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**HOT Lanes: A Comparative Evaluation of
Costs, Benefits and Performance**

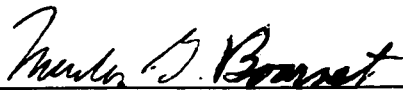
**A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Urban Planning**

by


Eugene J. Kim

2000

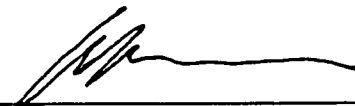
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ACRONYMS

AADT	Average Annual Daily Traffic
ADT	Average Daily Traffic
ARDFFA	Applied Research and Development Facilities and Activities
AVI	Automated Vehicle Identification
CAA	Clean Air Act
CARB	California Air Resources Board
Caltrans	California Department of Transportation
CBA	Cost-Benefit Analysis
CEQA	California Environmental Quality Act
CHP	California Highway Patrol
CMAQ	Congestion Management and Air Quality Program
CPTC	California Private Transportation Corporation
DOT	Department of Transportation
EPA	Environmental Protection Agency
ETC	Eastern Transportation Corridor
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
HOTL	High Occupancy Toll Lane
HOV	High Occupancy Vehicle
HOVL	High Occupancy Vehicle Lane
HTF	Highway Trust Fund
IM	Interstate Highway/Interstate Maintenance Program
IRR	Internal Rate of Return
ITS	Intelligent Transportation Systems
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Intelligent Transportation System
LOS	Level-of-Service
LOV	Low Occupancy Vehicle
LN	Natural Logarithm
LS	Log Sum
MOA	Memorandum of Agreement
MPO	Metropolitan Planning Organization
NPV	Net Present Value
PHT	Person Hours of Travel
PPH	Passengers Per Hour
RFP	Request For Proposals
RTIP	Regional Transportation Improvement Plan
SOV	Single Occupancy Vehicle
SANDAG	San Diego Association of Governments

SCAG	Southern California Association of Governments
SJHTC	San Joaquin Hills Transportation Corridor
STP	Surface Transportation Program
TCA	Transportation Corridor Agency
TDM	Transportation Demand Management
TCM	Transportation Control Measure
TEA-21	Transportation Equity Act for the 21st Century
TIP	Transportation Implementation Plan
TSM	Transportation Systems Management
UGPL	Uncontrolled General Purpose Lane
VHT	Vehicle Hours of Travel
VMT	Vehicle Miles of Travel
VPH	Vehicles Per Hour
VTTS	Value of Travel Time Savings

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ABSTRACT OF THE DISSERTATION

HOT Lanes: A Comparative Evaluation of Costs, Benefits and Performance

by

Eugene J. Kim

Doctor of Philosophy in Urban Planning

University of California, Los Angeles, 2000

Professor Brian D. Taylor, Chair

This dissertation compares the effects of HOTLs, congestion toll lanes, GPLs and HOVLs. A deterministic travel-demand model that estimates the comparative travel times under competing investment scenarios is adapted here to consider how tolls influence ridesharing. The results indicate that HOTLs, congestion toll lanes and GPLs provide a greater degree of system-wide delay-reduction benefits than HOVLs in most cases. Furthermore, when maximum mainline peak highway delays are between 20 and 40 minutes, congestion toll lanes provide a greater reduction in overall delays and emissions than GPLs.

This research provides support for the policy claim that in almost all local urban travel conditions, HOT lanes provide a greater degree of fiscal, consumer welfare, and environmental benefits than all other life-haul urban expressway investments. HOT lanes are the only urban highway facilities capable of withstanding induced growth effects, and preserving congestion-free service after an initial reduction in travel costs. In the few cases in which the delay reduction benefits of toll lanes and GPLs are roughly comparable, the revenue-producing nature of toll roads greatly lowers the comparative

social cost of long-term highway maintenance and rehabilitation. Although the HOT lane capital costs are significantly higher than HOV lanes, a 10-mile HOT lane facility can provide up to \$20 million in annual revenue (in 2000 dollars). Because HOT lanes preserve congestion-free service in the face of traffic growth, HOT lanes are more environmental beneficial than either HOVLs and GPLs. This research provides support for federal policies that expand the use of tolling on urban interstate highways, especially in non-attainment areas where states are ineligible for new highway construction funds.

1. INTRODUCTION

1.1 HIGH OCCUPANCY TOLL LANES IN PLANNING CONTEXT

The Regulatory Parameters of Transportation Finance in the 1990s

Since the early 1970s, the federal government has required states to develop and periodically update statewide and regional transportation improvement plans that identify how new transportation projects and improvements affect travel demand and progress toward clean air targets, especially in air quality non-attainment areas (Weiner 1986; Brown *et al.* 1998). Within this regulatory regime, states have experienced difficulty justifying federal funding for new urban highway projects in non-attainment areas. In addition, right-of-way costs in developed areas have skyrocketed and political opposition to urban highway construction in many cities is iron-clad. Consequently, urban highway expansion has slowed to a crawl.

Aside from regulatory factors, there is a consensus among transportation policymakers and analysts that simply adding more highway lane-miles does not effectively reduce peak congestion (Fuhs 1990; Downs 1992; Small 1993; Arnott and Small 1994; EPA 1997). In light of mounting evidence that highway expansion induces more demand for travel, the policy emphasis has shifted toward improving the efficiency of existing transportation services in a manner that maximizes social benefit without imposing punitive economic restraints on mobility (NCHRP 1991).

TSM Planning and Implementation

State highway programs have turned to low-cost transportation systems management (TSM) strategies like highway on-ramp synchronization and reserved High

Occupancy Vehicle Lanes (HOVLs) to improve the efficiency of existing highway facilities (Wachs 1991; Giuliano 1992). HOVLs are usually built along existing highway corridors, and thus tend not to open outlying areas to new travel (Fuhs 1991). HOVLs achieve benefits by (a) motivating people to shift to HOVs, which reduces the number of vehicle trips made by these travelers, and (b) extending priority treatment to vehicles with more than one occupant, allowing them to bypass the freeway queue ahead of other vehicles so that there is less delay to HOVs and more delay to LOVs (Fuhs 1991; Dahlgren 1994). State highway departments favor these projects because they are low-cost alternatives that have until recently enjoyed broad public support.

With so many private and public resources being invested in Intelligent Transportation Systems (ITS) research and development, TSM planning is placing increased emphasis on market segmentation, real-time information, and multi-modal integration – lending hope to the belief that ‘smart’ roads that can accommodate much higher volumes than today’s congested highways and solve urban traffic congestion problems (Repogle and Reinke 1998). While much of the promise of ITS technology has yet to be realized, recent technological innovations have allowed concepts heretofore relegated to theoretical abstraction to reach full project implementation.

Defining HOT Lanes

The most technologically sophisticated manifestation of TSM planning today is the High Occupancy Toll Lane (HOTL), hybrid HOV/toll lanes that charge a time-dependent toll to Single Occupant Vehicles (SOVs) and reserve priority access to HOVs,

vanpools and buses (via toll exemptions). Because there are only a few congestion toll lane projects currently in operation nationally (the I-15 Express Lanes in San Diego, California, the 91 Express Lanes in Orange County, California, and the Katy Freeway in Houston, Texas), the net impact of these projects on travel demand, consumer welfare, and social equity has yet to be fully understood. The preliminary evidence suggests that these projects produce dramatic traffic improvements that would otherwise be unattainable through more conventional investments, however it unclear the extent to which travel impacts of a given toll lane project are generalizable to other areas (Sullivan et al. 1998). The success of these projects has sparked policy interest in selling excess peak HOVL capacity to SOVs on HOVLs that have been chronically underperforming.

Because many HOVLs nationally perform well below designed capacity during peak hours, growing public dissatisfaction has recently sparked a strong anti-HOVL backlash, causing elected officials and state departments of transportation (DOTs) in New Jersey, New York, Texas, and California to reassess the merits of HOV priority treatment and consider alternative treatments (IT News 1998; Samuel 1998). How much longer HOVLs will remain the centerpiece of the TSM approach is uncertain. In states like New Jersey where the anti-HOVL backlash is greatest, lawmakers have even considered decommissioning HOVLs in direct defiance of federal law (Samuel 1998). In New Jersey, congressional delegates attempted to insert language into TEA-21, the 1998 federal transportation appropriations bill, granting New Jersey the right to turn the I-287 HOVL over to single occupancy vehicles. In other states like California and Texas

(where anti-HOVL forces are less politically mobilized), elected officials have focused attention on the prospects of SOV toll buy-ins to improve the performance of HOVLs on a case-by-case basis (*Los Angeles Times* 1999). This research, therefore, is intended in part to provide decisionmakers with analysis that compares the effects of HOVLs with those of converting to toll lanes and GPLs.

In California, congestion toll lane feasibility studies are currently underway for the SR-57 Freeway in Orange County, the Antelope Freeway in Los Angeles County, an eastern extension of the 91 Freeway in Riverside County, the SR-91 Freeway in Riverside County, and the US-101 in Sonoma County (Samuel 1998), but the California Department of Transportation (Caltrans) has undertaken no formal analysis of the feasibility of converting the state's HOVLs into congestion toll lanes *en masse*. In the near future, congestion toll lanes will likely be financed and built on a case-by-case basis with federal, state and local officials reacting cautiously to costs, benefits, and incidence of individual toll lane projects on urban travelers. Under TEA-21, federal funds will be provided for up to 15 toll lane demonstration projects around the country (Fritz 1998).

1.2 CURRENT POLICY

Under the TEA-21, which provides states with greater flexibility in transferring apportionments between various programs than under ISTEA, the partial lifting of the federal ban on toll on interstate highways may provide an opportunity to program congestion-relief improvements that do not disqualify recipient states from receiving apportionments under the Interstate Maintenance (IM), Congestion Mitigation Air

Quality (CMAQ), and Surface Transportation programs (STP). Unlike the case described above, efforts to toll HOVLS are eligible for federal support under the IM program and have received federal recognition as a legitimate approach to traffic management. The funding programs and provisions under TEA-21 allowing tolling on interstates are outlined below.

1.2.1 Interstate Tolling Under TEA-21

Before the passage of the landmark Transportation Equity Act for the 21st Century (TEA-21), federal law prohibited states from applying tolls on interstate highways. To assist local efforts to establish road pricing programs, Congress included a congestion pricing demonstration program in the Intermodal Surface Transportation Efficiency Act (ISTEA) that gave Federal Highway Administration (FHWA) the authority to exempt interstate facilities identified in proposal accepted under the program, however ISTEA continued the general ban on interstate tolling. Under ISTEA's demonstration program, FHWA funded ten projects and disbursed over \$30 million in support of project costs, administrative coordination and regional pricing workshops.

Due in part to the increased policy interest in congestion pricing stimulated by FHWA's pricing advocacy efforts and the successful implementation of projects supported by the demonstration program, Congress for the first time gave serious consideration to the merits of continuing the prohibition on interstate tolling in the debates surrounding ISTEA's reauthorization. Throughout 1997, there was strong disagreement over the proposed language lifting the ban. In its version of the

reauthorization package, the Clinton Administration gave states the unconditional authority to decide whether or not to opt interstate facilities within their jurisdiction out of the highway trust fund (HTF) and convert them to toll roads. After intense opposition from freight interests and consumer groups, Congress settled on a scaled down version allowing three states to experiment with interstate tolls (Simon, *Los Angeles Times*, September 28, 1997).

Under TEA-21, reconstruction or rehabilitation of a free Interstate highway segment and its conversion to a toll highway is allowed for three pilot projects (FHWA 1998). The stated purpose of the provision is to facilitate improvements on Interstate highways where the costs exceed available funding and improvements cannot take place without the collection of tolls. States can accumulate toll revenue credits to be applied to the non-Federal share of eligible highway projects (FHWA 1998).

1.2.2 Value Pricing Demonstration Program

The Value Pricing Pilot program under TEA-21 provides authorizations totaling \$51 million for FYs 1999-2003 for up to 15 new value pricing projects. A value pricing project under this program may involve tolling on Interstate highway segments and does not preclude the use of tolls on general purpose lanes (GPLs). In a direct reference to toll lane conversion efforts, the provision specifies that the implementing agency may permit vehicles with fewer than two occupants to operate in high occupancy vehicle lanes if the

subject facility is part of a value pricing program (FWHA 1999).¹

Awards are based on the following eligibility criteria:

- the condition and usage of the existing Interstate facility;
- interagency coordination with the local Metropolitan Planning Organization;
- evidence demonstrating that the Interstate facility cannot be maintained or improved with the use of tolls;
- a comprehensive management and financial plan

The Interstate facility that is part of the value pricing program is eligible for IM funds after the 10 year term limit.

