten-fold increase in the estimate of these costs amounts to only a 13% increase in the total cost of auto travel (and a somewhat higher percent of the internal costs of auto travel). Internalizing pollution costs should not be expected to have a great effect on auto demand given their low cost and the low price elasticity that has been found historically

.

1.2.3 Change in Tax Base with Alternative Fuels

In the absence of a property rights framework and a market solution for air pollution, policy makers have focused on regulation. California and the northeastern United States have mandated that a certain fraction of the new car fleet be either low emission or

zero emission vehicles (ZEV). ZEVs are intended to reduce air pollution, or at least relocate it to an area with fewer impacted people. While the precise rules are subject to change and delay (and have been altered several times to date), the trend toward switching to non-gasoline based fuels is at least nascent. To the extent that roads are financed with gasoline-based excise taxes, a shift to alternative fuels would result in a decrease in revenues for roads.

Some (albeit limited) evidence for this trend are incentives provided for ZEVs (ARB 1998). The federal government offers a tax credit of $4,000 toward the purchase of a ZEV. Several California air quality management districts offer "buy-downs" to a manufacturer for each ZEV sold for a limited number of sales. Some utilities offer discounted electricity rates for off-peak electric vehicle recharging. A memorandum of agreement was reached in 1996 between the California Air Resources Board and seven auto manufacturers which postponed the previously announced ZEV mandates. In its place there was agreement to produce (in total) 3,750 advanced battery-powered ZEVs in 1998, 1999, and 2000 (ARB 1996) and some measures to provide an equivalent emission reduction through production of cleaner light duty vehicles. While this level of non-gasoline based vehicles is unlikely to cause major financing shortfalls, future targets of 10% ZEV as in California policy, or even higher levels if technological breakthroughs in fuel cells manifest themselves, suggest that it may become a more significant issue in the future.

1.2.4 Congestion Pricing

Congestion reduction and more efficient allocation of resources are often cited as some of the main benefits of road pricing, particularly peak period pricing. Clearly road pricing is a necessary prerequisite to congestion (or time differentiated) pricing. Qualitatively, the idea behind congestion pricing is this: person H has a high monetary value of a trip, person L a low monetary value of a trip. Without pricing, persons H and L both travel at a slow speed. But if roads are priced, person H will be able to pay money and

travel faster, while person L will not pay the money and not travel at that time (or travel on more congested and slower alternative free roads). To increase the welfare of travelers (or potential travelers), the money collected needs to be redistributed to persons H and L in some fashion, either through lowering other taxes, through direct payments, or by reinvesting it in transportation. If person H's value of time saved plus the amount returned is greater than the amount paid, H is better off. If the amount of money returned to person L is greater than the cost of deferring the trip (or traveling at a slower speed), then L is better off. Road pricing will inevitably create both winners and losers (and usually losers) without redistribution of the toll which was collected. However, under the right redistribution policy, most people can be made better off.

The conventional explanation of road pricing, found in various sources, uses a variation of Figure 1.1. The y-axis measures generalized cost (e.g. price plus monetized time), while the x-axis measures flow in vehicles per hour. In the absence of any toll, equilibrium occurs at (Q_o, P_o), where demand intersects the short run average cost curve. Any traveler who values a trip more than P_o will travel, anyone who doesn't won't travel. The shaded area on the graph is considered the welfare loss, the benefit which is lost when tolls are not imposed. The loss is due to the difference between the cost a driver imposes on society (the short run marginal cost) by making everyone else's trip take a little bit longer, and the cost that driver bears personally which is time spent in traffic congestion due to all the other cars on the road (short run average cost). The imposition of a marginal cost toll moves the equilibrium to (Q^*, P^*) and eliminates the welfare loss due to the congestion externality.

Figure 1.1 Optimal Congestion Toll and Welfare Loss Without Toll

Price,
Cost   Marginal Cost, Short Run

                                    Average Cost, Short Run

        toll

P*
P_o

                                    Demand

                        Q* Q_o Quantity

Legend:

P* = Optimal Price with Tolls   Q* = Amount of Travel with Tolls

P_o = Price without tolls Q_o = Amount of Travel without Tolls

        Welfare Loss without Tolls
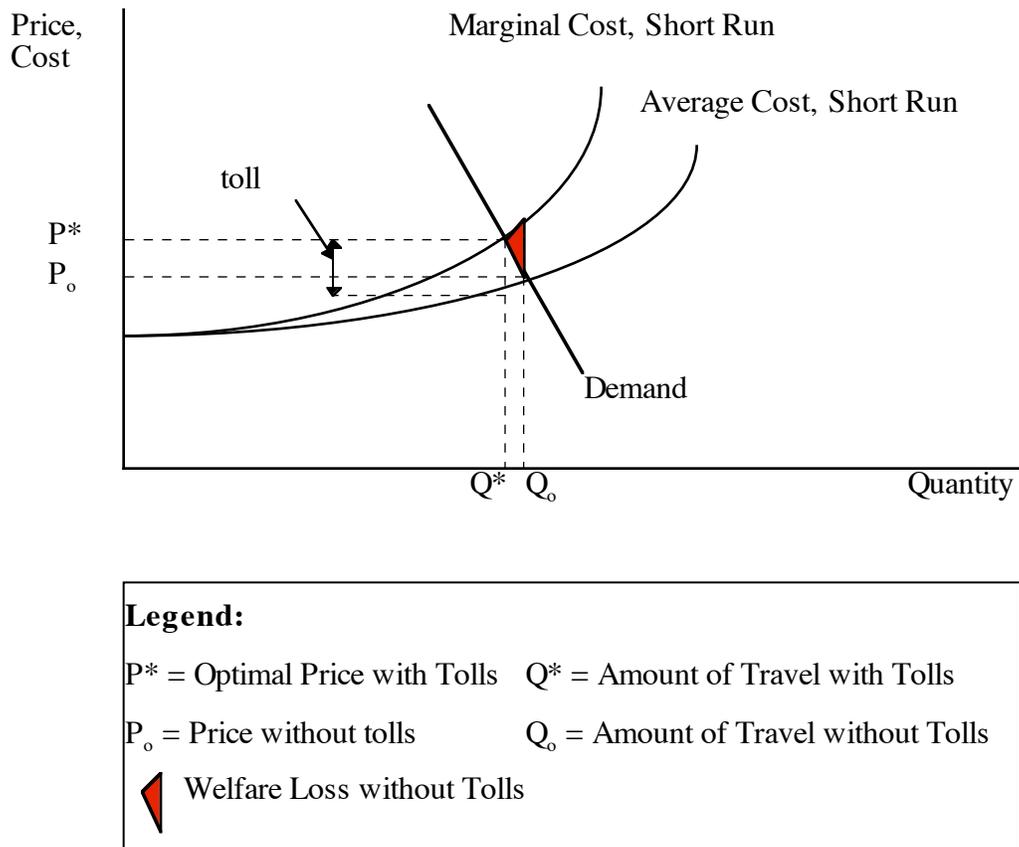
1.3 Research Overview

Subsequent chapters of this thesis consider the history of turnpikes, the theory necessary to analyze the hypothesis, construction of an analytical model, determining empirical values for the model's coefficients, and application of the model.

Chapter Two provides a positive explanation for both the rise and fall of turnpikes, as well as speculation about some of the necessary conditions for a significant re-emergence of turnpikes. The chapter considers turnpikes from their emergence in the United Kingdom and United States through their decline in the late 1800s. The reappearance of toll financing in the mid twentieth century is also investigated. The historical evidence is compared against specific analytical hypotheses about the effects of jurisdiction size and trip length on the choice of financing mechanism.

Chapter Three develops the underlying theory necessary to analyze the choice of the revenue mechanisms that a jurisdiction uses to finance its roads. It outlines alternative property rights structures and selects the one used for analysis Jurisdictions are defined as the agents responsible for building and maintaining roads within their borders. Jurisdictions are modeled using stylized objective functions. They are assumed to behave as if they are governed by one of those objectives (typically local welfare maximization is used, though others are examined). The actions of users are individually determined, and therefore do not comprise policy variables. However, there are several decisions which the network operator can take to satisfy the stated objectives. The set of decisions analyzed here is principally the selection of a revenue instrument (such as taxes or tolls, with various payment schedules) and the setting of a price structure. The main feature of this model is the joint production and consumption of the key good (network services) by the jurisdiction and its residents. Complexity arises because local network users may not be local residents, and local residents may use non-local networks. This is followed in sequence by a consideration of the components of operator profit, users' consumers' surplus, and wealth and land value. Then the free rider problems are identified and discussed. Finally the main analysis method, game theory, is introduced, including core assumptions that its use entails.

Chapter Four presents an analytical model of finance choice. It formally treats the specific factors of jurisdiction size relative to length of trips, transaction costs associated with the placement of tolls, and the implications of complementary jurisdictions. A model of an infinitely long roadway covered by multiple jurisdictions is used for the analysis. The policies selected by neighboring jurisdictions (the environment) need to be treated explicitly. The central element of the game is comprised of a jurisdiction's choice of a policy which is dependent on the choices of neighbors.   A production model, which identifies the major costs facing network providers (both the fixed and variable costs of building and operating the network and collecting revenue) is specified. A consumption model reflecting the sensitivity of demand between an origin-destination pair and the cost of the trip in terms of

money and time is explicated. Specific objective functions are formulated. Complications due to the discrete nature of tollbooths and the assumed continuous loading of the network require special treatment mathematically

Chapter Five places realistic valuations on those demand and cost model parameters so that the model can be applied in situations as similar as possible to actual experience. The purpose is not to find exact answers, because the ground truth varies from place to place, but rather to find reasonable starting points, so that sensitivity to the model results takes place under realistic situations, rather than using arbitrary model values. Empirical values derived from previous studies by the author and others are summarized and employed. The demand coefficients of value of time, freeflow speed, and private vehicle costs, as well as distance decay and trip density are considered. Then the network cost and collection cost variables are investigated. A model of long run total expenditures on infrastructure by states is presented. Data from California Bridges are used to estimate a model of toll collection costs. Finally the costs are summarized.

Chapter Six compares the consequences to a jurisdiction using cordon tolls or general tax financing when the road network is not perfectly excludable. With cordon tolls, as jurisdiction size grows, the free rider problem becomes more acute because ever-more trips are local to the jurisdiction and don't cross the cordon. In contradistinction, as the jurisdiction size grows under tax financing, the free rider problem is mitigated because a larger proportion of tripmakers are subject to taxation. Thus a tax based financing system, particularly in a small jurisdiction, is inequitable to local users. This inequity may not be politically stable. A cordon toll system is inequitable to non-local users, which does not raise the same political issues.

A second problem with cordon tolls comes about as jurisdiction size rises. Above a certain size it may become impossible for a jurisdiction to raise sufficient revenue to support the internal network on the backs of those crossing the cordon.

If one jurisdiction sets policy in a vacuum, it is clearly advantageous to impose as high a toll on out-of-jurisdiction residents as can be supported. However, other jurisdictions can set policy in response. This sets up a classical prisoner's dilemma consideration: in this case to tax or to toll. Even if both jurisdictions would together raise as much revenue from taxes as from tolls (and perhaps more since taxes may have lower collection costs), the equilibrium solution in game theory, under a one-shot game, is for both parties to toll. However in the case of a repeated game, cooperation (taxes and possibly revenue sharing) which has lower collection costs is stable.

This dissertation develops a positive understanding of how jurisdictions choose a revenue mechanism for their networks. The results from the analysis have specific policy ramifications about the design and reconfiguration of appropriate infrastructure financing. Chapter Seven, the conclusion of this research integrates the chapters to identify under what conditions highway networks are likely to be (and should be) financed by specific mechanisms. A scenario for possible deployment of road pricing is outlined. Effective deployment mechanisms are suggested, as any change from one financing system to another cannot take place instantaneously nor is it likely to take place universally. This chapter also suggests future extensions to the work.

2. CHAPTER TWO: ROAD PRICING IN PRACTICE

2.1 Introduction

Proposals to price road use for infrastructure financing, congestion mitigation, or air quality improvement have been surfacing at a regular pace over recent years (Small et al. 1989, TRB 1994, Roth 1996). However, the study of road pricing should consider the long history of turnpikes. In particular, fundamental factors in the historic rise and decline of turnpikes, such as transaction costs, jurisdiction size and trip length, and the nature of the free rider problem (in both the original and modern sense of the term) need to be understood before new efforts are likely to succeed. Hybrid solutions which have been tried in the past, and remain in limited current use, such as lower rates for local traffic and mixed financing between toll revenue and local tax rates may enable new efforts, while theoretically efficient solutions such as pure usage charges remain politically infeasible or economically impractical. This chapter provides institutional background both to corroborate the hypothesis posed in this dissertation and to show the complex issues which suggest that additional factors need to be considered to fully explain revenue choice.

Explanations for the decline of turnpikes in the 19th century cite the new modes of transportation, the canal and then the railroad, which diverted a great deal of long-distance traffic, while urbanization and its concomitant use of public transport further changed travel patterns (Goodrich 1960, Hilton 1960, Warner 1962, Gray 1967, Bobrick 1986, Smerk 1991, Dilts 1992, Martin 1992, Hood 1993). Yet the railroads brought with them an expansion of the economy and a growth in total traffic, if not an increase in long-distance road traffic. But when the automobile-truck-highway system emerged in the 20th century, toll financing did not resume its previous significance. A positive explanation for both the rise and fall, and the conditions for a significant re-emergence of turnpikes is called for.

This chapter examines the history of turnpikes while developing evidence for an explanatory hypothesis of the choice by jurisdictions to finance roads using tolls. It is

posited that jurisdictions generally attempt to maximize net benefits to their own residents. Jurisdictions consider the amount of additional revenue raised by tolls from non-residents against the inconvenience of tolls on their own residents and the costs of toll collection when choosing to tax or toll.   Whether toll roads are managed by government, quasi-governmental organizations, regulated franchises, or unregulated private firms is a secondary question. The underlying hypothesis predicts that when jurisdictions responsible for managing sections of the road network are relatively small compared to the length of trips, an attempt will be made to shift the financial burden from local residents (local trip-makers) to those who make through trips.

The hypothesis can partially explain the rise and decline of turnpikes. When trips by road were long distance (made by out-of-towners) they were expedient to toll by the simple placement of cordons across which one could not pass without paying a toll. But when long-distance trips were diverted to canals and rail, imposing sufficient tolls on local residents to raise the required revenue was politically difficult and inefficient, and the toll financing system collapsed. The hypothesis also suggests that in the present era one is more likely to see tolls on highways constructed by a small jurisdiction (such as Delaware or other states in the northeastern part of the United States), than on those constructed by large states (such as California or other western states)[1]. Furthermore, when roads are financed by a large integrated jurisdiction (like the United States federal government), where all trips are "local" in that they remain within the large jurisdiction, the motivation to reduce the transaction costs which have traditionally been associated with toll roads is higher than when financing is by a smaller jurisdiction (any state which is a subset of the larger United States).

The burden of the transaction costs of tolls in the smaller jurisdiction falls in part on those who don't vote in that jurisdiction. In the larger jurisdiction, where road use is pervasive (voters and road users are essentially identical groups), there is no apparent immediate gain to residents by using tolls rather than taxes (aside from the efficiency

arguments of congestion pricing and focused internal organization), while in the smaller jurisdiction, the benefits of tolls falling on non-residents is clear.   Still, if toll financing is the only means available to construct new roads, there are benefits even in the larger jurisdiction.

This hypothesis does not claim to be a total explanation under all circumstances, as a socio-political system like 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. Further, the influence of key players in business and politics with specific preferences are unpredictable and may greatly shape the decisions made over time. A third factor is the prevailing ideology of government. In the 18th and 19th centuries, a philosophy of limited, decentralized government, or *laissez faire*, was conducive to private enterprise at all levels, including roads. However, this philosophy declined in America in the twentieth century, at least through 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.

This chapter begins with a review of tolls in the ancient and medieval world and then the status of roads before modern turnpikes. The weakness of the pre-toll financing system of statute road labor is the progenitor of turnpikes. The next sections discuss the factors which led to the expansion, and ultimate contraction of, turnpikes. Following is a discussion of what has happened since the beginning of the twentieth century, the era of modern roads, which assumed importance first with the bicycle, then more importantly the automobile. A wave of turnpike construction beginning with the introduction of limited access highways and lasting to the beginning of the interstate highway system is examined. Finally, current efforts at building toll roads in the post-interstate era and various road pricing schemes are discussed. General conclusions are drawn from an examination of the history.

2.2 Tolls in the Ancient and Medieval World

The idea of charging for transportation was known in the ancient world, as the myth of Charon, the ferryman across the Acheron in Hades, tells. However, in fact, rather than myth "We know very little about commerce carried by land [in Greece] and the probable reason is that there was very little of it (Pritchett 1980)." In the Greek city-states, most intercity trade and travel occurred by sea. Roads in Greece were financed in one of two ways: either a levy on the rich was used to build the road or the roads were maintained by the adjacent property owners as mandated by Corpus Juris Civilis (Casson 1974).

References to tolls in Greek literature are ambiguous and thus conclusions are speculative. Tolls and tariffs were conflated in their collection, so conclusions about toll collection must be treated with caution. Fees from non-local traders were levied at ports and markets, though the revenue was not specifically dedicated to transportation, thus tolls in this era are different from later appearances. We might distinguish the idea of toll and tariff today, because tolls are for passage from here to there, while tariffs were assessed at the final destination, not necessarily on pass-through, which is generally exempt. Such distinctions were not so clear in the ancient and medieval world. Customs stations at ports, frontiers, and provincial boundaries exempted personal use items but items for trade were subject to duties.

In areas with more land transportation, road tolls were employed, Aristotle in Oeconomicus Book 2 notes land tolls in Asia's Satraps (Pritchett 1980). Similarly, Pliny in Natural History, cites tolls in the Arab parts of the Roman Empire (Chevallier 1976). Strabo, in an example from his Geographies, written in the time of Augustus, reported tolls on the Little St. Bernard's Pass maintained by the Salassi Tribe. In economic terms, the local mountain peoples were exploiting their monopoly on the passage to raise revenue from travelers. Part of the toll paid for guidance across the mountains and included portage. The practice employed by tribes such as the Arimani from Lombardy involved leading the traveler across the pass before demanding tolls. The tribes were given tolls concessions by

the Empire. As the empire declined, the central authority necessary to build and maintain a safe and free (to travelers) road system declined with it, so tolls (not necessarily authorized) became more widespread (Chevallier 1976).

Where the literary evidence is sparse, the archeological evidence may be used. Tolls may leave certain telltale signs: an unexplainable bend in a road on an otherwise flat plain, a lack of rut on an otherwise (intentionally) rutted road. However despite the occasional possible tollgate location, the absence of tolls in Greece is more notable than their presence. Speculatively, there are hints of tolls on the road between Athens and a quarry at Mt. Pentelichus (Casson 1974). Chavallier suggests some tolls in northern Italy by bends in the road.

In the middle ages tolls were widely used to support bridge construction and were less widely collected on roads in some areas (EB 1997). A major issue during the reign of Wenceslas as Holy Roman Emperor (1378-1400) was the insistence of territorial lords on imposing tolls on city merchandise in transit through their possessions. The justification of the road tolls on road and river traffic relied on the protection of merchants and their goods. However, the frequent spacing of toll stations hampered trade and provoked disputes often culminating in the lords seizing both merchants and their merchandise. Later reports from Montaigne in the late 1500s suggests long standing tolls in the Appenine mountains, across various passes (Chavallier 1976).

2.3 Roads Before Modern Turnpikes

The roadway network of Britain has been heavily studied, and as English common law has become the underlying standard throughout much of the world, it is a reasonable starting point for understanding the status of roads before the imposition of modern tolls. This section relies heavily on the history of English roads by the Webbs (1913).   It is believed that roads (in Britain and elsewhere) began as trails, running from high ground to fordable points on rivers or seaports. Through a process of cumulative causation - a cleared

path attracts more traffic, which helps keep the path clear - these tracks became ensconced as the backbone of the original transportation network. The Roman occupation of Britain resulted in the construction of four main roads, principally for military communication, and numerous minor ones. After the Romans left, road use may have diminished, though certainly did not vanish.

The road in this period is better conceived of as a right than an object. A road is a right of passage on another's land, rather than the paved surface owned by some central authority that we imagine today.   The highway constituted "good passage" rather than the beaten track, so if the track were in poor condition, travelers could skirt it. The English word "road" is of the same root as the word "ride" - the Middle English "rood" and Old English "rad" - meaning the act of riding (Webster's II 1984).

The first English law dealing with roads was the 1285 Statute of Westminster, requiring residents of manors to clear two hundred feet on each side of their roadway of "bushes, woods, or dykes" where a "man may lurk to do hurt". The wide right-of-way was to ensure protection from highway robbery rather than enhance movement.   However, the roadways began to deteriorate over the late middle ages and renaissance. An important cause is the decline of the religious orders associated with Henry VIII's break with Rome, which reduced pilgrimages and levels of traffic on the roads. Monasteries which had maintained roads were no longer able to, while the successors to their property had much less incentive.   As cumulative causation works in one direction creating the roads, it also can work in reverse leading to their deterioration through neglect.

The next legal milestone, "2 and 3 Philip and Mary, C.8.", was passed by the Parliament of 1555.   This law set the obligation of maintaining public highways upon several parties: the parish and every resident thereof, the newly created Surveyor of Highways for each parish, and the Justices of the Peace within the Parish's Division. Any or all of the parties could be brought before a judicial tribunal if they failed to fulfill their obligation. Parishioners with property were required to send plows, carts and horses to help

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maintain the roads, while others were required to labor for six consecutive days each year (about two percent of the working year) under the authority of the Surveyor of Highways.

As might be expected with growth in the economy and changes in the price level, over time the penalty for not performing the obligatory labor became less onerous than actually doing the work. By 1649, in some British localities, taxes were beginning to be assessed for road improvements to pay the Surveyor of Highways, formalizing the process. However the system of compulsory labor remained through the 1700s, until finally being eliminated in 1835. With the decline of the feudal manor system, this mechanism of "financing" road improvements was viewed as more and more inequitable. Furthermore, it became increasingly inefficient as steadily higher and higher quality roads were demanded. The efficient division of labor called for something other than everyone serving the same six day period on roads, it makes little sense to have people responsible for spreading gravel on the roads working (or not working) over the same six days as those who had to dig the gravel.

Similar laws existed in North America, for instance in New York in 1800 all free males over the age of 21 were assessed highway labor "in proportion to the estate and ability of each", with a minimum of one day and a maximum of 30 days as determined by town highway commissioners. Failure to contribute led to fines which steadily increased over time, commutation of labor cost 62.5 cents per day in 1801 (Klein and Majewski 1994) . These laws lasted into the twentieth century in some rural areas, including parts of Texas (Goddard 1994).

The American system collapsed for similar reasons to the British, the mandatory labor was viewed as a burden and the laborers did not contribute their utmost effort. There was no incentive to work hard in general, particularly so when your co-workers shirked. Unlike money which is fully fungible, labor's value depends on the effort put in as well as the amount of time spent. The stream of money for roads was inconsistent, coming from fines rather than any dedicated revenue, making planning difficult. The districts, which were

small, could only draw on local laborers for construction, even if the road which it governed served a broad area.

2.4 Turnpikes in Great Britain: 1656 - 1900

The initial deployment of turnpikes in seventeenth century Britain, their growth through the eighteenth and early nineteenth century, and decline in the late nineteenth century provides insight into current discussions of private toll roads. The English word "turnpike" derives from the spiked spear (pike) which was stretched across the road so it could be swung open for toll payers (McShane 1994). Turnpikes were comprised of both new and reconstructed roads (Buchanan 1990). In some important cases, the turnpiking of a road was accompanied by its reconstruction; in others, the government subsidized the reconstruction of an existing turnpike.

The first English turnpike is recorded in the Vestry of Radwell, Hertfordshire, which petitioned Parliament for road improvements in 1656. By 1663, Parliament permitted the placement of three toll gates to raise funds for the repair of the Great North Road by the County Justices in Quarter or Highway Sessions (Payne 1956). Some other toll gates followed. The upturn in turnpike acts in 1695 reflects a return to domestic stability in England after the Glorious Revolution. (Albert 1972, p12).

Turnpike acts were promoted by local residents (town councils, merchants, manufacturers, farmers, landowners) responsible for maintaining at least part of the road in question. The turnpikes covered multiple parishes, though only a large subset of those parishes were required to push through an act (Albert 1972, p24).

After 1706 in Britain, Parliament chartered "turnpike trusts" to improve selected roadways. A typical turnpike trust might have well over 80 trustees, though only a dozen or so attended meetings regularly (Payne 1956). The trusts were chaired by the treasurer, while the turnpikes were managed by an appointed surveyor (who generally did not serve as a trustee, to avoid the accusation of jobbery). The surveyor supervised maintenance and construction along the road, and was rarely limited to serving on only one turnpike.

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Ultimately, the collection of tolls was franchised to toll "farmers" who, after paying a fixed sum to the trust, were permitted to collect tolls at specified gates on the turnpike or turnpike system. Toll farming began as early as 1702, when the first leases were agreed to, only in 1773 were tolls auctioned using a formal procedure. Initially the toll farmers were local businessmen, but as the system matured the toll farmers became larger and larger.   By 1825 one partnership rented three/fourths of the tolls in London, amounting to between £400,000 and £500,000 (Albert 1972, p85).

Pawson (1977) provides the most comprehensive history on the deployment of turnpikes. Figure 2.1 shows the number of turnpike trusts in Britain, approximating the classic "S-curve" (the cumulative version of a normal distribution) through 1850. The theory underlying the S-curve is straight-forward. As knowledge of a technology and realization of its benefits spreads, the rate of adoption increases. Each project acts as a demonstration to potential new users. Furthermore, the advantages to adoption may increase with the number of users if there are network or inter-firm scale, scope, or sequence economies. As the technology diffuses, those who expect to attain the most benefit adopt it first. After a point, diminishing marginal returns set in. It is expected that, after complete exposure, technology is adopted by those who gain the most, and then by those who gain less and less from it, until it is fully deployed. The life of a technology may be cut short by competing technologies (such as canals and railroads in the case of turnpikes) or because a technological problem is discovered (as in the case of plank roads). Phillips and Turten (1987) describe two basic patterns of British roadways during Figure 2.1 deployment: radial roads focusing on towns (initially London and later others), and inter-regional roads serving intercity traffic.

Figure 2.1 Turnpikes in Great Britain: 1650 - 1900
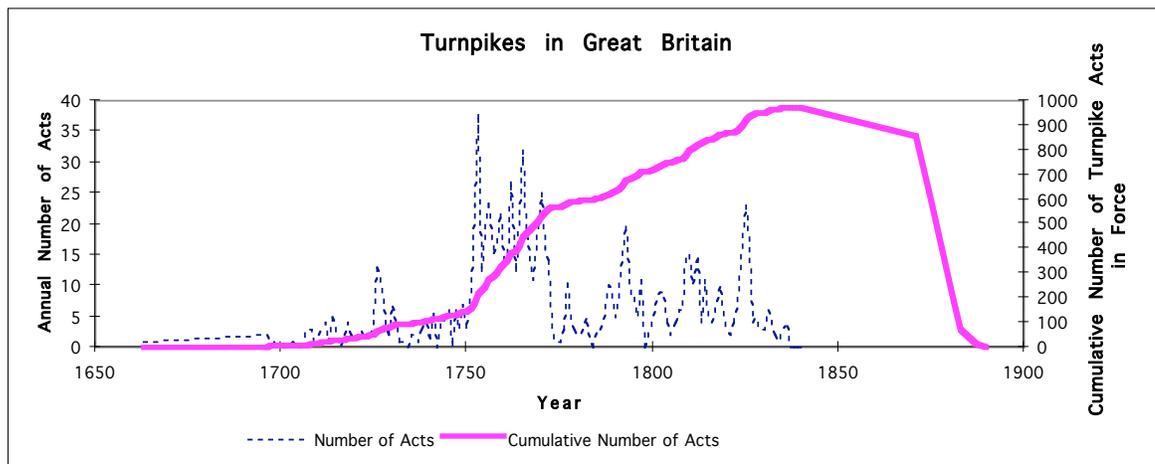
source, Pawson (1977), Webb (1913)

In Britain, not everyone was subject to tolls. The government paid an annual fee in lieu of tolls, while residents of the road's locality typically paid a fixed annual fee rather than a per-use charge (Payne 1956), thereby enabling some degree of free (or subsidized) riding. In economic terms, British turnpikes were viewed as local public goods, with outsiders able to pay for limited use, as with a club good (Cornes and Sandler 1996). It is unlikely the fixed annual fee provided revenue in proportion to the costs of use, though the financial situation in terms of costs and revenues on turnpikes in this era remains to be satisfactorily examined. In other locations, the mails and religious persons were exempt, as were the construction workers improving the roads (Copeland 1963). The tollgates, which generally formed, at minimum, a cordon around the part of the road network operated by a single authority, extracted revenue from trips originating and/or destined for areas outside the toll authority's coverage. The tolls were used to pay off mortgages incurred by the trusts for road improvements, including extending, resurfacing, straightening, and widening the turnpike, constructing footpaths, arching over sewers, and lighting the road in urban areas.

The deployment of turnpikes was not without some opposition. Prior to the turnpiking of a road, it had been open to free passage under English common law. But because "free" roads were of poor quality, carriages belonging mostly to the rich could not easily pass. The turnpikes, which improved road quality at a price, were thus viewed as a transfer from the poor, who could always pass for free with carts and horses before tolls, to the rich, who gained the most when the roads were improved. This was quite similar to the enclosure movement, which also created similar new property rights. The inequity led to several turnpike riots (Albert 1979). Colliers who resented the placement of tolls between the coal mines and market in Kingswood, Bristol smashed gates and tollhouses during riots in 1727, 1731, and 1749. However, unlike laborers in other sectors who also had resentments, the coal miners were far better organized and had been given fewer dispensations than local traffic elsewhere. To combat these riots, the government in 1727 raised penalties on destroying turnpikes or riverworks to 3 months in prison and public whipping for the first offense and seven years of transportation (being sent abroad to a penal colony) for the second. Yet the rioters were not deterred. In the 1730s resistance moved to the Gloucester and Hereford regions. The last 18th century riot took place in 1758 near Bradford and Leeds, where tolls had been doubled and new gates imposed. In 1843 the Rebecca riots took place in Wales (Duckham 1984), leading to a restructuring of turnpike management.

After the 1843 Rebecca riot, a Welsh commission recommended that turnpikes be consolidated at the county level (Duckham 1984). Further, tolls were to be made uniform throughout the six counties of Wales for each type of good, and toll booths were to be placed only every seven miles (12 km). Produce was to be exempt and agricultural inputs such as lime only tolled at half the normal rate. In an early recognition of the link between transportation and land use, the road taxes were deducted from the rent paid by tenant farmers. While the counties continued road maintenance, tolls were again farmed. The tolls were auctioned to the highest bidder, who over time became a representative of a national

organization who attained one main economy of scale - the spread of risk over multiple operations. Risk was steadily increasing in the mid 1800s due to the railroading of the countryside; as soon as a railroad arrived, toll revenues dropped. When a railroad came in, or for any other good reason, the toll farmers tried to obtain a reduction in their lease payments from the county boards, who only sometimes acquiesced.

It should be noted that revenue dropped when the road board operated tolls themselves (Duckham 1984). Several reasons have been suggested, including higher administrative expenses and less thoroughness in catching toll evaders. A third reason to note is that causation may be in the other direction; when toll revenues dropped, the county road board had to assume toll collection on the turnpike when the toll farmer defaulted. Toll farmers only paid a short period in advance for the right to collect revenue, minimizing capital outlay and providing them the opportunity for renegotiation with some leverage. While the tolls covered maintenance, the county still subsidized major capital expenses through the road rate (general taxes). In 1889 the county took over the road boards and dissolved the turnpikes.

The arrival and deployment of railroads from the late 1820s eroded the market share for inter-city transportation belonging to roads. The railroads, running on steam power, were significantly faster than horse-powered transport, a speed which made up for the increased access costs: the railroad depot may not have been the ultimate origin and destination, and trains ran on fixed schedules. Still, since much intercity transport was provided by carriage services, road transport in the mid-1800s more closely resembles a competition between bus and rail than car and rail.

The Times (of London) in 1816 editorialized on the inconvenience of toll collection every mile (1.6 km), describing the collectors as: "men placed in a situation unfavourable to civilized manners, and who might be usefully employed in mending the roads which they now obstruct in a most disagreeable manner" (Albert 1972, p65). Certainly tolls were not heralded with universal acclaim, and as the situation made itself amenable, pressure to

remove tolls increased. The Webbs (1913) date from the early 1860s the public

determination to rid themselves of tolls. Tolls were replaced by local tax revenue in Ireland

for funding roads in 1858, and the results were perceived adequate. Parliament member

George Clive's 1862 retirement was seen as the elimination of a key impediment to

removing tolls, more precisely, in not renewing the terms of turnpike trusts as had been

done in the past. The main complaints against tolls were that they were a costly and

wasteful means for collecting revenue, inconvenient to the public, that they impeded traffic,

and that the tax was inequitable. The recommended solution was to vest the roads in a

public authority (highway districts or the local highway parish). From 1865, tolls in

Scotland were abolished piecemeal. From 1864 onwards, turnpike trusts in Britain were

dissolved at a rapid rate, as shown on the right side of Figure 2.1. The final turnpike toll was

collected November 1, 1895 on the Shrewsbury and Holyhead Road.

The loss of turnpike revenue increased the financial burden on local authorities to

finance and maintain roads. Grants from the national government were intended to mitigate

these factors.   Eventually, authority for the roads moved up to the County level outside

urban areas, and was paid for by local taxes sent to the County, Town, or special district.

2.5 Turnpikes in America: 1785 - 1900

In the United States, turnpike deployment began about a century after Great Britain.

The causes were similar: the quality of the roads were insufficient to meet the demands

placed upon them. In particular, before turnpike deployment, there was a feeling of inequity

where rural residents paid to maintain roads used by urban dwellers for intercity travel.

Before bringing in private enterprise, states tried solve the problems themselves. Americans

unsuccessfully tried to emulate the British Turnpike Trust system, using taxes for

construction and tolls for maintenance, but turned to corporations formed by interested

merchants and well-to-do landowners after the earliest deployment. Thus the first turnpikes

often had the assistance of tax funding in the 1780s, but in later years, outside of

Pennsylvania, most turnpike companies received little state aid. The rationale for state

assistance was based on the premises of positive externalities or spillovers that roads would increase both land values and commerce (Durrenberger 1931, p37, 97). Without subsidy, it was believed that there would be an underinvestment in roads.

In 1785, Virginia authorized tolls on public, tax funded roads, and chartered a short distance turnpike from Alexandria to Berryville (USDOT 1976); Maryland followed suit in 1787 (Klein and Majewski 1994). The first significant U.S. turnpike company was chartered in Pennsylvania in 1792, connecting Philadelphia and Lancaster, and completed two years later (USDOT 1976). To look at the rate of deployment, Table 2.1 shows the number of turnpike companies chartered in several states from 1790 to 1845. Like turnpikes, bridges were private toll facilities. From 1786 to 1798, 59 toll bridges were chartered (Klein 1990). Baer et al. (1993) illustrate the basic pattern in New York as a series of roads radiating from that state's main artery, the Hudson River, and later the Erie Canal. In California, most toll roads were deployed in the mining counties of the Sierra Nevada (Klein and Yin 1996).

Table 2.1 Turnpike Incorporation in the United States, 1792-1845

State	1792-1800	1801-10	1811-20	1821-30	1831-40	1841-45	Total
New Hampshire	4	45	5	1	4	0	59
Vermont	9	19	15	7	4	3	57
Massachusetts	9	80	8	16	1	1	115
Rhode Island	3	13	8	13	3	1	41
Connecticut	23	37	16	24	13	0	113
New York	13	126	133	75	83	27	457
Pennsylvania	5	39	101	59	101	37	342
New Jersey	0	22	22	3	3	0	50
Virginia	0	6	7	8	25	0	46
Maryland	3	9	33	12	14	7	78
Ohio	0	2	14	12	114	62	204
Total	69	398	362	230	365	138	1562

source Fielding and Klein (1992)

The Federal Government was not permitted under the Constitution to collect tolls, according to President Monroe, who vetoed attempts to place tolls on the National Road (running from the Potomac River to the Ohio River), which was already beginning to

deteriorate less than ten years after its 1813 opening. By the 1830s, Congress turned over the road to the relevant states, who then imposed tolls to maintain the road (USDOT 1976).