1.2.3 State and Local Regulations

With increased federal support for tolling initiatives, states and regions have taken inventory of highway improvement projects and begun to identify tolling projects where such efforts are best able to meet stated objectives and garner public support. In California, the Southern California Association of Governments (SCAG) has identified the Antelope Valley (SR-14) freeway as a candidate HOTL projects in the 1998 Regional Transportation Improvement Plan for the Los Angeles metropolitan area. In Texas, Florida, Minnesota, and Washington, similar efforts are being undertaken in the development of transportation management plans. State legislatures must pass enabling

¹The implementing agency is required to consider the equity impacts of value pricing projects on low-income traveler and develop mitigation measures to address adverse financial impacts on low-income travelers.

legislation authorizing local MPOs and state DOTs to convert GPLs into toll lanes. Because tolling is controversial, a precondition to legislative support is strong local support.

1.3 INSPIRATION FOR RESEARCH

This research examines whether and under what conditions a HOTL could provide greater benefits than HOVLs or GPL additions. The impacts of toll lane service are worth investigating because it signifies the confluence of three distinct and separate transportation planning traditions: state highway planning, toll road finance and operations, and welfare economics. It is an opportunity to test theory, explore new methods of project finance, and gauge public opinion. The primary objective of this dissertation is to better understand the conditions in which HOVL conversion strategies ought to be considered and evaluate the relative costs and benefits arising from the conversion of an HOVL to HOTL, toll lane or GPL use.

It is important to be able to lay out a theoretical framework that predicts the distribution of costs and benefits resulting from behavioral shifts in response to new investments like HOTLs. Furthermore, it is important to test whether these theoretical models stand up to empirical rigor, in those rare cases where there is enough before/after data to quantify the effects of particular investment choices. This analysis will develop travel demand and supply structure models for peak travel, and seek an equilibrium consistent with both sets of theoretical models. Full treatment will be given to the relationship between pricing and short-term investment, two facets that have long been

considered the hallmark of urban transportation economics (Small 1992). This analysis will also include a highway congestion model which incorporates queueing, trip scheduling, and peak shifting, critical features that exert a significant influence on the impacts of pricing policies designed to alleviate peak highway congestion.

While the HOTL concept has generated interest among transportation policymakers, there is no widespread consensus regarding the comparative effects of building toll lanes along congested highway corridors. Much research has already been conducted on HOVL performance (Turnbull 1992a; Turnbull et al. 1992b; Guiliano, Levin and Teal 1990; Fuhs 1991; Kain et al 1992; Dahlgren 1994). We know that the effectiveness of HOVLs in motivating a shift to HOVs depends on the presence of delays on the uncontrolled highway lanes. In other words, for HOVLs to be effective, some peak congestion on uncontrolled lanes is necessary. Is the same true for HOTLs? With HOVLs, there is an upper limit beyond which the presence of an HOVL cannot motivate additional shifts to HOV. If there is excess peak capacity on the HOVL after all long-term shifts to HOV have been motivated, does allowing SOV toll buy-ins provide a greater degree of benefits than preserving these facilities as HOVLs or converting them to GPL?

1.4 DISSERTATION STRUCTURE

In Chapter 2, I provide a general overview of urban toll road finance and planning intended to familiarize the reader with some of the economic, political, legislative barriers to wider urban toll lane implementation; special attention is paid to the case studies in

California. Sections 2.4 and 2.5 focus on the performance of California's two congestion toll lanes, the 91 Express Lanes and the I-15 Express Lanes. Section 2.6 concludes with a discussion of HOVL theory, performance, and evaluation and links the critique of HOVLs to the emergence of the HOTL concept. While most of the HOVL performance literature can be characterized by studies that do not properly model the distribution of costs and benefits in any systematic economic modeling approach, Dahlgren (1994) provides a simple but elegant theoretical model that describes in great detail the limits of HOV priority treatment. Her emphasis on evaluating investment decisions based on the comparative distribution of costs and benefits among all competing alternatives inspires this work, which I believe to be a logical extension of her research efforts. This discussion is intended to provide a conceptual framework for evaluating the comparative effects of an HOVL versus toll lane. In Chapter 3, I provide an analysis of the comparative effects of converting an HOVL to HOTL, toll lane and GPL.

In chapter 4, I present theoretical models used to evaluate the behavioral impacts of adding an toll lanes. In chapter 5, I conduct a comparative analysis of the effects of converting an HOVL to toll lane or GPL based on the supply and travel demand models discussed in Chapter 4, and present empirical findings on the impacts of the 91 Express Lanes, the major case study of the dissertation. In chapter 6, I present a cost-benefit framework within which to analyze the welfare effects of converting an HOVL to toll lane and GPL, and estimate the economic benefits of competing conversion strategies. In Chapter 7, I present overall findings and policy implications. Overall, this research

provides support for the policy claim that under most urban travel conditions, congestion toll lanes and HOTLs provide a greater degree of fiscal, consumer welfare, and social benefits than alternative life-haul expressway treatments.

2. HOT LANES: CONVERGENCE OF TOLL ROAD AND HOVL PLANNING

2.1 HISTORICAL ORIGINS

Before the interstate era, toll roads were an expedient form of urban expressway development in areas where state funds for large-scale road projects were scarce (Klein 1990; Wuestefeld 1988). By 1930, states experienced a rapid transformation in urban travel, as automobile usage and vehicle ownership rates skyrocketed and the automobile became the predominant mode of intercity travel. The toll road, which bond underwriters believed yielded a reliable if unspectacular revenue stream, also appealed to state officials desperately wanting to modernize roads without raising general taxes. The Pennsylvania Turnpike, considered the first modern era toll road, was financed with \$29 million Public Works Administration grant and \$40.8 million in revenue bonds and opened to the public in 1940.

Inspired by the Henry Hudson Parkway, the Bronx River Parkway, the Merritt Parkway in Connecticut, and the Arroyo Seco Parkway in Los Angeles in 1934, the U.S. Bureau of Public Roads favored improving urban parkways over building intercity turnpikes (Pennsylvania Turnpike Commission 1999). After more than a decade of experience improving the design and construction of urban parkways, by 1950 there was a general consensus among federal and state lawmakers, transportation officials, and the auto industry in favor of a free, high-speed national expressway system financed through a pay-at-the-pump federal gasoline tax over a system of interstate toll roads (Gittings 1987). After 1945, turnpikes were not eligible for federal aid.

Toll roads were nevertheless built throughout the Midwest and Eastern states. Following the success of the Pennsylvania Turnpike, several other states – New Jersey, New York, Massachusetts, Maine, Indiana, Ohio, Illinois, Oklahoma, and Florida – built and financed their own intercity turnpikes even though such projects did not qualify for federal aid (Wuestefeld 1988)¹.

Since the mid 1960s, there has been a resurgence of interest in toll roads (International Bridge, Tunnel & Turnpike Association 1999; Samuel 1999). After a brief lull in toll road construction from 1959 to 1962, another 1,240 miles of toll roads were completed between 1963 and 1974 (Wuestefeld 1988). Between 1968 and 1981, over 20 new toll roads nationally opened: the Cimarron Turnpike (Oklahoma) in 1975, the Dulles Toll Road (Virginia) in 1984, Sawgrass Expressway (Florida) in 1986, Dallas North Tollway, Hardy Toll Road (Houston), and the Sam Houston Tollway (Houston) in 1989 (Wuestefeld 1988).

Today, there are over 40 toll roads in operation nationally, located primarily in the East and Midwest (International Bridge, Tunnel & Turnpike Association 1999). The combined length of all present toll roads is 4,500 center-line miles, including 2,371 miles carrying Interstate highway system designation, 703 miles on the federal-aid primary and urban systems, 32 miles of private sector-operated road, and the remainder on state and

¹

Because federal aid for the construction of toll road projects was expressly prohibited under the Federal-Aid Road Act of 1916 and the Federal-Aid Highway Act of 1921, which encouraged funding sources supported by general user taxes, serious consideration was never given to the use of federal aid for toll road development (Gittings 1987; Rush 1984; Wuestefeld 1988)

local road systems (Wuestefeld 1988; International Bridge, Tunnel & Turnpike Association 1999). 2,262 miles of toll roads were constructed prior to 1957, an additional 590 miles were added in 1957 and 368 more miles were completed in 1958 (Wuestefeld 1988). Since the late 1980s, California and Virginia have passed enabling legislation allowing for the construction of privately financed congestion-relief automated urban toll roads. California's three toll road projects -- the 91 Express Lanes (Orange county), the I-15 Express Lanes (San Diego county), and the San Joaquin Hills Toll Roads (also in Orange County) -- represent the most recent manifestation of the modern toll road tradition, and share unique operational and technological attributes that dramatically alter the economics of toll roads finance. Table 2.1 provides a summary of the length and toll for selected urban toll roads in the United States.

Bond Financing of Toll Roads

Because inflationary pressures increased the cost of toll road operations in the 1980s, toll road authorities were required to provide a minimum 1.25 coverage of annual debt service early in the project life cycle when issuing revenue bonds (Wuestefeld 1988). If operating costs exceed preliminary cost estimates, private bond markets could require the annual debt service coverage rate to be higher than the 1.25 standard coverage rate. While ETC increases capital costs on new toll roads, ETC deployment reduces toll road operations (most of which comprises personnel costs for manual toll collection), which may increase the number of new toll roads by decreasing debt service coverage requirements and increasing opportunities for revenue bond financing.

Forkenbrock and Schweitzer (1997) report that for every dollar of revenue

Table 2.1 Length and Per-Mile Toll Rates for Selected Urban Toll Roads in the United States

<i>Facility</i>	<i>Length (miles)</i>	<i>Toll</i>	<i>Per Mile Rate</i>
Buccaneer Trail	15.9	\$0.50	\$0.0314
Dallas North Tollway	9.8	0.50	0.0510
Airport Expressway	8.8	0.25	0.0284
Holland East-West Expressway	13.8	0.50	0.0362
Massachusetts Turnpike Extension	12.0	0.75	0.0625
Tampa South Crosstown Expressway	17.5	0.50	0.0286
New Jersey Turnpike	35.0	1.50	0.0429
New York State Thruway	45.2	2.50	0.0553
Pennsylvania Turnpike	47.0	1.60	0.0340
Richmond Expressway	6.3	0.50	0.0794
Virginia Beach – Norfolk Expressway	12.1	0.25	0.0207
J.T. Butler Expressway	12.2	0.50	0.0410
Sawgrass Expressway	22.8	1.50	0.0658
Houston West – Belt Tollway	27.5	2.10	0.0764
Houston Hardy Road Tollway	21.7	2.00	0.0922
91 Express Lanes	9.8	VAR	
I-15 Express Lanes	8.0	VAR	
Eastern Toll Road		2.00	
San Joaquin Hills Toll Road		2.00	

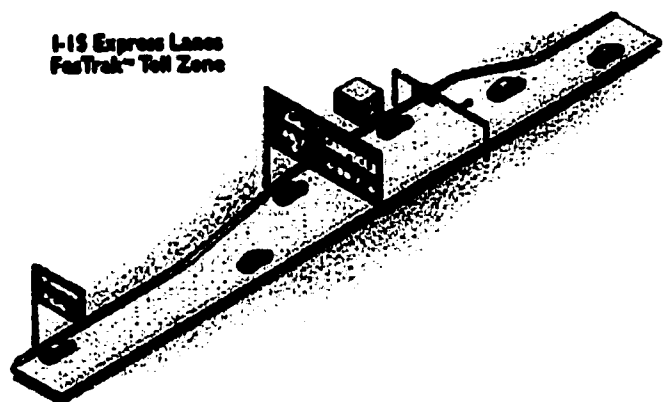
Source: International Bridge, Tunnel & Turnpike Association 1999

collected from traditional (non-ETC) toll roads, 15 – 20 percent goes to administrative overhead (Forkenbrock and Schweitzer 1997). The Oklahoma Turnpike Authority reported that after converting to ETC, annual toll collection costs decreased 91 percent (TRB 1997). California Department of Transportation (Caltrans) is currently in the process of installing ETC on the nine toll bridges owned by the state, and two new toll road projects, one in Orange County and the other in San Diego County (Samuel 1998). It is the intent of all the toll facility operators to allow transponders purchased for one facility to be used on all automated toll facilities statewide.

California's new toll roads – some of which are HOTLs – are qualitatively different from those toll roads built between 1968 and 1989 because electronic toll collection (ETC) has supplanted manual toll collection,² resolving perhaps the single biggest economic deficiency in toll road operations and finance

(Wuestefeld 1988; Poole 1992; Fielding 1994; Roth 1996). ETC works much like a pre-paid telephone card that allows the user to debit charges up to the account limit. After opening a pre-paid

Figure 2.1. Fastrak on the I-15 Express Lanes



²

Many of newer toll roads like Dulles Toll Road have been designed as ETC projects, and older toll roads built before ETC commercialization have begun implementing ETC to facilitate electronic tracking and billing.

account, the driver places a 'transponder' on the vehicle dashboard or windshield.

Whenever that vehicle passes underneath a designated electronic gantry (at highway speeds), tolls are electronically debited from the owner's pre-paid account (CPTC 1996).

Because ETC does not require vehicles to stop to pay a cash toll, traffic flows smoothly and ETC-equipped toll lanes can accommodate up to 1,600 vehicle per hour per lane and offer high Level-of-Service (LOS) throughout peak hours (Pete Kiewit & Sons 1998). The ETC system has been implemented on more than half of the nation's 180 toll roads and bridges, and implementation plans are currently underway to retrofit older turnpikes with ETC (Pete Kiewit & Sons 1998). ETC is currently in use on the 91 Express Lanes in Orange County, the I-15 Express Lanes in San Diego County, and the San Joaquin Hills Toll Roads (73 and 241) in Orange County.

2.2 TESTING VALUE PRICING ON HOTLS

Two of California's new toll road projects – the I-15 Express Lanes and the 91 Express Lanes – have generated keen interest among researchers, policymakers, lawmakers and citizen's groups because they implement *value pricing*, a time-of-day tolling system that allows the facility operator to maintain free-flow traffic conditions throughout the day by increasing tolls during peak hours and offering off-peak discount tolls during non-peak hours.³ On both facilities, the toll road operator has justified *value pricing* to reserve fixed peak capacity for HOVs and allocate remaining capacity to SOVs

³

The Federal Highway Administration defines value pricing as a method of tolling used on new urban roads designed to provide peak toll customers with the option to bypass congested highway and roads.

that leave entrenched public programs, private economic interests, and lifestyle preferences undisturbed, while providing an array of noticeable benefits (Altschuler, Womack and Pucher 1981). Altschuler, Womack and Pucher (1981) elegantly describe how the political survival of policy innovations are inextricably linked to the distribution of costs and benefits they are perceived to impose on competing interest groups in society:

Among measures that entail some compulsion, the most attractive are those that alleviate widely perceived problems at little or no cost and that either operate on corporate enterprises rather than individual travelers (for example, new-car performance standards) or entail the exercise of traditional governmental powers in relative unobtrusive ways (such as traffic management improvements). (Altschuler, Womack and Pucher 1981, pg. 136)

Because the economic burden of region-wide congestion pricing on urban travelers is immediate and widespread, congestion pricing has never received serious consideration as a transportation demand management policy.

Gomez-Ibanez (1994) argues that congestion pricing is likely to create more losers than winners. Among those groups likely to be worse off after region-wide congestion pricing, he identifies: (1) motorists who pay the congestion toll but place a low value on travel time, (2) motorists who shift from the tolled road to a competing untolled facility, (3) other users of the untolled roadway, (4) motorists who choose not to make the trip at all because of the toll, (5) travelers who switch from driving to HOV or bus services on the toll road (Gomez-Ibanez 1994).

In 1997 the REACH task force commissioned a study of public attitudes on region-wide congestion pricing and VMT tax initiatives, and administered an attitudinal survey to sample of Southern California residents. The survey was designed to estimate how respondents would vote in a hypothetical referendum on congestion fee policies under various revenue redistribution scenarios. Of the 1,743 individuals surveyed, 38 percent reported that they would support a congestion fee, with 56 percent opposed and 6 percent undecided. Of the 56 percent who opposed a regional congestion fee, over two-thirds were 'definite' in their

Table 2.2 REACH Taskforce Public Opinion Survey: Support for Base Congestion Fee Policy

Support		Oppose		Don't Know
38%		56%		6%
Probable	Definite	Probable	Definite	
23%	15%	17%	40%	6%

Source: Harrington 1998

opposition (Harrington 1997). The REACH findings are corroborated by numerous studies conducted in Minnesota, Hong Kong, Great Britain, and the Netherlands that find that voters in democratic societies overwhelmingly reject the congestion pricing based on equity and privacy issues (Borins 1988; Fowkes et al. 1993; NCHRP 210 1994; Jones 1994). While Small (1992) suggests that public attitudes against congestion pricing might soften if a politically viable revenue redistribution package can be cobbled together, Borins (1988), Olson (1994) and Harrington (1997) cite distrust of government as a major obstacle in overcoming public resistance to congestion pricing proposals that require some package of revenue redistribution.

Because voter opposition to region-wide congestion pricing is formidable, congestion pricing will be implemented only when the public and elected representatives accept tolling as a means of *financing the expansion of new highway services* rather than

as a means of *managing existing facilities more efficiently* (Gomez-Ibanez 1992; Giuliano 1992). In California, the willingness to experiment with toll roads (and congestion pricing) does not represent a triumph of policymakers in winning over a skeptical motoring public; rather, public acceptance of toll road planning efforts represents a last-ditch effort to expand roadway capacity in urban and suburban areas suffering from dramatic recent increases in traffic congestion.

The HOTL concept emerged in the early 1990s out of numerous policy discussions among policy analysts, highway engineers and transportation researchers seeking ways to improve on HOVL service at minimal public cost (Fielding 1993). The first formal treatment of the HOTL concept was presented by the Reason Foundation (1993), which published a report identifying the benefits of using variable pricing to improve to performance of underutilized HOVLs (Fielding 1993). Although the report's hypothesis linking public acceptance of highway tolling to the perceived benefits of converting one highway lane at a time to toll lanes remains unproven, its main recommendation of converting HOVLs to HOTLs emerged from a well established theoretical literature within transportation on the congestion pricing of urban highways.

Since this report, numerous regional, state and federally sponsored congestion pricing seminars, workshops and conferences have investigated political, implementation, legislative and technical barriers to wider toll road implementation (REACH Taskforce 1995; NCHRP 210 1994; FHWA 1992; EPA 1997; USDOT 1998). There is widespread agreement that congestion pricing on urban highways is likely to provide substantial time savings and environmental benefits, but apprehension about how tolling urban highways

will disrupt travel and lifestyle preferences has relegated congestion pricing to the political hinterlands (Gomez-Ibanez 1992; Orski 1992; Higgins 1994; Olson 1994; Rom 1994). Despite the growth of traffic congestion in metropolitan areas nationally, many researchers concede that congestion pricing is unlikely to ever become a politically acceptable traffic management policy. Toll roads built on unused highway rights-of-way or existing HOVLs have become identified as a viable means of testing the theoretical precepts of congestion pricing without disrupting the ensemble of interests in support of the current system of transportation delivery and finance.

Within the toll road industry, there has been spirited debate over whether toll operators should impose a flat rate or variable tolls on turnpikes, bridges and tunnels retrofitted ETC. To manage congestion effectively, economic theory states that tolls should be higher during times of day when traffic volumes

Figure 2.3 AM and PM Toll Schedule on the I-15 Express Lanes

Minimum Toll	Morning Period (Southbound)							
\$4.00								
\$3.00								
\$2.50								
\$2.00								
\$1.50								
\$1.00								
\$.75								
\$.50								
	5:45-6:30	6:00-6:30	6:30-7:00	7:00-7:30	7:30-8:00	8:00-8:30	8:30-9:00	9:00-9:15

Maximum Toll	Evening Period (Northbound)							
\$4.00								
\$3.00								
\$2.50								
\$2.00								
\$1.50								
\$1.00								
\$.75								
\$.50								
	3:00-3:30	3:30-4:00	4:00-4:30	4:30-5:00	5:00-5:30	5:30-6:00	6:00-6:30	6:30-7:00

approach or exceed capacity at the rated LOS, and lower or non-existent during off-peak times of day when volume is well below capacity. Toll are essentially price signals that

ensure that highway capacity is allocated to those who place the greatest value on them.

Tolls are determined by the consumers willingness to pay for them, which in turn is established by personal attributes such as income, trip purpose, and other factors (Gillen 1994; Evans, Small and Winston 1989; Levinson 1988). Allocating road capacity to those individuals who place the greatest value on peak period travel insures that social benefit is maximized for some given level of highway investment. By sending the correct price signal, it is possible to align peak demand with supply and maintain high LOS (Levinson 1987; McMullen 1992; Hau 1992; Small, Winston and Evans 1989). On *new roads in outlying areas* with low daily traffic, toll road operators like the Transportation Corridor Agency (TCA) have opted for a flat rate toll that they believe is simple for travelers to understand than dynamic, distance-based tolls (TCA 1997).

After more than three years in operation, the 91 Express Lanes has demonstrated that an optimal peak-load pricing structure can allow the facility operator to manage congestion throughout the peak period and assure toll paying customers free-flow conditions all day. Figure 2.4. shows the published toll schedule for the 91 Express

Figure 2.4 Eastbound Toll Schedule for the 91 Express

Time	Sun	Mon	Tue	Wed	Thur	Fri	Sat
Midnight							
1:00 AM							
2:00 AM							
3:00 AM							
4:00 AM							
5:00 AM							
6:00 AM							
7:00 AM							
8:00 AM							
9:00 AM							
10:00 AM	\$1.00						\$1.00
11:00 AM							\$1.00
NOON							
1:00 PM							
2:00 PM		\$2.95	\$2.95	\$2.95	\$2.95		
3:00 PM							
4:00 PM							
5:00 PM							
6:00 PM							\$1.00
7:00 PM					\$2.95		
8:00 PM	\$1.00				\$1.00	\$2.95	
9:00 PM						\$1.00	
10:00 PM							
11:00 PM							

Lanes. Because travel on the Riverside freeway is highly peak directional (with high travel demand traffic in the westbound direction in the morning and high travel demand in the eastbound direction in late afternoon), the toll price ranges from \$1.25 at 12:00pm and gradually rises to a high of \$3.35 at 4:00pm. It is worth noting that the complexity of the toll structure has been minimized because there is only one entry point into the Express Lanes (at each end of the 10-mile facility), obviating the need to index the toll to a per mile basis.⁴

Opinion surveys conducted since the opening of the 91 Express Lanes indicate that motorists strongly support the 91 Express Lanes project, a facility that Riverside officials now acknowledge has become perceived as an indispensable piece of the region's transportation puzzle (Sullivan *et al.* 1998). The owner, CPTC, reported that in 1996 80,000 new customers obtained transponders. ARDFA's study finds that over 37,000 subscribers use the Express Lanes per weekday, and that customers enjoy between 15 to 20 minutes of peak travel time savings (CPTC 1997). 91 Express Lane travel volume data are presented in Chapter 5.

2.3 LEGISLATIVE BARRIERS TO TOLL ROAD IMPLEMENTATION

While there is growing interest in automated toll roads among local, state, and federal transportation officials, there remain a number of significant legislative and

⁴

In October 1999, CPTC announced its desire to sell its interest in the 91 Express Lanes either to another party or back to the state of California, sparking a firestorm of controversy in Sacramento over the efficacy of private toll road development. It is worth noting that the current debate concerning toll roads is focused on the merits of privatization and not value pricing.

programmatic barriers to wider automated toll road implementation. Because states had been expressly prohibited from converting gas tax-financed Interstate highways into toll facilities (Section 129, Title 23, U.S. Code) under the Intermodal Surface Transportation Efficiency Act (ISTEA) and prior transportation bills, federal legislation must be enacted to exempt specifically identified federal interstate facilities in order to widen federal funding eligibility for candidate toll road conversion projects (Olson 1994). During the debate over ISTEA reauthorization, the Clinton administration proposed a version of the transportation bill that would have given states the authority to convert interstate highways within their jurisdiction into toll roads (Simon, *Los Angeles Times*, July 30, 1998). It was quickly shelved, however, in the face of strong opposition from the trucking industry, roadbuilders and consumer groups. A scaled back version of the Clinton proposal allowing three states to convert interstate highways into toll roads was eventually included in TEA-21 (Simon, *Los Angeles Times*, July 30, 1998). In addition to this provision, the Federal Highway Administration (FHWA) sponsored a *value pricing demonstration project* provision that expanded the number of eligible project under the *value pricing pilot program* from 5 to 15 and increase funding from \$25 million to \$75 million.