Much of the American turnpike construction was due to competition between towns to gain trade. Durrenberger (1931, p 47) argues "The rivalries and jealousies that existed among the states seems unbelievable today" and one can extend the observation to rivalries between towns. The subscribers to turnpikes, as with canals, were a mixed group including citizens, municipalities, and state governments, as well as foreign nationals in later years. Although the federal government had subsidized new turnpikes and roads through land grants in the public lands (western) states prior to 1830, attempts to have the federal government subscribe to turnpike company stock offerings were ended by President Jackson's 1830 veto of the Maysville Road Bill, which had been sponsored by the state of Kentucky to get federal funds for what Jackson deemed a purely local road. It was twenty years before federal subsidies to infrastructure, then railroads, came again (USDOT 1976). Despite the sparse federal involvement, town leaders realized that an early edge in attaining access to other areas, and thus becoming a key cross-roads would have long-term payoffs (Klein and Majewski 1994). Individuals would relocate to the towns with turnpike access, which would attract others individuals, provide revenues to the turnpike, and encourage additional transportation investments. Towns without access would wither.

Klein and Majewski (1994) argue that after the first few were chartered, turnpike investments were recognized as unprofitable, and were really an example of voluntary private provision of a public good for the good of the public. Towns and their leading citizens were looking for economic spillovers from the roads. Because towns were more autonomous in this era, citizens felt more obligated to contribute. Investors, constituting the social elites of towns, invested in turnpikes to promote the town's interest (and only indirectly their own). The voluntary private provision of public goods can be individually rational if the provider's contribution is outweighed by the benefits received from their own contribution (Olson 1965). Furthermore, social pressures were placed on members of the

elite to ensure sufficient subscription to new investment. These pressures enforced good

behavior (meeting social obligations) due to the repeated interactions of the local business

elite, in multiple spheres, which would socially or economically discipline a member who

shirked responsibilities. Gray (1968) finds similar practices in the chartering of the

Chesapeake and Delaware Canal.

Although there is some aspect of voluntary private provision of a public good with

possible private benefit from spillover in the construction of many turnpikes, other turnpikes

were just as surely speculative ventures attempting to be profitable in their own right.

Foreign (or even non-local) investment provides evidence of this (USDOT 1976).

However, Durrenberger (1931, p100) argues that "while foreign capital was in abundance

after 1815, it played a very minor part in turnpike finance", and that the largest part of

foreign impact was associated with dollars lent to the state of Pennsylvania. Durrenberger

suggests that capital was mostly local; at no time did state ownership exceed one-third of

invested capital, though in a few instances towns and cities did invest. He gives support to

the argument that turnpike "subscribers were usually more interested in the possible

benefits the new lines of communication would bring them than in the [profitability] of the

investment" because of the wide distribution of stock and the character and interests of

subscribers. From the point of view of dividends and capital return, turnpike stocks were

poor investments; at best returns were 8% annually, with 3% being more common, and

financial problems set in even before the deployment of canals and railroads.

In New York, toll booths were spaced at ten mile (16 km) intervals, thereby allowing

local trips to be free riders. The free rider problem was significant.   For instance,

Massachusetts law exempted people going to and from gristmills or church, people on

military duty, or on journeys within the toll-gated town for common and ordinary family

business (Rae 1971).   Furthermore, "shunpikes", illegal toll gate bypasses, frequently

arose to allow travelers to avoid the road section with the toll booth. These two factors

limited the profitability of turnpike.

The California turnpike experience differs from that in the eastern states. In addition to beginning about fifty years later in the wake of the gold rush, the rationales for the road differed. California law borrowed heavily from eastern states, including financial requirements that may have hindered the deployment of the new roads (Klein and Yin 1996). In the eastern states toll roads emerged from community enterprise, without a significant profit motive; in California turnpikes operated more like businesses, interested in the residual revenues from roads. It is unclear to what extent the California roads succeeded in being profitable enterprises: some were and some weren't, though the exact proportions are not known (Klein and Yin 1996). Many of the owners of California's toll roads were resource extraction companies such as mines and lumber companies. In addition, a number of tourist roads were built, including to Yosemite and on Mount Wilson (Klein and Yin 1996).

Spin-offs of turnpikes include taverns (early rest stops), which were a highly structured market. Three different kinds of taverns were typical, showing up as often as one per mile (1.6 km) on the heavily traveled Philadelphia and Lancaster Turnpike (Durrenberger 1931, p124). These include marketing to the relatively freer-spending stage passengers, to wagoners, and to livestock drovers. While stage passengers required food and sleep, wagoners needed yards and stables, and drovers needed pasture and feed for their droves.

The argument can be made that some of the toll roads were required as a component in the production process. For instance, roads and mines (particularly in California during the nineteenth century) are complements. A mine without access is useless, but the traffic to the mine does not utilize the full capacity of the road. Because roads exhibit economies of scope - it doesn't matter whether the trip is to the mine (or resort) or not, the road equally serves both - and are lumpy investments (the lanes of a road cannot be made significantly smaller in proportion to the scale of traffic, they represent an indivisibility), the California

road owners used tolls to capture rents from the external benefits associated with the necessary construction of a road.

In the first turnpike era, turnpikes were believed to increase the value of land where they were placed and decrease it elsewhere by changing the pattern of relative accessibility. The changes resulted in a reduction in rents in some areas in competition with those newly turnpiked. The consequence was a push to improve transportation accessibility in many localities, either to increase rents or prevent them from falling. Adam Smith (1776) notes that "not more than fifty years ago, that some of the counties in the neighborhood of London petitioned against the extension of the turnpikes into the more remoter counties. These remoter counties, they pretended, from the cheapness of labour, would be able to sell their grass and corn cheaper in the London market than themselves, and would thereby reduce their rents, and ruin their cultivation." The complementarity between transportation and the points they access has also been noticeable in the construction of streetcars and their associated suburbs in the late 19th and early 20th century (Warner 1962) and more recently in developer-financed roads, including some toll roads opening up new areas like the Dulles Greenway in Virginia.

As in Britain, opposition occurred in the United States, for many of the expected reasons. On principle, many thought that roads were a public not a private function, and that payment of tolls was a payment to usurpers of public roads (Durrenberger 1931, p81). More practically, locals were opposed to paying a toll when travel had been free; much of this opposition was mitigated by charters which enabled local residents to be free riders. Further, there was resentment of those who owned the turnpike, who would get rich (or at least were thought to get rich) at the expense of travelers. There was also opposition to the corporate form in general, which was new in the early 1800s (Klein and Majewski 1994). Over the long term, these opponents of corporate governance had little effect, as the corporate form has become the dominant means of organizing business. The opposition to urban highways that emerged after the interstate program was initiated was due to

destruction of local communities as well as NIMBYism (NIMBY is an abbreviation for Not In My Back Yard), opposition to any noxious facilities nearby. There is no record that opposition in the first turnpike era had any similar causes. As in Britain, laws protected infrastructure and punished vandalism. The main arguments for abolishing turnpikes drew from those opposing their establishment: that roads were utilities and should be free, that turnpikes drew patronage mostly from local traffic which meant taxing the farm class, that people would benefit from freer social intercourse, and that tolls were an annoyance to travelers (Durrenberger 1931 p162).

As in Britain, in the United States the driving forces behind disturnpiking were other modes: canals and railroads. At first these modes, particularly canals, killed the competing trunk roads, while in fact promoting the construction of complementary branches (Baer et al. 1993). The Erie Canal opened in 1825 and soon found its first victims: the First, Second, and Third Great Western turnpikes, which saw annual revenues decline. Just as the turnpikes declined, the fortunes of towns on the turnpikes declined, while those on the canal rose. Nevertheless, the turnpikes were not immediately put out of business.

Turnpikes were not helped by the Supreme Court's 1837 decision in the case Charles River Bridge v. Warren Bridge ((11 Pet. (36 U.S.) 420 (1837)) (Monroe in Hall 1992)). In 1785, Massachusetts legislators incorporated the Proprietors of the Charles River Bridge to build a connection between Boston and Charlestown. In 1828, the legislature authorized Charlestown merchants to build the new Warren Bridge, and to collect tolls until they were reimbursed, at which time that bridge would be free and revert to the state. The Charles River Bridge proprietors sought an injunction against the new bridge. The question turned on whether the Charles River Bridge proprietors had a vested right to a monopoly between the two locales, or simply permission to operate a bridge and collect tolls, while the ambiguity in the original contract permitted multiple interpretations. Taney, a Jackson democrat and recent judicial appointee wrote the opinion in a 4 to 3 vote which justified the destruction of old property "rights" so that new ventures might prosper. The

state was authorized to provide new charters so long as the narrow constitution of the private property right in the original charter was not diminished, that narrow interpretation being simply toll collection. The consequences of this decision were broad and not helpful for turnpikes, which had hoped to use exclusive franchises to delay competing canals and railroads (McShane 1994).

The roads in New York faced a second blow with the advent of major railroad construction beginning in 1848. "The turnpikes disintegrated in stages, abandoning their road piece by unprofitable piece (Baer et al 1993)." By the end of the 1850s New York's major trunk turnpikes were dissolved and became public roads. Partial abandonments were permitted, and this was the most common form of the dissolution of turnpikes (Durrenberger 1931, p156). However, as older turnpikes saw long-distance traffic wither and collapse, new feeder roads were being constructed as complements to the railroads. Rose and Durrenberger argue that the number of new charters did not diminish greatly until 1875 (Durrenberger 1931 p 154, Rose 1953). The number of charters from 1830-1860 exceeded the number from 1800-1830 in the middle Atlantic states, in Pennsylvania the numbers were 630 vs. 200, in New Jersey 124 vs. 48. Still, it must be remembered that the nature of the later roads was as feeder to intercity transportation via canal and railroad, while the earlier roads were themselves more often trunk roads (Durrenberger 1931, p139).

A brief exception to the decline of turnpikes occurred with the emergence (and disappearance) of plank roads between 1846 and 1857 (Klein and Majewski 1994). Plank roads overcame many of the competitive disadvantages suffered by gravel roads - they were smooth and thus enabled faster speeds. They were most prevalent in areas where lumber was cheap. Unfortunately, the planks deteriorated after only a few years, much sooner than expected, and shortly after they were deployed they were abandoned. In New York, the length constructed was over 3500 miles (5800 km) between 1846-1853, where the plank roads served principally as branch roads in the Erie Canal and Hudson River regions, as well as radial roads to several upstate cities.

Though the first turnpike abandonments were found in 1817 in New York, turnpikes did not die with a bang; in 1898 in Maryland there were still 497 miles (828 km) of turnpiked road, and in Pennsylvania in 1903 there were still 1101 miles (1835 km) of turnpike (Durrenberger 1931, p115). The Lancaster Pike, the first significant turnpike, was not finally dissolved until 1902 (USDOT 1976). Durrenberger suggests several main causes of unprofitability: poor organization and management, high overhead (fixed cost) of toll collection relative to their scale, early undercapitalization and excessive debts so that tolls were diverted to interest payments rather than maintenance, poor location and insufficient traffic due in part to speculative construction in advance of traffic which never materialized, and competitions from railroads and canals.

Turnpikes were established with charters which intended them to ultimately revert to the states, typically after a ninety-nine year run in the private sector or the achievement of some maximum return on capital. The actual method of reversion or disturnpiking was through abandonment, condemnation, or sale; few actually lived out their charters. In the 1870s counties and towns were given authority to purchase and disturnpike roads and bridges at local expense. By 1897, rules, such as those in New Jersey, were drawn permitting two-thirds of fronting property owners to petition the state public roads commission to disturnpike the road, sharing a fair and just price paid to the turnpike's owners between the state (33%), county (57%), and frontage properties (10%) (Durrenberger 1931 p164). In the early 1900s, as states established state highway systems, the remaining toll roads were acquired by state and local governments.

2.6 Turnpikes in America: 1900 - Present

The advent of the bicycle, and then the automobile, created a new set of needs for highways. While previously roads had been designed first for pedestrians and animals (pack animals to carry people and goods, cattle and swine being herded to market), wheeled

carts and carriages require an improved surface. The technological change of the wide(r)-spread adoption of wheeled vehicles, coupled with socio-economic factors and regional growth, led to a change in highway financing in the 18th century. Similarly, rubber-wheeled vehicles traveling at higher speeds required a smoother surface yet again. To support the new vehicle stock, roads needed to be improved with smoother surfaces and more gradual curves that could be taken at higher speeds. In the United States, two highway systems were deployed in the twentieth century to support the automobile. The first "U.S. Highways" created a national network of paved roads, the second "Interstates" created a network of grade separated freeways. Both were largely free of tolls. In 1914, before significant federal involvement, but after the beginning of the good roads movements, the United States had 257,293 miles (428,822 km) of surfaced roads, of which 75,400 miles (125,700 km) were macadam, 1,591 mi. (2652 km) were brick, and 2,349 mi. (3915 km) were concrete (Flink 1990).

Prior to federal involvement with "U.S. Highways", some modern 20th century roads had been toll financed, though this was limited in scope. In 1908, William Vanderbilt started a turnpike company to construct the Long Island Motor Parkway, intended for car enthusiasts in New York (McShane 1994); however the road, only one lane in each direction, never made much money and had technical problems with its surface. The toll idea was borrowed by Robert Moses, New York's Park Commissioner, to fund "parkways" throughout metropolitan New York from the 1920s (Caro 1974). Ironically, Moses' Northern States Parkway paralleled the Vanderbilt route, and bankrupted it in 1938 (the route became a power line right of way). The DuPont family built a similar private roadway in Delaware (McShane 1994).

Financing in the era of U.S. Highways was principally by gas tax, beginning in Oregon, New Mexico, and Colorado in 1919; by 1929 it was national in scope. In 1921 property taxes and general funds paid about 75% of the cost of roads, by 1929, 21 states no longer used any general funds or property taxes for funding, and most money came from

gas taxes (Flink 1990). The federal aid program paid for no more than 7% of the road miles in a state; by 1924, this amounted to $15,000 per mile ($9,000 per km). Beginning in Britain in 1909 came the idea of non-divertability of gas taxes, which said that gas revenue would be spent on roads, not on general budget issues or even for other transport modes. This concept disappeared in Britain in 1926 (Flink 1990), and later in the United States (in 1973 some gas tax revenue could be diverted to other transport modes and in 1993 a fraction of gas taxes were diverted to the general fund at the federal level).

Before the federal government's involvement in grade-separated roads, a number of states, particularly in the northeast, had already chartered turnpike authorities to construct those inter-city roads. Proposals by the Roosevelt administration for a transcontinental toll road from 1934 came to naught (Goddard 1994).   In 1939, the Bureau of Public Roads, a long-term opponent of tolls (Goddard 1994) published "Toll Roads and Free Roads" which argued that tolls would cover less than half the annual cost of a system of interstate roads (Rae 1971). However, their estimates were quite off, given the experience of actual toll roads opened in the next two decades; for instance, a projection of 715 vehicles per day on the Pennsylvania Turnpike versus actual demand in the tens of thousands (Rae 1971, Gifford 1983).   Gifford (1983) argues forcefully that the conclusions of the report to oppose federal toll roads would have been reversed had accurate demand forecasts been used and accepted. Even President Eisenhower thought the interstate system should be toll financed, though Congress, led by Senator Gore, Sr. disagreed (Goddard 1994).

Many tunnels and bridges were constructed as toll facilities, both before and during the interstate era. Those before the interstates include the Golden Gate and San Francisco Bay Bridges in the Bay Area, and the Holland and Lincoln Tunnels and George Washington Bridge in New York.

Just as the first American turnpike was in Pennsylvania, so was the first in the new era of limited access highways. The Pennsylvania Turnpike, constructed in part along the abandoned South Pennsylvania railroad right-of-way and through already partially bored

tunnels, opened in 1940 connecting Pittsburgh with Harrisburg along a higher quality and shorter route than the existing U.S. 30 (The Lincoln Highway) and U.S. 22 (The William Penn Highway). The South Pennsylvania had begun construction under the direction of Commodore Vanderbilt and Andrew Carnegie as a competitor to the Pennsylvania Railroad, which had a spatial monopoly on long-distance freight traffic through the state. Vanderbilt, who owned the New York Central, believed the Pennsylvania RR was supporting a competitor in New York, and the South Pennsylvania was begun as a competitive response. J. P. Morgan brokered a deal which led to the abandonment of both competitive projects (Cupper 1990). Though the road was built without any federal transportation funds, other New Deal financing sources were used, including a $29.25 million grant from the Public Works Administration and $40.8 million purchase of bonds by the Reconstruction Finance Corporation (Deakin 1989, Cupper 1990). The road was not only the first new era toll road, it was also the first long distance limited access highway built in the United States. The original toll was $1.50 end to end, or just over a penny a mile ($0.006/km), but that was not enough to keep the road uncongested. The first traffic jam occurred (27,000 vehicles on a single day) the sixth day the road was open, as Sunday drivers took advantage of views of fall foliage (Cupper 1990). The toll road was extended several times, ultimately to Ohio and to New Jersey, the road was widened and improved in places, and over time the toll has risen to 3.1 pennies/mile ($0.019/km) and traffic flow to 97 million vehicles per year in 1989.

Owen and Dearing (1951) note that the cost of collecting tolls ranged from 3.5% of total revenue on the Pennsylvania Turnpike to 18% on the Merritt Parkway, while the gas tax in the same era entailed a 4.0% collection loss. The capital cost of constructing toll booths on the Maine Turnpike was 1.3% of total costs. The advantages of turnpikes recognized at the time include a decentralized institutional structure enabling market evaluation and a limit to the misplaced uniformity (all roads at the same standard, a ubiquity of construction even in areas without demand) of a centralized publicly funded system. The disadvantages were empire building by a quasi-autonomous government agency which may

use cross-subsidies against the public interest and over-extension in the case where forecasts outpace actual demand.

There was considerable controversy over how to treat toll roads in the context of the toll-free interstate highway system, particularly whether states should be compensated for toll roads already constructed. Ultimately, 2700 miles (4300 km) of the pre-interstate toll roads were included in the interstate system. Over 4000 miles (6400 km) of toll facilities were built in the period from 1940-60 in over 30 states (Shaevitz 1991). These include the turnpikes shown in Table 2.2, as of 1963, and shown chronologically in Figure 2.2. As can be seen, the toll roads were built largely in the physically smaller eastern and midwestern states, while the large western states relied on "free" roads. At least two factors help explain this difference.

Table 2.2 Miles of Toll Highways in Operation in 1963

State	Mileage in Use	Cost (thousands)	Period Built
Colorado	17.3	$6,237	1952
Connecticut	193.9	502,092	1940-59
Delaware	11.2	30,000	1963
Florida	206.6	171,783	1950-64
Georgia	11.1	3,150	1924
Illinois	185.3	445,623	1958-59
Indiana	156.9	280,000	1956
Kansas	240.9	179,500	1956-59
Kentucky	204.7	185,500	1956-64
Maine	112.2	79,406	1955-57
Maryland	42.3	74,000	1963
Massachusetts	124.4	239,000	1957
New Hampshire	77.2	43,524	1950-57
New Jersey	309.2	821,200	1952-57
New York	628.8	1,130,951	1926-60
Ohio	241.0	326,000	1955
Oklahoma	174.3	106,714	1953-57
Pennsylvania	469.3	539,664	1940-57
Texas	30.1	58,500	1957
Virginia	34.6	75,150	1958
West Virginia	86.3	133,000	1954
Totals	3557.6	5430994	1940-64

source Rae 1971 after Bureau of Public Road data

Figure 2.2 Toll Roads in the United States: 1940-91
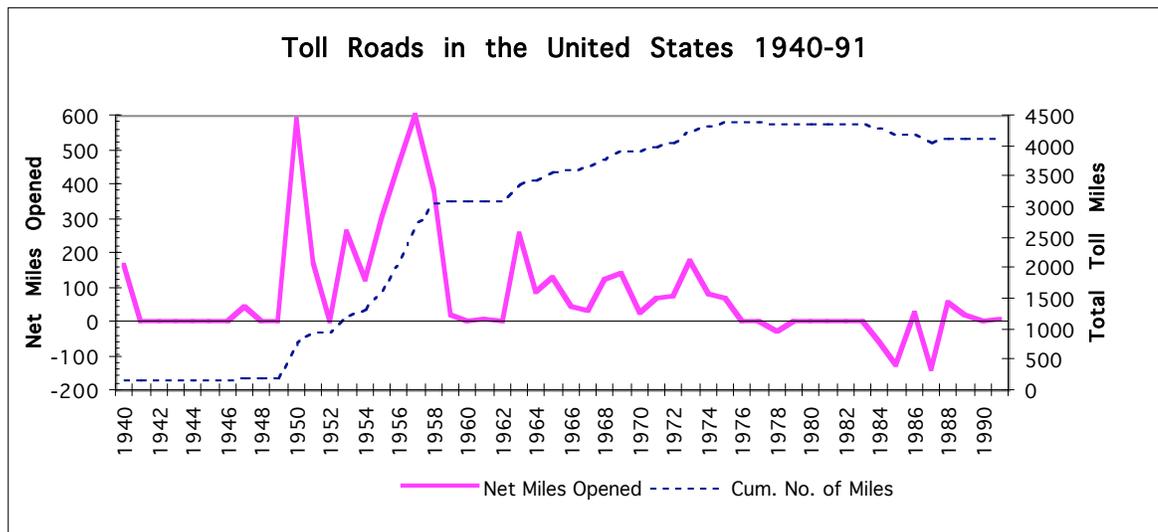
source Gomez-Ibanez and Meyer (1993)

The first factor explaining the difference between eastern and western states, which is the hypothesis of this research, relates to jurisdiction size relative to trip length. In general, a larger proportion of traffic in smaller states is made by residents of other states than in large states. The welfare of local residents increases when others (e.g. residents of other states) pay for a greater share of road construction, operation and maintenance. Thus we expect to find toll financing more in smaller states than in larger states. While taxes have lower collection costs than tolls, in small states this is more likely to be offset by the gains from non-local revenue than in large states, where almost all of the traffic is local. This hypothesis assumes that trip length distributions are similar, and are independent of jurisdiction size. This is not strictly true, but the differences in trip lengths are much less significant than differences in size between states in the east and west.

The second factor has to do with federal land ownership, which is significantly higher in western states, and led to higher federal matching shares for construction of "free roads". In eastern states, the federal match was only fifty percent before the advent of the interstate program; in the public lands states, the match was as high as eighty-five percent (Gifford 1983).

A few additional toll roads have been built since the completion of the interstate system, several under private ownership. Some thirty-five projects over 1900 km in length of new toll roads are under study, design, construction, or recently opened (Deakin 1989, Schaevitz 1991, Gomez-Ibañez and Meyer 1993, Reason 1994). Some of these roads are intended to accommodate new development, others to serve existing travel demands. The Dulles Greenway, a private road, has been built with major donations of land from adjoining landowners hoping to develop. Along California's SR91, in the median of an existing highway, High Occupancy/Toll lanes were constructed with control of the land transferred from the state to a private company.

2.7 Recent International Experience

While in the United States the twentieth century toll road experience has been almost completely public, the same is not true in other countries. In some countries, private sector toll roads have been constructed with the government's consent. Unlike many toll roads in the U.S., these roads apply perfect excludability, so no one can free ride on the roads. A price for this is longer spacing between exits than traditionally found in the U.S., where toll roads are more often (though not exclusively) cordons on a state line or across a waterway. A key transportation implication is the increase in back-tracking costs as users must drive beyond a destination to exit and then backtrack, or spend more time in travel on the slower parallel free roads.

France had granted concessions to private and mixed public-private corporations to finance, build, operate and receive revenue from intercity toll roads, while the government retained ownership and the right to repurchase at the end of a fixed time period. By the 1990s France had constructed 6000 km of intercity autoroutes, all but 500 of which are tolled (Gomez-Ibañez and Meyer 1993). However, the 1500 km of urban autoroutes remain untolled. The intercity routes compete with a 30,000 km network of untolled national roads, built to less stringent standards and often not grade separated. The eight major concessionaires originally had significant private sector involvement, but only one, Cofiroute, which operates 732 km, remains; the rest were taken over by government when they hit financial difficulties. Those difficulties were not solely the product of a free market; rather, the government in the 1970s took to regulating prices and allowing them to rise at a rate lower than that of inflation, hurting the companies' balance sheets. Mitterand's government forced consolidation and conversion of the private companies to mixed public-private companies, and implemented cross-subsidies between routes.

Spain began similarly to France, establishing Autopistas in the 1960s, a private concession to operate toll roads. This system was followed by an untolled publicly owned intercity highway system, the Autovias, promoted by the socialized government of Gonzalez

in the 1980s. Both systems are about 2000 km in size. The Autopistas system is comprised of 13 companies, nine of which are still private (Gomez-Ibañez and Meyer 1993).   In advance of the 1992 Olympics and World's Fair, some new Autopistas routes were established. Gomez-Ibañez and Meyer (1993) conclude that the system as a whole is profitable, though not each route.

Mexico established publicly owned toll roads in the 1950s and constructed about 1000 km by 1970 (Gomez-Ibañez and Meyer 1993). During the 1980s two concessions totaling 215 km were granted to the national development bank, with equity split between the bank, contractors, and state governments. In 1989, a program to build 4000 km of toll roads was proposed, the government selected the roads, performed the design and set the initial tolls, which would be permitted to rise with inflation. Twenty-nine new concessions, of an average duration of 11 years, were signed between 1989 and 1991, and roads were opened at the rate of 500 km per year. The toll rates were set high and the roads are thought to be underutilized. The government has subsidized construction on the less profitable routes. There has been a move to privatize the existing publicly owned toll roads as well as more recent discussion of nationalizing the private toll roads.

Malaysia, Indonesia, and Thailand have also experimented with private toll roads (Gomez-Ibañez and Meyer 1993). In Malaysia, a private firm connected with the government received a concession to collect tolls and operate 424 km of road that had already been constructed by the government with the in exchange for completing the 785 km road from Thailand to Singapore. The Indonesian government had built 318 km of toll roads and four bridges by 1990. As with Malaysia, firms with government connections were given the authority to build private joint-venture toll roads, where the government provided the right-of-way and the firm did construction.   Thailand has constructed public toll roads in and around Bangkok, and in 1989 signed a concession with a private firm to complete a beltway around the capital and construct spokes. Tolls are to be shared between the public and private roads.

Economists have long suggested widespread road pricing as a solution to the financing and congestion problems. However, comprehensive pricing has only been carried out in a few areas and to a limited extent. These experiments have all operated with the government acting as a central planner, dictating road prices to users. The best example may be in Hong Kong, where in the 1980s a full-fledged test of road pricing technology was implemented (Hau 1992). A sample of 2500 vehicles tested electronic road pricing. Each vehicle was fitted with an electronic license plate, and tolls were collected at 18 sites buried in the ground. While the system was technically successful, it failed the political test when it was perceived to be just another tax (despite government protestations that it would be revenue neutral) and enabled "big brother" to monitor travel, particular concerns with the transfer of Hong Kong to the People's Republic of China in 1997.

Singapore has had an area licensing scheme since 1975 (Hau 1992, McCarthy and Tay 1993), where in order to enter the downtown cordon, cars must possess a license, which can be read as the cars travel at full speed. The program did significantly reduce vehicle travel into the cordon, though off-peak traffic increased. Hau (1992) concludes that the government is using the area licensing scheme as a traffic management device rather than a revenue generator. McCarthy and Tay (1993) argue that the toll is too high, and that tolled "peak" period congestion is now lower than the untolled "off-peak".

Bergen, Norway has established a ring around the central business district and imposed tolls on the traffic crossing of that ring. Bergen allows the purchase of a seasonal pass which has zero marginal effect, as there is no immediate out-of-pocket charge, no delay, and no incentive not to travel after the pass is purchased. Traffic did decline somewhat after the program was put in place. The revenue was used to finance construction and expansion of the toll system. This system has been adopted by Oslo and Trondheim, and considered by many other cities. The tolls use electronic as well as manual collection, and provide volume discounts for frequent users (PRA 1996). The extent to which volume discounts increase automobile travel is not yet known.

2.8 Summary And Conclusions

Both push and pull factors created the pressure to charter and build turnpikes. Pull factors include the economics promoting more longer distance trade. The push factors were the difficulties in the existing system which utilized statute labor for maintaining roads. Toll roads have come in four eras. The first, which lasted from the 1700s and peaked in the early-to-mid 1800s, saw turnpikes under the control of local companies and trusts chartered by states or Parliament.

The difference between the American and British experience during the first era is instructive. In Britain, turnpikes were quasi-governmental organizations which sold bonds to fund construction. In the United States, turnpikes were owned and built by private companies, granted charters by the state to sell stock, and raise tolls on given roads. Turnpike authorities were permitted to lay out roads and negotiate with property owners whose property they needed to take; legal procedures were implemented when this was a problem. On both continents, the turnpike authority's obligations were similar, to maintain roads at an acceptable standard. In Britain, turnpikes were viewed as local public goods, with some club aspects, built by the community for the good of the community because no private individuals would build it themselves under the then current economic and legal circumstances. In America, turnpikes were privately provided. However, the motivations in the United States include both the case of voluntary provision of public goods - with profits foregone, and the attempt to undertake a profitable enterprise. Free riders were present in both America and England: first, shunpikes enabled the skirting of tolls; second, many classes of trips which crossed the toll gate were exempt; third, trips remaining within the toll cordon paid no tolls and raised no revenue, though they imposed costs on the turnpike authority. Local residents in Britain and some American towns subsidized the roads through annual taxes, or through municipal subscription to an unprofitable road, and even through use of required contribution of local labor on occasion, but whether these subsidies covered the full private cost of travel by local residents is doubtful. As the competition from

canals and rail diverted long-distance trips, toll revenue declined, even if local traffic did not, leading to the bankruptcy and abandonment of turnpikes in the United States and disturnpiking and public takeover of the quasi-autonomous trusts in Britain. Because more trips were local to the larger government level (states in the U.S. or counties in England), and revenue could be raised from multiple sources, tolls were removed.

A brief second wave came about with the automobile and the first significant deployment of smooth paved roads. However, in the U.S. most roads were financed by states, and later the federal government, by means of a gas tax. With the relatively slow speed of highway travel, most trips remained within states; through trips were not as significant as later in the twentieth century. However, a number of parkways featuring the property of excludability, were toll financed.

A third and significant wave of toll financing arrived with the deployment of grade-separated highways. As both vehicles and highways improved, trips of longer distances could be made in the same time and trip lengths increased. This in turn implied more trips between states, and the emergence of the free-rider problem when the basis over which roads were financed (taxes or tolls) did not coincide with those who used the system. Since financing was at the state level, turnpikes were effective for collecting revenue from all users and mitigating the potential free-rider problem. But when national financing became dominant, the definition of "local" changed to include everyone, and the revenue mechanism with lower collection costs (the gas tax) was preferred to tolls. As a result, new toll roads stopped being built in the U.S., though international experience varies. Furthermore, unlike earlier roads, grade-separated roads are easily excludable, that is, the number of entrances is limited and tolls can be cost-effectively assessed at each. The same is not true of roads without grade separations.

Finally, upon completion of the interstate (intercity grade-separated highway) system in the U.S., new road financing has largely become a local problem again, and new toll roads are being constructed, including some private roads. Because of the length of

trips, and because of the ease with which tolls can be collected on these excludable roads, as well as a reduction in toll collection transaction costs on both the government and traveler side with electronic toll collection, tolls are again a feasible option. New road pricing proposals depend on electronic toll collection. Further, cordon tolls are being placed around a number of cities internationally, which will collect revenue from non-local residents for traveling on urban streets. The cordons establish excludability for use of a network from outside, though not for any particular link once the network is entered. In places where cordons can easily be established, such as river crossings and ring roads, this is a feasible option for localities wishing to switch the road financing burden to suburban residents. Ironically, the attempts of localities subject to obsolete political boundaries to finance infrastructure for the "wrong" reason - the offloading of costs on non-residents - creates opportunities to achieve a more efficient infrastructure pricing and financing system.

From the evidence here, two key conditions are required to bring about more widespread use of toll financing emerge. First, a decentralization of the authority for road operation to the point where a significant number of the trips are non-local to the relevant decision-making authority would foster a willingness to use tolls, following the traditional saying "don't tax you, don't tax me, tax the fellow behind the tree". Second, a decline in transaction costs to the point where they are equal or lower than the costs of other revenue streams is necessary, where transaction costs include both delay to users and collection costs for operators. These two factors should shift beliefs about the utility of imposing tolls, as they are designed to toll someone else (not the individual making the decision to support them) and they raise at least as much revenue at the same amount or less inconvenience.

3. CHAPTER THREE: THEORY

3.1 Introduction

This dissertation analyzes roadway network financing, constructing a model that includes the basic features of the economic structure of transportation networks. It includes the demand and supply interaction, the choices available to actors (consumers and producers), and the linkage between the two when a jurisdiction owns its local network. The idea of decentralized, local control and multiple jurisdictions distinguishes this analysis from one where a central authority maximizes global welfare. The main feature of this model 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 use the network for traveling. Furthermore, production may also be provided by other network operators (for instance for travel to a different jurisdiction) and consumption of the local network may be undertaken by non-local users. Spatial complexity in this problem results from the fact that jurisdiction residents use both the local and non-local network, and the network is used by both local and non-local residents, while the network has monopoly power.

This chapter develops the general theory of network revenue choice elaborated and applied in this dissertation. The theoretical results should be consistent with what is empirically known about network financing, such as described in Chapter 2. It should thus explain what network revenue choices are made under various circumstances. Policies to affect the desired choice of revenue mechanism can then be drafted. The chapter begins by outlining alternative property rights structures and selecting the one used for analysis. The next section considers the feasible actions for the network operator, focusing on the revenue mechanism (choice of revenue instrument and the setting of a price level). The actions of users are individually determined, and therefore do not comprise policy variables. Then, the

objectives which represent the behavioral goals of the users and network operators are presented. This is followed in sequence by a consideration of the components of operator profit, residents consumers' surplus, and wealth and land value. Then the free rider problems are identified and discussed. Finally the main analysis method, game theory, is introduced, including core assumptions that its use entails.

3.2 Property Rights

The question of who owns and governs the road network is essential to determining the incidence of costs and the success of various policies in recovering those costs. If the right to access the network is independent of payment for the network, one particular solution emerges to the incidence of cost and success of policy. That solution differs from the situation when right of access depends on some payment, or there is no right of access, and permission is granted by existing owners. Many ownership possibilities exist: the network owner may be the jurisdiction, the existing residents of that jurisdiction, property owners in the jurisdiction, abutters to the specific road segment, or some private entity.

Here, a jurisdictions is defined as the agent responsible for building and maintaining the network within its borders, and thus can charge for use of the network. In this model there is no "foreign-ownership", that is none of the road is owned by non-local residents. It is assumed the jurisdiction cannot explicitly discriminate between apparently identical tax or toll-payers in the application of a revenue mechanism (though it can choose the instrument which does implicitly shift the burden between different users) . Thus for instance, in the case of a cordon toll, all travelers crossing the cordon pay the toll, independent of origin or destination. Similarly, a tax is assessed on all residents of the jurisdiction, but non-residents don't pay.

3.3 Actions

Network operators have several classes of actions. The revenue mechanism is the collective strategic selection of a revenue instrument (general tax, odomter tax, cordon toll, perfect toll) and the tactical setting of a rate of tax or toll . A jurisdiction can choose whether to pay for the roads all at once or over time (called the financing mechanism)[2]. A jurisdiction may also choose the capacity, durability, service level (speed), and geometry of the network (collectively called network geometry)[3]. Different revenue and financing mechanisms vary in their incidence over space, time, and user class. Because travel requires both user time and network provision, different network geometries vary in their costs to users and to the operator. This research focuses on the implications of different revenue instruments, and keeps as fixed the background assumptions about the network geometry and financing mechanisms.

Broadly, the two available revenue instruments are taxes and tolls. Before proceeding, the use of the terms tax and toll should be defined fairly specifically. As used here, a *toll* is a fixed sum of money charged for a specific service or privilege (for instance, the right to travel on a particular road, road segment, or a sub-network). In contrast, the term *tax* 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. The base of the tax may be land, income, or persons (a poll tax). While under certain assumptions (immobile populations, identical residents with the same behavior) the base of the tax does not matter, in other more reasonable assumptions it does. The distinction is in how specific or general the service is which is being provided and how closely it aligns with the revenue mechanism. Thus, a gas tax is more like a toll than a property, poll, or income tax is. Several basic financing instruments are identified in Table 3.1.

A general tax (denoted χ) levies on each resident of a jurisdiction a fixed fee (equivalent to a poll tax) to pay for transportation. For simplicity, we will assume that all local residents are network users. It is recognized that in reality local residents and network

users are not identical groups, so a cross-subsidy from the taxed population to the traveling population occurs. Assuming a property, a vehicle, or income tax instead of a poll tax affects the extent and nature of the cross-subsidy.

A cordon toll (τ) is a fee levied by the road authority as travelers cross a cordon which has a toll-booth. When referring to a toll-booth, we are not making any assumptions about the technology involved, it may be the more traditional human operated toll-booths or may be electronic toll collection which can operate at full speed travel.

An odometer tax (ω) results in each traveler being charged by their home jurisdiction in proportion to the total amount of travel undertaken (whether or not that travel is undertaken in the home juridiction). An odometer tax is similar to the gas tax. Modeling the gas tax however requires determining where individuals purchase gasoline. Travelers may always buy gasoline in their home jurisdiction except for very long trips. If that is the case, the effects of the gas tax are similar to the odometer tax. In a world where most trips are shorter than the distance traveled on a tank of gas, and travelers generally execute their option to purchase gasoline in their home jurisdiction, a gas tax only slightly improves upon the odometer tax in trying to eliminate the problem of non-residents acting as free riders.

A "perfect" toll (π) charges each traveler in proportion to the amount of travel undertaken in the jurisdiction levying the toll. If toll-booth cordons are sufficiently close together , the amount of travel is closely approximated by the number of cordons crossed. Thus with tight spacings and consistent charges per kilometer, cordon tolls approach perfect tolls in their effect.

Thus some instruments are assessed by the home jurisdiction (jurisdiction of residence) others by the jurisdiction of use (which may or may not be the same as the jurisdiction of residence). The basic revenue mechanisms are listed in order from least to most tied to use. Clearly, hybrids, joining two or more different instruments, are possible. These instruments are quite general, details such as time of day or class of vehicle distinctions may be added later.

Table 3.1 Revenue Instruments

Notation	Instrument	Example	Where Collected
χ	System Access Tax	Vehicle, Property, Poll, Income Tax	jurisdiction of residence
ω	Use-Based Tax	Odometer, Gas Tax	jurisdiction of residence, jurisdiction of use
τ	Cordon Toll	Toll to Enter/Exit Cordon	jurisdiction of use
π	Perfect Toll	Toll on Every Segment	jurisdiction of use

3.4 Objectives

Jurisdictions are modeled using stylized objective functions. They are assumed to behave as if they are governed by one of those objectives (profit maximization, welfare maximization, and welfare maximization with a cost recovery constraint). This analysis is intended to be descriptive rather than normative when those objectives are used, no claim is made that those objectives are comprehensively defined or desirable. The use of a single well-formulated objective is naive given the complex balancing of interests done in any political system. However, similarly naive welfare measures are used in project evaluation studies, which governments undertake to justify their major investment and policy decisions. Furthermore, the use of a single clearly defined criteria makes the analysis tractable. Local welfare maximization is the objective against which others are compared. It 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. However, in the analysis, this objective is compared with others, such as profit maximization on the part of the road operator, and welfare maximization with a cost recovery constraint. Profit maximization and welfare maximization are distinct because users of the network are not always local residents and because the network may have some monopoly power. In a competitive environment, however, the two objectives may produce the same result. For the important points developed in this dissertation, this welfare maximizing representation of jurisdictions is reasonable - as jurisdictions should be expected to care more about their own residents than residents of other jurisdictions.

It is always assumed that users behave in their own best interest. While the most realistic assumption if the two entities (the network and the user) are independent is that the network operator will maximize profit while users will maximize their own utility, in our model the residents own the network within the jurisdiction. So the jurisdiction which owns the network is comprised of residents who (collectively through their government) can set the revenue mechanism for the network to achieve a maximization of their own welfare. That is, *ceteris paribus*, when we assume the jurisdiction behaves as if it is welfare maximizing, then we assume that the jurisdiction tries to minimize the total costs borne by its residents in terms of money (tax or toll, and the private cost of traveling) as well as time (travel time, queueing due to congestion, and the time it takes to conduct transactions (paying taxes and tolls)) while maximizing revenue from non-residents. Complexity arises if we assume different individuals have different values of time, but we assume identical values of time. The objective of a jurisdiction managing a roadway to maximize welfare for its own residents, in addition to its obligation to cover costs, follows a long tradition of research concerning decision making in a political conext (Downs 1957). The next two sections consider profit and consumers' surplus, the two main components of welfare.

3.5 Profit

To evaluate welfare, we must know the sum of network revenue minus cost, which is the road operator's producers' surplus or network profit. Revenue and cost are considered in turn.

Total revenue depends on traffic flows by class and tax and toll rates applied to the specific classes. Flow by class also depends on taxes and tolls, as well as other factors. The system operator sets the revenue mechanism (choice of instrument (tax or toll) and rate) to satisfy its objective. Under the assumptions here, the revenue generated from tolls may be greater or less than cost. However when revenue is less than cost, the difference is made up for by local taxes.

The cost of the network to the operator is context specific, and may vary depending on whether we are dealing with original construction costs or replacement costs, and how those costs are defined. Three cost functions are relevant to the system, excluding user costs, which are addressed separately. The first is the long-run cost of building infrastructure, mainly land and construction costs. The size of the infrastructure deployed (for instance the width of the road) is expected to have some relation to flow, the more flow, the wider the road. The long run cost includes the cost of financing infrastructure (rather than paying for it out-of-pocket), such as interest charges and the number of payment periods. The second is the short-run cost of operating the facility including maintaining the infrastructure. Operating costs include periodic maintenance, law enforcement, administration, and the like. Third is the cost of collecting revenues: taxes or tolls. These costs include the cost of installing toll booths or electronic toll collection devices, as well as the cost of debiting accounts, the labor to collect revenue, etc. Each has a fixed and variable portion. The exact shapes of the functions are not defined in this chapter, though all depend on flow by user class. Infrastructure construction and operating costs depend as well on network geometry factors like freeflow speed, capacity, durability, and length. Collection costs depend on the number of collection points. Total costs are defined for links, and aggregated for all links managed by a jurisdictional road authority as the sum of the three component cost functions. There is an assumption that the cost components are additively separable functions of the independent factors discussed above.

There is a trade-off between infrastructure and operating costs to some extent. The road authority can choose to expend more money up-front in building infrastructure which requires less maintenance (thicker pavements for instance). Alternatively, the road authority can spend more on maintenance to put off long-term reconstruction. Similarly, the road authority can choose to provide a higher or lower level of service for its facility, a higher level of service implies lower user costs in terms of vehicle wear and tear or travel time (lower free-flow times or less delay). The higher level of service increases costs to the

system, and may lower costs to users, but should permit the road authority to charge higher prices for traveling on the facility.

Revenue collection imposes costs on both the administrator and on users (and potentially non-users). The level and distribution of these collection or transaction costs depends on the technology used. Historically tolls, requiring human toll collectors, have had the highest collection costs and high variable costs, though this may change with advanced toll collection technology such as automated vehicle identification or a system of electronic toll collection with radio tags and receivers (Chu and Fielding 1994), which may require higher fixed costs in deploying a new and pervasive toll collection infrastructure. In the case of toll booths, the costs were borne both by the agency collecting tolls who had to staff tollbooths as well as by travelers who were delayed every few miles by those gates.

3.6 Consumers' Surplus

Consumers' surplus is a traditional economic measure of welfare. It expresses the sum for all consumers of the difference between what each individual would pay for a good (their reservation price) and what that individual does pay. In our model, welfare is comprised of two sectors, transportation and non-transportation.

Consumers' surplus is an imperfect measure of welfare (as are all meaningful measures). It requires that utility be specified only in terms of prices and incomes. When we aggregate demand to measure consumers' surplus, we are valuing each individual by their willingness to pay a sum of money, which ignores that individuals have different marginal utilities of income.

Two measures of welfare changes are the equivalent variation and the compensating variation (Varian 1992). The equivalent variation uses current prices as a base and asks what income change at the current prices would be equivalent to a proposed change in terms of utility. The compensating variation uses new prices as the base and asks what income change would be necessary to compensate the consumer for the change. If we assume that

utility is quasi-linear then we know that the compensating variation equals the equivalent variation and both are equal to the change in consumers' surplus (the integral of the demand function between the original price and a changed price).[4]

This research employs consumers' surplus. Transportation consumers' surplus rises or falls with the direct price of transportation (which varies with tolls). Non-transportation welfare rises or falls with the taxes to pay for transportation (the difference between network costs and toll revenues).

3.7 Free Riders and Cross Subsidies

Who acts as "free rider" and who provides the subsidy: "us" or "them",   is central to the choice of revenue instrument. Our discussion of free riders returns to the original sense of the word, riding on roads without paying. A distinction is in order: perfect free riders pay nothing to engage in use, imperfect free riders may pay something, but not their full cost. The term "easy rider" has been used in some texts to describe imperfect free riders (Cornes and Sandler 1996). A "fair rider" pays exactly the "fair share" of travel, while "overburdened riders" (or "hard riders") pay more than their fair share for riding on the road, where "fair share" remains to be defined, though is often taken to be the average (or sometimes marginal) cost of travel.

Table 3.2 Types of Riders

Class of Rider	Share of Cost Paid
Perfect Free Riders	0%
Imperfect Free Riders or Easy Riders	$0\% < x < 100\%$
Fair Riders	100%
Overburdened or Hard Riders	$100\% < x$

Free riders are an issue for several reasons. First free riders are by definition underpriced and thus overuse the network, while not generating the resources necessary to appropriately size the network. Thus the revenue must come from other users (or non-users). In the absence of positive network externalities or scale economies, this subsidy

implies that overall the system can be no better off with free riders than with direct pricing, and may be worse off. Further free riding is inequitable, which creates other problems, both political and economic. Local residents, in an attempt to maximize their own welfare will try to shift the costs of road construction, operation and maintenance onto non-local residents to the extent possible, thereby allowing themselves to be free riders and not permit non-residents to be so.

This research focuses on the how geographic or spatial free rider problem determines what user class (defined by the location of their origin and/or destination) pays what share of the cost of traveling. The size of the agency or organization responsible for the facility or facilities relative to the length of trips will determine the proportion of trips which are local on at least one trip end and the proportion which are through trips.

The thesis of this dissertation is that the revenue mechanism jurisdictions select is greatly influenced by their preference of placing the burden of financing on non-local travelers in order to maximize local welfare. Therefore, in the case of local control there is a preference to tax through trips and exempt trips both originating in and destined for the jurisdiction (locals), thereby allowing locals to be the free rider. 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 travelers in proportion to use, as there are very few, if any, "locals". However if those who make through trips 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 collection cost.

The equity consequences of the various revenue instruments (a system access tax on residents, an odometer tax assessed on residents, a cordon toll, and a perfect toll) on the four general user classes (which will be defined more specifically in the next chapter) can be seen in the following table. This incidence table assesses whether the group has a free ride, easy ride, fair ride, or hard ride, that is whether the revenue they pay in falls short of, equals, or exceeds the cost they impose. Some mechanisms are ambiguous, and the degree of

subsidy may depend on the length of the trip in the jurisdiction. For instance a locally originating non-locally destined trip may use local roads for 1 km or for 100 km, so whether a trip of those groups is a net gainer or loser (easy or hard rider) under a particular mechanism depends on its specific location. A distinction is made between residents and non-residents. It is assumed that all trips made with both local origin and destination are by residents, and trips with neither local origin nor destination by non-residents. Trips with either local origin or destination are assumed to be made half by residents, half by non-residents.

Table 3.3 Incidence of Costs by User Group and Revenue Mechanism

		User	Group	
Origin	Local	Local	Non-Local	Non-Local
Destination	Local	Non-Local	Local	Non-Local
Instrument				(Through)
System Access	Hard	Hard - residents	Hard - residents	Free
Tax		Free - non-residents	Free - non-residents	
Use-Based	Hard	Hard - residents	Hard - residents	Free
(Odometer) Tax		Free - non-residents	Free - non-residents	
Cordon Toll	Free	Hard/Fair/Easy	Hard/Fair/Easy	Hard
Perfect Toll	Fair	Fair	Fair	Fair

3.8 Game Theory

This dissertation analyzes situations with multiple jurisdictions constituting multiple actors. The revenue decisions of one jurisdiction affect the consumers' surplus of the residents of another jurisdiction, leading to interactions and possible gains to both jurisdictions by cooperating.   Because we are not dealing with only one jurisdiction, but systems of jurisdictions, a framework is needed to analyze this problem.

Game Theory, developed by Von Neumann and Morgenstern (1944), presents an analytic approach to explain the choices of multiple actors (agents) in conflict with each other with scope for cooperation, where the payoffs are interdependent (Hargreaves-Heap and Varoufakis 1995, Osborne and Rubinstein 1994, Taylor 1987).   This is distinct from decision theory, where the opponents are states of nature and are passive (Rapoport 1970). Games are generally classified by the number of players and whether the game is zero sum

or not. Non-zero sum games engender benefits from cooperation which are absent in zero sum games.

The application of game theory requires acceptance of certain assumptions about the behavior of actors (in this case jurisdictions) and their level of knowledge. The key assumptions are described in this section and evaluated with respect to the specific context of the choice of revenue mechanism. There are two questions that are raised with these assumptions, first to what extent do they hold, second, what happens if they don't. These will be addressed in subsequent chapters. However these analyses deal with stylized situations to gain understanding of the key variables. So the fact that the assumptions don't strictly hold in a precise representation of reality does not obviate the advantages of the use of game theory as a tool for understanding.

First, it is assumed that actors are instrumentally rational. Actors who are instrumentally rational express preferences (which are ordered consistently and obey the property of transitivity) and act to best satisfy those preferences. For instance, preferences may be for more rather than less of some item, so that 10 items are better than 9 which are better than 8 and so on. Actors will act to obtain more of that item to the best of their ability.

In our case, it is assumed that jurisdictions act rationally to satisfy specific preferences, e.g. increasing local welfare. While in general, this is a huge assumption, in the narrower single-dimension context of network finance, this assumption is reasonable. It may require converting all components of welfare to a single metric (e.g. money or time).

Second, it is assumed that there is common knowledge of rationality (CKR). Common knowledge of rationality assumes that each actor is instrumentally rational, and that each actor knows that each actor is instrumentally rational, and that each actor knows that each actor knows, and so on. If we assume that each actor is instrumentally rational, it seems reasonable to assume that actors hold this belief about other actors. This implies that each actor, in choosing an action, will take into account that other actors will also rationally choose actions simultaneously. This assumption may lead to situations, depending on the

formulation of the game, which return multiple equilibria or no equlibrium. In these situations a probabilistic strategy may be better than single deterministic one. While that may pose difficulties for analysis, should non-unique, unstable, or unpredictable equilibria arise in a model that better describes reality (in that multiple intelligent actors are more realistic than one actor and an unresponsive environment), it should be acknowledged, examined, and understood.

Third, it is assumed that there is a consistent alignment of beliefs (CAB). A consistent alignment of beliefs means that each actor, given the same information and circumstances, will make the same decision - no actor should be surprised by what another actor does. In our case, jurisdictions will assume that other jurisdictions have the same motivation, even if situated differently.

Last, it is assumed all players know the rules of the game, including all possible actions and the payoffs of each for every player. This assumption of perfect knowledge is strong, but may be a reasonable approximation in a simple, highly structured game. Since this model is simple and highly structured (at the strategic level each jurisdiction has only two basic choices, tax or toll, and within that the tactical selection of the best rate of toll), the assumption that each jurisdiction knows the consequences of its actions on other jurisdictions is not unreasonable. In more complex situations (including those involving chance such as forecasting the stock market, etc.) perfect knowledge clearly should not be assumed, for if it were, the future would be determined and there would be no role for entrepreneurs or policy makers, much less analysts.

The "prisoner's dilemma" game is the most frequently described example. It involves two players who are accused of a crime (which they may or may not have committed) and are held in custody by the authorities. The players have two choices, to "cooperate" with each other and not confess (and receive the highest joint payoff) or to "defect" and get a better deal by turning state's evidence against the other player (which gives the highest individual payoff if the other individual did not confess). The defect

(turning state's evidence) option is a Nash equilibrium, in that defect is better for the individual than cooperate as a strategy in both cases: first, where the other player defects (if he turns you in, you had better turn him in), and second where the other player cooperates (you get a pardon by turning the other player in if you are not turned in). But if both players cooperate, their payoff collectively is higher than any other option because the state cannot convict either.

This dissonance between individual and collective payoffs in a one-time game may disappear in a repeated game. A one-shot game is played once, with each player making their move simultaneously. A repeated game is played either a finite or infinite number of times, and while in every turn, each player moves simultaneously, the results of previous moves are known for subsequent moves (Hargreaves-Heap and Varoufakis 1995).

While both the one-shot and the finitely repeated prisoner's dilemma give unique solutions, the indefinitely repeated prisoner's dilemma does not ensure a unique solution. The "Folk Theorem" demonstrates that in infinitely and indefinitely repeated games, any of the potential pay-off pairs in repeated games can be obtained as a Nash equilibrium with a suitable choice of strategies by the players. There are always multiple equilibria in an indefinitely repeated game, though some strategies have higher collective payoffs than others.

However, there is one solution with the highest mutual payoff in a prisoner's dilemma, cooperation by both players. Cooperation can be rationally sustained in an indefinitely repeated game provided a sufficiently high probability that the game will be repeated on the next round. Indefinite repetition in the game allows defection to be "punished" and cooperation to be "rewarded" within the confines of the game, an opportunity unavailable in the one-shot game. For instance, defection in a turn (T) by player A can beget defection in the next turn (T+1) by player B, which results in lower payoff (over multiple turns) for player A than would have been received under a cooperation strategy. One strategy which has been successful in tournaments between strategies playing

the prisoner's dilemma game is tit-for-tat (Axelrod 1984). In a tit-for-tat strategy, player A does on a turn (T) the same move which player B did on the previous turn (T-1), with an opening move of cooperate. Tit-for-tat is the equilibrium strategy which gives the highest total payoff under specific circumstances.

3.9 Summary and Conclusions

This chapter considered the theory necessary for developing an analytical model of revenue choice. The property rights structure defined gives the residents of a jurisdiction communal ownership over its roads in proportion to population. Network operators are permitted to select a revenue mechanism (tax or toll) and set a rate. In general the objective for the network is to maximize local welfare, defined as the sum of consumers' surplus and profit to the network operator. The issue of free riders is considered, under cordon tolls, local residents can free ride, while under general taxes, through trips free ride. Game theory is introduced, and provides a mechanism for analyzing the problem where each jurisdiction's favored policy depends upon its neighbors. The next chapters will apply this theory and develop a mathematical model for analyzing the problems identified here.

Our theory suggests that each jurisdiction has incentives to offload costs to non-residents wherever possible, and thereby minimize the costs to its own residents. Spatially this implies that non-residents should be taxed/tolled wherever possible. The proportion of trips using the network which originate in a specific jurisdiction directly shapes the local welfare resulting from a particular revenue mechanism, and itself is a function of jurisdiction size. The choice of revenue instrument must trade off the number of spatial free riders, system users who don't pay tolls or taxes because of the location of their residence or the origin and destination of their trips, and the costs of collection. The price charged with a given instrument is limited by the elasticity of demand for use of the network on those who are charged.

4. CHAPTER FOUR: A MODEL OF NETWORK FINANCING

4.1 Introduction

This chapter develops the models necessary to analyze four alternative revenue mechanisms: general taxes, cordon tolls, odometer taxes, and perfect tolls. Cordon tolls are becoming a popular method of restricting traffic in cities (such as Singapore, Oslo, Trondheim, and Bergen) and financing new infrastructure. Cordons, such as a toll gate on a major highway without tolls on entrance and/or 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 trips which cross the cordon do. On the other hand, general tax financing has been common both historically (initially the tax was in terms of labor), and more recently for local roads, which are funded through general revenues. Taxes also rely on a "cordon," the boundary of the jurisdiction assessing them. When employing the odometer tax, the home jurisdiction taxes residents in proportion to the amount of travel that the resident undertakes both inside and outside his home jurisdiction, for instance by reading the odometer once per year. This is distinct from the perfect toll, which tolls all travelers in proportion to the amount traveled in each jurisdiction, and in the absence of transaction costs may be considered ideal from an efficiency perspective.

The central argument offered in this thesis is that, since jurisdictions try to do well by their residents, who are both voters and travelers, the choice of a revenue instrument depends primarily on its effects on local residents. Chapter Two considered the thesis from a historical perspective, Chapter Three developed the theory necessary to analyze this problem economically. This chapter approaches the question analytically developing a model of the choice of revenue mechanism in a multijurisdiction environment. Subsequent chapters apply the model under various circumstances and extend it where necessary.

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It is posited that the choice of revenue mechanism, while being historically contingent, is a function of ahistorical or economic factors. These include the length of trips, the size of the jurisdiction, the transaction costs of collecting revenue, the level and elasticity of demand, and the cost of providing infrastructure. These properties determine how the cost burden is divided between the free and hard riders under various revenue instruments, where a free rider is someone who uses the system without paying his full cost, and a hard rider pays more than his or her fair share. In the case of tax-only financing (either general taxes or odometer taxes), travelers 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, travelers entering and exiting the network within the toll cordon pay nothing. A perfectly excludable toll system, which captures everyone entering and exiting each link, may be costly, and cannot necessarily be implemented everywhere. In realistic situations of highway transportation, there are transaction costs involved in collecting revenue. The existance of these transaction costs suggest that a complete and perfect revenue instrument may not be cost effective. The models presented in this chapter provides a strategic framework for assessing the outcome of alternative revenue instruments in such circumstances.

This chapter begins by first outlining the network geometry, and user classes required to structure the equations. The objectives (welfare maximization, profit maximization, welfare maximization with a cost-recovery constraint) are then written out. The next section concerns consumption, and formulates the demand model and consumers' surplus equations. This is followed by the production side, which considers the calculation of profit for the network authority, the cost functions, and the revenue equations for tax and toll policies. Then the four main revenue mechanisms (general tax, cordon toll, odometer tax, perfect toll), which result in different prices faced by different classes of users and different revenue levels received by jurisdiction, are spelled out and the environmental assumptions detailed. Two approaches to toll-setting: non-cooperative and cooperative are

considered. The methods of solution are presented and discussed. The chapter is then summarized and the groundwork is laid for the following chapters.

4.2 Network Geometry

The network geometry analyzed here consists of an infinitely long road, as illustrated in Figure 4.1. 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 away 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 toll-booths are located on jurisdiction boundaries, but not that all jurisdiction boundaries necessarily have toll-booths.[5] Each jurisdiction which has cordon toll-booths has them both at the entrance and at the exit of the jurisdiction.

This geometry can be directly interpreted in an intercity context. The geometry can represent one jurisdiction (among many) which 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 center and periphery of an urban region.

4.3 User Classes

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 $\left\{J_{-1}, J_{-2} ... \in S_{-}\right\}$,

the jurisdiction of interest $\{J_0\}$, and the area comprised of all jurisdictions east of J_0

$\{J_{+1}, J_{+2}... \in S_+\}$.

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 chapter analyzes a one-way road, but assumes underlying symmetric demand functions, and round trips.[6] On a one-way road, the number of relevant section-to-section interactions is reduced from the number S^2 as trips can't exit upstream of where they enter. Furthermore, trips which 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 the following table:

Table 4.1 General Trip Classification

		Section of	Destination	(y)
		S_-	J_0	S_+
	S_-	G_{--}	G_{-0}	G_{-+}
Section of Origin (x)	J_0	G_{0-}	G_{00}	G_{0+}
	S_+	G_{+-}	G_{+0}	G_{++}

note:	shading indicates trip classes of interest on a one-way road.

0 indicates jurisdiction J_0 ; -,+ indicates jurisdiction in S_-, S_+ respectively

Figure 4.1 One-Way, Long Road and Classes of Trips

Long Road

Class G_{00} Trips

s.t. $y > x$ for all trips
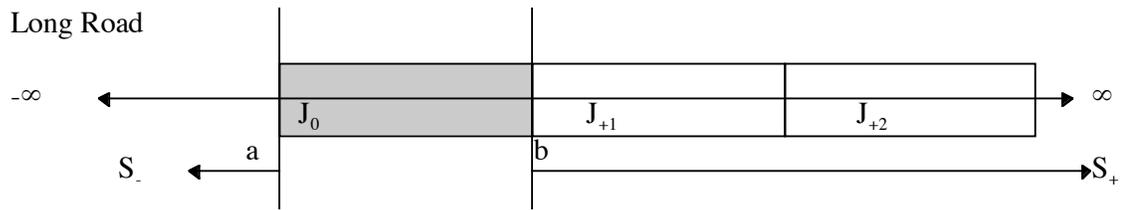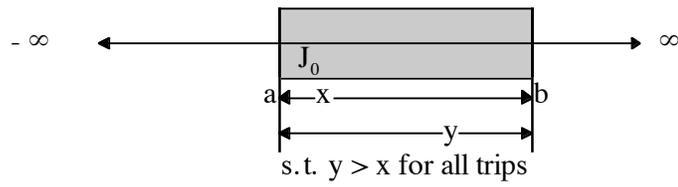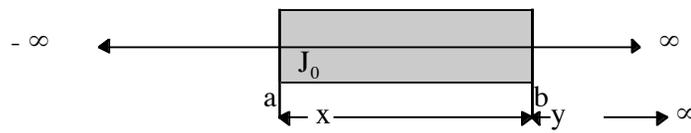
Class G_{0+} Trips

Class G_{-0} Trips
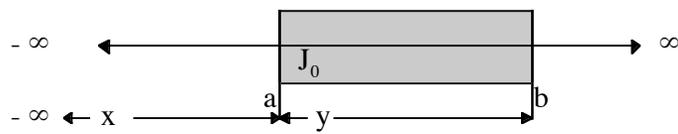
Class G_{-+} Trips
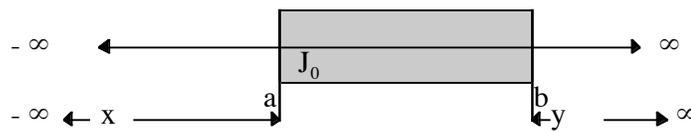
To illustrate, in the class-by-class drawings of Figure 4.1 the area denoted by x indicates the location of trip origin, while the area denoted by y indicates the location of trip destination.

In particular, we define *external trips* as those which remain entirely outside J_0, such as trips from J_{+1} to J_{+2} (class G_{++} and G_{--}).[7] We reserve the definition of pure *through trips* (class G_{-+}, and in the opposite direction: G_{+-}) as those that both originate and are destined for locations outside J_0 (for instance, originate in J_{-1} and are destined for J_{+1} or J_{+n}), but which travel through J_0 to get there. We define *local trips* as those with both an origin and destination in J_0 (class G_{00}). Finally, we define *boundary crossing* classes as those with one trip end in J_0 and the other outside J_0 (G_{0+} and G_{-0}, and in the opposite direction: G_{+0}, and G_{0-}).

4.4 Jurisdiction Objectives

The main objective functions which jurisdictions are assumed to employ are outlined in Table 4.2. While the local welfare maximization objective (W_L) is assumed for most analyses, profit maximization (Π_L) and welfare maximization with a cost recovery constraint (W_{LCR}) are detailed for comparison purposes.

Table 4.2 Objective Functions

Objective	Problem
Welfare Maximization	$\underset{P_I}{Max}\ W_L = \Pi_i + U_i$
Profit Maximization	$\underset{P_I}{Max}\ \Pi_L = \Pi_i$
Welfare Maximization with Cost Recovery Constraint	$\underset{P_I}{Max}\ W_{LCR} = U_i$ $s.t.\quad \Pi_i = 0$

where:

Variable	Definition
Π_i	Producer's Surplus (Profit) on network owned by jurisdiction i
U_i	Consumers' Surplus (transportation and non-transportation) of residents of jurisdiction i
P_I	Vector describing price of infrastructure, a function of location of trip origin, destination, location of toll-booths, revenue mechanism (incl. rate of odometer tax, cordon toll, or perfect toll and the basis of that toll), detailed later in text

In general, it is assumed that jurisdictions have the objective of local welfare maximization (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.

The local profit maximization objective (Max Π_L) simply does not consider the utility of the residents of J_i. This represents conditions when the network is privately controlled, for instance to compare the consequences of unfettered private control with the public control of the network. To the extent that the welfare losses associated with private control are not excessive, it may be a reasonable organizational form for jurisdictions to consider.

Finally, we can analyze the objective of welfare maximization with a cost-recovery constraint (Max W_{LCR}). This objective, applied under toll policies, requires that tolls be high enough to recover costs but that toll revenue cannot be raised in excess of costs. In local welfare maximization, a tax-only policy recovers only cost, since there are no welfare advantages to recovering more than costs. There may not always be a solution to this problem, since costs may exceed the maximum revenue recoverable from tolls.

Welfare (or profit) can be maximized locally or globally, global welfare maximization is the same as a cooperatively local welfare maximizating (assuming fixed locations for toll-booths), and nearly the same as local welfare maximization for a very large jurisdiction. Similarly, global profit maximization is the equilivalent of cooperatively local profit maximizing, again assuming fixed toll-booth locations.

The partial equilibrium model developed in this and subsequent chapters incorporates the actions and reactions of multiple agents, representing both the infrastructure system and its users. Users travel on roads forming the network owned either by their own jurisdiction or by another. The travelers on any given road may live in that jurisdiction or another. The three components: profit, travel consumers' surplus, and non-transportation welfare need to be treated together because actions taken (sizing the network, setting prices) may influence each of the components. How profits are treated is somewhat arbitrary, they can be either kept separate (as $\prod_i$), or redistributed to residents, however the underlying welfare implications are the same. Because profits are (or can be) redistributed to local residents, treating a jurisdiction and its residents as a single block is not unreasonable. Changes in the cost of transportation or taxes levied to finance may have a price and income effect on the demand for non-transportation goods, though those details will not be specifically addressed.

4.5 Consumption

4.5.1 Demand

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

$$f(z) = \int\limits_{x<z} \int\limits_{y>z} \rho\big(P_T(x, y; P_I(x, y))\big) dx dy \qquad (4.1)$$

where:

Variable	Definition
$f(z)$	flow past point z
$\rho(P_T(x,y;P_I(x,y)))dxdy$	demand function representing the number of trips that enter facility between x and x + dx and leave between y and y + dy
$P_T(x,y;\ P_I(x,y))$	generalized cost of travel to users (defined below)
x	where trip enters road
y	where trip exits road
$P_I(x,y)$	Price of infrastructure as function of location

This description of flow will be utilized and developed in this chapter. 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_{+1} which affects the demand for trips using roads in both J_0 and J_{+1} (such as G_{0+} trips) may affect prices faced by travelers in J_0 (say G_{-0} trips), even if they do not travel in J_{+1}. This price-demand interdependence can be explained by the following chain of logic: First the optimal tolls in any jurisdiction, including J_0, 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; and third those trip classes that use links in more than one jurisdiction - depend on prices on the links in each jurisdiction.

As defined, the four classes have different number of trips (section to section flows), $F_{[x1x2\ y1y2]}$, where the section of origin is defined to occupy the space between *x1* and *x2* and the section of destination occupies the space between *y1* and *y2*.

$$F_{[x1x2\ y1y2]} = \int\limits_{x1}^{x2} \int\limits_{y1}^{y2} \rho\big(P_T(x,y; P_I(x,y))\big) dx dy \qquad (4.2)$$

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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 (α), as well as a multiplier (δ) representing the number of trips generated per unit length:

$$\rho(P_T(x,y; P_I(x,y))) = \delta e^{\,\alpha P_T(x,y; P_I(x,y))} \qquad (4.3)$$

$$= 0 \qquad\qquad \text{otherwise}$$

where: α, δ = coefficients: $\alpha < 0$; $\delta > 0$

x<y (to account for the fact that it is a one way road)

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 (cordon tolls, perfect tolls, or odometer taxes, but not general taxes), and will be discussed in more depth in a subsequent section.

Private vehicle costs (P_V), depend on the distance traveled (|y-x|), the cost per unit distance (v) as well as a number of fixed components (ζ) depending on the age and type of vehicle used. Chapter 5 will discuss in more detail private vehicle costs.

Freeflow travel time costs (P_F) depend on trip length (|y-x|) and freeflow speed (S_F), as well as the value of time (V_T). Congested travel time is not dealt with here[8]. Implicit in this model is that jurisdictions have the obligation of maintaining a level of service with a resulting freeflow speed which is 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.[9]

$$P_T(x,y) = P_I(x,y) + P_V(x,y) + P_F(x,y) = P_I(x,y) + \left(\zeta + v|y - x|\right) + V_T\left(\frac{|y - x|}{S_F}\right) \qquad (4.4)$$

where:

Variable	Definition
P_T	Total price users pay for travel
P_I	Direct infrastructure charges
P_F	Freeflow travel time costs
P_V	Private vehicle costs
x,y	Location of Trip Origin, Destination
S_F	Freeflow speed
V_T	Value of time
ν	Cost per unit distance
ζ	Fixed user costs

4.5.2 Consumers' surplus

The sum of transportation consumers' surplus[10] for all trips originating in jurisdiction J_0 (U_0) for the relevant user classes (U_{00}, U_{0+}, U_{-0}) can be computed. Recall that one half of any boundary crossing trips are due to local residents. Also note, that because of symmetry, $U_{0+} = U_{-0}$. Therefore $0.5U_{-0} + 0.5U_{0+} = U_{0+}$. Thus consumer's surplus is given by the following equation:

$$U_0 = U_{00} + 0.5U_{0+} + 0.5U_{-0}$$

$$= \int_a^b \int_x^b \int_{P_I(x,y)}^{\infty} \rho\big(P_T(x,y;p)\big)dpdydx + \sum_{n=1}^{\infty} \int_a^b \int_{n(b-a)}^{(n+1)(b-a)} \int_{P_I(x,y)}^{\infty} \rho\big(P_T(x,y;p)\big)dpdydx \qquad (4.5)$$

where:

Variable	Definition
U_0	Consumer's Surplus for Jurisdiction J_0
U_{00}	Consumer's Surplus for Local Trips
U_{0+}, U_{-0}	Consumer's Surplus for Boundary Crossing Trips
$\rho(P_T(x,y;p))dxdy$	demand function
$P_T(x,y;p)$	generalized cost of travel to users at price p
n	index for number of toll-booths on road
a,b	juridiction J_0 cordon locations
p	user monetary cost (integrated from P_I to infinity)

The rate of cordon toll (r_τ), perfect toll (r_π), or odometer tax (r_ω) that is assessed by jurisdictions on trips of the appropriate group multiplied by the basis over which the rate is assessed to compute the price paid (P_I). Local trips (G_{00}) don't pay cordon tolls (because they don't cross the toll cordon), but do potentially pay perfect tolls or odometer taxes to jurisdiction J_0. Locally originating, non-locally destined trips (G_{0+})[11] are potentially subject to all three revenue mechanisms (though each jurisdiction is limited to one revenue mechanism at a time). Cordon and perfect tolls on these trips (G_{0+}) are assessed both by the home jurisdiction (J_0 assesses r_τ or r_π) and by other jurisdictions (which may assess r_τ or r_π). Because jurisdictions are identical, the effective price under identical policies is identical across jurisdictions (though the rate of the toll depends on whether a cooperative or non-cooperative toll-setting equilibrium is established, as discussed in a later section).

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, so long as a function is continuous over real space, the order of integration of a multiple integral does not matter. So the results would be the same, independent of how the markets are defined.