At the state level, state statutes and local government ordinances often contain restrictions on roadway pricing and the allowable use of toll revenues. In California, state senator Tom Hayden (D - Santa Monica) carried SB144 in 1996, intended to prohibit the Los Angeles Metropolitan Transportation Authority (LAMTA) from implementing congestion pricing on any mixed flow or HOVL programmed under the Regional Air

Quality Strategy. Bill Lockyer (D-Hayward), at the time a high ranking state assemblyman and now state Attorney General, strongly opposed urban toll road planning initiatives on the grounds that the tolling of public roads is unfair to low-income motorists, and has publicly stated that he will oppose any efforts to introduce congestion pricing on California highways.

Because local jurisdictions often lack the sufficient legal authority to plan, finance, and build new toll road facilities, such powers must be assigned to them by state legislatures. In California, the state legislature has acceded authority to localities in cases where (1) they have sufficiently demonstrated that the proposed toll road project has a financially viable source of project funding, (2) an appropriate program design and the potential to resolve local transportation problems at minimal public cost. In the following sections, I describe the journey from concept to project implementation for the 91 Express Lanes and the I-15 Express Lanes. Special attention will be paid to state and local politics, the *ad hoc* process of legislative coordination between local, state and federal agencies, recent changes in federal and state law with respect to toll road planning, and factors influencing program design decisions.

2.4 91 EXPRESS LANES: FROM CONCEPT TO IMPLEMENTATION

Assembly Bill 680 of 1989, the enabling legislation authorizing four private toll road projects in California, emerged in a period during which the legislative urgency to act on key transportation finance issues was motivated by fiscal crisis (Brown et al. 1998). In 1980, Caltrans announced a \$912 million shortfall in the five-year State Transportation Improvement Plan (STIP), which immediately focused public attention on

the growing disparity between the cost of upgrading the highway system and shrinking gas tax revenues (Brown *et al.* 1998). Many in the legislature felt that motor vehicle taxes (which had not been raised in twenty years) needed to be raised but were unsure about voter sentiment, and how much to raise taxes to meet the funding gap (Brown *et al.* 1998).

To alleviate the fiscal crunch, the legislature enacted SB 215 in 1981-1982 session, which increased gasoline and diesel taxes from 7 to 9 cents per gallon and authorized counties to enact their own county gas taxes, effective September 1981 (Brown *et al.* 1998). Periodic additional tax increases would be needed to keep pace with inflation, but the political will to resolve this structural dilemma eroded in subsequent years as the legislative desire to fix the state's transportation finance problems lost political urgency (Wachs 1996). Of the twenty transportation bills introduced in the 1980s, only SB215 and SB1560 were ever signed into law (Brown *et al.* 1998)

By the late 1980s, transportation again reappeared on the legislature's radar screen as urban and suburban voters statewide expressed frustration with worsening traffic congestion (Baldassare 1990). The legislature responded by passing AB471 and SB 300, which resurfaced from the twelve motor vehicle tax increase proposals introduced during the 1989-1990 legislative session (Brown *et al.* 1998). SB 300 increased the gas tax to 18 cents per gallon (from 14 cents) and raised commercial vehicle weight fees by nearly 60 percent. AB471 raised diesel fuel taxes to 18 cents per gallon. The two bills passed the legislature and were sent to Governor Deukmejian's desk along with proposals for a special state sales tax increase to repair earthquake damage and an earthquake retrofit

bond measure (Brown *et al.*1998).

SB 300 and AB 471 were packaged as part of a ten-year finance program called the *Transportation Blueprint for the Twenty-first Century* (Brown *et al.*1998). The spending bills increased projects transportation revenues by \$18.5 billion over ten years through gas tax, diesel tax, and vehicle weight fee increases. Revenue raised by these tax increases was directed to a host of highway and transit capital, operations, and maintenance projects (Brown *et al.*1998). Because AB 471 and SB 300 authorized gas tax increases exceeding constitutional limitations, the two pieces of legislation had to be submitted to voters as a proposed constitutional amendment, Proposition 111, the Traffic Congestion Relief and Spending Act of 1990 (Brown *et al.*1998).

While the tax bills worked through the legislature, the newly established Office of Privatization at Caltrans campaigned in Sacramento for a private toll road bill, an initiative that did not generate widespread interest within the legislature but intrigued Assemblyman Tom Baker, its eventual sponsor (FHWA 1992). Caltrans also presented its idea to Governor Deukmejian, who agreed to throw his support behind the initiative (FHWA 1992). In exchange for Governor Deukmejian's support for the transportation expenditure bill of 1990, the state legislature agreed to pass AB 680 in 1989, which allowed up to four private tollway demonstration projects. In 1990, California voters approved Proposition 111 (Brown *et al.*1998).

The primary objective of AB 680 was to test the market feasibility of financing and building new toll roads that could incorporate state-of-the-art automated toll collection technology without the use of public funds (FHWA 1992). The bill authorized

Caltrans to negotiate 35-year franchise agreements with private entities under the Build-Operate-Transfer (BOT) model. Caltrans could exercise the power of *eminent domain* on behalf of a tollway project if private efforts to acquire right of way are not sufficient. The entity to whom the state awarded a franchise was to be solely responsible for financing the construction and maintenance of the toll road facility, and operating the toll road for the duration of the franchise agreement (Caltrans 1990). After the construction phase, property rights were to be reassigned to the state, and the franchisee would then pay an annual lease in exchange for the right to operate the facility for the length of the franchise. Toll rates are not regulated, but the franchise agreement includes a ceiling on rate of return, with any excess revenues going to a state highway fund (Caltrans 1990).

AB 680 authorized Caltrans to enter into agreements with private entities for the construction by, and lease to private entities of four demonstration projects.⁵ Caltrans solicited participation in the transportation privatization program from sponsors with transportation projects contemplated under the 1990 State Transportation Implementation Plan (STIP). The 1990 STIP contemplated median improvements to SR-91 to expand capacity for high occupancy vehicle lanes and scheduled improvements in fiscal year 1995-1996. Because this HOVL project was one among hundreds of projects listed in the

5

AB 680 authorized the department to lease rights-of-way in, and airspace over or under state highways, to grant necessary easements, and to issue permits or other authorizations to enable private entities to construct transportation facilities supplemental to existing state-owned transportation facilities, and to lease those facilities to private entities for up to 35 years. The legislative intent of AB 680 was to demonstrate the feasibility of tapping private bond markets to finance badly needed roadway facilities that would be paid back through toll revenues.

STIP, the Orange County Transportation Commission (OCTC) submitted a proposal for the SR-91 private transportation project (Best, Best and Krieger 1994).

Explosive subdivision growth in western Riverside County – the fastest growing county in the United States – fueled a population boom in the 1980s that caused unexpected increases in peak traffic on SR-91, the only major highway connecting Riverside county's new subdivisions to job sites throughout central and southern Orange County. Throughout the 1980s, SR-91 experienced an annual traffic increase of 8.4% per year, carrying an average daily traffic (ADT) of 188,000 by 1985, 190,000 by 1990 and 192,000 by 1995 (Caltrans 1994). By the mid-1980s, morning traffic conditions in the westbound direction and late afternoon traffic conditions in the eastbound direction dramatically worsened (Caltrans 1985). Figure 2.5, which presents a time series of Capacity Adequacy (CA) between 1980 and 1995,⁶ shows that between 1977 and 1985, CA averaged 88.9 – indicating that traffic volumes in the Present Design Hour (PDH) just exceeded the rated highway capacity. Between 1985 and 1995, CA averaged 68.6 –

6

Capacity Adequacy (CA) is defined as the ratio of the highway's rated capacity divided by a measure of peak hour travel flow (volume during the present design hour), multiplied by 100. Rated capacity is based on level-of-service criteria that take into account the type of highway, lane width, geometry, terrain, and other conditions that affect traffic flow. The present design hour (PDH) is the 30th highest volume hour for rural highways and the 200th highest volume hour for urban highways. Locations with CA less than 100 are congested at the present design hour; conversely, locations with CA greater than 100 are not congested. The

Boarnet, Kim and Parkany (1998) develop a technique for aggregating CA for highway segments, cities, counties and SMSA and the state. See Boarnet, Kim and Parkany (1998) for a description of the aggregation technique.

indicating a substantial worsening of peak hour traffic conditions

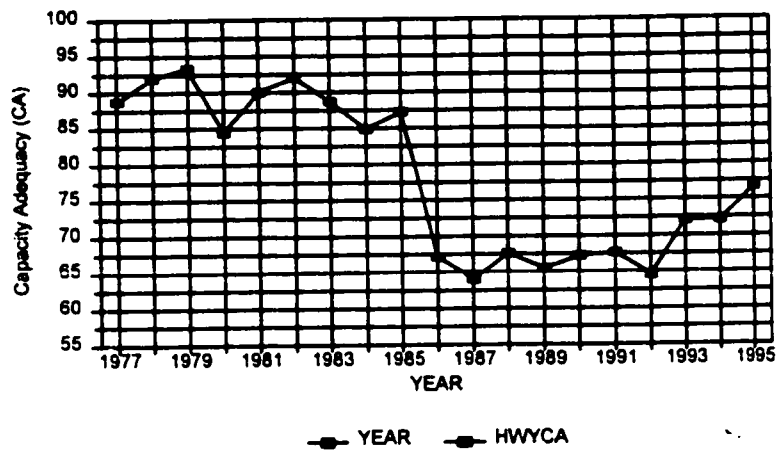
along the Riverside freeway, a trend fueled by the dramatic population and employment

growth in western

Riverside and San

Bernardino Counties and employment growth in Orange County.

Figure 2.5 Capacity Adequacy (CA) for the Riverside Freeway (between I-15 and SR-55)



Widespread frustration over the pace of the state highway program and political frustration with traffic congestion eventually resulted in Riverside county voter approval of a half-cent sales tax for transportation improvements in 1988, one year prior to the passage of AB680 (Interview with Jack Reagan 1997).⁷ Proceeds from the transportation sales tax were to be earmarked for a number of highway improvements, including an HOVL on the Riverside freeway. Immediately after passage of the sales tax initiative, Riverside County officials pursued a memorandum-of-understanding with Caltrans and OCTC in which a tentative agreement to cooperate in the planning and construction of an HOVL on the Riverside freeway (between the junction of I-15 and SR-91 and the

⁷

Sales tax receipts were to be dedicated toward a variety of transportation-related purposes: operating subsidies for the commuter rail program, freeway improvements, and the construction of an HOV facility along SR-91 in accordance with the 1990 STIP.

Orange/LA county border) was struck (Interview with Jack Reagan 1997). Because Orange County voters rejected transportation sales tax measures throughout the 1980s and county officials had little hope that county voters would support a sales tax in the near future, OCTC officials signed the memorandum of understanding with Riverside county to build an HOVL on the Riverside freeway, but hedged their bets by submitting a proposal for the Riverside freeway to the Private Transportation Project under AB680. After receiving eight proposals, Caltrans selected four projects, two in southern California and two in the San Francisco Bay Area.

In August 1990, Caltrans issued a negative declaration for an umbrella project designed to provide exclusive HOVLs in the median of SR-91 extending from the interchange with SR-57 in Anaheim to Magnolia Avenue in Riverside county, a distance of 23.8 mile (Best, Best and Krieger 1994).⁸ In the months prior to the issuance of the negative declaration, Caltrans and the FHWA facilitated extensive interagency involvement and participation during the preparation of the environmental documentation for the 23.6-mile umbrella project (Best, Best and Krieger 1994). Armed with local funding for HOV improvements within its jurisdiction, Riverside County Transportation Commission (RCTC), which administers the half-cent sales tax and is responsible for transportation planning and programming within Riverside county, consulted with

⁸

Under the California Environmental Quality Act (CEQA), public agencies are required to conduct an environmental impact report (EIR) that provides an comprehensive account of how major capital project affect the environment. A negative declaration is a statement certifying that a given project will have

Caltrans, OCTC and FHWA over operational and financial characteristics of the proposed HOVL in 1990 (Interview with Jack Reagan 1997).