True taxes to support transportation, by their definition in Chapter 3, must be drawn from outside the transportation sector, and decrease non-transportation welfare. Recall that this definition excludes gas taxes, which are between true taxes and true user charges. To the extent that these taxes are non-distortionary lump sum taxes, then the change to consumers' surplus they provide is as a transfer of costs from the price directly paid to use transportation (tolls) (and thus taxes provide higher transportation consumers' surplus) to a non-transportation charge (generating lower non-transportation welfare), as well as associated changes in demand associated with changes in revenue instruments. Income

effects, and subsidy and deadweight losses in both the transportation and the non-transportation sector are dealt with here only cursorily, as this remains a partial equilibrium analysis. The decline in non-transportation welfare is thus assumed to be the amount of total costs associated with a tax based financing system, which can be represented as negative profits for the network operator (assuming revenue = 0) or by subtracting total costs from utility, while assuming the network operator just recovers costs (assuming costs equal revenue). These two representations are equivalent here.[12]

4.6 Production

4.6.1 Profit

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

$$\Pi_i = R_T - C_T \tag{4.6}$$

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 transportation demand are assumed to be independent, taxes don't need to be measured explicitly.

4.6.2 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_S), traffic flow (C_ρ), and variable and fixed toll collections (C_{CV}, C_{CF}). We assume a linear model, that is there are no (dis-) economies of scale or scope.

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 (γ) of constructing and operating infrastructure. The second cost category, cost as a function of traffic flow, depends on the vehicle distance traveled in the jurisdiction, which is multiplied by a cost per vehicle distance traveled (ϕ). We assume that the network is sized to ensure a given (uncongested) level of service. Therefore, the long run 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 an uncongested 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 the jurisdiction and flow at each toll booth z_k ($f(z_k)$), as well as the cost per collection transaction (θ). The fixed portion simply multiplies a fixed cost per toll booth (κ) 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). Sensitivity to lower transactions costs due to technologies such as electronic toll collection will be tested in later chapters.[13]

The model can be expressed as below:

$$C_T = C_S + C_\rho + C_{CV} + C_{CF} = \gamma|b-a| + \phi\int_a^b f(z)dz + \theta\sum_{k=1}^{K_i} f(z_k) + \kappa K_i \qquad (4.7)$$

where:

Variable	Definition
C_T	total costs to the network operator
C_S	cost as a function of jurisdiction size
C_ρ	cost as a function of traffic flow
C_{CV}	variable toll collections
C_{CF}	fixed toll collections
$|b\text{-}a|$	size of the jurisdiction and
γ	cost per unit distance of constructing and operating infrastructure.
ϕ	cost per vehicle distance traveled
K_{ix}	number of toll-booths
z_k	toll booth
$f(z_k)$	flow at each toll booth z_k
θ	cost per collection transaction
κ	fixed cost per toll booth

4.6.3 Revenue

Revenue depends on the specific instrument chosen, the rate, and the quantity. The following table gives the equations for revenue, as a function of the unit rates (rate of cordon toll (r_τ), perfect toll (r_π), or odometer tax (r_ω)) and the quantity over which each unit rate is applied (number of tolls crossed, kilometers traveled) by user group where the revenue varies with group. For instance the revenue from tolls collected at toll-booths in jurisdiction i (K_i) (k=1, ..., K_i) on the road is given in the table. In the case of jurisdiction based cordon tolls, K_i=2 (*a* and *b*). The more toll-booths the lower the rate of toll per toll-booth to achieve the same revenue.

Table 4.3 Total Transportation Revenue (R$_T$) to Jurisdiction by Policy

Policy in J$_0$	Units of r	Transportation Revenue (R$_T$)
General Tax (χ)	$	0
Cordon Tolls (τ)	$/crossing	$r_\tau \sum_{k=1}^{K_i} f(z_k)$
Odometer Tax (ω)	$/km	$\int_a^b \int_x^\infty (y-x) r_\omega \, \rho\big(P_T(x,y,P_I(x,y))\big) \partial y \, \partial x$
Perfect Toll (π)	$/km	$\int_a^b \int_x^b (y-x) r_\pi \rho\big(P_T(x,y,P_I(x,y))\big) \partial y \, \partial x \; +$ $\int_a^b \int_x^\infty (b-x) r_\pi \rho\big(P_T(x,y,P_I(x,y))\big) \partial y \, \partial x \; +$ $\int_{-\infty}^a \int_a^b (y-a) r_\pi \rho\big(P_T(x,y,P_I(x,y))\big) \partial y \, \partial x \; +$ $\int_{-\infty}^a \int_b^\infty (b-a) r_\pi \rho\big(P_T(x,y,P_I(x,y))\big) \partial y \, \partial x$

4.7 Policies

In our analysis, each jurisdiction may employ any one of four revenue mechanisms (general tax (χ), cordon toll (τ), odometer tax (ω), perfect toll (π)) as policy. These policies have specific consequences for the price of infrastructure (P$_I$) paid by users and the revenue (R$_T$) collected from travelers by the network operator or jurisdiction. Furthermore, each policy is implemented in an environment where other jurisidictions also set policies. We will begin by examining the possible environments in which a jurisdctions acts, then focus on the jurisdiction polices and their resultant infrastructure prices born by residents and/or travelers.

4.7.1 Environment

Four idealized sets of policies associated with the environment will be considered when analyzing the revenue mechanism decision. These environments describe the behavior

(policy) chosen by other jurisdictions. Each case assumes all jurisdictions (aside from the jurisdiction of interest J_0) impose a single policy (general tax, cordon toll, odometer tax, perfect toll). These are called all-tax, all-cordon, all-odometer, and all-perfect respectively.

The reasons for making relatively simple assumptions about the environment are straight-forward. First, we wish to consider the particular cases which give the most insight to all possible cases. Second, we want to reveal equilibrium properties of the system, which are most likely to be encountered when all jurisdictions (J_0 and the environment) behave identically.

Figure 4.2 illustrates regular environments. The first row shows the all-tax and all-cordon toll environments. The next row shows regular environments where the policy in the section the west of J_0 (S_-) differs from that in the section to the east (S_+). The final row illustrates regular mixed environments, where the spacing between tollbooths outside J_0 falls at regular intervals, every dth jurisdiction.

Figure 4.2 Illustration of Alternative Regular Environments

all-tax environment ($E^{\chi\chi}$)	all-cordon toll environment ($E^{\tau\tau}$)
... χχχχχχJ_0χχχχχχ ...	... ττττττJ_0ττττττ ...
tax-cordon toll environment ($E^{\chi\tau}$)	cordon toll-tax environment ($E^{\tau\chi}$)
...χχχχχχJ_0ττττττ...	...ττττττJ_0χχχχχχ...
mixed cordon toll-tax environment ($E^{M,\delta=2}$), d=2	mixed cordon toll-tax environment ($E^{M,\delta=3}$), d=3
... τχτχτχJ_0χτχτχτ...	... τχχτχχJ_0χχτχχτ...

The calculations of demand in the environment with tolls are more complicated than the all-tax environment.[14] The complications are described later in this chapter. Even a tax policy in an all-cordon environment requires more complicated calculations, as different travelers pay different tolls, a problem non-existent for a tax policy in an all-tax environment.

Other random environments (e.g. ...τχττχχτχτχττJ_0χτχχτττχττχτχ...) are more difficult to analyze because the regularity assumptions about spacing, which enable the

equations to be reduced, can no longer be used. Thus the number of relevant classes can become very large, all of which must be considered discretely.

It can be argued that in a system of adjacent large jurisdictions, we only need to look at the adjacent one or two jurisdictions to capture the vast majority of trips, so that a randomly mixed environment lends itself readily to analysis. However, in small jurisdictions that is not necessarily the case, depending on the value of time, objective function and constraints of the jurisdiction, and elasticity of demand. However, these other (random) cases are certainly very specific, and don't add much to our general knowledge.

4.7.2 Jurisdiction Policies

In general, the price of infrastructure is a function of unit rates (rate of cordon toll (r_τ), perfect toll (r_π), or odometer tax (r_ω)) and the quantity over which each unit rate is applied (number of tolls crossed, kilometers traveled). 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. Table 4.4 summarizes these prices, which are discussed below.

Table 4.4 Decomposition of Price of Infrastructure (P_I)

Policy	User Group	Amount paid to J_0	Amount paid to jurisdictions other than J_0
General Tax (χ)	All	0	0
Cordon Tolls (τ)	G_{00}	0	0
	G_{0+}, G_{-0}	r_τ	$r_\tau(2n-1)$
	G_{-+}	$2r_\tau$	$r_\tau(2n-2m-2)$
Odometer Tax (ω)	G_{00}, G_{0+}	$r_\omega(y-x)$	0
	G_{-0}, G_{-+}	0	0
Perfect Toll (π)	G_{00}	$r_\pi(y-x)$	0
	G_{0+}	$r_\pi(b-x)$	$r_\pi(y-b)$
	G_{-0}	$r_\pi(y-a)$	$r_\pi(a-x)$
	G_{-+}	$r_\pi(b-a)$	$r_\pi(y-b)+r_\pi(a-x)$

where: n, m are indices representing number of toll-booths crossed to the east, west of J_0

General Tax

Under a general tax policy, user payment for infrastructure is independent of the amount or location of travel. The price of infrastructure as used here is 0 for all user groups.

Odometer Tax

Under an odometer tax policy, user payment is proportional to the amount of travel, but independent of the location of travel. Non- residents make no payment to a jurisdiction imposing an odometer tax, so the effect of the policy outside J_0 is 0. Travel demand does depend on odometer tax rates, so the price of infrastructure as used here is the rate of the odometer tax (r_ω) multiplied by the distance traveled.

Perfect Toll

Under a perfect toll policy, payment for infrastructure is proportional to the amount of travel in the jurisdiction where that travel takes place. Travel demand does depend on perfect toll rates (r_π), so the price of infrastructure as used here is the rate of toll multiplied

by the distance traveled in each jurisdiction, and thus depends on the distance traveled both inside and outside J_0.

Cordon Tolls

The price of infrastructure under cordon tolls deserves some discussion. A toll policy is more complicated than a general tax policy, as tolls affect demand while taxes don't. 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 $(I(x,y, k_n))$ which represents whether toll-booth k_n is crossed for trips between x and y. Infrastructure charges also depend on the toll per crossing $(r_{\tau k})$, which is a policy variable available to the various jurisdictions. This can be represented as:

$$P_I(x, y) = \sum_{n=1}^{\infty} r_{\tau kn} \left[I(x, y, k_n) \right] \qquad (4.8)$$

where:

Variable	Definition
$P_I(x,y)$	Price of infrastructure born by users
n	index of toll-booths
$r_{\tau kn}$	rate of toll at toll crossing k_n
$I(x,y, k_n)$	toll incidence matrix.
	$I(x,y, k_n) = 1$ if $x < L(k_n) < y$;
	$I(x,y, k_n) = 0$ otherwise
$L(k_n)$	location of toll-booth k_n

When a cordon toll policy in J_0 is imposed, all boundary crossing trips entering and exiting J_0 (G_{+0}, G_{0-}) pay a toll of r_τ at the cordon. Local trips (G_{00}) do not cross cordons, and thus have $I(x,y,k) = 0$. Through trips (class G_{-+}), pay the toll of r_τ at both the entry and the exit cordon, and so have a total payment of $2r_\tau$ in J_0.

Similarly, the cordon toll environment is more complicated than the general tax environment and also warrants some discussion. When all other jurisdictions impose taxes on their own residents to finance their roads, we set external tolls to zero $(r_\tau=0, r_\omega=0)$. However, when those other jurisdictions impose a cordon toll policy, the analysis includes

tolls for all other jurisdictions (r_{τ}). It is assumed, to simplify the calculations, that all jurisdictions are identically sized.[15] It is also assumed that, since jurisdictions are identical, the toll assessed by each other jurisdiction in an all-toll environment is the same as the optimal toll assessed by jurisdiction J_0 under toll policies and an all-toll environment at equilibrium.[16]

When either J_0 or other jurisdictions or both use tolls, then we must recognize that a certain fraction of boundary crossing and through trips pays tolls at more than one toll-booth. For instance, with a toll policy in J_0 and an all-toll environment, all G_+ trips must pay tolls at the exit of J_{-1}, the entrance of J_0, the exit of J_0, and the entrance of J_{+1}. Some of the longer trips must also pay at the exit of J_{+1} and entrance of J_{+2}. An even smaller fraction must also pay at the exit of J_{+2} and entrance of J_{+3}, and so on. This is illustrated in Figure 4.3. Similarly, though not shown, some trips enter the network before J_{-1}, fewer before J_{-2}, and so on.

Figure 4.3 Distance Decay and Tolls in All Cordon Toll Environment.
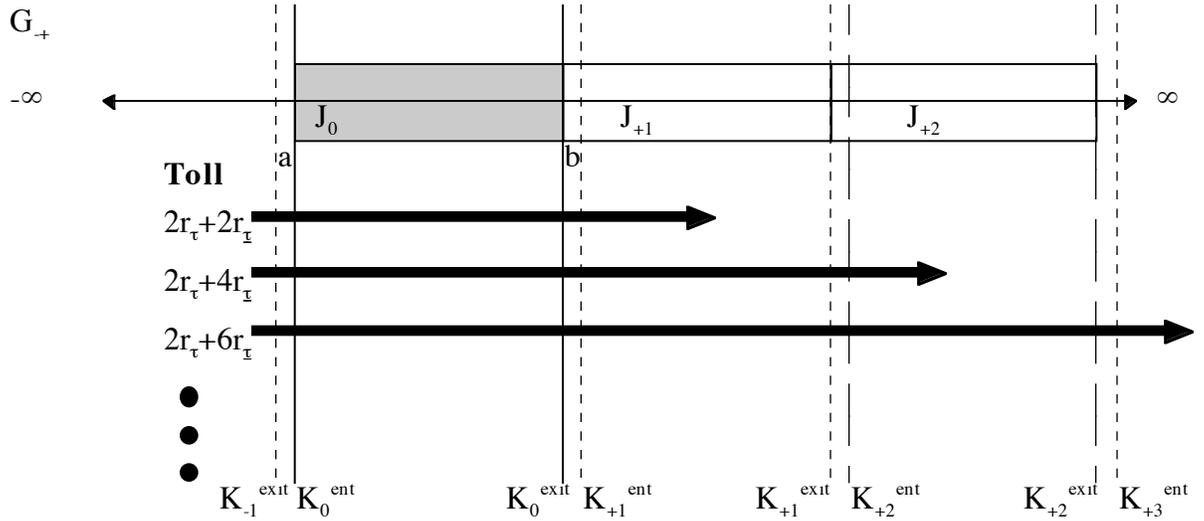
The number of trips which travel to a cordon n units away from their origin must be computed (for instance n*(b-a) if toll-booth spacing is proportional to jurisdiction size). At that cordon, the trip must pay the exit toll for the jurisdiction it is leaving and the entrance toll for the jurisdiction it is entering. So through trips (class G_{-+}) don't all pay the same toll. If tolls are spaced regularly, then under a policy of discrete cordon tolls the flow that through trips face can be represented by an infinite series of integrals. Similar reasoning can be applied to both classes of boundary crossing (G_{0+} and G_{-0}) trips.

Flow under cordon tolls:

Boundary crossing trips (G_{0+}) (equivalent to (G_{-0}))

$$F_{0+}^{\tau\tau} = \sum_{n=1}^{\infty} \int_{a}^{b} \int_{n*(b-a)}^{(n+1)*(b-a)} \rho(x,y,n,r_\tau,r_{\underline{\tau}})\partial y \partial x \tag{4.9}$$

Through trips (G_{-+})

$$F_{-+}^{\tau\tau} = \sum_{m=-\infty}^{-1} \sum_{n=1}^{\infty} \int_{m*(b-a)}^{(m+1)*(b-a)} \int_{n*(b-a)}^{(n+1)*(b-a)} \rho(x,y,n,m,r_\tau,r_{\underline{\tau}})\partial y \partial x \tag{4.10}$$

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4.8 Toll-Setting

The discussion to date still leaves some latitude in how to solve the tactical problem of toll-setting.   The issue, in solving for the J_0's toll (r_τ) , is what toll ($r_\underline{\tau}$) does J_0 assume the other jurisdiction use when it is known what policy they choose. The same argument applies to perfect tolls (r_π, $r_\underline{\pi}$). Two approaches can be considered: non-cooperative and cooperative equilibria.

4.8.1 Non-cooperative Toll-setting

First, if we assume no collusion (implicit or otherwise) or a one-shot or finitely repeated toll-setting game, we attain a non-cooperative Nash equilibrium for toll-setting. 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. For each iteration, we assume J_0 sets its payoff maximizing 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 other jurisdictions' tolls ($r_\underline{\tau}$) are equal to J_0's toll in solution round i-1: $r_{\underline{\tau}}^i = r_\tau^{i-1}$ The algorithm says: given $r_\underline{\tau}$ and all the other pertinent variables, J_0 finds the welfare maximizing r_τ, updates $r_\underline{\tau}$, and solves until equilibrium ($r_\tau^* = r_\underline{\tau}^*$).

4.8.2 Cooperative Toll-setting

In the case of a prisoner's dilemma, cooperation will give higher overall welfare (profit) than the tolls resulting from the non-cooperative equilibrium above. However it will

be to the advantage of any jurisdiction to cheat (i.e. raise tolls) if the other jurisdictions don't cheat or retaliate but retain the cooperative tolls resulting from this solution. This solution is only sustainable as an equilibrium in indefinitely repeated games.

Simply, the issue again is how to treat r_τ. The Nash equilibrium conditions state that when all jurisdictions are identical, each jurisdiction will try to achieve the highest welfare for themselves, recognizing that other jurisdictions will do the same. However in an indefinitely repeated prisoner's dilemma game, strategies which enforce cooperation by punishing "defection" can be employed to maximize overall welfare. To solve for this best overall welfare, each jurisdiction under this framework includes both its own and other jurisdictions tolls as variables in its welfare maximization calculations. (Under non-cooperative equilibrium, other jurisdictions tolls could be treated as constants).

The overall payoff maximizing result can be achieved by setting $r_{\underline{\tau}}^i = r_\tau^i$ in the equations, and solving for the toll such that: $r_{\underline{\tau}}^* = r_\tau^*$. Economic theory argues that this should result in the rate of toll equal to the marginal cost of travel for those paying the toll. Of course, the marginal cost is somewhat difficult to compute because the rate of toll is applied to all users equally, but each user has a different marginal cost (trips are of different lengths within the jurisdiction). The marginal cost of the average toll-payer (for instance, the toll-payer with the average trip length) will be different than the average marginal cost of all toll-payers.

In an infinitely repeated games context, this is the best result that jurisdictions can attain over the long term, and though other solutions are also equilibria, no other solution improves on this one overall (though a single jurisdiction raising tolls - violating the equal tolls provision, may have a higher individual welfare or profit).

In contrast with the usual application of cooperative equilibria for analyzing industrial organization of competitive markets, the best repeated game (cooperative) equilbrium toll is lower than the Nash equilibrium (non-cooperative) toll. Furthermore, the

lower toll results in higher welfare and profit. The main reason for this is that we are dealing with complementary rather than substitute goods in our revenue mechanism game. Thus, cooperation to lower tolls allows higher welfare in an application similar to the serial monopolists game.[17] A second reason is that the objective function includes not just profit, but also consumers' surplus.

4.9 Mathematical Solution

As might be expected the full, expanded forms of the cost, revenue, and utility expressions are quite long. However, they have many common terms and thus can be reduced. This section looks at the general tax and cordon toll policies and environment together, as the general tax is simply a special case of the cordon toll policy, with the rate of toll set to zero. It also looks at the odometer tax policy with the environment of either an odometer or general tax. The perfect toll policy cannot be solved exactly due to the nature of the equations as formulated, however, it can be approximated very closely with the cordon toll analysis, where the cordon tolls are spaced very tightly and collection costs are significantly reduced.

There are 16 potential cases we could consider, with regular,consistent environments. In this dissertation, we only consider the 6 with an N or C in the table marked below, where the N and C signify non-cooperative and cooperative toll-setting equilibria respectively.

Table 4.5 Policies Examined in this Dissertation

Environment: J_0:	General Tax (χ)	Cordon Toll (τ)	Odometer Tax (ω)	Perfect Toll (π)
General Tax (χ)	N	N		
Cordon Toll (τ)	N	N,C		
Odometer Tax (ω)			C	
Perfect Toll (π)				C

where: N = non-cooperative toll-setting equilibrium, C = cooperative toll-setting equilibrium

4.9.1 General Tax and Cordon Tolls

These reduced forms are given in Tables 4.6 - 4.8, which are discussed below. With the coefficients and jurisdiction size fixed (while tolls remain variable), many of the terms become constants for purposes of analysis.

The general expression (for utility, cost, revenue) (Y) can be written in the form of:

$$Y^{P\underline{P}} = g_G(r_\tau^{P\underline{P}}, r_{\underline{\tau}}^{P\underline{P}}) \, \beta_{YG} \tag{4.11}$$

where: $g_G (r_\tau^{q\underline{q}}, r_{\underline{\tau}}^{q\underline{q}})$ is a function of tolls and crossings associated with user groups (G).

$\quad\quad g_G \quad$ = 1 when Y represents a fixed cost (C_S, C_{CF}).

$\quad\quad\quad\quad$ = equation given in Table 4.7 otherwise.

$\quad\quad$ q, $\underline{q}$ denotes policy (tax or toll) of J_0, other jurisdictions

$\quad\quad$ r_τ, $r_{\underline{\tau}}$ denotes rate of toll of J_0, other jurisdictions

β_{YG} is the portion of the expression specific to the cost/revenue/consumers' surplus category.

Table 4.6 displays the constant β_{YG} component, which is common to all four comibinations of J_0/environment policies, but differs for each cost/revenue/consumers' surplus category (Y) and user group (G). An attempt was made to further reduce this (that is to attain a simpler β_Y component, applicable across all user groups for a given component), but the simplification could only be achieved at the expense of the constancy in the g_G component across user groups.

Table 4.7 develops the component associated with user groups (g_G). This component is complex because it captures the interface between the continuous demand functions and the discrete location of toll-booths. This component is formulated to be general as to handle both tax and toll policies in both all-tax and all-cordon toll environments. The form of the g_G equation can be simplified in the absence of tolls in either J_0 or other jurisdictions or both, as then the respective tolls (r_τ) or ($r_{\underline{\tau}}$) can be set to 0.

Table 4.8 shows the underlying assumptions about the rate of toll in J_0 (r_τ) and in the other jurisdictions (the environment) ($r_{\underline{\tau}}$) under the various J_0 policy and environment conditions. By substituting the appropriate toll value into the g_G and β_{YG} equations, those equations can be solved for different policies in J_0, (P) and in the environment E, ($\underline{P}$).

Table 4.6 Model Components: General Tax and Cordon Toll

Y	Description	User Group	β_{YG}
C_{CV}	Variable Collection Costs	G_{00}	0
		G_{0+}, G_{-0}	$\theta\delta$
		G_{-+}	$\theta\delta$
C_{CF}	Fixed Collection Costs	All	κK_i
C_ρ	Variable Network Costs	G_{00}	$\varphi\delta w^3 v^3 u(t\ln(t) + \ln(t) - 2t + 2)$
		G_{0+}, G_{-0}	$\dfrac{-\varphi\delta wv(1+t)(-1+\ln(t))}{(1-t)}$
		G_{-+}	$\varphi\delta(b-a)$
C_S	Fixed Network Costs	All	$\gamma wv\ln(t)$
R	Toll Revenue	G_{00}	0
		G_{-0}, G_{0+}	$r_\tau\delta$
		G_{-+}	$2r_\tau\delta$
U	Consumers' Surplus	G_{00}	$\delta w^3 v^2 u(1 - t + \ln(t))$
		G_{0+}	$\dfrac{-\delta}{\alpha}$
		$G_{-0} \, G_{-+}$	0

where: $v = \dfrac{1}{\psi}$, $\quad w = \dfrac{1}{\alpha}$, $\quad t = e^{\alpha\psi|b-a|}$, $\quad u = e^{\alpha\zeta}$, $\quad \psi = v + \dfrac{V_T}{Sf}$,

equation form: $Y = g_G\beta_{YG}$

note: Utility tax financing (all i-originating trips): $U_{00} + U_{0+} = \delta w^3 v^2 y\ln(t) = U_{\chi i}$

Flow dependent costs tax financing (all trips using network in jurisdiction J_0):

$C\rho_{-+} + 2C\rho_{0+} + C\rho_{00} = \varphi\delta w^3 v^3 y\ln(t) = C\rho_\chi$

$K_i = 2$ when policy = toll, 0 when policy = tax.

Fixed costs (C_{CF}, C_S) do not vary with demand, and thus $g_G = 1$ for fixed costs.

Table 4.7 Estimation of Mathematical Solution Associated with User Class (g_G) for General Tax and Cordon Toll Policies in J_0 and Environment

Class	Discrete estimation
G_{00}	$g_{00} = 1$
G_{-0}, G_{0+}	$g_{0+} = \dfrac{\left(e^{\alpha\left(\zeta-2a\psi+r_\tau+r_{\underline{\tau}}\right)}\left(e^{\alpha a\psi}-e^{\alpha b\psi}\right)^2\right)}{\left(e^{\alpha(a\psi)}-e^{\alpha\left(2r_{\underline{\tau}}+b\psi\right)}\right)\alpha^2\psi^2} = \dfrac{\left(e^{\alpha\left(\zeta+r_\tau+r_{\underline{\tau}}\right)}\left(1-e^{\alpha B\psi}\right)^2\right)}{\left(1-e^{\alpha\left(2r_{\underline{\tau}}+B\psi\right)}\right)\alpha^2\psi^2}$
	$g_{0+} = w^2v^2\,\dfrac{ue^{\alpha\left(r_\tau+r_{\underline{\tau}}\right)}(1-t)^2}{\left(1-te^{\alpha 2r_{\underline{\tau}}}\right)}$
G_{-+}	$g_{-+} = \dfrac{e^{\alpha\left(\zeta+(2b)\psi+2\left(r_\tau+r_{\underline{\tau}}\right)\right)}\left(e^{\alpha(-1(b-a)\psi)}-1\right)\left(-e^{\alpha(b-a)\psi}-1\right)}{\left(e^{\alpha(a\psi)}-e^{\alpha\left(2r_{\underline{\tau}}+b\psi\right)}\right)^2\alpha^2\psi^2}$
	$= \dfrac{e^{\alpha\left(\zeta+(2B)\psi+2\left(r_\tau+r_{\underline{\tau}}\right)\right)}\left(e^{\alpha(-1(B)\psi)}-1\right)\left(-e^{\alpha(B)\psi}-1\right)}{\left(1-e^{\alpha\left(2r_{\underline{\tau}}+B\psi\right)}\right)^2\alpha^2\psi^2}$
	$g_{-+} = w^2v^2\,\dfrac{ue^{\alpha 2\left(r_\tau+r_{\underline{\tau}}\right)}\left(-1-t^2\right)}{\left(1-te^{\alpha 2\left(r_{\underline{\tau}}\right)}\right)^2}$

Note: B=Jurisdiction Size = b-a when a=0

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Table 4.8 Rate of Toll Under Various Policies

		Environment			
		tax		toll	
J_0 Policy	tax	$r_\tau^{\chi\chi}=0$	$r_{\underline{\tau}}^{\chi\chi}=0$ $\quad r_\tau^{\chi\tau}=0$		$r_{\underline{\tau}}^{\chi\tau}=r_\tau^{*\tau\tau}$
	toll	$r_\tau^{\tau\chi}=r_\tau^{*\tau\chi}$	$r_{\underline{\tau}}^{\tau\chi}=0$ $\quad r_\tau^{\tau\tau}=r_\tau^{*\tau\tau}$		$r_{\underline{\tau}}^{\tau\tau}=r_{\underline{\tau}}^{*\tau\tau}$

note: r_τ = toll set by J_0, $r_{\underline{\tau}}$ = toll set by all other jurisdictions

Assuming the demand functions described, and keeping toll rates fixed, we may draw some basic conclusions in the case of cordon tolls. As the size of jurisdiction J_0 increases, that is as |b-a| gets large:

1. While the total number of trips crossing cordon a remains the same or increases, the ratio of non-through (F_{-0}) to through (F_{-+}) 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 toll-booth rather than two.

2. Similarly, the total number of trips crossing cordon b remains the same or increases as the ratio of non-through (F_{0+}) to through (F_{-+}) increases.

3. The total number of trips originating in or destined for jurisdiction i (F_{00}, F_{0+}, and F_{-0}) increase. However, the number of non-local (F_{0+} and F_{-0}) trips approach a limit (the maximum flow past the cordon) while local (F_{00}) trips increase with jurisdiction size.

4.9.2 Odometer Tax

The objective assumed in the case of the odometer tax is to maximize welfare. All revenue (R_ω) under an odometer tax policy comes from local residents. The rate of the odometer tax is denoted by r_ω. This section considers the odometer tax when the environment is either also using the odometer tax or using general taxes.

$$R_\omega = \int_a^b \int_x^\infty r_\omega(y-x)\delta e^{\alpha(r_\omega(y-x)+\zeta+\psi(y-x))}dydx \qquad (4.12)$$

$$R_\omega = \frac{r_\omega \delta e^{\alpha\zeta}(b-a)}{(\alpha(r_\omega+\psi))^2} = \frac{r_\omega \delta uvw^3 \ln(t)}{(r_\omega+\psi)^2} \qquad (4.13)$$

Total cost is a function of variable and fixed network cost components.

$$C_V = \int_a^b \int_{-\infty}^z \int_z^\infty \delta e^{\alpha(r_\omega(y-x)+\zeta+\psi(y-x))}dydxdz \qquad (4.14)$$

$$C_T = C_\rho + C_S = \frac{\delta\phi e^{\alpha\zeta}(b-a)}{(\alpha(r_\omega+\psi))^2} + \gamma(b-a) = \frac{\delta\phi uvw^3 \ln(t)}{(r_\omega+\psi)^2} + \gamma vw \ln(t) \qquad (4.15)$$

Consumers' surplus for this policy can be formulated as:

$$U_\omega = \int_a^b \int_x^\infty \int_{r_\omega(y-x)}^\infty \delta e^{\alpha(p+\zeta+\psi(y-x))}dpdydx \qquad (4.16)$$

which gives the following

$$U_\omega = \frac{\delta(b-a)e^{\alpha\zeta}}{(\psi+r_\omega)\alpha^2} = \frac{\delta vw^3 \ln(t)u}{(\psi+r_\omega)} \qquad (4.17)$$

4.9.3 Perfect Toll

Under the perfect toll policy, welfare, in particular consumers' surplus, cannot be calculated with a closed form solution. However, with some minor modifications, we can apply the cordon toll approach to the perfect toll. As tolls become spaced closer and closer together, the cordon toll results approach the perfect toll result. The error associated with this approximation is expected to be small. Define a *subarea* as the distance between cordons within a jurisdiction. Redefine user classes so that local trips (G_{00}) don't cross a cordon (rather than not crossing jurisdiction boundary), boundary crossing (G_{-0}, G_{0+}) trips

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only cross a subarea boundary (not necessarily a jurisdiction boundary), and through trips (G_{-+}) cross a subarea, but not necessarily a jurisdiction.

The main difference is that the jurisdiction is now larger than the subarea. The methodology for cost and revenue are virtually identical, only the cost per subarea must be multiplied by the number of subareas per jurisdiction. The methodology for consumers' surplus must be revised. As subareas get small, local trips (G_{00}) approach zero. A subarea may have mostly through trips, but those trips will be boundary crossing from another subarea, and thus will be recognized in the consumers' surplus expression as boundary crossing (G_{0+}) trips from the subarea in which they originate.

We must alter our assumptions about collection costs, otherwise the tight spacing will cause these costs to become exceedingly large. In our analysis, we assume that both variable and fixed collection costs under perfect tolls are zero. We could establish a collection cost per km, though that has the same effect as variable network costs, and thus can simply be examined when we do a sensitivity analysis on variable network costs.

4.10 Summary and Conclusions

The purpose of this chapter 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, the level and elasticity of demand, and the cost of providing infrastructure. The chapter began by developing the network geometry of a long road, and identifying user classes along that road relative to the jurisdiction under analysis. The objective functions, welfare maximization, profit maximization, and cost-recovery constrained welfare maximization were expressed. Then the demand model was specified, with the propensity to make a trip a negative exponential function of time and cost. The cost functions facing the network operator were specified, comprising fixed and variable network and toll collection costs. The policies that a jurisdiction may undertake (general tax, cordon toll, odometer tax, perfect toll) were considered in the context of the policies that other

jurisdictions (the environment) undertakes. These policies affect the price of infrastructure faced by travelers, and dictate the formula used for the solution of the mathematical problem. Two alternative equilibrium methods: cooperative and non-cooperative and their solution were discussed, the basic difference being the assumption that a jurisdiction makes about the policy which the environment chooses. Finally, the mathematical solution to the calculus problems laid out in this chapter is offered.

The gas tax, a financing mechanism which is neither a pure tax nor a pure toll, is often used for certain classes of roads. We did not directly structure an analysis of financing through a gas tax, as it relies on a large number of behavioral assumptions about where and when gas is purchased. However, the effects of a gasoline tax can be bounded by two extreme cases considered here. In the first case, called the odometer tax, travel is taxed by the home jurisdiction in proportion to the amount of travel that a resident undertakes both inside and outside his home jurisdiction. This models the gas tax as if all gasoline is purchased in the home jurisdiction. The second case, called the perfect toll, tolls all travelers in proportion to the amount traveled in each jurisdiction. This models the gas tax as if all gasoline is purchased in each jurisdiction in proportion to the amount of travel in that jurisdiction.

This information will be used in subsequent chapters to analyze the finance choices facing jurisdictions. In Chapter 5, we will find empirical values for the many constants and coefficients developed in this chapter. In Chapter 6 we apply the models to various conditions using the empirical values from Chapter 5 and varying policies and structural parameters such as jurisdiction size. Sensitivity tests will be undertaken and elasticities of welfare and tolls or taxes with respect to the model coefficients will be computed.

5. CHAPTER FIVE. EMPIRICAL JUSTIFICATION OF MODEL PARAMETERS

5.1 Introduction

This research employs a number of model parameters to describe the demand and cost functions. This section will attempt to put realistic valuations on those parameters so that the model can be applied in situations as similar as possible to actual experience. The purpose is not to find exact answers, because the ground truth varies from place to place, but rather to find reasonable starting points, so that sensitivity to the model results takes place under realistic situations, rather than using arbitrary model values.

This chapter considers the various model parameters in the demand and cost equations presented in Chapter 4. Empirical values derived from previous studies by the author and others are summarized and employed. The demand coefficients of value of time, freeflow speed, private vehicle costs, density of trips, and sensitivity of demand to price are considered. Then the network cost and collection cost variables are investigated. A model of long run total expenditures on infrastructure by states is presented. Data from California Bridges are used to estimate a model of toll collection costs. Finally the costs are summarized.

5.2 Demand

The key equations from the demand models were described in Chapter 4. Several variables are the object of study in this dissertation, including the price of infrastructure (P_I), and so are not considered in this chapter. The key demand variables which must be examined are the value of time (V_T), freeflow speed (S_F), and variable and fixed private vehicle costs (v, ζ). These variables are discussed in turn. Then the way that all user costs affect demand is discussed.

5.2.1 Value of Time (V_T)

The value of time depends on mode of travel, the time of day, the purpose (business, non-business) of the trip, the quality or level of service of the trip (including speed), the amount of time, whether the time is spent waiting or in motion, whether the time was expected or unexpected, and the specific characteristics of the trip-maker, including income, among other factors (Hensher 1995). Numerous studies have estimated the value of travel time (FAA 1989, Miller and Fan 1992). These studies use several approaches, often grouped under the willingness to pay rubric. This dissertation assumes a value of time (V_T) of $10 per hour, though the sensitivity to this parameter will be tested.

5.2.2 Freeflow Speed (S_F)

The freeflow speed is a facility specific variable. The model we develop should be applicable to many different kinds of facilities, but in practice, we need to examine one type here. The facilities most likely to be subject to tolls in the near future are limited access facilities. Typical posted legal speeds on limited access facilities in the United States range from 88 kph to 120 kph. For that reason, we assume a freeflow speed (S_F) of 100 kph. To simplify the analysis, we consider the ratio of the value of time to freeflow speed (V_T / S_F). Using our assumed values, this is $0.10 /pkt.

5.2.3 Private Vehicle Costs (ζ, ν)[1]

The cost of operating a vehicle depends upon numerous factors, such as the size of the vehicle. In 1995, the most popular cars were intermediates, and that is the type assumed in this analysis of cost. The operating costs considered in the analysis include gas, oil, maintenance and tires.

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[1] This section is adapted from Levinson and Gillen (1998).

The issue of transfers must be considered carefully. For instance, the full cost of accidents can neither be considered solely a social cost nor solely a private cost. Insurance simply transfers part of the financial incidence of accidents from drivers to an insurance pool. Insurance costs (fire/theft, collision, and property damage/liability) borne by the user are not considered here, though the sensitivity analysis explores a range of user fixed costs which cover insurance costs.

The costs of constructing, maintaining, and operating the highway system can be considered transfers from users to the network (at least in part) and must not be double counted. These expenses appear in the tolls or taxes that a user pays, rather than as an expense associated with the vehicle. So in our model these expenses either appear in r_τ and affect demand, or appear as taxes and do not.

We can express the private vehicle price to users as:

$$P_V(x,y) = \zeta + \nu \mid y - x \mid = (P_g + P_o + P_t)Y + \zeta_i P_i + \beta_1 A + \beta_2 AY \qquad (5.1)$$

where: $P_V(Y)$ = private vehicle price to users ($/yr.)

P_g = Price of Gas ($/vkt)

P_o = Price of Oil ($/vkt)

P_t = Price of Tires ($/vkt)

P_i = Price of Insurance ($/yr.)

Y = Output in distance traveled (km)

A = Age (years over which car is depreciates), for purposes of our analysis

note: A=1 when determining annual depreciation

β_1, β_2 = model coefficients from used vehicle model discussed in the following

section

The hypothesis of the user cost model is that the amount of depreciation increases with age and miles. It is known that depreciation occurs for two main reasons: wear and tear on the vehicle and changing demand. Demand for an aging (unused) vehicle is replaced by the demand for a newer vehicle which comes equipped with more technologically advanced features.   Demand is also affected by changing preferences. In order to estimate the various cost components of depreciation, and thus to distinguish between average (stand-alone) cost or the marginal (incremental) cost, we developed a database of used car asking prices from an internet site for used car trading selecting Honda Accords and Ford Tauruses.

A model with the following form was estimated using ordinary least squares regression, the results are shown in Table 5.1:

$$P = ß_0 + ß_1 A + ß_2 AY + ß_3 M$$

(5.2)

where:

Variable	Definition
P	asking price (current \$).
A	Age of automobile = 1996 - Model Year
Y	Distance Traveled per Year (estimated in miles) for that particular car
M	Make 1 if the car was a Ford Taurus, 0 if it was a Honda Accord
$ß_n$	model coefficients

Table 5.1 Car Price Model Estimation

Variables	Coefficients	Standard Error	t Stat.	P-value
$ß_0$ - const.	20053	758	26.44	0.00
$ß_1$ - A	-1351	201	-6.69	0.00
$ß_2$ - AY	-0.0234	0.0152	-1.53	0.13
$ß_3$ - M	-2738	791	-3.46	0.00

Statistic	Value
Adjusted R Square	0.861
Standard Error	1858
Observations	34

The model estimates that the car loses \$0.023/vmt (\$0.014/vkt) and \$1351 per year in value . The model also implies that Tauruses sell for \$2740 less than Hondas, all other things being equal. The intercept term suggests that a new Honda Accord (1996) with zero miles is valued at \$20,053. These are not actual transaction prices, but asking prices so we can probably assume that an additional 10-20 percent markup is included in the price. For a car that is driven 16,000 km per year, the model gives an annual depreciation of \$1581, most of which is due to aging. Even considering markup, this is less than the depreciated value of \$2883 given by the American Automobile Association (AAA) (1993). Used cars suffer the

problem of adverse selection, so prices may tend to underestimate their actual value because of the possibility of "lemons". The buyer offers a price lower than what he would pay if he were certain that the car is good.

There are two ways to estimate operating costs: Stand-alone (average) costs or incremental (marginal) costs. In our case, stand-alone costs reflect the cost of owning the car and are predicated upon the assumption that intercity travel is not only routine but that it is also one of the primary reasons for owning the car. The incremental cost assumes that the car is already owned (or leased or rented), and that only the incremental cost of making the trip (ignoring a large part of the depreciation for instance) should be counted. We compute the average unit cost and average incremental or marginal cost of car ownership, shown in Table 5.2. In all likelihood, the user perceives the cost of the trip as the marginal cost, if not lower, since he is likely to disregard the cost of oil, tires and depreciation from his calculation.

Table 5.2 Average Unit and Incremental Cost of Car Ownership

Variable	Value
P_g - Price of Gas ($/vkt)	$0.015
P_o - Price of Oil ($/vkt)	$0.014
P_t - Price of Tires ($/vkt)	$0.0054
P_i - Price of Insurance ($/yr.)	$617
$ß_1$ - Age Depreciation ($/yr.)	$1351
A - Age (yr.)	1
Y - Distance/Year (km)	16,000
$ß_2$ - Distance Depreciation ($/vkt)	$0.014
Average Unit Cost ($/vkt)	$0.130
Marginal Cost ($/vkt)	$0.049

The AAA (1993) estimates a series of unit costs for transportation, including a gas cost of $0.036/vkt, excluding tax. However, the retail price of a gallon of gas (excluding

tax) at the end of 1995 is about \$0.70/gallon though noticeably higher in 1996. At 28 miles per gallon, the Corporate Average Fuel Economy standard for new cars, which all manufacturers must achieve as a fleet average, this translates to \$0.015/vkt for gas. The cost for gas and oil we use are close because we remove special excise taxes from the price of gas (we consider them a transfer to infrastructure and are assuming either tax or toll financing), while we include general taxes on oil in the price. We adopt the AAA (1993) estimates for the price of oil and maintenance and tires, as well as their estimate of insurance costs per year. As noted above, we estimated depreciation ourselves, and found a lower level than that given by AAA. Our estimates for average unit costs and marginal cost are summarized at the bottom of Table 5.2.

Individuals consider the marginal costs on a specific trip (and we assign the fixed costs elsewhere), so we take $\nu = \$0.049$. This allows us to calculate the combined coefficient on distance (ψ):

$$\psi = \nu + V_T / S_F = 0.049 + 0.10 = \$0.15/\text{vkt}. \tag{5.3}$$

The fixed cost of vehicle ownership (ζ) (annual depreciation of vehicles) = \$1351 per year (Levinson and Gillen 1998), which at an assumed 3 trips per day per vehicle, 365 days per year, 1 person per car, gives \$1.23/person trip. However, whether fixed costs actually affect travel is debatable.

5.2.4 Sensitivity of Demand to Price and Distance (α)

The total price to users is only the argument of the demand model. In the demand model user demand decreases with increasing distance and cost, the coefficient α. In our model, the coefficient must appear before both monetary cost and time. To determine α, we can review the results of Levinson and Kumar (1995), who estimated a simple trip distribution model of a similar form for Metropolitan Washington DC. The data for this trip distribution model consists of detailed person travel surveys conducted by the

Metropolitan Washington Council of Governments (MWCOG) for 1987-88, and the results were validated against 1968 data (MWCOG 1968, MWCOG 1988). The 1987-88 sample involved 8,000 households and 55,000 trips. Each household was assigned a specific 24 hour "travel day" and information was collected on all trips made by members of that household on that day. A trip was defined as one-way travel from one address to another. The location of both ends of the trip was reported along with the time of departure and arrival. Trip duration was obtained by subtracting time of departure from that of arrival. Though the model was estimated for seven different modes, only single occupant auto will be reported here, since we are only interested in a general number. Similarly, though the model was estimated for several different trip purposes (including various trip chaining combinations), only home to work trips are reported here.

The 1988 Household Travel Survey was used to determine the number of trips by five minute time band for each mode and purpose. Using Ordinary Least Squares (OLS) regression, impedance functions were estimated for application in the gravity model. Travel time served as the independent variable. The dependent variable was number of trips in each five minute time band, after controlling for the number of opportunities. Since this was an aggregate analysis, the control for the number of opportunities was assumed to be simply dependent of the amount of area covered, with speeds constant (so that time-area and distance-area are directly proportional.) Thus the average density of opportunities available in each five minute time band is assumed uniform. The dependent variable (X) for all trips $F_{[y1y2]}$ traveling y_1 to y_2 minutes away from the origin was defined as:

$$X = \ln\left[\frac{F_{[y1y2]}}{\left(y_2^2 - y_1^2\right)\pi}\right] = \zeta + \psi T \tag{5.4}$$

The model thus estimated the parameters ζ and ψ, as a function of travel time T. A more rigorous methodology could employ a geographical information system to estimate

the number of opportunities in true travel time contours around each zone. However for an aggregate analysis, this is unlikely to provide a significantly different model parameters.

Making that model consistent with the variable nomenclature used throughout this dissertation, for drive-alone peak period work trips the coefficient (ψ) on time (in minutes) to be 0.08 when $\zeta = 0.97$ and $\alpha = -1$ in the form below:

$$f(C_{ijm}) = e^{\alpha(\zeta + \psi T)} = e^{-(0.97 + 0.08T)} \tag{5.5}$$

If we assume an average travel speed for the peak on urban roads of 33 kph or 0.55 km/min, a coefficient of \$0.08/min is equivalent to a coefficient of \$0.14 /vkt. Note that the 33km/hr here is to convert this model, estimated for urban roadways into a form compatible with the calculations above, and that this value of 33 kph differs from the 100 kph freeflow speed assumed above in the intercity context.

When we assume that $\alpha = -1$, the coefficient on vehicle kilometer traveled (ψ) is \$0.14/vkt from the gravity model, which compares favorably with \$0.15/vkt from the user vehicle costs (equation 5.3). These two data sets, markedly different in their collection, and undergoing very different types of analysis, give similar coefficients for (ψ) when $\alpha = -1$. This gives us some confidence in using numbers in the range of those above.

5.2.5 Density of Trips Along Road (δ)

The demand multiplier (δ) depends on the density of trips. We consider the case of density along an arterial. If we assume a suburban density of 540 persons per km^2, (typical of Montgomery County, Maryland in 1990) and a distance between arterials of 1 km, and assuming that all trips load the network on roads in the north-south direction, each road has to serve the access needs of 540 persons per linear km. Conceptually this is illustrated in Figure 5.1. If we assume 0.333 peak hour vehicle trips per person, then we have 180 trips loading the road per linear km per hour. The actual value depends very much on site

specific circumstances, a freeway will carry more trips than arterial, etc. A range of values are explored in the sensitivity analysis.

Figure 5.1 Schematic of Road Loading Patterns

1 Square Kilometer (~540 Persons)

Arterial (where trips load)

Direction of trips loading
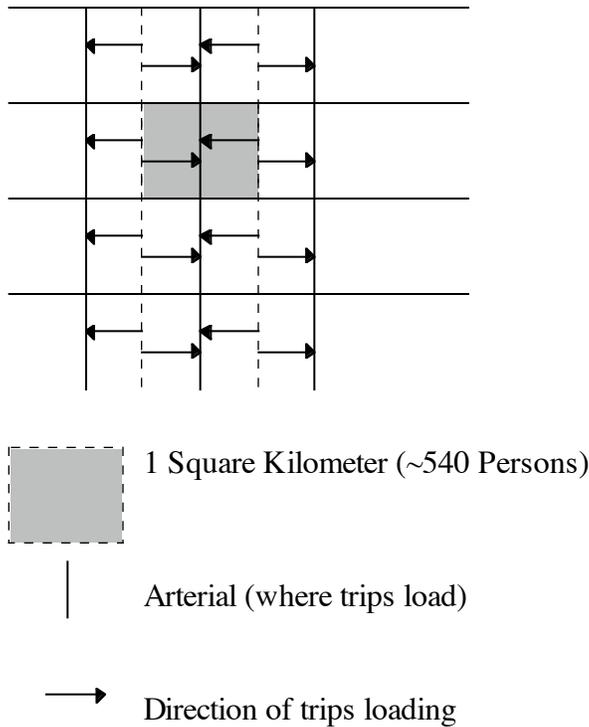
5.3 Network Costs (γ, ϕ)[2]

In this section, we estimate a model predicting long run total expenditures on infrastructure as a function of price inputs (interest rates, wage rates, and material costs), and outputs (distance traveled by passenger vehicle, single unit truck, and combination truck). The hypothesis of the expenditure model is that total expenditures increase with outputs, and with prices, so all signs should be positive. However, the amount of increase with output depends on the nature of the output. This model will indicate the fixed and variable network costs that jurisdictions face.

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[2] This section is adapted from Levinson and Gillen (1998).

Total expenditures data are developed from two sets of information: data compiled by the Federal Highway Administration on maintenance, operating, and administrative costs (FHWA 1993); and capital stock data collected by Gillen et al (1994). The capital stock series was inflated from 1988 to 1993 levels (a 20% inflation was taken), and then was discounted to reflect an annualized cost. The annual cost was assumed to equal the total cost multiplied by the price of capital or interest rate - a state with a higher interest rate has a higher opportunity cost for investing money in fixed assets. The annualized capital cost (C_k) was added to annual expenditures on maintenance (C_m) and operations and administration (C_l) to create an estimate of long run total expenditures (E_{LR}).

Three classes of output (Y) are defined from the FHWA Highway Statistics Report (1993): passenger cars (Y_a), single unit trucks (Y_s), and combination trucks (Y_c) in millions of vehicle miles traveled per year. Because of their relative damage to the roadway, costs associated with passenger cars are expected to be less than those associated with single unit trucks, which is less still than those associated with combination trucks. However, this may not be the case if there are economies of scope associated with roadways. For instance, suppose a network is designed for peak rush hour flows, and that these flows are dominated by passenger cars. In the off-hours, capacity is underutilized. If it is during those hours that trucks use the roadway, then the government expenditure on transportation to serve those trucks may in fact be less than that for passenger vehicles. At a minimum, because these two effects (efficient capacity utilization vs. greater damage) are offsetting, the relative additional costs to serve trucks would not be as great as that indicated by an engineering analysis based solely on damage which does not consider scope economies.

Several price measures are included in the model. The first, to measure the price of capital (P_k), including the entire built stock of the highway network, is measured by taking the interest rate, which reflects the cost of borrowed money. States with lower bond ratings or higher interest rates must pay more to borrow, and have a higher opportunity cost for fixed investment. We used Moody's ratings for each state (Bureau of the Census, 1993)

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and typical interest rates paid for lower rated bonds garnered from recent offerings to estimate the price of capital.

Second, the price of labor (P_l) is measured by taking the average wage rate of state government employees (normalized to the national average) for 1993 (BLS, 1995). The third main input is the price of materials (P_m). The principal material used in highway construction is bituminous concrete for pavement. We computed indices of construction materials prices by taking the price of an input (FHWA 1994), and dividing by the national average of the price of that input.   The indices, reflecting relative prices, with a mean at 1, can then be added to create a composite index for construction materials.   For instance, the price of bituminous concrete in a state, and divided by the national average of the unit price of bituminous concrete, provides an index representing the relative price of bituminous concrete. The materials for which data was available (bituminous concrete (price per ton), common excavation (price per cubic yard), reinforcing steel (price per pound), structural steel (price per pound), and structural concrete (price per cubic yard) were included in the database. Boske (1988) discusses the data and the use of indices with this data, though only bituminous concrete was used in our final regressions.

The model of long run total expenditures is estimated two ways, first using ordinary least squares (OLS) and then using feasible generalized least squares (weighted least squares (WLS)). WLS, where the reciprocal of variance is used as a weight, corrects for the clear heteroskedasticity in the data, wherein the size of the residual is correlated with the size of the dependent variables. Two functional forms: a linear model and a Cobb-Douglas (using the log of both dependent and independent variables) model were estimated. The results are given below. The coefficients from the log-linear (Cobb-Douglas) weighted least squares are used for further analysis, the other regression results are available in Levinson et al (1996) for information purposes.

Table 5.3 Long Run Total Expenditures Results

Variable	Description	B	T	Sig.-T
ln(Pk)	Price of Capital	1.831	11.247	.0000
ln(Pl)	Price of Labor	.786	3.346	.0020
ln(Pm)	Price of Materials	.00494	.222	.8257
ln(Ya)	Automobile VMT	.439	9.824	.0000
ln(Ys)	Single Truck VMT	.179	4.885	.0000
ln(Yc)	Combination Truck VMT	.225	5.016	.0000
	(Constant)	11.280	20.050	.0000
	Statistic	Value		
	Adjusted R Square	.99527		
	Standard Error	.99311		
	F	1402.4		
	Sig. F	.0000		

Largely, the hypotheses were borne out as shown in Table 5.3, the signs were generally in the expected direction. The variable P_m, the price of materials, was not significant. More importantly, there is wide variance around the estimate of the coefficient for Y_c, combination trucks. Other regressions, with different sets of independent variables have shown coefficients on Y_c about 50% larger, indicating that the true value is probably higher and multi-collinearity, which is obviously an important factor in this data, may be causing some uncertainty in parameter estimates.

The long (E_{LR}) run total expenditures can be expressed as the equations below:

$$E_{LR} = C_k + C_l + C_m = f(Y_a, Y_s, Y_c, P_k, P_l, P_m) \tag{5.6}$$

$$= \beta_0 Y_a^{\beta 1} Y_s^{\beta 2} Y_c^{\beta 3} P_k^{\beta 4} P_l^{\beta 5} P_m^{\beta 6}$$

$$= 79221 \, Y_a^{0.439} Y_s^{0.179} Y_c^{0.225} P_k^{1.83} P_l^{0.786} P_m^{0.00492}$$

Using the total expenditure functions (E_{LR}), we can compute marginal cost functions for the three classes of vehicles (i). These are solved for average values (the values for each

state are given in Levinson et al (1996)). Applying the marginal cost equations to the national totals for Y_a, Y_c, Y_s and national average prices, we get the long run marginal costs given in Table 5.4. Data for the individual states, which show the range over which these costs can vary, are also given in the table.

Table 5.4 Long Run Marginal Infrastructure Costs and Scale Economies

	Long Run Marginal Costs	Range of State Level Data
Auto	0.0188	0.0072-0.0331
Single Truck	0.0431	0.0205-1.3300
Combination Truck	0.0514	0.0193-0.1349

Note: in $/vkt, Parentheses refer to range of state level highway agency costs.

We can compare the econometric approach taken above with other studies. Miller and Moffet (1993) calculate total annual road capital and operating expenses attributable to cars as $85.7 billion per year, including $48 billion of pavement wear costs, $24.8 billion of other maintenance, and $12.6 billion of expansion and construction costs. They subtract road user fees from cars and light trucks of $21.5 billion, and estimate an annual capital and operating cost of $64 billion per year or $0.0087/vkt. To estimate the full cost, not including user payments (which are simply transfers), application of their methodology produces an estimate of $0.011/vkt average cost, which is about 50% lower than our estimate of $0.017/vkt long run average cost and $0.019/vkt marginal cost. Obviously the methodologies are dissimilar, which explains the difference in part. We take an econometric approach. They adopt an engineering approach, but extrapolate the results to the national system. Furthermore, they adopt FHWA (1982) cost estimates of pavement wear as a fixed $/ESAL-mile, with passenger cars responsible for 0.05 ESAL per mile. However the damage per mile is non-linear function of axle-loadings, ESAL's increase with the third or fourth power of axle-loading depending on pavement wear (Small,

Winston, Evans 1989). This suggests that the amount of pavement damage attributed to automobiles by the Miller and Moffet (1993) study is significantly overstated.

It seems reasonable to assume that states take into account long run, rather than short run costs. Implicitly the study set $\gamma = 0$, and since network size is not a policy variable in this analysis, that should not pose important difficulties. Should network size (fixed network costs) be a variable in the analysis? Macroscopically, we might assume that states have an implicit level of service standard. This would mean that as travel times rise due to congestion, roads are expanded (new roads are built) to return them to a faster time. If this is done widely and relatively continuously, in the long run network size can be considered a variable rather than fixed costs. This would eliminate any need for a variable reflecting fixed costs of network expansion from our analysis.

5.4 Collection Costs (θ, κ)

Collection costs depend on the technology used to collect tolls. The two main turnpike toll collection systems on limited access facilities are dubbed cordon (or open) and perfect (or closed). Open, or cordon, tolls use a mainline barrier, this allows local, short-distance traffic to use the facility without paying tolls, but all traffic crossing the barrier must pay the toll. Examples of open systems include the Connecticut Turnpike and Bee Line Expressway in Florida. Closed, or perfect, tolls use tickets (or their electronic equivalent). Toll booths are located at each point of entry and exit, tickets are issued at the entry points and revenue collected at the exit based on the amount of travel in the system. Examples of closed systems include the New Jersey, Pennsylvania, and Ohio turnpikes. There are numerous hybrid combinations between these two idealized types, which mix use of mainline barriers and entry and exit tolls to increase the probability of getting revenue for each trip without imposing as high a collection cost as a closed system. Hybrid systems will generally be more equitable than open systems and less equitable than closed systems, where equity is defined as paying in proportion to use. Examples of hybrid systems include

the Illinois Tollway and Garden State Parkway. For a single link (such as a bridge), with one entry and one exit, open and closed systems are identical.

Existing non-toll limited access highways have a higher density of interchanges and are more accessible than typical closed-system toll roads. This is due to the high cost of collecting revenue on a closed system. Thus imposing perfect (closed) tolls implies increasing the backtrack or slowtrack (early exit to a slower speed route) costs of users.

Table 5.5 Interchange Spacing on Free and Closed-Toll Highways

Type	State	Facility	Length	Interchanges	Spacing
Free	Ohio	I-70	255	70	3.64
Toll		Turnpike	241	19	12.68
Free	Pennsylvania	I-80	318	62	5.12
Toll		Turnpike	358	28	12.78

ref.: Gittings 1987,   note: Distances in miles

In general, the cost per barrier on a closed system will be much smaller than an open system, since the closed system's barrier typically only guards one lane (the entry or exit ramp), while the open system must operate an entire toll plaza. However, the lower unit cost is unlikely to mitigate the increased number of barriers which must be constructed. Also, though we are not dealing with delay directly, it should be noted that an open system with three or more barriers likely has more user delay due to tolls than a closed system (where a user only faces two barriers).

We need to estimate the collection cost coefficients: (θ, κ). There are several ways to approach this problem. We begin by estimating the costs empirically from the data for California toll bridges. Table 5.6 gives the data for the bridges, Table 5.7 gives the result of an OLS regression. The regression from Table 5.7 states that annual toll collection costs are:

$$Cc = \kappa + \theta \text{ (Total Vehicles)} = \$334523 + \$0.085/\text{vehicle}. \tag{5.9}$$

Allocating the $334523 daily (divide by 365), and then to the peak hour (divide by 10) gives $91.65 per hour for collecting tolls on all lanes per bridge, the empirical value we use for fixed collection costs (κ). If we have 300 vehicles per toll-lane per hour, then the fixed cost of collection amount to $0.03/vehicle, compared with $0.085/vehicle variable costs.

An alternative approach would estimate the cost components (labor, facilities, etc.) directly. To provide an extremely rough estimate, if we assume that one operator can serve 300 vehicles per hour, and assume a wage = $20 per hour, we get $0.0667/veh trip. Add in overhead (say 50%), and we get $0.10/veh trip, very close to the empirical results.

Bridges of course have somewhat different flows, costs, and constraints than do cordon (open) tolls on highways or turnpikes, or especially perfect (closed) tolls. In general, because turnpikes have more flexibility about where to place tolls than do bridges, one would expect, all else equal, slightly lower fixed costs due to the cost of land and construction. On the other hand, bridges are significant bottlenecks, and thus handle very heavy flows, thereby utilizing the fixed resources more evenly and completely throughout the day, and so may have lower variable costs than turnpikes.

Table 5.6 Data from California Toll Bridges

Toll Bridge	Toll Collection Cost/ Personal Services	Toll Revenue	Total Vehicles	$/$	$/Veh.
Antioch	721495	2295992	1725682	0.31	0.42
Vincent Thomas	426153	2594557	5516885	0.16	0.08
San Diego-Coronado	1176076	5841903	11561448	0.20	0.10
Dumbarton	1086844	8848114	10186540	0.12	0.11
Richmond-San Rafael	1175158	11121952	10061298	0.11	0.12
San Mateo-Hayward	1591771	14084517	13810444	0.11	0.12
Benicia-Martinez	1939555	18262540	16324802	0.11	0.12
Carquinez	2139573	23242817	18730742	0.09	0.11
San Francisco - Oakland Bay	4251142	48463860	46832208	0.09	0.09
Total	14507767	134756252	134750049	0.11	0.11
Average	1611974	14972917	14972228	0.11	0.11

ref.: Caltrans 1995

Table 5.7 Regression on Collection Costs from California Bridges

	Coefficients	Standard Error	t Stat.	P-value
Intercept (κ)	334523	115270	2.90	0.02
Total Vehicles (θ)	0.085	0.006	14.33	0.00

Statistic	Value
Adjusted R Square	0.96
Standard Error	219238
F	205.35
Sig. F	1.91E-06

Turnpikes in New York and Pennsylvania lose between 14% and 19% of revenue collected to collection costs using current (labor-intensive) technology (Gittings 1987). This compares with 9% to 31% found on California's Bridges, with the highest efficiency on the most heavily traveled San Francisco - Oakland Bay Bridge. When tolls doubled on California's Bridges in 1998, the cost of collection relative to revenues collected was halved (aside from additional delays due to making more change). While looking at percentages is interesting, it does not help solve the problem, because there is no reason to expect these percentages to remain stable as tolls vary.

5.5 Conclusions and Summary

In summary, Table 5.8 provides the empirical coefficients on the demand and supply models. These data can be used to apply the model developed in Chapter 4. Chapter 6 will use these results, and pivot off of them, to explore the model under various conditions.

Table 5.8 Empirical Coefficients on Demand and Cost Models

Coefficient	Used In	Value Employed
zeta (ζ)	fixed cost of vehicle ownership ($/veh-trip)	$1.23
psi (ψ)	variable cost of travel ($/vkt) ($\psi = \nu + V_T / S_F$)	$0.15
alpha (α)	rate of decay	-1
delta (δ)	total demand multiplier (trips)	180
kappa (κ)	fixed collection cost ($/toll-booth/hour)	$90
gamma (γ)	fixed network cost ($/km)	$0
theta (θ)	variable collection cost ($/vehicle)	$0.08
phi (ϕ)	variable network cost ($/vkt)	$0.018

ref.: Levinson and Gillen 1998, Levinson and Kumar 1995

6. CHAPTER SIX. THE CHOICE OF REVENUE MECHANISM

6.1 Introduction

Previous chapters have outlined the theory of network finance, formulated a model of the choice of revenue mechanism (general tax, cordon toll, odometer tax, perfect toll) faced by jurisdictions along a long road, and then estimated empirical values for the model coefficients. This chapter employs that model under various conditions, examining the choice under conditions where all other jurisdictions tax or all other jurisdictions toll, for jurisdictions of different sizes, over a range of model coefficients, in the case of alternative objectives (welfare maximization, profit maximization, cost recovery), under repeated and non-repeated games, and with and without cooperative price-setting between jurisdictions.

This chapter begins by providing an overview of the game which is used for analyzing a jurisdiction's strategic choice of revenue mechanism and tactical selection of a rate of tax or toll. We measure a jurisdiction's welfare as that jurisdiction's rate of toll varies. We develop the welfare maximizing taxes and welfare maximizing tolls under two environments: all other jurisdictions tax and all other jurisdictions impose cordon tolls. At the strategic level, a prisoner's dilemma game results - each jurisdiction has two choices: to "cooperate" with the other jurisdictions (by taxing) and receive the highest joint payoff (if all other jurisdictions also tax); or to "defect" (by tolling), which gives both a higher individual payoff both if the other jurisdiction cooperated, and if the other jurisdiction didn't cooperate.

To understand better the significant factors which lead jurisdictions to choose to a particular revenue mechanism, the application of the model is extended. First, jurisdiction size is varied for the four main jurisdiction and environment policy combinations of general tax and cordon tolls assuming non-cooperative toll-setting with the objective of welfare maximization. Policy choice under a range of fixed and variable collection costs and

jurisdiction sizes is examined in the context of a one-shot game. This section considers more deeply the two player game, by examining the range of collection costs and jurisdiction sizes for which each policy alternative satisfies the conditions of a Nash equilibrium. A Nash equilibrium implies that the jurisdiction of interest can do no better (by changing policies) given what every other jurisdiction is doing, while each other jurisdiction also can do no better given everyone else's decision. The level of government administering the road is evaluated, comparing cases with one vs. two governments covering the same area, this kind of analysis can also be interpreted as if jurisdictions formed federations which would then have authority over local roads.

The technical properties of the model are then examined. The stability of the equilibrium is considered by comparing the sensitivity of tolls in the jurisdiction of interest (J_0) to tolls in other jurisdictions, developing reaction curves for tolls. Then the uniqueness of the solution is demonstrated by varying the starting non-local tolls for the equilibrium analysis, and showing the convergence to a single result. Model values are varied and an elasticity analysis conducted to determine which variables are significant.

The previous sections assumed non-cooperative toll-setting, local welfare maximization, and a one-shot game. These assumptions are relaxed one at a time. We compare non-cooperative with cooperative toll-setting. One important aspect is that a cooperative toll-setting equilibrium can be viewed as equivalent to global welfare maximization, assuming a particular spacing of toll-booths. At the strategic (tax or toll) level, a one-shot prisoner's dilemma results. This leads to a result which may be considered dysfunctional. However, indefinitely repeated games (or supergames) may overcome that problem. Thus strategies which depend on the previous actions of other players are examined, and the range of discount factors for which each strategy is a stable solution is determined. Two alternative objectives, profit maximization and welfare maximization with a cost recovery constraint, were presented in Chapter 3, these are compared with the objective of welfare maximization.

In previous chapters, besides general tax and cordon tolls, two additional revenue mechanisms were identified. Perfect tolls (really just cordon tolls with infinitesimal spacing solved with cooperative toll-setting) are considered in comparison with the odometer tax. To the extent that collection costs continue to drop, perfect tolls have equity advantages over cordon tolls. Similarly, odometer taxes have efficiency advantages over general taxes. Under cooperative toll-setting for our case, the two alternative methods are virtually identical.

6.2 Revenue Choice: A Simple Game

We first employ non-cooperative game theory to analyze the strategic interactions between multiple jurisdictions under various conditions and objectives. The game involves multiple, identical players. We therefore focus on one *representative jurisdiction* in the game. The other jurisdictions form the *environment* of the representative jurisdiction. Depending on trip lengths and jurisdiction sizes, this environment may be largely irrelevant, dominated by adjacent jurisdictions, or include a large number of neighbors as significant players. Two decisions are considered: first, the strategic choice of revenue mechanism (tax or toll); and second, the tactical selection of the rate of tax or toll given the strategic choices by jurisdiction J_0 and the other jurisdictions (the environment).

Payoff functions are defined for each jurisdiction dependent on the policy taken by both itself and the other jurisdiction(s). The source of interaction between jurisdictions derives from residents of the jurisdiction of interest (J_0) traveling on the roads of another jurisdiction (J_{+n} or J_{-n}) (and vice versa). Thus the revenue policy of that other jurisdiction (J_{+n}) alters the payoff of residents of the jurisdiction of interest (J_0). Further, the pricing policy of a given jurisdiction J_{+n} alters the demand for the roads of both jurisdictions.

A simple version of the game can be represented in normal form as shown in Table 6.1. We assume that all jurisdictions are identical in size, travel demand, and all other model

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parameters, so that under identical policies and identical environments they attain identical payoffs. We assume only two policies in this representation: a general tax (independent of use) such as a poll tax, and a cordon toll. The cordon toll policy is really a mixed tax/toll strategy when toll revenue is insufficient to cover costs; and when toll revenue exceeds costs, the profits are returned to residents of the jurisdiction. The representation in Table 6.1 ignores mixed environments, cases where some jurisdictions tax and others toll. These environments are not explicitly considered here.

The evaluation of this game when it is played once differs from the solution which obtains when the game is repeated an indefinite number of times. In the one-shot game, the normal form represents a static game of complete information where the players (jurisdictions) act simultaneously. The payoffs to the jurisdictions are common knowledge, so each player knows the payoff of the other and vice versa. The objective is to find the Nash equilibrium (equilibria) of the game, where a Nash equilibrium is defined as a set of actions (or strategies) such that no player, taking his opponents' actions as given, wishes to change his own action.

To see which policy a jurisdiction will choose in a one-shot game we must compare its alternatives given the policy of the other jurisdictions. For instance, when all other jurisdictions impose taxes (the environment is all-tax), we need to evaluate which results in a higher payoff: taxes or tolls ($P_0^{\chi\chi} \lessgtr P_0^{\tau\chi}$). Similarly, when all other jurisdictions impose tolls (the environment is all-cordon toll), which produces a higher payoff: taxes or tolls ($P_0^{\chi\tau} \lessgtr P_0^{\tau\tau}$). If the same policy emerges independent of what the other jurisdictions do (for all jurisdictions), we have attained a Nash equilibrium solution, so that no actor (jurisdiction) has an incentive to change policies.

Figure 6.1 shows how welfare (the sum of profit and consumer's surplus) changes in J_0 as it varies its tolls assuming all other jurisdictions employ a tax, keeping fixed jurisdiction size (at 10 km) and all other factors. Tolls of zero are computed both with and

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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 maximizing toll (r_τ*) can be read as $0.70, lower than the profit maximizing toll ($1.10). This reflects that consumers' surplus as well as profit are included in the welfare objective function. The serial (complementary) nature of the network creates interactions which don't necessarily exist in a strictly competitive market analysis. Welfare can remain positive despite the lack of cost-recovery, suggesting that under certain circumstances welfare maximization may result from a combination of cordon tolls and tax financing used to subsidize 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 assumed to be returned to the jurisdiction's residents through reduced taxes or a direct payout.

In the all-toll environment, the welfare and welfare maximizing toll of a given jurisdiction depend upon the tolls of other jurisdictions. Here we solve the tactical, toll-setting problem by assuming jurisdictions don't 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 maximizing toll takes the same value. Figure 6.2 plots consumers' surplus, profit, and total welfare of a jurisdiction against the toll it sets, assuming other jurisdictions are assessing the Nash equilibrium toll. Observe (by comparing Figures 6.1 and 6.2) 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 maximizing 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.

Table 6.2 presents the payoff to J_0 from tolling and taxing, for the cases in which all other jurisdictions are tolling and taxing. In constructing this table, it is assumed that J_0 assesses the welfare maximizing toll when other jurisdictions are taxing, and the Nash equilibrium toll, as explained above, when other jurisdictions are tolling. It is apparent that J_0's best policy is to toll in either case. Generalizing, this means that if all jurisdictions tax, any individual jurisdiction has an incentive to defect from this arrangement by imposing a toll. On the other hand, if all other jurisdictions are tolling, J_0's best policy is also to toll. In other words, at the strategic level of determining whether to tax or toll, there is a Nash equilibrium in which all jurisdictions impose a toll, but it is not a Nash equilibrium for all jurisdictions to tax.

In this case, the Nash equilibrium policy pair (in the case of a one-shot game) is [Toll, Toll], where the total payoff from [Tax, Tax] is in fact higher than any other cell. Thus, the choice of revenue instrument involves a classic prisoner's dilemma for the set of parameters assumed here, there is a collective benefit if all jurisdictions tax. This game is predicated upon the empirical values discussed in Chapter 5, referred to as the baseline scenario, and reproduced below in Table 6.3, other values may lead to different conclusions.

In the case of a one-time prisoner's dilemma game, "defect" may be the equilibrium solution, but in the case of a repeated game, that is not necessarily the case. In a repeated game, [Tax, Tax] may be both an welfare maximizing and an equilibrium solution for all parties when some mechanism to enforce this policy is in place. Cooperation has two advantages. First cooperation protects local citizens from the negative effects of other jurisdiction's pricing policies. Second, cooperation eliminates the profit-damaging finance externality which reduces demand for local roads from non-local residents. Other mixed policies (alternating [Tax, Toll] and [Toll, Tax] for instance) may also achieve higher results. Enforcement mechanisms include the ability to "punish" and "reward" neighbors in a repeated game, a government in the case of many players (jurisdictions), or a negotiated treaty, contract, or compact. This is discussed in a later section.