As a trustee agency, RCTC expressed concern that the toll road project within the Orange county jurisdiction could potentially undermine the performance of the Riverside County HOVL east of the Orange/Riverside County border (Interview with Jack Reagan 1997). Some RCTC officials argued that building a toll road along what would have been an HOVL constituted “double taxation,” as Riverside county residents who were already paying a sales tax for the HOVL would be subject to a toll to continue west into Orange County on the HOVL (Interview with Susan Cornelison 1997). RCTC lobbied for HOV2+ toll exemption, but CPTC opposed the HOV2+ toll exemption on the grounds that exempting tolls for HOV2+ would undermine the financial viability of their investment. RCTC signed a memorandum of agreement (MOA) with Caltrans, CPTC, and OCTA on January 8, 1992 on the condition that Caltrans and CPTC modify certain aspects of the franchise agreement to resolve RCTC’s concerns about the status of HOVs, the placement of ingress/egress points, and the physical configuration of the toll zones (Best, Best and Krieger 1994). The MOA also reflected a compromise between RCTC and CPTC on the HOV2+ toll exemption issue. CPTC and RCTC agree to a compromise allowing toll exemption for HOV3+ on the condition that CPTC could unilaterally charge a half-toll to HOV3+ if future traffic growth merited a change in toll pricing (Best, Best and Krieger 1994).

In September 1992, Caltrans and CPTC modified the project by removing all intermediate ingress and egress access points, a change that RCTC officials felt violated

CEQA because Caltrans did not provide public notice of the environmental reevaluation of the modification. RCTC threatened legal action against the project. In May 1994, RCTC sued to enjoin action on the project on the grounds that Caltrans violated CEQA “by continuing with the implementation of the Project when it has been substantially and significantly changed, without preparing a subsequent EIR (Best, Best and Krieger 1994).” RCTC withdrew its legal action shortly thereafter on the condition that Caltrans and CPTC would provide assurances that ingress/egress points would be built at some future date.

Since its opening, the 91 Express Lanes has been a lightning rod of political controversy, igniting a volatile debate over the merits of roadway privatization. By its third year in operation, the 91 Express Lanes turned a thin profit margin, but ridership levels leveled off and dipped following the opening of the Eastern Transportation Corridor (CPTC 1999). Amid investor concerns over profitability, CPTC announced in September 1998 the sale of the 91 Express Lanes to NewTrac, a non-profit, private company. The idea behind a sale to a non-profit was to allow the new entity to sell tax-exempt bonds through the State Infrastructure Bank, thereby lowering borrowing costs. The buyer, NewTrac, planned to sell \$274 million in tax-exempt bonds through the California State Infrastructure Bank to purchase the facility and cover operating expenses (Jeff Collins, *Orange County Register*, September 12, 1998).

Three separate but related issues derailed the potential sale. First, the buyer failed to disclose to the IRS and other public agencies that CPTC had initiated the idea to form the non-profit company, helped to create it, and loaned it \$1 million to facilitate the sale

(McKim and Kelleher, *Orange County Register*, December 10,1999). When Riverside county sued NewTrac, Treasury Secretary Phil Angelides indefinitely postponed the sale over concerns that relationship between the CPTC and the NewTrac was too cozy. Second, critics charged that there was no independent appraisal of the sale price, which appeared to be too high. Based on proprietary information, the seller estimated a sale price of \$225 million, which would have provided CPTC, which initially invested \$20 million, with a \$90 million profit (McKim and Kelleher, *Orange County Register*, December 10,1999). In a December 1999 teleconference held to promote the bond sale, investors questioned the accuracy of revenue projections used to arrive at the \$225 million sale price, forcing the buyer to concede that it could not justify revenue projections based on year 2000 ridership projections. The failure to convince bond underwriters to finance the sale reinforced the rising public impression that CPTC was structuring the sale to reap a hefty profit from their struggling investment (McKim and Kelleher, *Orange County Register*, December 10,1999).

The sudden political backlash against the proposed sale triggered a series of investigations at the state and local level. In December 1999, the State Attorney General's office launched a formal investigation into the deal between CPTC and NewTrac. In the face of rising public anger and the threat of legal action, CPTC terminated the sale shortly after the sale was postponed.

In the aftermath of the failed sale, state officials focused attention on the role of the state Infrastructure and Development Bank, which stood accused of agreeing to the bond sale without investigating conflict-of-interest matters carefully. The proposed sale

also focused intense negative publicity on Caltrans, which was strongly criticized for including a provision in the franchise agreement allowing CPTC to veto any capital improvements to SR-91 and local arterial and residential streets within the designated 'noncompetition' zone. Prior to the sale in December 1999, CPTC sued Caltrans to stop the state from adding new highway lanes to SR-91. In a legislative hearing held on February 1, 2000 focusing on Caltrans' role in the proposed sale, Caltrans acknowledged that it agreed to approve the sale to NewTrac on the condition that CPTC drop its lawsuit. Caltrans was also criticized for failing to require CPTC to prove that adding highway lanes to SR-91 would result in a \$100 million economic loss, a claim that CPTC acknowledged it could not back up (Kindy and McKim, *Orange County Register*, February 2, 2000). Instead, it agreed to a settlement that prohibited the state from adding new highway lanes on SR-91.

Since AB 680's passage in 1989, only one of four private toll road proposals – the 91 Express Lanes -- has been fully implemented, and the botched sale has cast a negative light on AB 680, the franchise agreement signed between Caltrans and CPTC, and the merits of privatization. Today, investors considers the 91 Express Lanes a marginal investment, worthy of a triple B– bond rating (just one tier above junk-bond status) (Kindy, Kelleher, and Berry, *Orange County Register*, December 12, 1999). In January 2000, CPTC released financial data showing a \$500,000 operating deficit in 1999 after ridership and revenues declined following the opening of the Eastern Transportation Corridor. CPTC estimates that it will run operating deficits through 2004 unless it can refinance its debt or find a new buyer (McKim, *Orange County Register*, January 25,

2000).

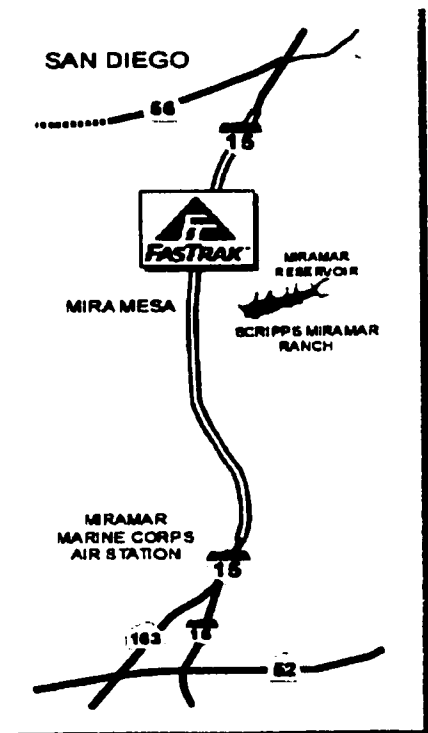
2.5 I-15 EXPRESS LANES

The concept for the I-15 Express Lanes emerged from San Diego Association of Governments' (SANDAG) development of a Transportation Demand Management Program and Transportation Control Measures as part of the Regional Air Quality Strategy (SANDAG 1996). In April 1991, local officials and policymakers gathered to lay out a comprehensive transportation agenda in accordance with federal and state environmental compliance requirements, and focused attention on regional transportation investments that could meet RTIP regulatory mandates. Among the various projects discussed, the I-15 HOV lanes received special attention.

Opened to traffic in October 1998, the 8-mile I-15 HOV lanes consisted of two-12-foot wide concrete reversible lanes with two, 10-foot wide asphalt shoulders, all separated by barriers from the main travel

lanes (SANDAG 1996). Access to the HOV facility to the north is from I-15 near the Ted Williams Parkway (SR-56) and to the south from I-15 or SR-163 near the I-15/SR-163 interchange. The HOV lane was open southbound 6:00AM to 9:00AM and northbound 3:00PM to 6:30PM. Soon after opening, the performance I-15 HOVLs came under scrutiny as peak hour traffic was well below pre-implementation traffic forecasts.

Figure 2.7 Map of I-15 Express Lanes



SANDAG reports that in 1994 the peak hour volume in the southbound, AM peak period was approximately 900 vehicles per lane per hour (SANDAG 1996). The far right column of Tables 2.4a & b, which summarizes I-15 HOVL AM and PM average peak volume data for the week of 10/07/97, shows CA for each time interval within the peak period. In both AM and PM peak periods, capacity is grossly underutilized, as shown by the range of CA well in excess of 100, which represents optimal lane usage. Over the next three years, the chronic underperformance of the I-15 Express Lanes troubled planners and produced a spate of negative media coverage of the HOV lane program in San Diego county (SANDAG 1997).

In the course of numerous technical and policy committee meetings in April 1991, SANDAG officials grappled with the issues of maximizing the use of existing roadway facilities and funding transit improvements. SANDAG boardmember Jan Goldsmith proposed an SOV buy-in program on the I-15 HOVLs as part of the process to develop air quality transportation control measures.

After the project was included in the Transportation Control Measures Plan for Air Quality in April 1991, SANDAG applied for a Federal Transit Administration (FTA) grant and received \$230,000 to initiate the project in October 1992. In January 1993, Assemblyman Jan Goldsmith authored AB713, which authorized SANDAG to implement the I-15 project in cooperation with Caltrans. In October 1993, the state legislature passed AB713 by a large margin. The following year, the I-15 Express Lanes project was submitted to the FHWA under ISTEA's Congestion Pricing Demonstration Program and was subsequently approved for funding.

**Table 2.3 Average Peak Period Traffic Volumes on I-15
HOV Facility, Week of 10/07/97**

a.

b.

AM Peak Hour (Southbound)

Time	S.R. 16	I-15	Total	CA
5:4	3	1	5	1428.
6:0	13	6	19	418.8
6:1	16	8	24	321.2
6:3	22	10	33	236.6
6:4	22	12	35	227.2
7:0	25	15	41	195.1
7:1	28	19	48	165.6
7:3	28	19	47	167.0
7:4	23	18	42	190.4
8:0	22	13	35	223.4
8:1	20	11	31	257.2
8:3	18	11	29	273.0
8:4	17	9	27	291.9
9:0	12	6	19	408.1
9:1	2	2	5	1403.
9:3	8	9	1	4705.

PM Peak Hour (Northbound)

Time	S.R. 16	I-15	Total	CA
2:3	2	6	8	930.2
2:4	11	10	22	360.3
3:0	13	12	26	299.6
3:1	16	14	31	255.5
3:3	18	18	37	215.0
3:4	19	17	37	215.0
4:0	21	19	41	192.7
4:1	23	19	42	188.6
4:3	23	21	44	178.1
4:4	26	21	47	167.7
5:0	26	22	49	163.2
5:1	27	19	47	168.4
5:3	24	20	45	176.2
5:4	20	15	36	222.2
6:0	17	13	30	261.4
6:1	12	8	21	372.0
6:3	3	5	4	2000.

Source: SANDAG, 1997

By March 1995, the approved the project and Statement of Work and a cooperative agreement between the FHWA and Caltrans was completed in August 1995. An RFP for Phase I was issued in March 1996 and contract work for Phase I began in August 1996 (SANDAG 1997).

On December 2, 1996, the 8-mile HOVL on I-15 in San Diego County was opened to a limited number of paying, solo motorists. The project was implemented in two phases. In Phase I, SANDAG auctioned 500 permits per month for \$50. The objective of Phase I was to evaluate and monitor the impact of adding additional vehicles to the HOVL. By Phase II, SANDAG installed a fully automated toll collection and enforcement systems that utilizes value pricing in a manner similar to the 91 Express Lanes (SANDAG 1997). The I-15 Express Lanes received 80 percent of its funding through the Federal Congestion Pricing demonstration pilot program, 15 percent from FTA, 3 percent from Transportation Development Act (TDA) funds, and 2 percent from local sales tax funds (SANDAG 1997).