Table 6.1 Normal Form of Revenue Mechanism Game

		Representative Jurisdiction	
		All-Tax	All-Cordon Toll
J_0	Tax	$[P_0^{\chi\chi}, P_n^{\chi\chi}]$	$[P_0^{\chi\tau}, P_n^{\chi\tau}]$
	Cordon Toll	$[P_0^{\tau\chi}, P_n^{\tau\chi}]$	$[P_0^{\tau\tau}, P_n^{\tau\tau}]$

note: P_0^{qq} indicates the payoff for player J_0 when player J_0 chooses policy q and other players select policy q

Table 6.2 Payoffs of Revenue Mechanism Game: J_0 vs. Representative Jurisdiction

		Representative Jurisdiction	
		All-Tax (χ)	All-Cordon Toll (τ)
J_0	Tax (χ)	[3087, 3087]	[2309, *3555*]
	Cordon Toll (τ)	[3555, *2309*]	[2418, 2418]*

note: Values in total welfare per jurisdiction (J_0 or representative other jurisdiction).

Jurisdiction Size=10, Baseline Scenario Empirical Values

The italicized cases (the environment's representative jurisdiction payoff from the [τ, χ] and [χ, τ] cases), are really just the mirror of J_0 for those situations, and were not computed directly. The non-italicized cases were directly computed, the tax cases assumed that taxing jurisdictions did not pay collection costs, the toll cases assuming that collection costs were paid.

Table 6.3 Baseline Scenario: Empirical Values of Model Coefficients

Variable	Description	Value
zeta (ζ)	fixed cost of vehicle ownership ($/veh-trip)	1.23
psi (ψ)	$\nu + V_T / S_F$ variable cost of travel ($/vkt)	0.15
alpha (α)	coefficient relating demand to price	−1
delta (δ)	total demand multiplier (trips)	180
kappa (κ)	fixed collection cost ($/toll-booth/hour)	$90
gamma (γ)	fixed network cost ($/km)	0
theta (θ)	variable collection cost ($/vehicle)	0.08
phi (ϕ)	variable network cost ($/vkt)	0.018

ref.: see Chapter 5

Figure 6.1 Welfare in J_0 as a Function of J_0 Toll in an All-Tax Environment

J_0 Welfare v. J_0 Toll, All-Tax Environment

note: Jurisdiction Size=10, Baseline Empirical Values
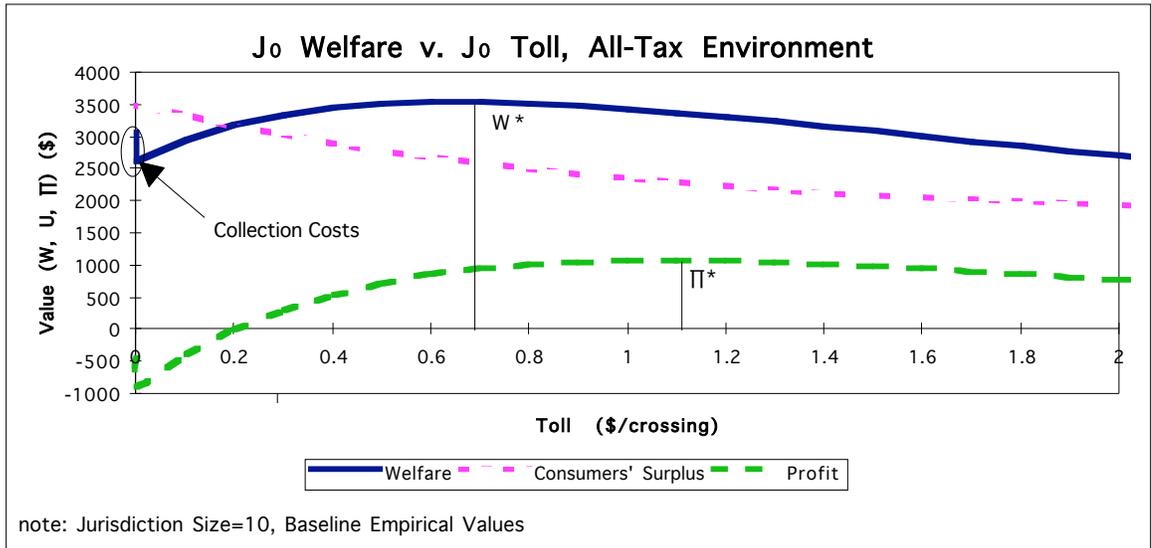
Figure 6.2 Welfare in J_0 as a Function of J_0 Toll in an All-Cordon Toll Environment

J_0 Welfare vs. J_0 Toll, All-Cordon Toll Environment

note: Jurisdiction Size=10, Baseline Empirical Values
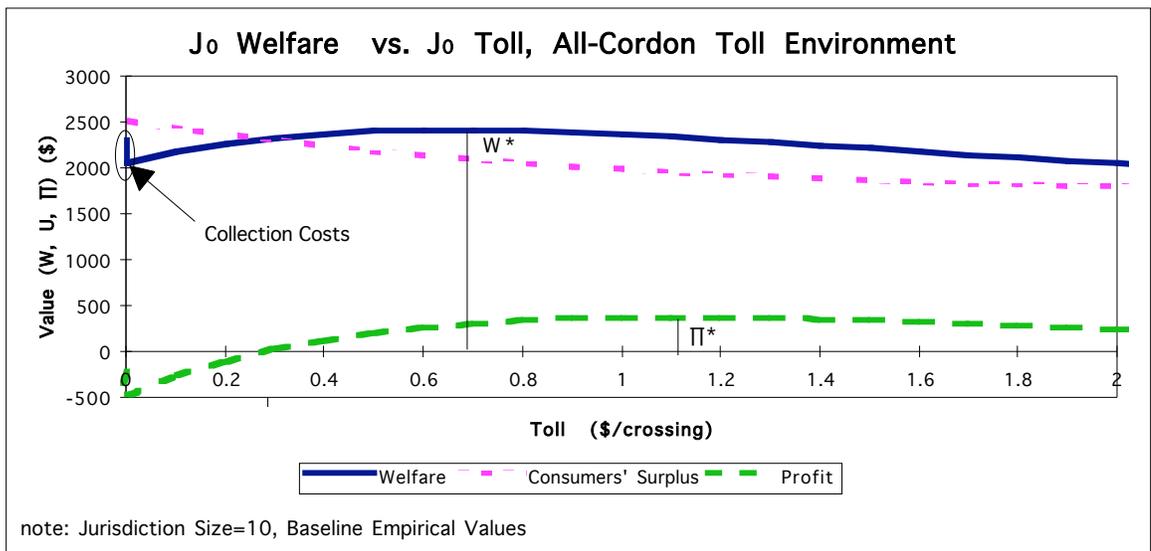
6.3 Revenue Choice, Jurisdiction Size, and Collection Costs

This section considers directly the strategic decision of how a jurisdiction selects a particular revenue mechanism, and how that selection varies with the size of the jurisdiction, other jurisdictions' policies, and with the fixed and variable costs of collecting tolls. This section assumes a one-shot game and non-cooperative toll-setting. For all cases in this section, the default assumptions are the baseline scenario presented in Table 6.3. First we evaluate how welfare varies with jurisdiction size under the main policy alternatives with different environments. We must determine the payoffs to jurisdictions under the four main jurisdiction-environment policy combinations ($P^{\chi\chi}$, $P^{\tau\chi}$, $P^{\chi\tau}$, $P^{\tau\tau}$) to evaluate the game presented. The payoffs are then put into a game structure, and the collection costs which result in different equilibria are computed. Then the differences in welfare due to one or multiple jurisdictions setting tolling policies are determined.

6.3.1 Welfare and Jurisdiction Size

All-Tax Environment

When the revenue instrument is taxes, it is fairly clear that to achieve a maximum of local (transportation and non-transportation) welfare while still recovering costs, the rate of taxes must be set such 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 affect travel demand, there is no per capita variation in welfare, cost, or consumers' surplus. This is illustrated by the horizontal line (denoted by "W(Tax)/Size") in Figure 6.3, which displays the welfare resulting from both tax and toll policies in an all-tax environment.

The toll which maximizes welfare can be found by solving the welfare maximization problem, that is by setting the first derivative of the welfare expression to zero and solving for the toll (so long as the second derivative is decreasing). As can be seen from the slew of

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equations developed in Chapter 4, this is a rather long expression in its full (expanded) form.

Figure 6.3 also shows how welfare (W), profit ($\prod$), 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 transportation consumers' 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 leveling 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 through 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 maximizes 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)/Size" with "W(Tax)/Size". However, the differences get smaller as jurisdiction size gets larger.

All-Cordon Toll Environment

Figure 6.4 illustrates the welfare over a range of jurisdiction sizes. The curve denoted "W(Tax)/Size" illustrates the case when Jurisdiction J_0 imposes taxes. While welfare rises with jurisdiction size, it does so at a decreasing rate. This is so because as jurisdictions get larger, the impact of other jurisdictions on local welfare diminishes, non-local policies affect a smaller proportion of locally-originating trips. So the curves in very large jurisdictions 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), consumers' surplus (U), and profit (Π) from a cordon toll policy in an all-cordon toll environment are also shown in Figure 6.4. Welfare is maximized 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 through above 20 km). This peaked shape is due to the interaction of jurisdictions. Closely spaced tollbooths (found in small jurisdictions) have a much greater finance externality than a farther spacing, so demand for longer trips increases with spacing of tollbooths. 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.

6.3.2 Policy Selection

We can define four cases which describe a jurisdiction's possible strategic decision with regard to tax or toll policy:

1. Always Tax

2. Always Toll

3. Mixed (Do the opposite): Toll when everyone else is taxing, but Tax when everyone else is tolling

4. Mixed (Do the same): Tax when everyone else is taxing, but 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. Rather 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 behavior 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 ($W_{\tau\chi} = W_{\chi\chi}$), and

the all-cordon toll environment ($W_{\tau\tau} = W_{\chi\tau}$). The equations in the case of the all-tax environment are given below (the equations in the all-cordon toll environment are similar):

$$W_{\tau\chi} + C_{CF} - C_{CF}{}' - W_{\chi\chi} = 0$$

$$C_{CF}{}' = W_{\tau\chi} + C_{CF} - W_{\chi\chi}$$

Figure 6.5 illustrates policy selection as fixed collections costs (per jurisdiction) and jurisdiction size 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 maximizing 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 behavior of neighboring 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 gets larger, the *always tax* area gets larger (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 (C_{CV}) is more complicated than as a function of fixed collection costs. Though the welfare maximizing tolls are independent of fixed collection costs, they depend on variable collection costs.   Similar to the case of fixed collection costs, we need to find the necessary variable cost coefficient (θ_n)

where welfare from tolling ($W_{\tau\chi}$) equals the welfare from taxing ($W_{\chi\chi}$) under both the all-tax and the all-cordon toll environment. However we must make sure that the welfare is computed using tolls consistent with that variable cost coefficient. For the all-tax environment, we have the following equations (the equations in the all-cordon toll environment are similar):

$$Let \quad C_{CV}{}' = \frac{C_{CV}}{\theta}$$

$$W_{\tau\chi} + C_{CV} - C_{CV}{}' * \theta_n - W_{\chi\chi} = 0$$

$$\theta_n = \frac{W_{\tau\chi} + C_{CV} - W_{\chi\chi}}{C_{CV}{}'}$$

Figure 6.6 shows the results where the welfare is calculated using the collection costs (θ_n) which are consistent with the welfare maximizing tolls resulting from those necessary variable collection costs: $\tau\,(\theta_n)$. This calculation uses a recursion procedure to solve for both the welfare maximizing toll and the collection cost necessary to equalize 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 a jurisdiction will toll, but the larger the jurisdiction size, the more likely 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, indicating 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 gets smaller and the *always tax* area gets 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.

6.3.3 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 traveler using two serial monopolists over an area is more than if the area were under the control of a single monopolist.

Table 6.4 summarizes the welfare maximizing tolls from the analysis above of a toll policy in an all-cordon toll environment as jurisdiction size varies. For instance traveling 20 km through two 10 km jurisdictions, our analysis finds that a traveler pays four tolls of $0.59 ($2.36). However, traveling 20 km through one 20 km jurisdiction, the traveler only pays two tolls of $0.62 ($1.24), much less. Similarly, for a cooperative toll-setting equilibrium (discussed in a later section), traveling 20 km through two 10 km tolling jurisdictions, one pays $0.09 four times ($0.36), compared to $0.12 two times ($0.24) for a 20 km jurisdiction.

Table 6.4 also summarizes 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. It should be noted that the difference with cooperative toll-setting equilibrium between the two scenarios is less than 1%, while with the non-cooperative toll-setting, the difference is nearly 10%.

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 gets 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 consituencies. Logrolling can lead to inefficient investments as the incentives for efficiently managing other people's money are less than for managing one's own.

Table 6.4 Comparison of Tolls and Welfare for Different Jurisdiction Sizes

	Tolls		Welfare	
Jurisdiction Size (km)	Non-Cooperative Toll-setting	Cooperative Toll-setting	Non-Cooperative Toll-setting	Cooperative Toll-setting
10	$0.59	$0.09	2581	3063
2x10	$1.18	$0.18	5162	6126
20	$0.62	$0.12	5690	6167

source: author's analysis of toll policy for J_0 and all-cordon toll environment

Figure 6.3 Welfare in J_0 at Welfare Maximizing Tolls as Jurisdiction Size Varies in an All-Tax Environment
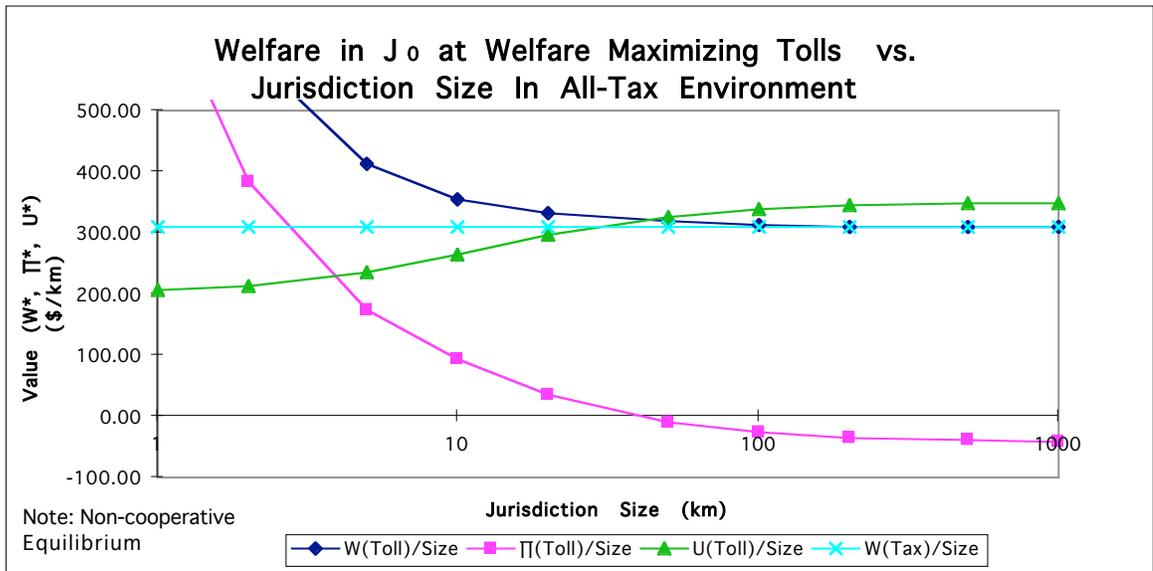
Figure 6.4 Welfare in J_0 at Welfare Maximizing Tolls as Jurisdiction Size Varies in an All-Cordon Toll Environment
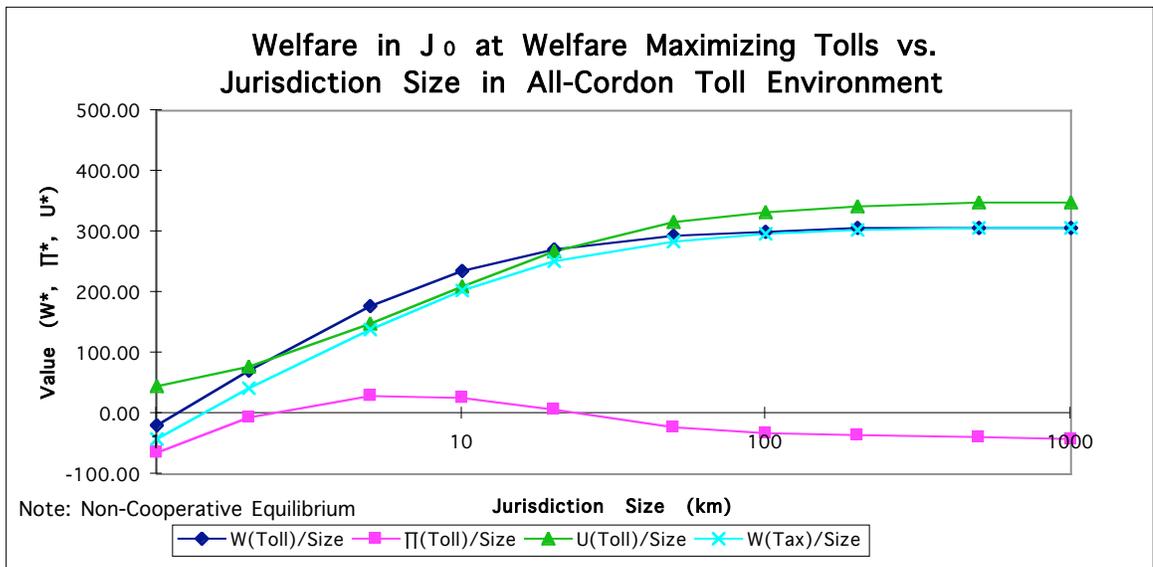
Figure 6.5 Policy Choice as a Function of Fixed Collection Costs and Jurisdiction Size

Policy Choice as a Function of
Fixed Collection Costs and Jurisdiction Size (W $_L$)

Always Tax

Toll if Environment
All-Tax,
Tax if Environment
All-Cordon Toll

Always Toll

Fixed Collection Cost ($)

Jurisdiction Size (km)

Note: Non-cooperative Equilibrium

k-necessary (all-tax) — k-necessary (all-toll) — k-empirical
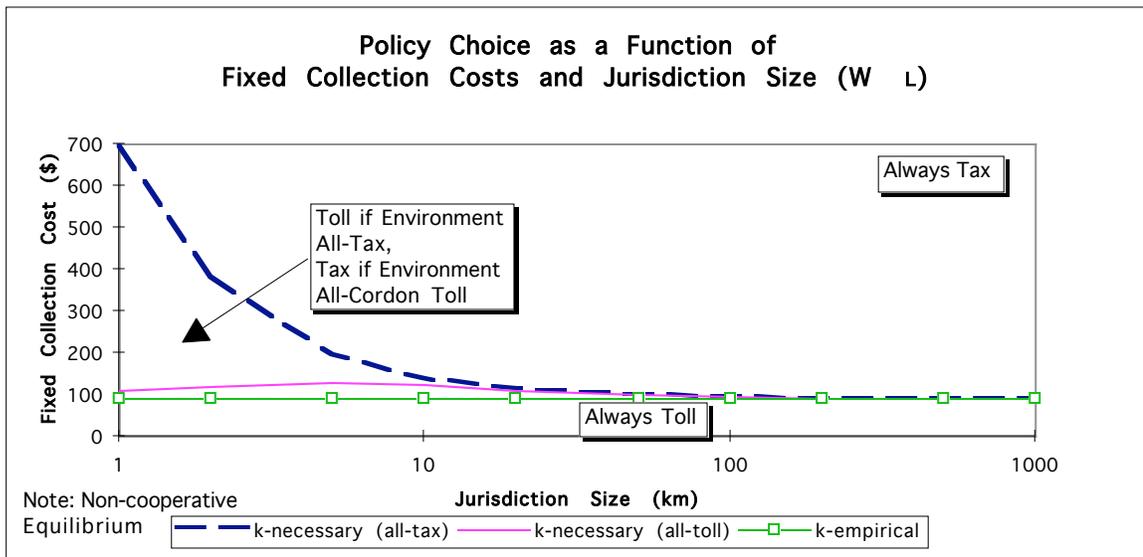
Figure 6.6 Policy Choice as a Function of Variable Collection Costs and Jurisdiction Size

Policy Choice: Variable Collection Costs Where Wtax=Wtoll and
Tolls are Consistently Estimated w/Cost, Non-Cooperative
Equilibrium

Always Toll

Always Tax

Value of Collection Cost (Theta) and Toll (Tau) ($/crossing)

Jurisdiction Size (km)

Theta-Default — All-Tax:Theta-Necessary — All-Toll:Theta-Necessary
All-Tax: Toll — All-Toll: Toll

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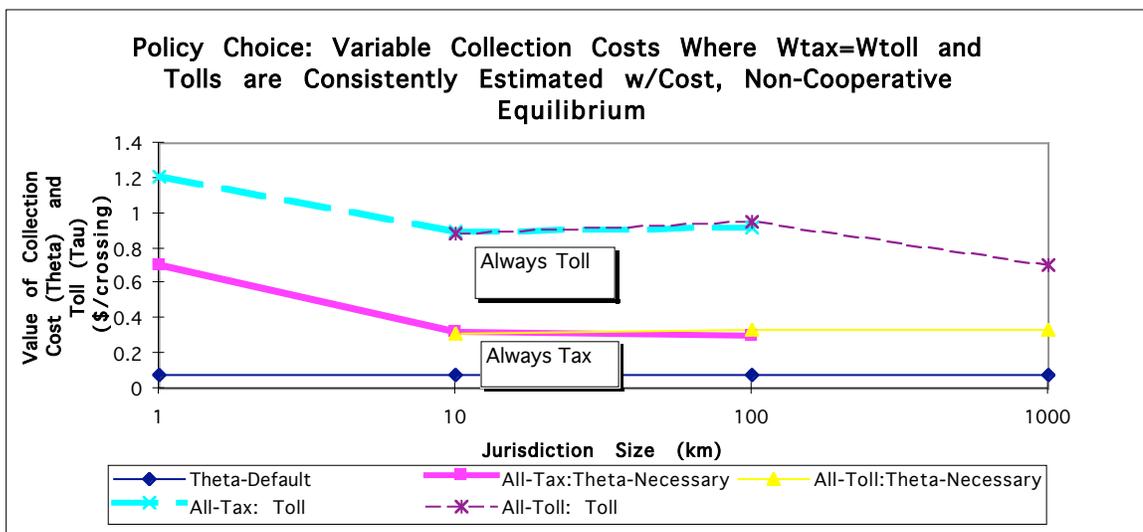
6.4 Technical Properties

This section considers three sets of technical properties associated with the model: the stability of tolls in J_0 with respect to tolls in other jurisdictions, the uniqueness of the solution, and the elasticity about the mean of the model with respect to changes in coefficients.

6.4.1 Stability and Uniqueness of Tolls

We now consider how a jurisdiction's payoff maximizing toll depends upon its neighbors' tolls. Figure 6.7 constructs reaction curves for four cases: two objectives (profit maximizing ($\prod$*) and welfare maximizing (W*)) each solved at two different jurisdiction sizes (1 km and 10 km). These two sizes were chosen as they are the most likely to show differences. As jurisdiction sizes get large, the interaction between the tolls at one cordon and the next gets small. All other conditions are identical to those assumed in the previous sections. Under welfare maximization, the tolls in jurisdiction J_0 are almost completely (but not entirely) independent of the tolls in other jurisdictions. To the extent they interact, welfare maximizing tolls are negatively correlated (a rise in one begets a fall in another). Under profit maximization, 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 maximizing toll is higher than the welfare maximizing toll, all else equal.

The increased sensitivity to other jurisdiction's tolls of the profit maximizing objective in comparison with welfare maximizing objective should not be surprising. The welfare maximizing objective depends on the consumers' surplus of local residents, while the profit maximizing objective doesn't. Rises in the price level will increase profits to a point, but will always reduce consumers' surplus, so welfare maximization is subject to more offsetting factors than profit maximization.

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The diagonal (45º) 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 maximization, 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 maximization, Nash equilibrium tolls are $0.98 and $1.12.

The welfare maximizing tolls presented in earlier sections under an all-cordon toll environment were computed with an algorithm which began by assuming that other jurisdictions had a given "seed" toll ($r_\tau^{i=0}$), 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 6.8 illustrates this for one set of assumptions (jurisdiction size = 1 km, welfare maximizing, 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 6 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.

6.4.2 Sensitivity to Model Coefficients

This section examines the sensitivity of the basic welfare measures to model coefficients, under standardized assumptions of a local welfare maximization objective, a 10 km 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 6.3. Table 6.5 summarizes the elasticity about the mean for each of the key variables. The elasticity is calculated by calculating the change in welfare (revenue, cost, consumers' surplus, profit) over the difference between two values of the variable in question, where one value is the mean, and the other is a one percent increment on the mean.

The sensitivity of demand to cost in general, the variable alpha (α), 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. The density of trip origins, the variable delta (δ), is evaluated with a default value of 180. As the density of trips increase, 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. The private fixed costs per trip, the elasticity for the variable zeta (ζ), 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 variable psi (ψ) 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 variable gamma (γ) 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 variable, phi (ϕ), is the coefficient which reflects the variable cost to the jurisdiction as a function of vehicle flow, with a default value is \$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 (θ), 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

maximizing tolls drives away more traffic (and thus reduces costs) than the increase in

variable collection costs increases costs.

Table 6.5 Elasticity About Mean

Variable		Welfare	Revenue	Cost	Cons. Surplus	Profit
|Alpha|	sensitivity of demand to cost	-3.070	-3.437	-1.758	-2.785	-5.320
Delta	density of trip origins	1.038	1.000	0.699	1.000	1.337
Zeta	private fixed costs	-0.424	-1.150	-0.498	-0.239	-1.879
Psi	sensitivity of demand to trip length	-0.094	-0.143	-0.119	-0.065	-0.156
Gamma	fixed costs associated with network length	-0.044	0.000	0.250	0.000	-0.596
Phi	variable cost associated with network use	-0.049	-0.028	0.277	-0.017	-0.251
Theta	variable collection costs	-0.016	-0.013	0.053	-0.009	-0.065

Note: Elasticity of Welfare (Revenue, Cost, Consumer's Surplus, Profit) About Mean of Alpha (Delta, Zeta, Psi, Gamma, Phi, Theta)

Figure 6.7 Reaction Curves: Best J_0 Toll as Tolls Vary in an All-Cordon Toll Environment

Reaction Curves:
Best J_0 Toll in All-Cordon Toll Environment

Note: Non-Cooperative Equilibrium

Legend:
∏-Jurisdiction Size=10 km
W-Jurisdiction Size=10 km
∏-Jurisdiction Size=1 km
W-Jurisdiction Size=1 km
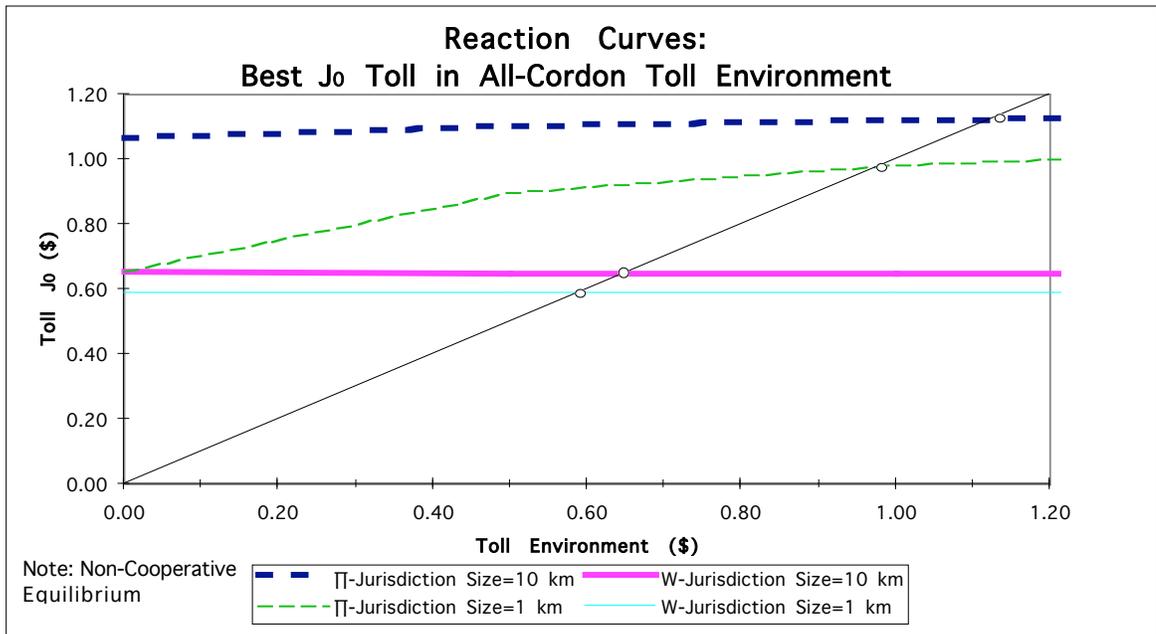
Figure 6.8 Uniqueness: Non-Cooperative Welfare Maximizing J_0 Toll as Initial Toll for Other Jurisdictions Varies in All-Cordon Toll Environment

Uniqueness: Equilibrium Tolls as Starting Point (S) of Other Jurisdiction's Tolls Varies

Note: Welfare Maximizing, Non-Cooperative Toll-Setting, Jurisdiction Size=1 km

Legend:
S=-1   S=0   S=1   S=10
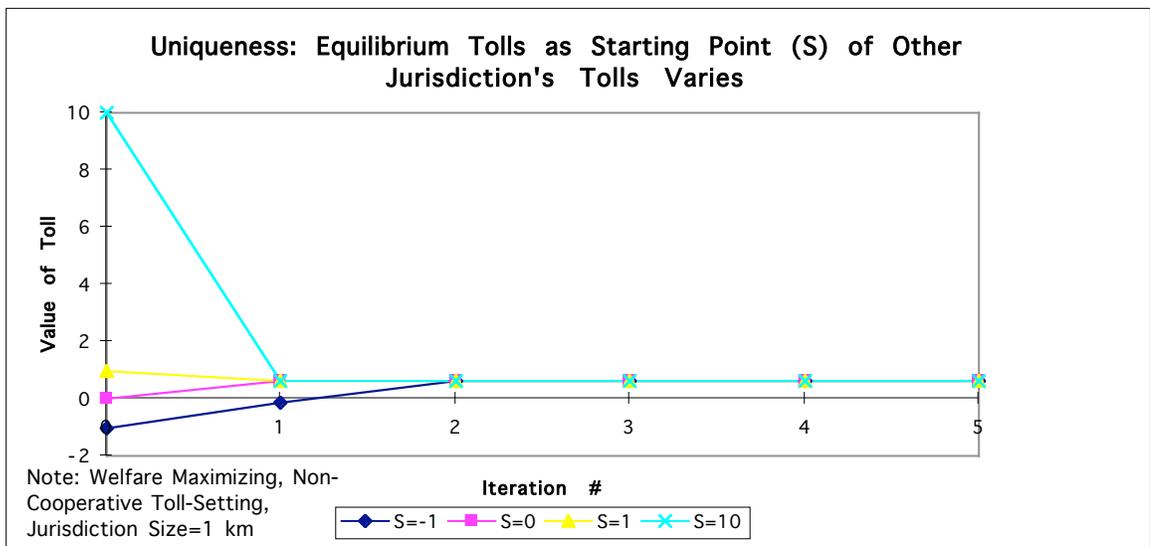
6.5 Jurisdiction Behaviors

Up to now, we have made some rigid assumptions about the behavior of a jurisdiction. Until now we have assumed non-cooperative toll-setting, in this section we consider cooperative toll-setting as well. Previously, we have assumed a one-shot game, though a repeated game is more realistic, so we consider the consequences on the equilibrium of repeating indefinitely the game between jurisdictions (involved in non-cooperative toll-setting). We assumed that only one objective (local welfare maximizing), but two others (profit maximizing and local welfare maximizing with a cost-recovery constraint) are investigated in this section.

6.5.1 Cooperative vs. Non-Cooperative Toll-Setting

Our research considers two decisions, the strategic decision to tax or toll, and the tactical decision what rate of tax or toll to set. Therefore, there are two types of cooperation: *strategic cooperation* (deciding to tax rather than toll), and *tactical cooperation* involving the setting of the rate of toll. This section considers tactical cooperation, given the strategic decision to toll. Earlier sections assumed an equilibrium derived from non-cooperative toll-setting. Jurisdictions engage in non-cooperative toll-setting when a jurisdiction sets tolls given the other jurisdiction's tolls and vice versa, such that no one jurisdiction can improve its welfare by changing tolls unilaterally. However, if the jurisdictions cooperate with each other, they can mutually improve welfare. The results are lower (or zero) tolls and higher welfare. Cooperation is achieved, as discussed in Chapter 4, by endogenizing the other jurisdictions' tolls in the toll that jurisdiction J_0 sets.

For comparison, we consider three scenarios: tolling in an all-tax environment, and tolling in all-cordon toll environment under both non-cooperative and cooperative toll-setting. Tolling in an all-tax environment does not involve interaction with other jurisdictions at the tactical level, and therefore can be thought of as non-cooperative. There

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would be no cooperative toll-setting analog in the all-tax environment. Figure 6.9 compares tolls for these three scenarios. Clearly, the cooperative equilibria has significantly lower welfare maximizing tolls than a non-cooperative equilibrium. As noted in the section on reaction curves, other jurisdictions' rate of toll (zero in the all-tax environment, and identical tolls in the all-cordon toll environment under non-cooperative equilibrium) have little impact on the toll imposed by the jurisdiction of interest (J_0).

While the tolls are lower, the welfare is higher for the cooperative toll-setting equilibrium. Simply put, the cooperative equilibrium trades profit for consumers' surplus. Figure 6.10 shows the welfare resulting from toll policies and all-cordon toll environments, under both a non-cooperative equilibrium (seen in the previous section) with a cooperative equilibrium. Welfare is uniformly higher in the cooperative equilibrium than the non-cooperative equilibrium.   However, it is always better to be in a position where others tax than to be in situation where others toll. Another point to observe is that the welfare from cooperative equilibria, while lower at small jurisdiction sizes, does not become negative, while the welfare for a non-cooperative equilibria does. A third point reiterates what was noted earlier, small jurisdictions have a great incentive to toll when their neighbors don't, however the gains diminish as jurisdictions get larger.

The cooperative equilibrium results in very similar patterns to the policy choice found with a non-cooperative equilibrium. The curves were slightly shifted so that a cooperative equilibrium results in tolling at somewhat higher collection costs that could be sustained in a non-cooperative equilibrium.

The cooperative equilibrium is equivalent to the objective of global welfare maximization (W^*_G) when the placement of tollbooths is fixed. This objective resembles what a super-jurisdiction would employ, for instance the federal government compared with states. Global welfare maximization is just local welfare maximization when all trips are internalized.   The relationship between welfare and policy choice depends on two main factors: collection costs and the marginal costs and benefits of road use. So long as toll

collection costs are significant and the marginal costs of road use are small compared with the marginal benefit, tax policies result in higher overall welfare than toll policies. That is, there are no gains to the super-jurisdiction for imposing tolls except reducing marginal costs.

Figure 6.9 Comparison of Tolls Under Cooperative and Non-Cooperative Equilibria
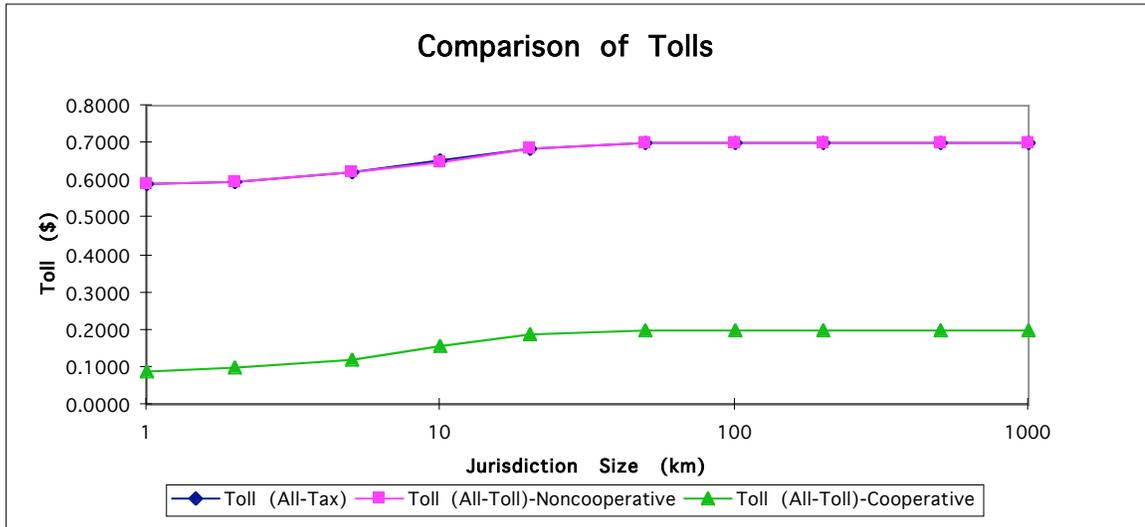
Figure 6.10 Comparison of Welfare Under Cooperative and Non-Cooperative Equilibria
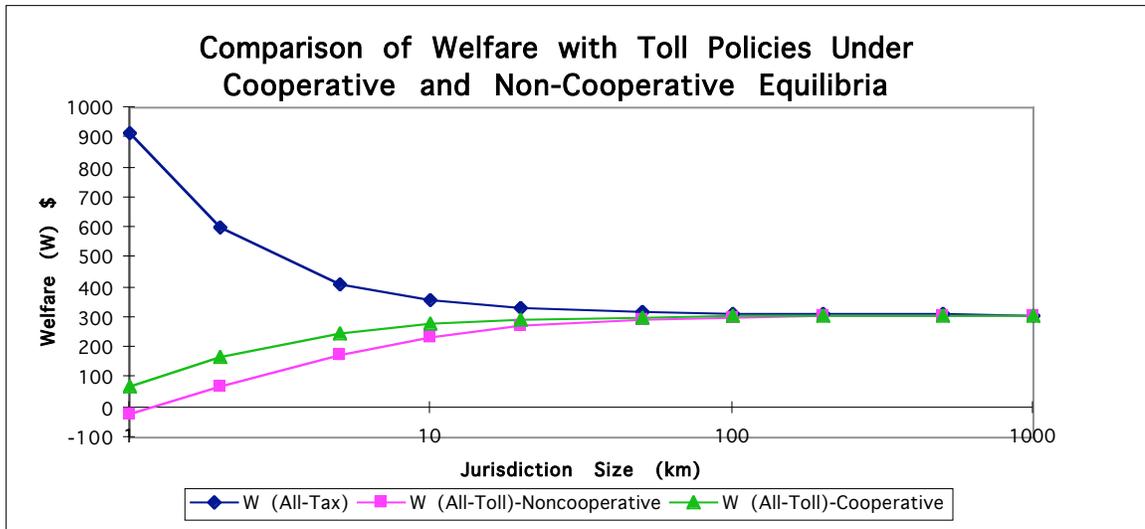
6.5.2 Repeated Games

The previous sections solved a one-shot game, this section analyzes the strategic policy selection (tax or toll) in the context of a repeated game. Under the one-shot game, we saw that the Nash equilibrium solution was not the one with the highest payoff. Rather, the [Tax, Tax] case had a higher overall welfare than the Nash equilibrium [Toll, Toll]. If a mechanism could be found to achieve the higher welfare associated with [Tax, Tax], then both jurisdictions would be better off. The question is how strategic cooperation between jurisdictions can be achieved. A mechanism which can result in strategic cooperation without actual negotiation is the enforcement available in repeated games. In an indefinitely repeated game, one jurisdiction's behavior can be disciplined by another's. Cheating on an agreement (for instance tolling when taxing was agreed to) by jurisdiction J_0 in one round can be punished by jurisdiction J_1 in the next round. The punishment is that J_1 would toll, thereby hurting the payoff to jurisdiction J_0. This section applies the mathematics underlying repeated games, and computes the necessary discount factors for strategic cooperation to be stable between rational jurisdictions.

To begin we will examine the conventional two strategy one-shot game. Consider the representation in Table 6.6 (after Taylor 1987) of the payoffs for two strategies of the two player prisoner's dilemma game, where the traditional prisoner's dilemma cooperate strategy is associated with imposing a general tax (χ) and the defect strategy with imposing cordon tolls (τ). As noted above the strategy pair [Toll, Toll] is a Nash equilibrium in this one-shot game. The letters w, x, y, and z are used to denote the payoffs in this section as shown in the table.

Payoffs from repeated games (or a supergame) can be thought of as the summation of a series of payoffs from one-shot games, discounted so that this game is more valuable than the next and so on. If we define a discount factor for jurisdiction i, a_i, (and a discount

rate: 1- a_i), then we can compute the supergame payoff (X) from a strategy which results in the payoff x on every turn as $X = x(a_i + a_i^2 + a_i^3 + ...)$, or $X = x(a_i / (1- a_i))$, and similarly for any other payoffs (w, y, z). It should be noted that $1 \geq a_i \geq 0$, and other values are invalid (suggesting either future payoffs are more valuable than the present if $a_i > 1$, or that future payoffs are negative in value if $0 > a_i$). It should also be noted that the discount factor can vary for different jurisdictions.

Strategies in a sequence of games can be formulated which result in stable equilibria for each player and higher payoffs. We will consider four supergame strategies: tax on every round (χ^∞), toll on every round (τ^∞), conditionally tax with initial trust (B), and conditionally tax with initial distrust (B'). The first conditional strategy (B), (also called *tit-for-tat*) begins by cooperating (imposing a tax) on turn 1, and then on all subsequent turns does what the other player did in the previous turn. A variation on this strategy (B') is also *tit-for-tat*, but begins by defecting (imposing a toll) on turn 1, and then doing what the other player did.

We can conclude that in the repeated game, the strategy pair of both jurisdictions choosing to toll on every round, independent of what the other players are doing, $[\tau^\infty, \tau^\infty]$, is an equilibrium. Neither player can improve their position if the other plays τ^∞. However, this is not necessarily the best equilibrium. The strategy of taxing every round, again independent of what the other players are doing (χ^∞), is never an equilibrium. If your opponent is playing χ^∞, there is always a gain possible from any other strategy. The conditional supergame strategies, where the policy employed by one jurisdiction depends on what other jurisdictions did on a previous turn, are more complicated.

We can reformulate the game in terms of supergame strategies, shown in Table 6.7. The three supergame strategies which are sometimes equilibria (B, B', τ^∞) can be played by jurisdiction J_0 and J_1. The cells in the table show which conditions (of Table 6.8) hold for the supergame strategy to be a repeated game equilibria. It can be shown (Taylor 1987) that

the results shown in the first column of Table 6.8 hold when the conditions in the second column bear out.

To use the general results derived for two-player games, we need to make several simplifying assumptions to our network model. Increasing the analytical complexity for repeated multi-player games is not expected to provide additional insight to this case. First we redefine the network as being covered by two infinitely long jurisdictions, one ranging from the point $-\infty$ to a boundary point b, where a toll-booth may be located, the other covering the area from point b to $+\infty$. We directly assume a two way road in this case. This is illustrated in Figure 6.11.

Because the jurisdictions are infinite in size, we are not interested in total welfare, rather only in welfare crossing the boundary point b. Thus consumer's surplus is only comprised of local boundary crossing trips, the cost imposed by boundary crossing trips, and the revenue from boundary crossing trips. These revised equations are shown in Table 6.9. The prisoner's dilemma for the new one-shot game is illustrated for this case in Table 6.6, showing the welfare implications to J_0 and J_1 of boundary crossing trips using the equations above, assuming non-cooperative toll-setting.

The final column of Table 6.8 gives the value associated with the right hand side of the condition in the table. Applying those conditions to the strategy pairs of Table 6.7 we get the solution to the repeated game equilibria, shown by the range of discount factors shown in brackets in that table. We assume that if there are multiple equilibria in the game, that jurisdictions will choose the one which results in the highest welfare to them so long as it results in the highest welfare to other players. Just as in the one-shot game, if there is one stable equilibrium which does provide the highest welfare to all players, it can be anticipated to be chosen. We see several policy pairs are valid (repeated game equilibria). Significantly for discount factors in the range: $1 \geq a_i \geq 0.16$ (or discount rates between 0% and 84%), mutual cooperation [B, B] is a stable equilibrium, and since it has the highest payoff, we can assume that it would be the selected equilibrium.

This alternating policy pair [B', B] or [B, B'] emerges as stable for the range of discount factors: $0.16 \geq a_i \geq 0.04$ (or discount rates between 84% and 96%). Implicitly this assumes that the fixed costs due to cordon tolls can be constructed and removed at no loss, or at least result in no charge during the off-turn, though the extent to which this is true is empirical. A similar policy is for one jurisdiction to always play cooperate and the other defect, so long as revenues are shared equally between them. Whether this can actually be enforced depends on the institutional arrangements between the jurisdictions. However, if we assume that these jurisdictions can cooperate at that level, it is unclear why they would select the alternating policy pair unless it had a higher payoff.

A range of discount factors ($0.04 \geq a_i \geq 0$) (discount rates between 96% and 100%) allows the policy pair of [B', B'] to be stable, which in practice is the equivalent of mutual defection $[\tau^\infty, \tau^\infty]$. Similarly $[\tau^\infty, B']$ and $[B', \tau^\infty]$ are stable when one or the other jurisdiction has such a low discount factor ($0.04 \geq a_i \geq 0$). These policies are also the equivalent of mutual defection $[\tau^\infty, \tau^\infty]$.

Figure 6.11 Illustration of Infinitely Long Road Covered Completely by Two Jurisdictions
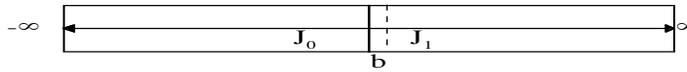
Table 6.6 Welfare of Boundary Crossing Trips on Infinite Road Covered by Two Jurisdictions

$J_0 \setminus J_1$	General Tax (χ)	Cordon Tolls (τ)
General Tax (χ)	$[x, x] =$ [1403, 1403]	$[z, y] =$ [940, 1477]
Cordon Tolls (τ)	$[y, z] =$ [1477, 940]	$[w, w] =$ [961, 961]

where: $y > x > w > z$, numeric values indicate payoff from model

Table 6.7 Conditions for Supergame Strategies to be Equilibria

$J_0 \setminus J_1$	B	B'	τ^∞
B	(1) & (2) for J_0, J_1 $[1 \geq a_i \geq 0.16]$	(3) & rev. (2) for J_0, J_1 $[0.16 \geq a_i \geq 0.04]$	Never equilibrium
B'	(3) & rev. (2) for J_0, J_1 $[0.16 \geq a_i \geq 0.04]$	(4) & rev. (3) for J_0, J_1 $[0.04 \geq a_i \geq 0]$	(4) & rev (3) for J_1 $[0.04 \geq a_1 \geq 0]$
τ^∞	Never equilibrium	(4) & rev (3) for J_0 $[0.04 \geq a_0 \geq 0]$	Always equilibrium

Note: rev. denotes reversing the $\geq$ in the equation (i.e. making it $\leq$). Conditions are defined in Table 6.8

[] indicates results of conditions for game

Table 6.8 Conditions for Supergame Strategies, and Results from Equations Above

Result	Condition	Value of RHS
(1) B is superior to τ^{∞} if	$a_i \geq \dfrac{y-x}{y-w}$	0.14
(2) B is superior to B' if	$a_i \geq \dfrac{y-x}{x-z}$	0.16
(3) B' is superior to τ^{∞} if	$a_i \geq \dfrac{w-z}{y-w}$	0.04
(4) Mutual B' is stable if the reverse of condition (3) holds and	$a_i \leq \dfrac{w-z}{x-z}$	0.04

Table 6.9 Equations for Two Jurisdiction System

Component	Equation
Consumer's Surplus (U_{ij})	$U_{ij} = \dfrac{\delta e^{\left(r_\tau + r_{\underline{\tau}} + \zeta\right)}}{\alpha^3 \psi^2}$
Cost Network Flow ($C_{\rho ij}$)	$C_{\rho ij} = \dfrac{\delta \phi e^{\left(r_\tau + r_{\underline{\tau}} + \zeta\right)}}{\alpha^3 \psi^3}$
Cost Collection (C_{CVij})	$C_{CVij} = \dfrac{\delta \theta e^{\left(r_\tau + r_{\underline{\tau}} + \zeta\right)}}{\alpha^2 \psi^2}$
Revenue (R_{ij})	$R_{ij} = \dfrac{\delta r_\tau e^{\left(r_\tau + r_{\underline{\tau}} + \zeta\right)}}{\alpha^2 \psi^2}$
Welfare	$W = U_{ij} + 2 * R_{ij} + 2 * C_{ij} + 2 * C_{CVij}$

6.5.3 Alternative Objectives

Three different objective functions which a jurisdiction may utilize have been identified. These are welfare maximization (W^*), welfare maximization with a cost-recovery constraint (W^*_{LCR}), and profit maximization (Π^*). Up to now, we have only considered welfare maximization (though profit maximization was touched on briefly in the analysis of reaction curves). The profit maximization objective basically disentangles the ownership of the network from the community which encompasses it. This objective represents the case where the network is owned by the private sector and unregulated. It provides a benchmark for comparison, because if the welfare consequences are not too large, and there are true operating efficiencies or cost savings enabled by private sector management, then a private, unregulated organizational structure may be efficient for networks. Local welfare maximization with a cost recovery (W^*_{LCR}) constraint simply says that the jurisdiction attempts to avoid a profit or loss through its revenue policy. This policy resembles in practice what many states do with their highway financing system, which are run so that revenues from various transportation tax sources (gas taxes, licenses and registration, etc.) match expenditures as closely as possible.

This section compares the three objectives for the case of cooperative and non-cooperative toll-setting under cordon toll policies and an all-cordon toll environment. This section assumes for each curve that all jurisdictions are behaving identically. Thus a profit maximizing curve under cooperative equilibrium is computed assuming that all jurisdictions are cooperatively profit maximizing. Mixed objectives (where different jurisdictions have different objectives) are not considered here.

It should be noted that the cost recovery constraint can only be satisfied over a small range of jurisdiction sizes (between 2 and 20 km inclusive). Thus the curves in the graphs for the constrained welfare maximizing case (W_{LCR}^*) are only shown for that range.

Both smaller and larger jurisdictions result in negative profits for that objective. A second point to note is that the cooperative and non-cooperative toll-setting equilibria for that case are identical, as the constraint eliminates any benefits from cooperating. Local welfare maximization under a tax policy and all-tax environment is no different with or without the cost recovery constraint. The case under a cordon toll policy is somewhat more complicated.

Figure 6.12 shows the rate of toll for the three different objectives under cooperative and non-cooperative equilibria. In order from highest to lowest tolls, the cases are ranked as follows: profit maximizing non-cooperative, welfare maximizing non-cooperative, profit maximizing cooperative, welfare maximizing with a cost recovery constraint, and welfare maximizing cooperative. This ranking is stable over the whole range of jurisdiction sizes. It might further be noted that welfare maximizing non-cooperative and profit maximizing cooperative converge to the same toll at and above 20 km jurisdiction sizes. In general tolls rise as jurisdiction size increases. The exception is the case of welfare maximizing with a cost recovery constraint, which declines for a range of jurisdiction sizes before rising. For the same type of equilibrium, profit maximizing tolls are higher than welfare maximizing, which is consistent with the results presented in the section considering reaction curves.

Figure 6.13 plots the welfare from the three objectives under the two equilibria. In order from greatest to smallest welfare, the cases are ranked in the reverse order of the ranking for tolls: welfare maximizing cooperative, welfare maximizing with a cost recovery constraint, profit maximizing cooperative, welfare maximizing non-cooperative, and profit maximizing non-cooperative. Here, for the same type of equilibrium, as might be expected, the welfare maximizing objective produces greater welfare than the profit maximizing objective. At large jurisdiction sizes, the results converge, again welfare maximizing non-cooperative and profit maximizing cooperative converge, in this case to the same welfare at and above 20 km jurisdiction size.
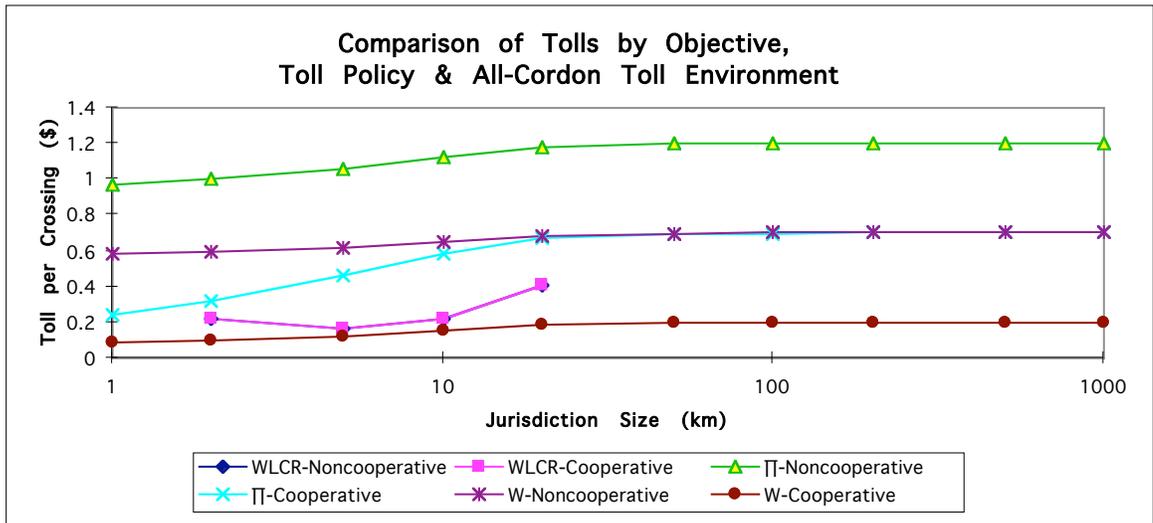
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Figure 6.14 graphs the profits for the six cases. By definition the case of welfare maximizing with a cost recovery constraint results in zero profit. The rankings of the other cases here are somewhat different than above. From greatest to least profit, we get in order profit maximizing cooperative, welfare maximizing non-cooperative, profit maximizing non-cooperative, and welfare maximizing cooperative. What is interesting here is that cooperative equilibria are at the extremes, the greatest profit from a cooperative toll-setting equilibrium of profit maximizing jurisdictions, the greatest loss from a cooperative toll-setting equilibrium of welfare maximizing jurisdictions. These rankings are generally stable, though the value of profit may be either positive or negative depending on jurisdiction size, and thus cross the zero profit line associated with the constrained welfare maximizing case. Three of the cases have positive profits (profit maximizing cooperative, welfare maximizing non-cooperative, profit maximizing non-cooperative) for at least some jurisdiction sizes, while the case of welfare maximizing cooperative has below zero profits. The pattern is single peaked, generally the greatest per capita profits are found between jurisdictions of 5 and 10 km in length. Larger jurisdictions have excessive costs, smaller jurisdictions suffer from a significant finance externality and thus have lower demand.

It might also be noted that the differences between the profit and welfare maximizing objectives in the case of an all-tax environment are slight, with welfare diminished by only a few percentage points. This suggests that profit maximizing is a close approximation to welfare maximizing in the all-tax environment, and if the profits are returned to the residents, this objective may be useful as a surrogate for welfare. However if profits are are not returned to residents, the welfare outcome is quite different. Under the all-cordon toll environments the differences are greater.

Cooperation results in higher welfare under both objectives, and higher profits for profit-maximizing jurisdictions. Thus cooperation would seem to be globally preferred to non-cooperation regardless of the objective. However, profit maximization results in significantly lower welfare than welfare maximization, so unless other benefits to this

objective which we have not directly considered (cost savings from efficient private operation, ease of coordination in the private sector compared with the public sector, etc.) are significant, unfettered profit maximization of a monopoly link in a serial network will not serve the interests of all.

Figure 6.12 Comparison of Tolls by Objective, Toll-Setting Equilibrium

Comparison of Tolls by Objective,
Toll Policy & All-Cordon Toll Environment

WLCR-Noncooperative WLCR-Cooperative ∏-Noncooperative
∏-Cooperative W-Noncooperative W-Cooperative

Figure 6.13 Comparison of Per Capita Welfare by Objective, Toll-Setting Equilibrium

Comparison of Per Capita Welfare by Objective,
Toll Policy & All-Cordon Toll Environment

WLCR-Noncooperative WLCR-Cooperative ∏-Noncooperative
∏-Cooperative W-Noncooperative W-Cooperative
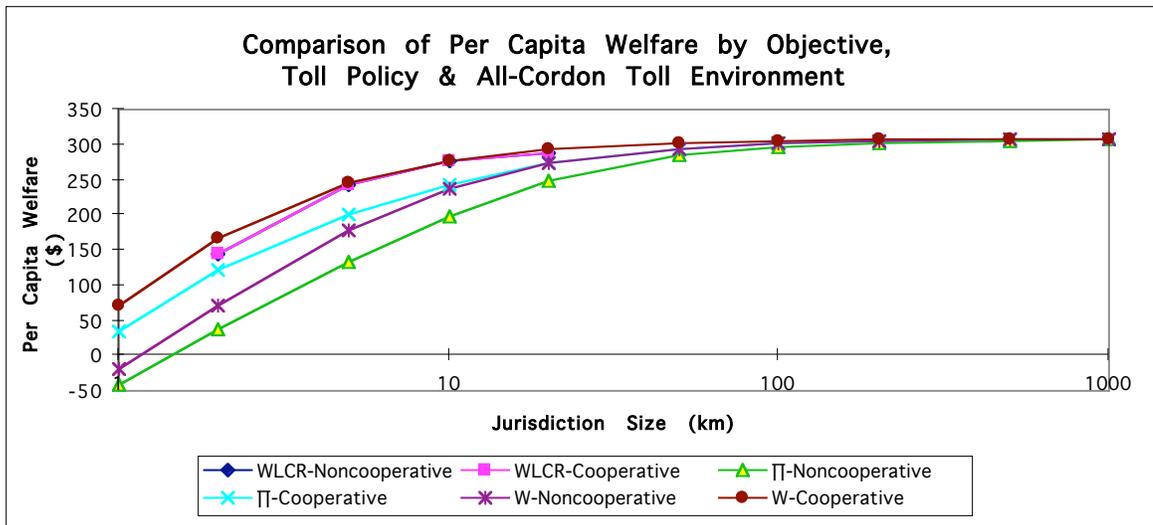
Figure 6.14 Comparison of Per Capita Profit by Objective, Toll-Setting Equilibrium

Comparison of Per Capita Profit by Objective, Toll Policy & All-Cordon Toll Environment
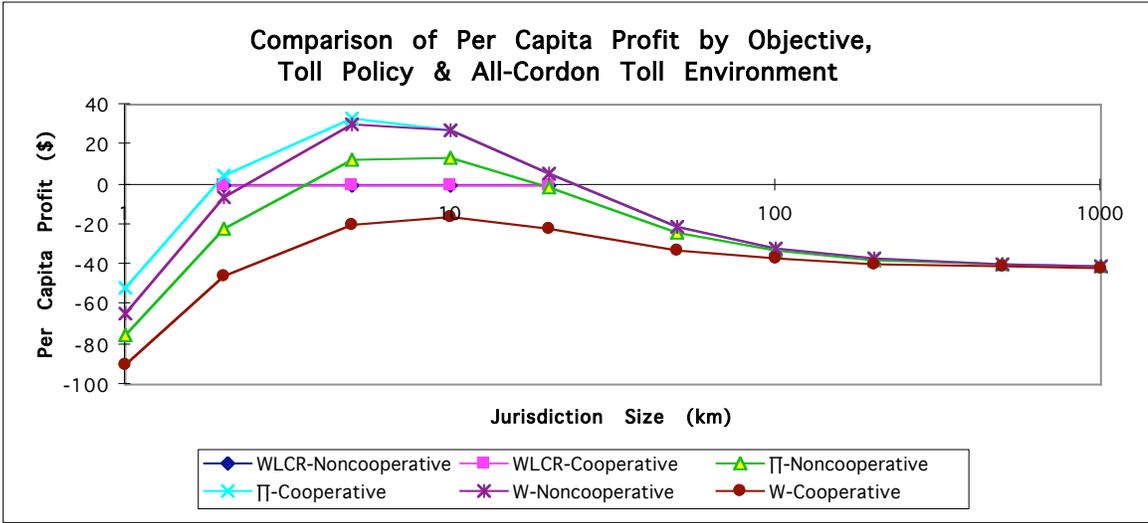
6.6 Perfect Tolls and Odometer Taxes

Until now we have examined the general tax and cordon toll revenue mechanisms. This section considers two other revenue mechanisms: perfect tolls and odometer taxes. These mechanisms are considered together because, for the network geometry we assume and the case of cooperative toll-setting, they turn out to have the same results. We assume cooperative toll-setting because it is more likely that tolls will be coordinated (at least for long lengths of road) if toll collection is perfect. We analyze "perfect" tolls by considering very small "jurisdictions" (down to 0.00001 km in length) and assuming zero collection costs. This discrete approximation of a true perfect toll negates the need to introduce a new set of equations.

It should be emphasized that the network is continuously loaded, and thus toll-booths here are simply demarcations where revenue is collected, and would likely entail electronic toll collection. Other technologies for collecting revenue under perfect tolls are likely to be more efficient, but as we have assumed zero collection costs, those technologies are not expected to result in different levels of demand, welfare, or rate of toll in $/km.

The odometer tax mechanism taxes each resident of a jurisdiction in proportion to the amount of travel they undertake, whether or not that travel is within the jurisdiction. In a sense, this is analogous to a gasoline tax under the assumption that all gasoline is purchased in the home jurisdiction (while a perfect toll is analogous to a gas tax when gas is purchased along a link in a jurisdiction in proportion to the amount of travel on that link and in that jurisdiction). The odometer tax welfare measurement uses a different set of equations from the general tax, cordon toll, or perfect toll, which are all of the same form (with special assumptions). As a consequence, welfare cannot be measured directly, however, we can find the odometer tax (r_ω) which optimizes welfare.

Figure 6.15 compares tolls for a variety of spacings between "toll-booths" with the rate of tax per km for odometer taxes. We note that the differences in welfare or effective tolls ($/km) between jurisdictions of 0.0001 km to jurisdictions 1.0 km in length is unobservable on the graph at this resolution, suggesting that if collection costs are an issue, tolls need not be perfect in the sense of capturing every last tenth (or ten-thousandth) of a km traveled (though of course shunpikes etc. need to be avoided). Effective tolls ($/km) are higher the more perfect (the more tightly spaced) the tolls are, though actual tolls ($/crossing) are higher the less perfect the toll.

The welfare maximizing odometer tax under cooperative equilibrium of $0.018/km can be compared with rates of tolls above. Under perfect tolls, discussed in the previous section, the effective rate is also $0.018/km as both perfect tolls and this odometer tax result in zero profit. In general odometer taxes are no more efficient than perfect tolls. Under a welfare maximizing non-cooperative toll-setting equilibrium, at a jurisdiction size of 10 km, tolls (in terms of $/crossing) were welfare maximizing at about $0.60/crossing, which translates to on the order of $0.06/km at typical trip lengths, for those crossing the cordon (and $0.00 for those not crossing).

Figure 6.16 compares the welfare resulting from these two revenue mechanisms. It should be noted that profits are zero for perfect tolls and odometer taxes. This indicates that revenue equals cost, in concordance with the notion of efficient (welfare maximizing) pricing that price = marginal cost (since there are no fixed costs by assumption, marginal cost equals average cost in this scenario). For perfect tolls, welfare is highest for the tightest spacing here. The welfare under these two cases is higher than with [Tax, Tax] or [Toll, Toll] strategies under cooperative equilibria because the free rider problem has been eliminated.

Figure 6.15 Tolls under Perfect Tolls & Odometer Taxes as Tollbooth Spacing Varies.

"Perfect" Tolls & Odometer Taxes:
Tax/Toll in J_0 vs. Tollbooth Spacing/Jurisdiction Size

Note: Cooperative Equilibrium, No Collection Costs
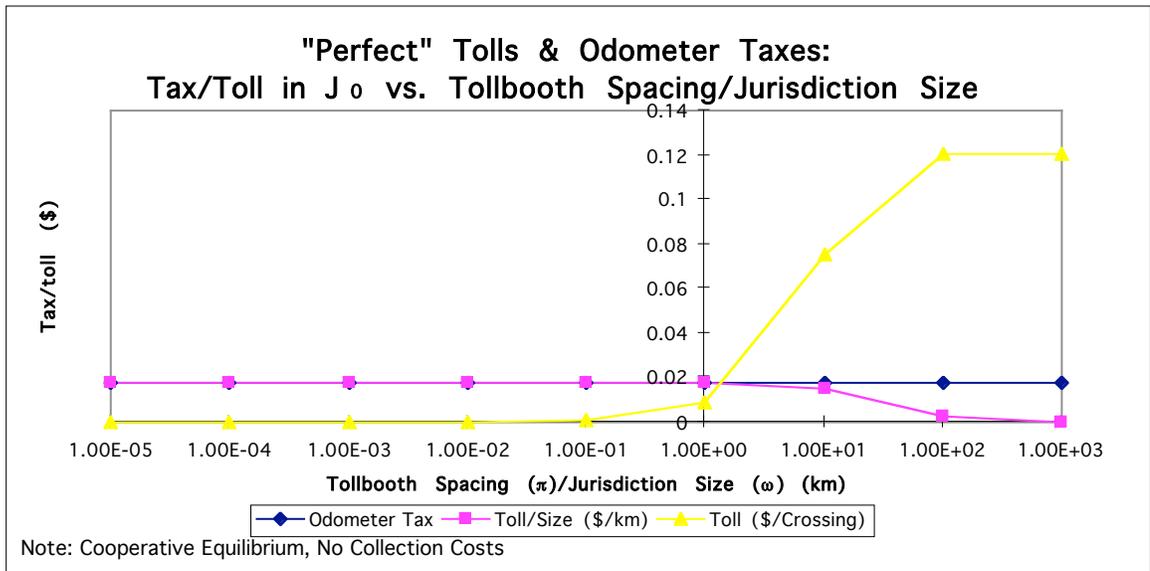
Figure 6.16 Welfare under Perfect Tolls & Odometer Taxes as Tollbooth Spacing Varies.

"Perfect" Tolls & Odometer Taxes:
Welfare in J_0 vs. Tollbooth Spacing/Jurisdiction Size

Note: Cooperative Equilibrium, No Collection Costs
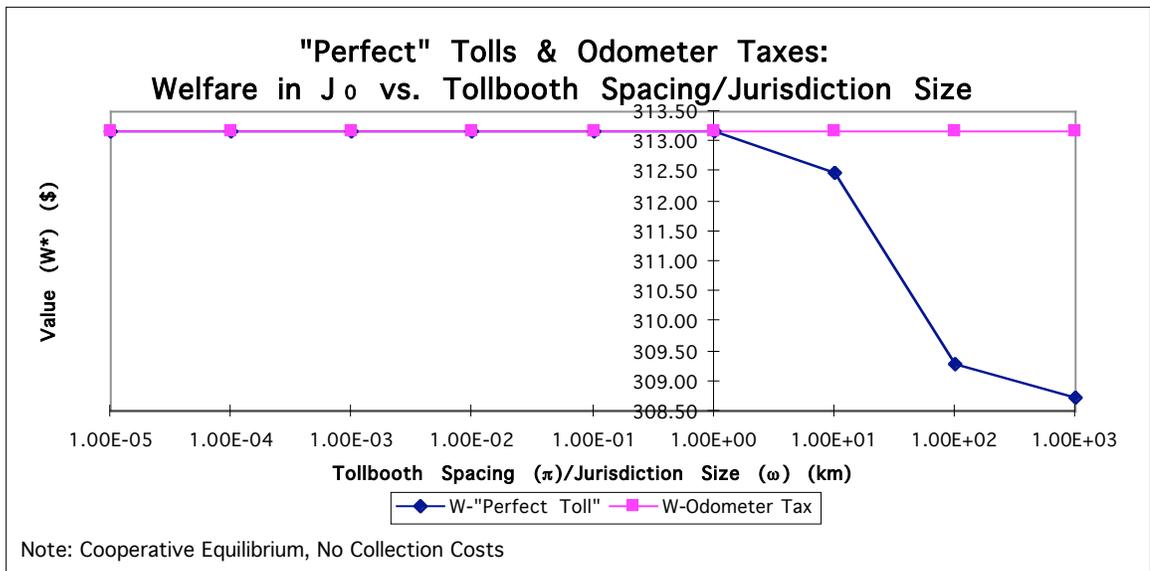
6.7 Summary

The purpose of this chapter was to employ a model to explain under what conditions jurisdictions choose to tax or to toll as a function of the length of trips, the size of the jurisdiction, the transactions costs of collecting revenue, demand, and the cost of providing infrastructure. While the broad policy conclusions will be discussed in the following chapter, solving our model we reach a number of technical conclusions:

1. For our given set of assumptions, there is a unique, stable welfare maximizing toll with non-cooperative toll-setting. Similarly, there is also a unique welfare maximizing toll under cooperative toll-setting.

2. Welfare may be positive even if costs exceed revenues, suggesting that in many cases, a mixed tax/cordon toll policy has higher welfare than one policy or the other.

3. Welfare is highest for a jurisdiction which tolls when other jurisdictions don't. Thus, the incentives to toll when other jurisdictions tax are much greater than when other jurisdictions toll.

4. The choice between tax and cordon toll policies (or mixed tax/toll policy) is often of the form of a prisoner's dilemma, with the better overall solution not being a Nash equilibrium under a one-shot game.

5. Welfare varies with jurisdiction size, the policies of the environment and the policies of the own jurisdiction. Large jurisdictions have smaller differences between welfare of different policy combinations than small jurisdictions. Thus, the incentives for small jurisdictions to toll are much greater than the incentives for large jurisdictions.

6. Management of the network by a government higher in the hierarchy of jurisdictions (e.g. national rather than state) may increase welfare if there are no diseconomies associated with the higher level of government such as span of control or logrolling.

7. Tolls under welfare maximization are largely independent of the tolls charged by other jurisdictions. Under profit maximization, tolls in one jurisdiction are much more interdependent on tolls in adjacent jurisdictions. Tolls do not depend on the initial (seed) value of the other jurisdictions' tolls in the equilibration algorithm.

8. Sensitivity analyses suggest that welfare is highly sensitive to (in order: (δ) density of trips, (α) sensitivity of demand to price, (ζ) user fixed costs of travel, (ψ) user cost as a function of trip distance.) Welfare is much less sensitivity to the cost coefficients (fixed network costs (γ), variable network costs (ϕ), and variable collection costs (θ)) As might be expected, profit is more sensitivity to the network cost variables, though sensitivity of demand to price, private fixed costs of travel are also significant. Profit is largely insensitive to variable collection costs (θ) and user cost as a function of trip distance (ψ).

9. Global welfare maximization is the equivalent of a cooperative toll-setting equilibrium of local welfare maximization, and can be computed as such, assuming a fixed position for toll-booths. The welfare maximizing cooperative toll is lower than the non-cooperative toll.

10. In a repeated game, the [Tax, Tax] strategy pair results in the highest overall welfare for the assumptions used here, but is not a Nash equilibrium in a one-shot game.

11. Under profit maximization, tolls are higher than under welfare maximization, and welfare lower, suggesting that unregulated monopoly has costs which are significant, and may outweigh efficiency of administration. However, cooperative profit maximization has total welfare which is the same as non-cooperative welfare maximization, suggesting that under the right conditions, private sector management is an alternative which can be considered.

12. The presence of a cost recovery constraint results in lower welfare than its absence. This constraint makes toll collection unsustainable for large jurisdictions, as not enough tolls can be recovered to cover costs.