The implementation of the I-15 Express Lanes demonstrates the feasibility of a federally funded, publicly owned toll road that combines the advantages of HOVL service with the efficiencies of variable tolling. While this project is unique insofar as it received limited funding support through a limited federal demonstration program, the successful implementation of the facility provides support for the argument that HOTLs can provide substantial public benefits in cases where such projects are unlikely to generate substantial rates of return. In other words, many toll road projects that are considered marginal investments in a strictly financial sense may provide substantial public benefits

that exceed those other alternatives. These benefits will be explored in greater detail in Chapters 4, 5 and 6.

3. TOLL LANE EVALUATION AND PERFORMANCE

3.1 HOVL AND TOLL LANE EVALUATION AND PERFORMANCE

From Busway to HOVL

The HOV concept originated in 1963 as a rapid transit busway facility combining the flexibility of a low-cost bus system with the advantage of high-speed rapid rail transit service. Buses would operate on exclusive rights-of-way during the trunk-line portions of the route and distribute passengers along arterials to business and residential areas (Crain 1963; Meyer, Kain and Wohl 1965; Fuhs 1992). By 1975, the Urban Mass Transit Administration (UMTA) embraced the HOVL concept by making federal financial assistance to urban areas contingent on the implementation of traffic management plans, among which dedicated bus lanes were included (Fuhs 1992).

Opened in September 1969, the reversible, two-lane busway in the median on the Shirley Highway in Washington, D.C. became the first facility in the interstate highway system to be dedicated to exclusive bus use (Kain 1992). Ridership on the Shirley highway HOVLs increased from 3,800 AM peak riders in 1969 to 4,500 in 1970 and to 9,000 by 1971 (Kain 1992). After the Shirley highway HOVL was extended from 4.5 miles to 12 miles in 1971, ridership continued to increase annually from 13,500 AM passengers in 1973 to over 16,000 by November, 1974 (Kain 1992). Despite the substantial annual increases in ridership, planners observed that the HOVL could accommodate more than the 350 buses using the HOVL in the AM peak period. To improve peak performance on the Shirley HOVLs, planners opened the lanes to vanpools

and carpools with four or more people in 1981. By 1981, the number of peak vehicles and passengers using the facility climbed rapidly, reaching over 2,000 and 18,000 respectively (Virginia Department of Highways and Transportation 1988). Since 1975, there has been a trend away from exclusive bus use and towards the combined use of carpools and buses. As of June 1994, Fuhs (1994) reported that only 12 out of 93 HOVLs nationally remain reserved exclusively for buses (Fuhs 1994).

California's HOVL Planning and Operations

Because they are convenient, relatively low-cost investments, HOVLs have been programmed in urban areas throughout the nation for decades. Nationally, there are over 1,921 HOV lane-miles and over 1,958 HOV more lane-miles planned with the greatest concentration of HOV lane mileage in metropolitan areas in California, Texas, Virginia, Florida and New Jersey (Fuhs 1992).¹

California has been at the forefront of HOVL planning, implementation, and evaluation. Since the early 1970s, Caltrans has constructed over 200 miles of HOVLs on urban freeways throughout the state where such projects are feasible and receive the support of local and regional agencies, with the highest concentration of HOVLs in Southern California (Caltrans 1992). Caltrans' District 7 (Los Angeles and Ventura county) and District 11 (Orange county), which boast the nation's most extensive HOV

¹

The Federal Clean Air Act Amendments of 1990 and the Intermodal Surface Transportation Efficiency Act of 1991 limit new highway construction to HOV lanes in urban areas that have not achieved compliance with clean-air requirements. Southern California is one of six non-attainment areas in the country.

program, have developed plans to add HOVLs to almost every Southland freeway at a capital cost of roughly \$1.6 billion (Samuel 1998). When complete, District 7 and District 11 will have more than 300 lane-miles of HOVLs in place, with funds provided through local Proposition C sales tax receipts, and federal and state transportation earmarks (LAMTA 1998). By the end of 1997, Los Angeles County had 282 lane miles of HOV facilities, approximately 42 percent of the HOVL throughout the state of California (Caltrans 1997).

Until recently, HOVL additions enjoyed broad public support, but the decommissioning of HOVLs in New Jersey has sparked a nationwide reappraisal of the benefits of HOV priority treatment (Samuel 1998). In 1998, California State Assemblyman McClintock has authored a bill requiring California to decommission those HOVLs found to be chronically underperforming.

Evaluating HOVL Performance

Because federal law limits new highway construction to HOVLs in urban areas not yet in compliance with clean air requirements, it is important to evaluate how HOVLs perform, the extent to which HOVLs perform as theory suggests, and whether or not HOVLs are better able to contribute to federal air quality attainment goals than transportation capital investments of comparable size and cost. Moreover, an evaluation of HOVL performance provides the ideal setting in which to analyze the underlying assumption that *ridesharing* is a key to achieving greater levels of congestion reduction, travel time savings, and emissions reductions. HOVLs may reduce average person delays to HOVs – an objective that, by itself, may be enough to justify HOVL planning.

However it unclear whether HOVLs provide a greater degree of overall reduction in traffic congestion and vehicle emissions than alternatives.

In the HOV literature, the primary objectives of HOV priority treatments are three-fold: 1) to provide a cost-effective means of moving greater volumes of persons at higher levels of service than conventional highways by reserving dedicated lanes for multi-person modes – buses, vanpools and carpools, 2) to promote ridesharing by setting aside reserved HOVLs and offering travel time savings and reliability for HOVs, and 3) to reduce trip times for existing HOVs during congested times of day (Fuhs 1992; NCHRP 413 1998). Minimum occupancy restrictions (i.e. 2+ vs. 3+ carpools) should be set to avoid both underutilization and overcrowding (NCHRP 413 1998). The underlying theory behind HOV priority treatment is that the potential time savings gained by bypassing congested GPLs can promote ridesharing and transit use, indirectly relieving traffic density on adjacent highway facilities. When HOVLs function properly, these facilities are supposed to have a favorable impact on air quality and energy consumption, and lower vehicle operating costs. An individual's decision to switch her commute from SOV to HOV is assumed to be socially and environmentally beneficial (Fuhs 1992; Turnbull 1992; NCHRP 413 1998).

Many studies of HOVL performance have been criticized because these evaluations apply no standard approach and lack appropriate measures of performance. Turnbull (1992) cited the following problems with current HOVL studies: unclear goals and objectives, lack of consensus as to which criteria or benchmark measures should be used, use of statistically questionable study designs, the scarcity of "before" data, and the

lack of ongoing monitoring and evaluation efforts (USDOT 1992). She recommends clear articulation of project goals and objectives, identification of measures of effectiveness and information needs, development of study design, “before” and “after” data collection, and ongoing monitoring and evaluation.² As it stands, researchers have found that the vagueness surrounding stated objectives can produce flawed analyses, compromising the accuracy of benefits calculations and producing misleading findings. Further, reliance on measures such as vehicle occupancies, person per lane volumes, travel times and travel speeds reflects the lack convenient modeling tools that effectively incorporate the dynamic nature of freeway delay and traffic congestion (Dahlgren 1994; Turnbull 1992).

Most studies of HOVL performance simply take peak vehicle and passenger counts for HOVLs and GPLs (GPLs), obtain average travel speed and travel time data via on-site surveys (after implementation), and conclude that because HOVLs move more peak passengers than GPLs, they are good investment choices. These studies rarely consider the full range of behavioral effects, such as shifts in trips from other routes or times, nor compare the benefits of HOV priority treatment to simply adding a GPL or improving transit service (Dahlgren 1994). In addition, they rarely include comparative estimates of emissions.

²

The NJIT-IT report on the performance of the I-80 HOV lanes acknowledged that data on traffic conditions before implementation were not used in evaluating the effectiveness of the HOV facility, but did not find that the lack of viable “before” data compromised their findings that “adding an HOV lane to an existing highway can increase its efficiency by increasing its people moving capacity.”

The belief that HOVLs encourage ridesharing and move more persons per peak hour is shared by most state DOTs (IT News 1998). Caltrans has stated that “HOV lanes demonstrate the potential to improve capacity on congested freeways because they encourage carpooling and transit usage by providing preferential service to carpools, vanpools and buses . . . As long as traffic on HOV lanes moves significantly faster than that on mixed flow lanes, there is an incentive for people to form and stay in carpools.” (Caltrans 1988, pg. 4) In a 1998 evaluation of the I-80 HOVL in Morris County, New Jersey, researchers at the Institute of Transportation (IT) at the New Jersey Institute of Technology (NJIT) reported that “adding an HOV lane to an existing highway can increase its efficiency by increasing its people movement capacity, offering high-speed travel opportunity, providing incentives for choosing ridesharing and decreasing vehicle operating costs.” (IT Spring 1998, pg. 2)

The empirical data suggest that the impact of HOVLs on ridesharing is tenuous at best. In Los Angeles and Ventura Counties, Caltrans’ District 7 reports in its *1997 Annual HOV Report* that between January 1995 to December 1997 the total volume of carpooling on District 7’ freeways grew by only 2 percent. The *1997 Annual HOV Report* also provides data suggesting that District 7 HOVLs are being utilized more efficiently than minimum recommended peak volumes (Caltrans 1997). In 1997, HOVLs in Los Angeles County averaged 1,110 vehicles per peak hour and 2,800 people per peak hour, which exceed recommended volumes of 800 vehicles per hour or 1,800 passengers per hour outlined in the *HOV Guidelines for Planning, Design, and Operations* (Fuhs 1992; NCHRP 413 1998). The 1,110 peak hour vehicle average, however, falls significantly

short of the maximum HOVL capacity of 1,650 vehicles per hour. In Table 2.5, several HOVLs (SR-91, I-105, I-210, and I-110) have peak hour volumes that approach the HOVL maximum capacity of 1,650, but more HOVLs (SR-118, SR-134, SR-170, I-405, and I-605) have peak hour volumes well below the 1,650 volume threshold.

Caltrans reports that the peak hour average person-trip volume of District 7 HOVLs was 1.6 times greater than that of a typical mixed-flow lane, which suggests that HOVLs carry more passengers than GPLs. Figures 3.1 and 3.2 show a comparison of vehicles per peak hour and passengers per peak hour between the SR-57 HOVL and a typical GPL. Although the HOVL peak volume is lower than the peak volume of a GPL (1,041 vph to 1,511 vph), the HOVL carries far more passengers per peak hour than a typical GPL (2,212pph to 1,569pph). This represents the ideal HOVL performance conditions.

Do all HOVLs perform as well as the SR-57 HOVL? Caltrans' *1997 Annual HOV Report* presents data suggesting that ideal conditions may depend on a narrow range of peak volumes and carpool formation rates that are not present on all freeways with HOVLs. For example, Figure 3.2 reveals that on SR-134 the peak HOVL volume is significantly lower than the peak volume of a typical mixed-flow lane (761 vph to 2,258vph) and that the HOVL carries far fewer peak hour passengers than a typical GPL (1,575pph to 2,389pph) (Caltrans 1997). Although Caltrans reports that average peak hour volumes on HOVLs represent LOS C and that most GPLs have peak hour LOS E-F, it does not compare the benefits of HOVL service to other treatments.

Despite the advantages of HOV priority treatment as a low-cost TSM investment

alternative described above, researchers have identified several shortcomings in HOVL performance that undermine some of the critical theoretical assumptions linking HOV priority treatment to ridesharing (Small 1977; Dahlgren 1995). HOVLs can on average achieve from 3 to 20 times more person movement than GPLs during peak hours, but the volume of traffic of most busway/HOVLs during peak hours occupies only 10-50 percent of total HOVL capacity (Parsons Brinckerhoff 1990; Kain 1989; Fuhs 1992; Caltrans 1997). Peak underutilization may indicate that the link between HOV priority treatment and ridesharing is much more complex than theory suggests, and that constructing an HOVL will not necessarily provide greater benefits than simply adding a GPL (Dahlgren 1994).

The primary benefit of adding an HOVL is that total highway capacity is expanded, causing preexisting HOVs to divert onto the new HOVL and allowing SOVs to share GPL space with fewer vehicles. After this initial effect takes place, the resulting travel time differential between the HOVL and GPLs induces secondary shifts from SOV to HOV. The travel time differential is assumed to be stable throughout the peak period, thereby insuring long term incentives to rideshare.