13. Perfect tolls are modeled as very closely spaced cordons with zero collection costs in an environment in which all other jurisdictions also employ perfect tolls. At close spacings (less than 1km between tollbooths), the results are virtually indistinguishable, and profits are approximately zero, suggesting that price equals marginal cost. While tolls measured as $/km rises as tollbooth spacings become closer, measured as $/crossing tolls decline. The more perfect the toll, the higher the welfare, though this depends on assuming zero collection costs.

14. Odometer taxes are modeled with a different set of equations than the previous revenue mechanisms. When welfare is maximized and cooperative toll-setting employed, the odometer tax per km is the same as the level of perfect tolls.

7. CHAPTER SEVEN: SUMMARY AND CONCLUSIONS

7.1 Introduction

A reconsideration of the existing highway revenue mechanisms, in particular the gas tax, is in order. The original decision to utilize the gas tax for highway finance relied upon certain underlying fundamental conditions. This dissertation's introductory chapter identified several key changes underway in our society which challenge the assumptions in place when the decision to employ gas taxes was made. These changes include the increasing importance of social costs, the shift in the vehicle fleet toward alternative fuels or electric power, the rise of congestion, the scarcity of financial resources and resistance to general taxation, the emergence of new intelligent transportation technologies and electronic toll collection, and changing priorities (from construction to maintenance) associated with a mature technology while America's highway finance system favors ribbon cuttings to repairs.

The prospects for the future success of toll roads depend on several factors, in particular the relative centralization of control of the highway sector and the costs of collecting revenue. This dissertation's research has shown that if the governance were to become more decentralized, and collection costs continue to drop, tolls could return to prominence as the preferred means of financing roads for both local and intercity travel.

Proposals to price road use for infrastructure financing, congestion mitigation, or air quality improvement have been surfacing at a regular pace over recent years (Small et al. 1989, TRB 1994, Roth 1996). Congestion pricing has long been a goal of transportation economists, who argue that it will result in a more efficient use of resources. Outside transportation economics, road pricing is seen mainly as an alternative financing mechanism. The path for implementing road pricing has been strewn with political potholes because pricing, particularly congestion pricing, inevitably produces winners and losers. An

alternative approach, one which would create the local winners necessary to implement road pricing, is required before it can be expected to become widespread.

This research suggests one approach, one that would decentralize the decision about whether to tax or toll rather than attempting to impose road pricing from the central government. This research shows that in certain cases tolls are the only rational financing mechanism which produces a stable equilibrium. This is especially true for sufficiently small jurisdictions, particularly with the advent of electronic toll collection systems.

Road pricing ties revenue to need more closely and directly than a tax system can. It should result in more efficient, and less political, road financing decisions, with less waste due to the log-rolling and pork-barrel politics which infests current infrastructure spending. It is easier to raise revenue for transportation from user fees which directly result in better service than general taxes. Just as gas taxes substitute more efficiently for general taxes, direct road pricing could substitute for gas taxes.

Road pricing is a necessary prerequisite to the economists' goal of congestion pricing. One can reasonably argue that it is not nearly as difficult to vary tolls once tolls are in place, as it is to place tolls (varying or fixed) on untolled roads in the first place. Over time, direct road pricing can be structured to provide off-peak discounts, and can thus be converted to time-of-day pricing, which is more efficient than "one size fits all" pricing. Congestion pricing requires peak-period road users to pay for the additional capacity that travel during the peak requires, while not requiring off-peak users to pay for the excess capacity they don't need. However it is clear that the acceptance of toll roads is required before time-of-day differentiation, much less dynamic pricing, can be deployed.

This chapter first summarizes key findings of this dissertation. Some general trends suggesting a growing importance for road pricing, including a reduction in transactions costs, decentralization, deployment of new advanced highway infrastructure, privatization, and federal rules on toll roads. Deployment scenarios for electronic toll collection, new toll

roads, and the conversion of existing roads to toll roads are offered. Any change from one financing system to another cannot take place instantaneously nor is it likely to take place universally. Finally future extensions including an empirical model of revenue choice, determining the optimal spacing of toll-booths, financing over time, financing the network hierarchy, network differentiation, generalizing the network geometry, and application to real world conditions are presented

7.2 Summary of Research

7.2.1 History of Priced Roads

Chapter 2 examined the history of priced roads, including both their initial deployment and the subsequent disturnpiking. The first significant wave of turnpikes, which lasted from the 1700s and peaked in the early-to-mid 1800s, saw turnpikes under the control of local companies and trusts chartered by states (in the United States) or Parliament (in the United Kingdom). Rationales for tolling included the rise of long-distance trade and difficulties in the then existing system which utilized statute labor for maintaining roads. In this pre-automobile era, roads were financed with tolls when it was recognized that they served non-local residents. Non-residents neither pay local taxes nor perform statute labor to maintain local roads, and thus would act as free riders without tolls. Local residents often got discounts or paid lump sum charges to use the roads rather than being inconvenienced by the tolls.

The early 1900s saw the first significant deployment of smooth paved roads. However, in the U.S. most roads were financed by states, and later the federal government, by means of a gas tax. With the relatively slow speed of highway travel during the early automobile era, most trips remained within states; through trips were not as significant as later in the twentieth century. However, a number of parkways, featuring the property of excludability, were toll financed.

Another significant wave of toll financing arrived with the deployment of grade-separated highways. As both vehicles and highways improved, trips of longer distances could be made in the same time and trip lengths increased. This in turn implied more trips between states, and the emergence of the free rider problem when the basis over which roads were financed (taxes or tolls) did not coincide with the use of the system. Since financing was at the state level, turnpikes were effective for collecting revenue from all users and mitigating the potential free-rider problem. But when national financing became dominant, the definition of "local" changed to include everyone in the nation, and the revenue mechanism with lower collection costs (i.e. the gas tax) was preferred to tolls, especially when the goal was simply cost-recovery rather than profit. As a result, few new toll roads were constructed in the U.S. during the interstate era, though international experience varies. Furthermore, unlike earlier roads, grade-separated roads are easily excludable, that is, the number of entrances is limited and tolls can be cost-effectively assessed at each. The same is not true of roads without grade separations.

Finally, upon completion of the interstate system in the U.S., financing new roads has largely become a local problem again, and new toll roads are being constructed, including some private roads. Because of the length of trips, and because of the ease with which tolls can be collected on these excludable roads, as well as a reduction in toll collection transaction costs on both the government and traveler side with electronic toll collection, tolls are again a feasible option. Road pricing proposals now assume electronic toll collection. Further, cordon tolls are being placed around a number of cities internationally, which will collect revenue from non-local residents for traveling on urban streets. The cordons establish excludability for use of a network from outside, though not for any particular link once the network is entered. Where cordons can easily be established, such as river crossings and ring roads, it is feasible for localities to switch the road financing burden to suburban residents. Ironically, the attempts of localities, often subject to obsolete political boundaries, to finance infrastructure for the "wrong" reason -

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the offloading of costs on non-residents - creates opportunities to achieve a more efficient infrastructure pricing and financing system.

7.2.2 Theory and Model of Revenue Choice

In our modeling of the choice of revenue mechanism, we assume that jurisdictions responsible for network financing have the objective of local welfare maximization (where local welfare is defined as the sum of the consumers' surplus of residents of the jurisdiction and the profits accruing to the locally controlled network authority that the jurisdiction owns and manages.) The main complication is the joint production and consumption of the key good (network services) by the jurisdiction and its residents. Jurisdiction residents use both local and non-local network links, and the local links are used by both local and non-local residents. The idea of decentralized, local control and multiple jurisdictions distinguishes our approach from one where a central authority maximizes global welfare. Decentralized control is thus a critical issue in the deployment of road pricing. Smaller jurisdictions are more likely to have non-local trips, a local welfare maximization criteria suggests they will have greater incentives to toll.

The network operator has several actions which can be taken to maximize local welfare. The set of actions of interest to us are the revenue mechanism, the strategic selection of a revenue instrument (taxes or tolls) and the tactical decision involved in setting of a price level. The proportion of trips using the network which originate in a particular jurisdiction directly shapes the local welfare resulting from a given revenue mechanism, and itself is a function of jurisdiction size. The choice of revenue instrument trades off the number of free riders, system users who don't pay their cost because of the location, and the costs of collection. The price charged with a given instrument is limited by the elasticity of demand for use of the network on those who are charged.

7.2.3 Modeling Results

This dissertation asks what revenue policy jurisdictions can be expected to employ for their roads, and in Chapter 6, identifies the conditions where tax, toll, or mixed tax/toll policies are preferred. It depends on assumptions about their behavior: profit maximizing behavior is more likely to lead to tolls than welfare maximizing; cooperation is more likely to lead to taxes, or lower tolls, than non-cooperation; re-evaluation of the decision periodically is more likely to lead to cooperation than a one-time decision. It depends on the various empirical constants defined here which relate to the unit cost of various cost components and demand elasticity: the lower the cost of collecting revenue, the higher the marginal cost of travel, and the more inelastic the demand, the more likely tolls will be used. It also depends on their size and the proportion of local and non-local traffic, the smaller the jurisdiction and less local the traffic, the more likely tolls will be used.

Cordon tolls (tolls placed on jurisdiction boundaries) by themselves are economically unsustainable as jurisdictions get large. Here, the model of cordon tolls is really an unconstrained maximization, involving taxes or subsidies in addition to tolls, while the tax-only solution does not permit tolls. Large jurisdictions are more likely to impose taxes or a mixed financing policy than only cordon tolls because cordon tolls alone raise insufficient revenues to cover costs. Toll revenue levels off above a certain point. In uncongested conditions with low variable costs, use of interior (non-cordon) tolls does not enhance local welfare as any additional revenue raised compared with cordon tolls comes from local residents, except to the extent that the tolls reduce over-use and social loss.

Similarly, the higher the cost of collecting tolls, the less likely tolls will be the preferred revenue mechanism. The welfare maximizing toll may not fully recover costs, and thus still require subsidy (thus toll-only financing may be unsustainable). 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. Hence collection costs need to be fairly high before no tolls is a better solution than some tolls.

The gains to a jurisdiction of imposing tolls exceeds the gains from taxes under certain circumstances. The gains come foremost 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 are borne by a different set of people, not all of whom are local.

7.3 General Trends

From a positive perspective, many general trends can be cited which suggest road pricing will become more rather than less likely in the future. Some key trends (reducing transaction costs, decentralizing decisions, deploying new infrastructure technologies, privatizing roads, and implementing new federal rules) are discussed in turn.

7.3.1 Transaction Costs

An important result was the lower the transaction costs for collecting tolls, the more likely toll collection becomes. How likely is it that toll collections will become less costly? Electronic Toll Collection (ETC) is a set of technologies which automate the manual in-lane toll collection process so that that drivers do not have to stop and pay cash at a toll booth, thereby reducing the cost to the user of transacting the collection of tolls. Three major technologies are employed: automatic vehicle identification, automatic vehicle classification, and video enforcement (ETTM 1997). It can also be expected that the variable costs (if not the fixed costs) of electronic toll collection will be lower than with traditional toll-booths which require labor. Friedman and Waldfogel (1995) estimate significant welfare gains from switching to electronic toll collection using data from New Jersey and Massachusetts. Including the reduction in vehicle delay, $5,000 a day would be saved from ETC. Fourteen ETC systems were operational by the end of 1995, and since then, numerous others have

been deployed. It seems reasonable to suppose that ETC will become a standard feature of toll roads in the future.

7.3.2 Decentralization

To the extent that decentralization is applied to roads, it indicates an increased likelihood of toll financing.   This dissertation showed that small jurisdictions have a strong temptation to toll.   How likely is it that roads will be governed by more local jurisdictions? There is a broad though not universal trend toward shifting authority from the central government to the more local entities. In different contexts, this is called decentralization, devolution, or The New Federalism. The best known recent example of devolution of power is in the United Kingdom, where the power over local policies for Scotland and Wales will be shifted from London to Edinburgh and Cardiff following recent referenda. In the United States, the term "The New Federalism" denotes the shift in the balance of powers and responsibilities between localities, the states, and the federal government. The intent is to more effectively administer government programs by playing to the strengths of each governmental level (Urban Institute 1997). At the core of the shift is the belief that the federal government (and to a lesser extent each state's government) is rigid and its "one size fits all" notion is not the most effective way of implementing policies, while states, counties, and cities are closer to the needs of their citizens and are thus more able to flexibly respond to local needs. Welfare reform is the programmatic change which has received the most notice, though many programs have been given by the federal government to the states to administer with more general block grants rather than specific rules. Similarly, a significant amount of transportation planning and decision-making authority has been shifted from states to metropolitan planning organizations in the most recent highway bills. To the extent that this trend continues, road pricing becomes more probable, especially the implementation of urban or metropolitan toll cordons.

7.3.3 Deployment of Advanced Highway Infrastructure

This dissertation has shown that cross-subsidies from voters to road users becomes less likely when the road users and voters comprise an increasing distinct population. Two cases where they are distinct groups are when road users live out of district, or when the users of a particular facility are a small sub-population of the voting population. The second case has direct bearing on the deployment of new Intelligent Transportation Systems such as Automated Highway Systems. Automated Highway Systems which are supposed to result in vehicles being driven without the active participation of drivers for at least part of the journey. While the degree of centralization of control vs. autonomy for the automobile is not certain, the system may require separate facilities for automated vehicles and the existing fleet to take advantage of automation (tighter spacing and higher speeds). These facilities will not be free and will not, at first, serve the entire population. In particular, the first users are likely to be a self-selected wealthy subgroup willing to pay for advanced technology. Some special purpose financing mechanism, such as tolls or a subscription, is likely to be necessary to build these facilities.

7.3.4 Privatization

An unregulated private firm operating the road can be expected to employ an objective such as profit maximization, as analyzed in Chapter Six. It was found that at and above 20 km jurisdiction sizes, a cooperative profit maximizing firm (typical of a vertically integrated road) generated the same overall welfare (distributed differently) as a non-cooperatively toll-setting welfare maximizing jurisdiction (typical of local public sector ownership at the city or town level or larger). Private toll roads if properly organized and regulated, may be able to serve as a substitute for public sector ownership. How likely are private toll roads? As noted in Chapter 2, there are a number of private road facilities throughout the world. The deployment of private (usually toll-financed) roads appears to be a growing trend. Several models of privatization are used, including build-operate-transfer

(BOT) and design-build-finance-operate (DBFO), and variations on these with forms of public subsidy. In the past year, following the BOT model, the private Northumberland Strait Crossing and the Highway 104 Western Alignment Tollway in Nova Scotia were opened in Canada. In Britain, the DBFO model, including shadow tolls rather than real tolls, has been employed for some recent private roadways. Shadow tolls involve payment from the government (rather than travelers) to the road operator, in proportion to the amount of traffic. In 1996 eight DBFO franchises were awarded in Britain. France and Germany have also authorized recent projects, France a $2.2 billion dollar 10 km tunnel in the Paris ring road. Portugal is considering selling the state owned toll authority and has approved several private toll road projects. Eastern European countries including Hungary, Croatia, Poland, and Romania are progressing in plans to use the BOT model for new roads. Several projects in Latin America are in the planning stage (Poole 1997). Clearly the use of the private sector to finance, build, and operate toll roads is an increasing trend.

7.3.5 Federal Rules on Toll Roads

Just as smaller governments have a strong incentive to impose tolls, larger governmental units have an incentive to use more general financing mechanisms. In general, the U.S. federal government has had a long-standing prohibition against funding toll facilities. Four major exceptions to prohibitions on federal toll funding have been identified (Gittings 1987). First, in 1927 the government permitted tax funding of tolled bridges and their approaches and connections to the federal aid highway system. Second, in 1956, approaches to toll roads on the interstate system were able to receive federal support. Third, also in 1956, pre-existing toll roads incorporated into the interstate system could receive funding. And finally, in 1978, federal Interstate 4R funds could be applied to interstate system toll roads. However, in the first, second, and fourth cases, upon the retirement of bonded debts, the tolls must be removed. This has happened in several states (Connecticut, Kansas, and New York). On the other hand, roads may be converted to toll status once all

contributed federal money for the road's construction and maintenance is repaid. This repayment requirement is the principal cost of converting existing roads from untolled to tolled. The construction of toll barriers has been estimated at about one-twentieth the cost of repayment (Gittings 1987). Proposals for the most recent highway bill, dubbed "NEXTEA" or "ISTEA-2" may permit states to impose tolls on interstate highways under certain circumstances, though the actual form of these rules awaits final passage of the bill. To the extent that new federal rules are more sympathetic to both decentralization of power and more experimentation on the part of the states, road pricing will be more widely seen on the federally funded interstate highway systems.

7.4 Speculations on the Deployment of Priced Roads

Physical networks require long lead times to construct, and are extremely durable. The deployment of a new transportation technology is unlikely to take place quickly for both political and technical reasons. Perhaps the ultimate application of road pricing technology will require advanced highway systems. In an era of smart cars and smart roads, one can conceive of quasi-competitive highways dynamically altering their tolls in response to demand (and travel time), while drivers (or pre-programmed cars) select routes in response to the posted prices and their individual value of time. However, in the interim, a path for deploying the currently available road pricing and electronic toll collection technologies is needed. Three different road pricing deployment problems are identified and discussed in turn: deployment of electronic toll collection (ETC) on existing roads, constructing new toll roads, and converting existing untolled roads to toll roads.

7.4.1 Electronic Toll Collection on Existing Toll Roads

The first issue concerns the deployment of electronic toll collection on existing turnpikes, and toll roads, bridges and tunnels. As noted in the section on general trends, toll facilities are presently converting from human toll operators and automatic coin deposit boxes to electronic toll collection systems. However, different systems use different

technologies. While this may suffice for the vast majority of local trips, and may be a necessary interim step to winnow out technological winners and losers, over the long term some standardization is necessary before road pricing becomes widespread. With the provision of compatibility between regions, users can use multiple toll facilities, each under different management, while only having one electronic toll collection device in their vehicle. As many individuals use different toll facilities from time to time, the presence of an electronic toll collection unit in the vehicle will become common, at least in certain parts of the country. Thus, the transaction costs (such as delay due to stopping, labor costs, and construction of toll booths) associated with implementing tolls on a new facility could be minimized if new facilities were tolled using a standard ETC system. Costs of ETC should decline as the fixed costs of development and initial deployment are spread over a wide number of users. Network externalities can be exploited by the adoption of a standard electronic toll collection mechanism by special facilities which are already tolled, such as tunnels, bridges, turnpikes, selected new highways, parking garages, and high occupancy/toll (HOT) lanes.

7.4.2 New Toll Roads

A second issue is the construction of new toll roads. Since the completion of the interstate highway system, new highway construction has been relatively sparse. In some sense, applying the idea of the S-curve, the mature limited access highway network has reached saturation. Much of the new, albeit limited, highway construction is being toll financed because of scarce resources. First, finding financing from a higher level of government for local projects is difficult in the absence of a national road-building program. Second, roads paid for by one jurisdiction serve both local and non-local residents - generating revenue from non-local residents requires a mechanism like tolling.

Furthermore, the dearth of new construction implies that travel speeds on highways will decrease, as current roads get saturated with traffic which continues to grow. Proposals

to construct automated highway systems (AHS), which promise both higher travel speeds and traffic flow, will require a new financing mechanism to be implemented. As these systems will, at least initially, only support a subset of the vehicle fleet, it seems reasonable to suppose that a special financing mechanism (tolls) will be preferred to a more broadly based mechanism (funding out of general revenue). If AHS were to become a dominant technology, it can be expected to bring tolling back as the primary revenue mechanism. The toll collection mechanism for these roads should be consistent with the technology used elsewhere, so that users need only support one in-vehicle toll communication device.

This dissertation suggests that under certain circumstances, including vertical integration of monopoly road segments, new roads can be financed by the private sector without significant welfare losses compared with uncoordinated local roads. As the welfare losses are small or non-existant, the opposition to new toll roads will be less strong than might be expected if losses were large. As the construction of new private roads becomes increasingly common, as suggested in the trends section, toll roads will impose themselves as a significant component of the transportation landscape.

7.4.3 Tolling Existing Unpriced Roads

The third and hardest case is the tolling (or re-tolling) of presently unpriced, publicly controlled roads, presumably utilizing electronic toll collection. The idea of local welfare maximization with decentralized decision making should be employed. It was shown that the more decentralized the decision making, the more likely that tolls will be employed.

The following is a scenario of how tolling might be deployed on the existing "free" network. Central cities would establish cordon rings in lieu of or in addition to other financing mechanisms so long as the dollars collected remain within the transportation sector. This is akin to a commuter tax which several cities already assess on individuals working but not living within their geography. The idea of cordon rings is not as unlikely

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as it seems. Already several cities (Singapore, Oslo, Bergen, and Trondheim) have imposed explicit cordon rings. Other places, like Manhattan in New York have implicit cordon rings, one cannot enter that island without paying tolls from most directions. Similarly San Francisco has a partial cordon ring from the north and east, though the revenue collected remains with the bridge authorities rather than being used for city streets. Cordons can be established at convenient locations, most often natural barriers like bodies of water, but also artificial barriers like beltways. Whether these are imposed by central cities or by metropolitan areas, the point remains that those inside the ring are distinct from those outside, though both groups may have to cross from time to time.

In response, suburbs (or exurbs) would likely establish cordons to toll city residents at convenient boundaries. It would be perceived as unfair that suburban residents pay tolls to enter the city, but city residents can drive on suburban roads without a similar charge. Whether the suburban cordons would require separate facilities from the city cordon, or simply share the revenue from those crossing the cordon is a secondary issue to its presence.

Once they are initially constructed, cordon rings can be made more efficient as they get drawn tighter and tighter over time. The smaller the area enclosed within a cordon, the more direct the pricing of the network, and the more use and revenue coincide. For a very tight cordon, this method approaches link specific tolls, particularly on excludable facilities. The traditional downside of "perfect" tolls on excludable facilities is that spacing between exits is increased, so backtracking and slowtracking costs are increased. However, with low transaction costs associated with ETC, this problem need not arise.

It should be emphasized that these tolls primarily substitute for existing road financing systems (gas tax and general revenue), a substitution which is more efficient because it directly collects revenue from users on a specific facility and thereby can be used to provide incentives to reduce the welfare loss associated with excess use (where marginal

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cost exceeds marginal benefit). Of course, the burden associated with tolling will shift, but if decision-making is sufficiently decentralized, the shift will be politically palatable because the burden shifts from local to non-local residents.

At first, pricing would likely be applied to limited access links dedicated to longer distance movement. These roads have a cost structure where users face increasing costs as demand rises. Cordons around subareas, networks used mainly for access and short movement, are the second candidate for road pricing - although this would be mainly to recover fixed costs and some maintenance costs rather than to increase the size of the local network or reduce congestion. Local streets are more likely to be operating on the left side of the U-shaped cost curve, the area of declining average costs.

7.5 Future Research

The analysis presented herein is a simplified representation of reality. Several logical extensions to this research are discussed here. One extension is the estimation of an empirical revenue choice model, examining state level data and determining the relevant factors explaining their tax/toll revenue split. An empirical revenue choice model would corroborate (or refute) the hypotheses presented in this dissertation. Just as the choice of revenue mechanism and rate was determined with a maximization approach, the optimal spacing of toll-booths, or the optimal size of network operators also lends itself to analysis. The question of how different levels of the network hierarchy are financed should be explored. This research would investigate how scale, scope, and sequence economies and vertical integration of feeder and mainline routes interplay with this decision. Network differentiation, so that different links would be allocated to serve heterogeneous users with different values of time could be studied. The analysis of network differentiation requires endogenizing congestion and travel times as a function of use as well as considering public vs. private ownership and various kinds of horizontal integration, competition in the network between alternative routes, and multiple owners and different numbers of owners of

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alternative routes.   Just as we examined financing over space in this dissertation, similar issues about financing over time arise. The problem of free riders and financing can be reconstructed as a dichotomy between existing and future residents rather than local and non-locals. Our research was fairly constrained in that it considered a single, monopolistic, infinitely long link. The consideration of autonomous links in the context of alternative, or general, network geometries may provide additional insights. Policy may benefit from the application of our model structure to model to real-world circumstances, so that many of the abstractions of this model would disappear.

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9. END NOTES

[1] To demonstrate the point that intercity roads in western states carry more local (in-state) traffic than in eastern states, we can look at trip length distributions between the various areas. While trips are on average slightly longer in western than in eastern states, the difference is not significant compared with their size differences.

Travel Distance in Miles (km), All Trips

Region	Mean	Std. Dev.	N
Northeast	10.8 (18.1)	39.7 (66.2)	24591
Northcentral	10.5 (17.6)	41.2 (68.6)	24175
South	10.9 (18.1)	40.2 (67.0)	28756
West	11.5 (19.2)	50.8 (84.7)	16248

source: 1990/91 Nationwide Personal Transportation Survey (FHWA 1991)

[2] While the revenue mechanism determines how revenue is raised from users to pay for the cost of the roadway, the financing mechanism determines how and when the jurisdiction pays for the cost of the roadway. We might assume that the road authority purchases the road (or the necessary inputs to create a road) from another agent or set of agents (for instance a construction company, land owners, labor). The money to purchase the road either comes from out-of-pocket funds (the road is self-financed by the local jurisdiction) or from borrowed money (the money for the road is borrowed). Clearly this choice effects costs (for instance the need for lump sum money or the payment of interest), and thus influences the choice of revenue instrument and rates. This choice also depends on questions of risk, which are not addressed here.

[3] How revenue is generated is one component of actions that a network operator may choose. A second component involves the size and structure of the network. The network can be described in terms of a number of variables: link width, length, free-flow speed, durability, and the geometry of the network. Fundamentally, they all determine the travel time between points in freeflow and congested conditions, the wear and tear on vehicles, and the cost to the operator of building and maintaining the road. In order to explore variations in the revenue instrument, many of the variables describing network geometry will be kept as background assumptions throughout the rest of this discussion. Several key assumptions about the network may be made. One is irreversibility, once built, the network cannot be eliminated. A second is indivisibility, that is the network is comprise of discrete

components (lanes), which are either constructed or not constructed in integer values. A fraction of a lane is not a meaningful entity in this analysis. A third assumption relates to network ownership, or more broadly, who determines who can use the network at what cost - here the community is assumed to own the road.

[4] A quasi-linear utility function $v()$ varies in prices and income such that:

$v(p,m) = v(p) + m$

where: p = prices, m = income

[5] In principle, toll-booths may be located within jurisdictions as well as on the boundary, but from a simple local welfare point-of-view in the absence of congestion, there are few advantages to a jurisdiction to placing internal (non-boundary) toll-booths. This will be discussed in some more depth in later chapters.

[6] Basically the assumption of symmetric demand means that the four boundary crossing classes (G_{0+}, G_{+0}, G_{-0}, and G_{0-}) all have the same flow levels (and thus costs, revenues, and consumers' surplus), which is convenient for analysis. Recall, G_{0+} trips are defined as trips made from J_0 to S_+ while G_{+0} trips go from S_+ to J_0. If all trips are "round", then G_{0+} and G_{+0} trips represent the same people, and produce the same flow levels over the long term (a similar argument can be made for G_{-0} and G_{0-}). Applying the theory developed in Chapter 3, the jurisdiction J_0 takes into account the welfare from the boundary crossing trip classes (G_{0+}, G_{+0}, G_{-0}, and G_{0-}) made by residents of jurisdiction J_0. If demand is spread evenly on a two-way road, the welfare which J_0 considers is one-half of the trips in each boundary crossing class (G_{0+}, G_{+0}, G_{-0}, G_{0-}). Thus we only need to measure one-half of the consumers' surplus of each class. But since the trips are round, the total number of G_{-0} and G_{0+} trips are the same as G_{0-} and G_{+0}, , and we can simplify the analysis and only consider the entire consumers' surplus from locally originating boundary crossing trips (G_{0+} and G_{0-}) trips and ignore the consumers' surplus for locally destined boundary crossing trips (G_{-0} and G_{+0}). The analysis employs a one-way road. The two-way road is equivalent to two one-way roads in opposite directions, and so, by the property of symmetry, only a one-way road needs to be considered. Thus, trips which travel in the west to east direction (G_{0+} and G_{-0}) are included and the east to west trips (G_{+0} and G_{0-}) excluded. Because of symmetric demand functions and the use of one-way roads, all of the consumers' surplus from G_{0+} can stand in for half the consumers' surplus of G_{0+} and G_{-0} .

[7] Class G_- and G_{++} trips are irrelevant for immediate taxing and tolling purposes, though they influence the tolls that residents will pay when entering the other jurisdiction.

[8] Delayed time costs depend on the value of time (V_T), traffic flow ($f(z)$) (which is the sum of the flow from all user classes at a given point), and vectors of variables describing system

capacity, and the number of stops, the last two of which are policy variables available to the jurisdiction. While this chapter explicitly assumes that delay is equal to zero, the notion of a delay function is useful for later development. Of course delay is central to the idea of marginal cost or congestion pricing, but that field has been thoroughly investigated in the literature and so is not examined here.

[9] External costs, such as air pollution, noise, accidents, or the congestion impacts on other drivers are not included. This exclusion is because those external costs are not borne by the drivers, and thus do not enter into their decisions, rather than because the costs do not exist. External costs are excluded for welfare analyses for similar reasons, they are not generally account for when the externality falls on another jurisdiction (for instance air pollution).

[10] Consumers' surplus here is defined assuming that all trip-makers have identical demand functions, and are identical except for their trip origin and destination. It can be argued that longer trips are more valuable than shorter trips, otherwise those long trips would not be undertaken. Clearly there is some relationship between the amount of time/money expended in travel and the value of the activity at the end of the trip, as is reflected in a typical demand curve (D). This is illustrated in the figure below.

Figure: Welfare Comparison
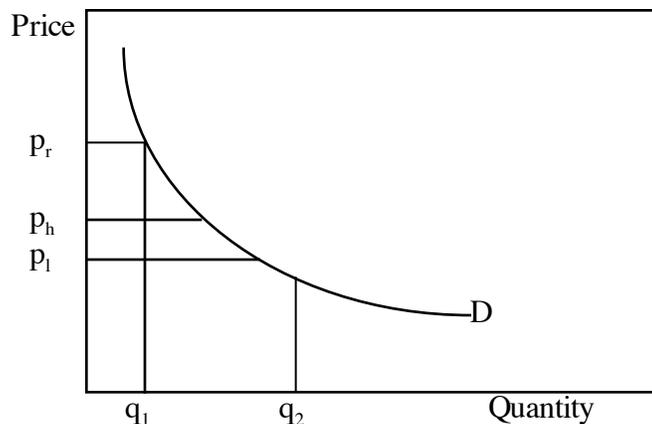
Given an activity of a certain value, traveling for a greater time or at greater cost decreases welfare, the cost of travel is in fact, a cost, not a benefit. In the figure, if p_r is the reservation price for trip q_1 and p_h is a higher price, and p_l a lower price, clearly welfare is improved by paying the lower price, that is: $((p_r - p_l) > (p_r - p_h))$. However, at any given price or travel time, the welfare associated with trip q_1 is greater than the trip at q_2.

To keep the analysis simple, the demand function is assumed independent of trip length so that long trips are less probable than short trips, just as costlier trips are less likely

than cheap trips. Therefore, consumers' surplus measured by number of trips, not the length, is most appropriate. To do otherwise would suggest that a jurisdiction should encourage, rather than discourage, longer trips through instruments such as negative tolls.

[11] In computing consumers' surplus, we assume that all locally originating boundary crossing trips G_{0+} can stand in for half of each of the two boundary crossing trip classes (G_{0+} and G_{0-})

[12] Because all residents are assumed to travel, there is no cross-subsidy between travelers and non-travelers when general taxes are relied upon. There remain cross-subsidies between trips of different lengths under certain tolling policies.

[13]   Gittings (1987) identifies several additional costs associated with tolls that are not present in the absence of tolls. His first category, which is addressed here, are the direct capital and operating costs of toll collection. Second are the direct costs to users of paying the toll in terms of delay, vehicle operating costs, and decreased safety. We don't deal with delay or other externalities here for reasons identified above, and expect that increased vehicle operating costs should be modest and can be ignored at the scale of this analysis. User payments for tolls are included in the P_T variable discussed above. Third, some users may divert to avoid the toll, which increases their cost above free travel (though presumably below the cost of paying the toll), and fourth, those diverting users impose costs on vehicles previously using the alternative routes. However, since diversion is ignored (we are assuming only a single road, which can stand in for complete cordon coverage), the third and fourth categories of cost are not addressed here. We do assume elasticity of demand, so that price changes are reflected in reduced demand for the road in question, but where that reduced demand goes is not determined.

[14] The all-cordon toll environment is in a sense the "serial monopolist problem" (Chamberlin 1933), and will result in an overall toll paid by residents of more than if the two jurisdictions were under single control.

[15] The assumption that all jurisdictions are identically sized is unnecessary in an all-tax environment, as the spacing of jurisdiction boundaries besides those for J_0 in an all-tax environment has no effect on demand.

[16]   Strictly speaking, the assumption that the tolls in an all-cordon toll environment are identical is unlikely to be true if J_0 imposes taxes. In that case, the adjacent jurisdictions (J_{+1}, J_{-1}) border on one side a taxing jurisidction, and on the other side a tolling jurisdiction (J_{+1} and J_{-1} face a mixed environment). They should be able to leverage the absence of tolls

on one side and raise their own tolls as a result. However, that difference in policy will ripple across space, affecting the tolls in the jurisdictions adjacent to them (J_{+s}, J_{-s}), which then affects further jurisdictions and so on. The degree to which this difficulty poses a real problem is low, as a tax policy in an all-cordon toll environment is unlikely to be sustainable in the first place.

[17]   For example, we imagine two autonomous links, I-J and J-K, which are pure monopolies and perfect complements, one cannot be consumed without consuming (driving on) the other.

$$I --- J ---- K$$

In this case, demand depends on the price of both links, so we can illustrate by using the following general expression, and a linear example :

$$Qd = f(Pij, Pkl) \tag{1}$$

$$Qd = ß_0 - ß_1 (Pij + Pjk) \tag{2}$$

Again we assume no congestion costs. When we profit maximize, we attain a system which produces a Nash equilibrium that is both worse off for the owners of the links, who face lower profits, and for the users of the links, who face higher collective profits, than a monopoly. Simply put, the links do not suffer the full extent of their own pricing policy as they would in the case of a monopoly, where the pricing externality is internalized.

$$\pi ij = Pij \, Qd(P) = Pij \, (ß_0 - ß_1 Pij - ß_1 Pjk) = ß_0 Pij - ß_1 Pij^2 - ß_1 \, Pij \, Pjk \tag{3}$$

$$\pi jk = Pjk \, Qd(P) = Pjk \, (ß_0 - ß_1 Pij - ß_1 Pjk) = ß_0 Pjk - ß_1 Pjk^2 - ß_1 \, Pij \, Pjk \tag{4}$$

f.o.c.

$$\partial\pi/dPij = ß_0 - 2 \, ß_1 Pij - ß_1 Pjk = 0 \tag{5}$$

$$Pij = (ß_0 - ß_1 Pjk) / 2 \, ß_1 \tag{6}$$

$$\partial\pi/dPjk = ß_0 - 2 \, ß_1 Pjk - ß_1 Pij = 0 \tag{7}$$

$$Pjk = (ß_0 - ß_1 Pij) / 2 \, ß_1 \tag{8}$$

solving the f.o.c. simultaneously yields:

$$Pij = Pjk = ß_0 \, (2 \, ß_1 - 1) / (4 \, ß_1^2 - ß_1) \tag{9}$$

checking the s.o.c.:

$$\partial^2\pi/\partial Pij^2 = - 2 \, ß_1 < 0 \tag{10}$$

$$\partial^2\pi/\partial Pjk^2 = - 2 \, ß_1 < 0 \tag{11}$$

At $ß_0 = 1000$ and $ß_1 = 1$, the solution is $Pij = Pjk = 333.33$, which gives $Qd(P) = 333.33$, $\pi ij = \pi jk = 111,111$, which is less total profit than the case of the simple monopoly. This situation results in total profit to both firms of 222,222, and a consumer surplus of

55,555, or total social welfare of 277,000, which is less than the results from the case of a simple monopoly.

Similar arguments apply to three (or more) perfect complements, which are more and more dysfunctional if operated autonomously. The general formula for N autonomous perfectly complementary links, with linear demand and $ß_1=1$, is given by:

$$P = Qd(P) = ß_0/(N+1). \tag{12}$$