Research on mode choice identifies a number of significant barriers to greater levels of ridesharing: 1) the need for advanced arrangements, 2) restrictions on one's choice of when to travel, 3) lack of common origin-destination combinations, and 4) lack of common trip times, among a multitude of other factors. Taken together, these factors suggest that a person's decision to form a carpool rather than drive alone may not be very sensitive to in-vehicle freeway travel time (Small 1977; McFadden and Talvitie 1977;

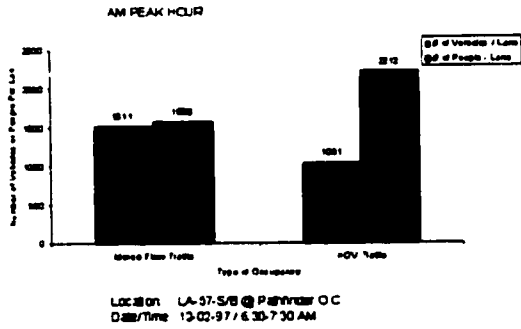
Koppelman 1983). Because the propensity to rideshare may not be very sensitive to travel time savings of 5, 15, or even 25 minutes, a substantial travel time differential must be maintained to motivate long term shifts to HOV. The proportion of preexisting HOVs on the highway critically affects an additional HOVL's advantages compared to a GPL addition. In general, about 20 percent of the vehicles on a three-lane highway must be HOVs for an HOVL addition to be effective and still offer enough of an incentive to rideshare (Dahlgren 1995). If enough peak travelers shift to HOVs to take advantage of travel savings, however, they erode the relative time savings difference (by reducing average peak travel speeds on the HOV facility), thereby dampening the motivation for further shifts to HOVs over the long term. Consequently, there is an upper limit beyond which the benefit of HOV travel time savings cannot promote increased ridesharing and reduce average person delays (Dahlgren 1995). Ultimately, HOV priority treatment may be a flawed strategy because it is ineffective in lessening overall travel delays beyond a self-limiting threshold. What results is chronic underutilization of HOVLs.

A troubling paradox of HOVL service is that it induces the greatest number of shifts from LOV to HOV when highway congestion is at its worst. In other words, the lesser the congestion, the less appealing HOVLs are; the worse the congestion, the more attractive HOVLs are. Thus, contrary to claims by HOVL proponents that they can lower traffic congestion, HOVLs actually rely on the presence of highway congestion to be effective. Except for a limited number of conditions, Dahlgren (1995) argues that simply adding a GPL instead of an HOVL would be more effective in reducing overall person-delays.

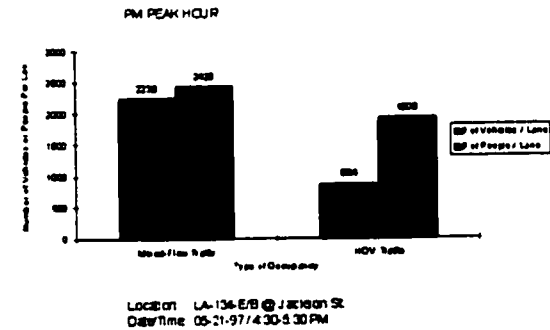
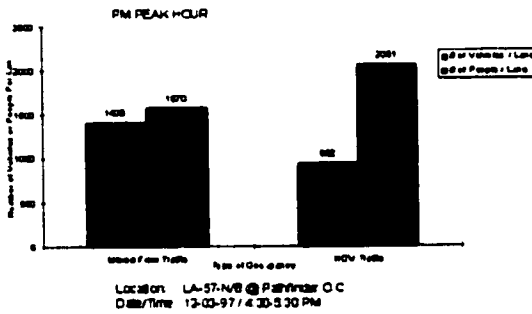
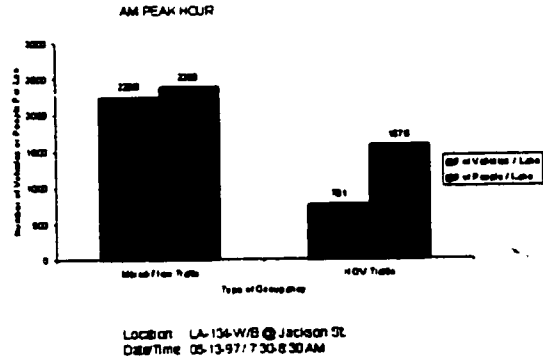
Figures 3.1 Peak Hour Comparison of Vehicles and Passengers per Lane between SR-57 HOVL and GPLs

Figures 3.2 Peak Hour Comparison of Vehicles and Passengers per Lane between SR-134 HOVL and GPLs

PEAK HOUR COMPARISON



PEAK HOUR COMPARISON



91 Express Lane Evaluation Study

Because there are few congestion toll lanes in operation worldwide, little has been published on the short-term and long-term travel behavior impacts of toll lane service until recently. With the implementation of the 91 Express Lanes in Orange County, Caltrans awarded a research contract to a research team at Applied Research and Development Facilities and Activities (ARDFFA). After four years of an extensive data collection effort, in May 1998, the research group published their findings in a final report entitled "Evaluating the Impacts of the SR 91 Variable-Toll Express Lanes Facility," the first major impact study of an HOTL facility. The travel impact study investigated a four year period, collecting 18 months of "baseline" data against which to compare 18 months of post-opening data.

Description of Data

The empirical findings presented in this report are based on three data sets: (1) freeway/ramp loop data, and (2) arterial speed run data, and (3) Origin/Destination (O-D) and opinion surveys.³ Loop detector data consists of five-minute count and speed data

³

The O-D and opinion surveys contains original responses tabulated for each survey. The travel surveys used conventional origin-destination (O-D) survey questionnaires administered to a sample of 1,300 peak period SR-91 users in the fall of 1995, just prior to the opening of the express lanes (in December 1995). A second O-D questionnaire was administered to 1,001 peak users in fall/winter 1996/97, a year after the opening (Sullivan et al. 1998). The traveler survey samples were drawn to achieve consistent statistical accuracy targets for a few representative measures typical of the parameters commonly estimated from O-D data. In addition to O-D trip and traveler characteristics data, the research team collected information of traveler's opinions about the express lanes in the fall of 1995 and the Fall/Winter 1996/97.

averaged separately for GPL, HOVL, and ramp loops, for zones within the study area and at control sites in Los Angeles County. The research team also collected arterial speed run data, which contains information on cumulative travel times to cross-streets.

Compared to many HOVL evaluation studies, the ADRFA final report is methodologically more rigorous because the evaluation consists of extensive before- and after- data, allowing for an comprehensive analysis that distinguished secular traffic growth trends from shifts from other routes and times and traffic growth above and beyond prevailing trends.

The key features of the facility are: (1) the use of electronic time-of-day pricing, allowing the concessionaire to maintain high LOS throughout peak periods and incentivize off-peak usage, (2) the requirement for customers to pre-register for Express Lane service, and (3) the use of discount pricing as an incentive to HOV3+. The ARDFA study presents findings in the following areas of analysis: (1) overall changes in traffic and travel behavior, (2) vehicle occupancy, (3) traveler demographics, (4) rail and bus ridership, (5) traffic operations and safety, and (6) public opinions (Sullivan et al. 1998).

Preliminary Findings

In the months following its opening, the Express Lanes attracted and maintained a substantial share of east-west traffic using the Riverside freeway corridor. Sullivan et al. (1998) report that by the end of the study's post-opening observation period, the total two-way average daily weekday traffic (ADT) on the Express Lanes approached 37,000 vehicles per day (which equates to roughly 13 percent of the total traffic using the Riverside freeway corridor) and average weekend ADT reached 17,000 vehicles per day.

Sullivan et al. (1998) also discovered that the total ADT following the capacity increase resulting from the opening of the 91 Express Lanes increased 14 percent in the first year. The increase of approximately 28,000 vehicles per day was approximately equal to the amount that average weekday Express Lanes traffic grew during the same time period. Based on travel surveys, Sullivan et al. (1998) report that of total increase in ADT, 21 percent represents travelers who previously diverted to arterial routes that returned to SR-91 due to improved traffic conditions, 20 percent represents secular growth trends (growth that would have occurred had no capacity been expanded), and 59 percent represents induced demand (Sullivan et al. 1998).

Perhaps the most interesting finding in the ARDFA report is how the addition of the Express Lanes has ameliorated induced demand effects on the Riverside freeway corridor. A recent University of California Transportation Center (UCTC) study quantifying the induced demand effects of widening congested highways reveal that a 10 percent increase in new lane-miles generates a 9 percent increase in traffic (Hansen 1995). Stated another way, although widening a congested highway may cause a short-term reduction in peak travel delays, over time the decrease in travel costs along the widened highway will induce new trips that wash out the travel time benefits caused by the initial highway widening.

Sullivan et al. (1998) report that the increased capacity of two new toll lanes in each direction substantially reduced peak hour congestion on the Riverside freeway, giving short-term travel time benefits to all commuters in the corridor. In the six months after the opening, the typical PM peak trip delay on the uncontrolled highway lanes fell

TABLE 3.1 Breakdown of Riverside Freeway Corridor ADT Growth Following the 91 Express Lanes Opening in Dec 1996

Travelers previously diverting to arterial routes who return to SR-91 due to improved traffic conditions	5,880	21%
Secular growth in traffic	5,600	20%
Induced traffic resulting from improved peak traffic conditions	16,520	59%
TOTAL	28,000	100%

(Source: Sullivan et al. 1998)

from 30 to 40 minutes to less than 10 minutes per trip. Twelve months later, the PM peak trip delay increased by approximately 5 minutes to the 12-13 minute range, reflecting both time shifts in travel demand and the effect of the underlying long-term traffic growth trend. The key finding of the report is that the substantial reduction in corridor delay continued even though the ADT diverted from the uncontrolled highway lanes to the 91 Express Lanes during the first twelve months of operation matched the increase in the total SR-91 ADT. Sullivan et al. (1998) find:

Apparently, an equilibrium has been established between the free lanes and express lanes. One result of the new equilibrium is that, during the first half of 1997, average monthly growth in ADT for the entire SR-91 highway (averaging 500 vehicles per day each month) was about equal to the average monthly growth in express lane traffic. (Sullivan et al. 1998, pg. 16)

Two months after the Express Lanes opened, congestion on the uncontrolled highway lanes was substantially reduced. A full treatment of travel demand effects is presented in

Chapter 5.

3.2 INTENDED BENEFITS OF CONGESTION TOLL LANES

Although the conversion of an HOVL to toll lane service may not technically be considered an expansion of highway capacity, it marginally affects vehicle trip demand by extending express lane service heretofore reserved for HOVs to toll paying SOVs. Certainly, the primary determinants of vehicle trip demand are the intensity and distribution of regional trip generators and attractors, however vehicle trip demand is also influenced by the level of access and mobility provided by the transportation system. The scheduling, lane choice, and mode choice for an individual's trip along a given highway route is a function of:

- (1) the value of the activity the trip makes possible
- (2) the desired arrival time, travel time on mixed flow lanes and express lane, and travel time on alternative routes
- (3) the cost of the trip (tolls)
- (4) the attractiveness of HOV travel
- (5) the availability and comparative attractiveness of buying into congestion-free express lane service as an SOV (if the trip occurs during the peak period).

The interaction between these factors, as shown in Figure 3.1, will influence the cumulative effects of conversion to toll lane.

On congested highways with excess median space available, state highway departments have traditionally responded to increased travel demand along a highway corridor by (a) building an HOVL, or (b) adding a GPL. Although HOVLs often carry

more peak hour passengers than a typical GPL, there has been political pressure to revert HOVLs to general purpose use because they are often underutilized (Kain 1992; Fuhs 1992; Turnbull 1992). While some states have attempted to decommission HOVLs in response to political pressure, other states have given consideration to toll lanes as a way of improving HOVL performance without abandoning the goal of preserving supply-side HOV incentives. In the following discussion, I will evaluate three competing alternatives that are the basis for the modeling analysis in the subsequent chapter: (a) converting an existing HOVL to toll lane (with no toll exemption for HOVs), (b) reverting an HOVL to GPL use, and (c) leaving an HOVL as is. The behavioral effects are discussed below.

3.2.1 Adding an HOVL: Initial Delay Reductions, Secondary Effects, and Equilibrium Conditions

When an HOVL is added to a congested highway, there is an immediate reduction in delay for both LOVs and HOVs. HOVs are diverted to an HOVL, and LOVs share GPLs with fewer vehicles (Dahlgren 1994). This initial travel delay reduction will cause three secondary shifts: (1) from LOV to HOV, (2) from alternative routes to the freeway, and (3) from other time periods to the peak, which now has less delay.

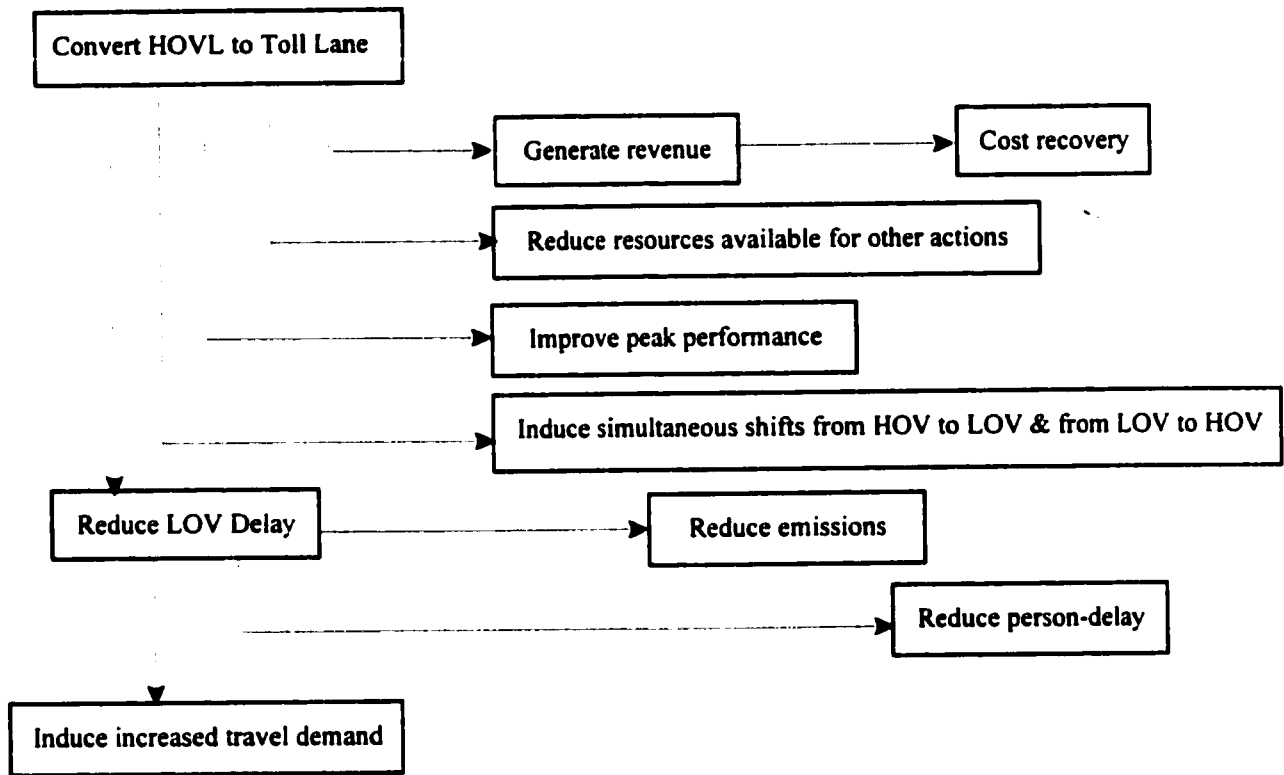
Some travelers will shift from LOV to HOV because the addition of an HOVL results in a travel time differential between mixed flow lanes and the HOVL. Once HOVs shift to the HOVL and some SOVs become HOVs, causing a reduction in delay on mixed flow lanes, both HOVs and LOVs who favored alternative routes will return to the highway. Likewise, those morning travelers who departed earlier to avoid congestion costs will depart later, and evening travelers who scheduled their departure times later to

avoid congestion will depart earlier (Dahlgren 1994). Finally, some travelers who previously avoided peak trip-making will be induced to travel, all of which contribute to a slight increase in travel delay after the initial reduction brought about by adding an HOVL. Once these secondary effects take place and evolve towards a stable equilibrium, Dahlgren (1994) points out that travel time differentials between the mixed flow lanes and the HOVL will not be sufficient to induce additional shifts from LOV to HOV and motivate shifts from other routes, times and latent demand.

What this means is that the effectiveness of HOVLs depends largely on the initial proportion of HOVs and the level of congestion on mixed flow lanes. If the initial proportion of people in HOVs is low, then adding an HOVL will be unlikely to induce shifts from LOV to HOV, especially if enough HOVs are diverted to the HOVL to eliminate congestion on GPLs. A low initial proportion of HOVs and the inability of the HOVL to produce enough of a travel time differential to motivate shifts from LOV to HOV will result in underutilization of the HOVL.

If the initial proportion of people in HOVs is high and the volume of HOVs that divert onto the HOVL is greater than HOVL capacity, then delays on the HOVL will erode the travel time differential between mixed flow lanes and the HOVL, which in turn undermines incentives to shift from LOV to HOV. In this case, an HOVL does not cause a significant increase in the low initial proportion of people in HOVs, and the HOVL performs quite poorly. In both instances, Dahlgren (1994) finds that a GPL addition may be more effective than an HOVL in reducing average person-delays. When the initial proportion of HOVs is low, a GPL addition will attract a peak volume greater than an

Figure 3.3 The Effects of Converting an HOVL to Toll Lane



HOVL addition, which results in greater average person-delay reductions. When the initial proportion of HOVs is high, then the HOVL addition will not provide greater average person-delays benefits than a GPL addition, since the HOVL addition will experience person-delays comparable to GPLs.

3.2.2 Converting an HOVL to Toll Lane (without an HOV toll exemption)

Some HOVLs perform well and others underperform or perform unevenly. When do toll lanes outperform HOVLs? When do HOTLs outperform HOVLs? HOVLs that have high peak utilization may not have sufficient capacity to sell to SOVs without dropping the HOV toll exemption. Consequently, HOTLs may not be as flexible an investment alternative as toll lanes without HOV toll exemptions. In this section, I evaluate cases in which an HOVL is converted to a toll lane (without an HOV toll exemption) and consider the effects of tolling on ridesharing.

Initial Reduction in SOV Delay

The primary effect of converting an HOVL to a toll lane is that toll-paying LOVs will gain travel time savings that would not have otherwise been available. The largest initial effect of converting an HOVL to a toll lane is a reduction in delay for LOVs, both for those that remain in GPLs and those that buy into the toll lane. The *reduction in travel delay* effect for LOVs is manifested in two forms. First, those LOVs who divert onto the toll lane derive a travel time savings benefit, which they gain in exchange for payment of a toll. The initial diversion of LOVs onto the toll lane causes a reduction in peak travel delay on GPLs, since LOVs on GPLs share peak capacity with fewer vehicles.

Shifts from HOV to LOV and from LOV to HOV

Since HOVs must now pay a toll to gain express lanes service (where before it was free), tolling will induce some shifting from HOV to LOV. Before the HOVL was converted to toll lane, all travelers who could have induced a shift to HOV presumably had already done so. HOVs made better off by disbanding the HOV in favor of SOV toll service will shift from HOV to LOV. Those that shift will be made better off even though the toll equals the time costs associated with HOV travel, or they would not have made the shift. Likewise, some travelers will disband HOVs simply because the diversion of SOVs onto the toll lane will cause enough of a reduction in delay on GPLs to make HOV travel no longer worthwhile.

Empirical data on the I-15 Express Lanes suggest tolling may simultaneously encourage ridesharing (SANDAG 1999). SANDAG found that commuters are more likely to maintain carpools when they can be assured of the same travel schedule and travel time on days when their carpool partner is unavailable. In other words, the option of a congestion-free toll alternative provide insurance against the risk of commuting uncertainty and travel time variability, and allows travelers who would not ordinarily rideshare consistently to maintain their carpools. Based on empirical data, this insurance effect can outweigh the reduction in HOVs due to lowered SOV travel costs, resulting in a net increase in HOVs after the HOVL is converted to a toll lane.

Shifts from Other Routes and Times

The travel time reduction on GPLs and the presence of toll lane service will induce two other secondary shifts: (1) from alternative routes to the subject highway, and

(2) from off-peak to peak, which is now less congested. With reduced delay on GPLs, LOVs that had previously shifted to alternative routes to save time will return to the highway via GPL or toll lane. With reduced delay on the highway, both HOVs and LOVs that had previously shifted to alternative routes to save time will return to the highway.

The presence of the toll lane creates two separate scheduling modification effects. First, those travelers who previously departed earlier in the morning peak to avoid congested conditions will enter the highway later than before because delay has been reduced. Second, SOVs who choose toll service can schedule their departure times even later, since they can expect no queuing delays on the toll lane. Likewise, for evening work-to-home trips, the conversion of an HOVL to toll lane will create two scheduling modification effects. Some travelers will depart earlier than previously in response to delay reductions on the mixed flow lanes. The reduced delay also induces additional trips that would otherwise have been forsaken.

Second-order Effects and Long-Run Equilibrium

The marginal shifts from other times of day and locations, coupled with the induced trips and growth caused by the reduction in peak highway delay, will gradually increase peak highway volumes, offsetting some of the delay reductions caused by extending express lane service to toll-paying SOVs. These effects will interact, evolving toward an equilibrium in which the relative cost of toll lane and GPL travel is no longer sufficient to motivate additional shifts from HOV to LOV and delay will stabilize to the point where additional shifts to and from other times and other routes are no longer induced.

3.2.3 Converting an HOVL to HOTL

Initial Reduction in SOV Delay

The primary effect of converting an HOVL to HOTL is that toll paying LOVs will gain peak travel time savings. The largest initial effect of converting an HOVL to HOTL is a reduction in delay for LOVs, both for those that remain in GPLs and those that buy into the HOTL. The *reduction in travel delay* effect for LOVs is manifested in two forms. First, those LOVs who divert onto the HOTL derive a travel time savings benefit, which they gain in exchange for payment of a toll. The initial diversion of LOVs onto the HOTL causes a reduction in peak travel delay on GPL, since LOVs on GPLs share capacity with fewer vehicles. In this analysis, I assume that the HOTL operator charges a variable toll to optimize peak HOTL utilization.

Shifts from HOV to LOV and from LOV to HOV

After an existing HOVL is converted to HOTL, the SOV toll buy-in feature will induce some shifts from HOV to LOV. Before the HOVL was converted to HOTL, all travelers who could have induced shift to HOV presumably had already done so. Therefore, opening the HOVL to SOVs is unlikely to increase or even maintain existing levels of ridesharing. HOV travelers that are made better off by disbanding the HOV in favor of paying for HOTL service as an SOV will shift from HOV to LOV. Likewise, some travelers will disband HOVs simply because the diversion of SOVs onto the HOTL will cause enough of a reduction in delay on mixed flow lanes to make HOV travel no longer worthwhile.

As mentioned earlier, the hedge against travel time uncertainty provided by tolling

may cause many HOVs that would otherwise have disbanded to continue. Therefore, the cumulative impact on ridesharing may or may not be beneficial, depending on the intensity of the effects described above. On the I-15 Express Lanes, researchers have discovered that the insurance effect significantly outweighs the travel time reduction effect, resulting in an absolute increase in ridesharing after the conversion of the HOVL to HOTL. To the extent that an HOV toll exemption on a HOTL encourages ridesharing slightly more than a toll lane (with no HOV toll exemption), HOTLs may promote ridesharing slightly more than toll lanes. However, the overall benefits of toll lane versus HOTL service must be considered in light of revenues, average person-delays, cost recovery, capital and operating cost, and overall emissions.

Shifts from Other Routes and Times

The travel time reduction on GPLs and the presence of HOTL service will induce two other secondary shifts: (1) from alternative routes to the subject highway, and (2) from off-peak to peak, which is now less congested. With reduced delay on GPLs, LOVs that had previously shifted to alternative routes to save time will return to the highway via GPL or HOTL. With reduced delay on the highway, both HOVs and LOVs that had previously shifted to alternative routes to save time will return to the highway. Both groups are by definition better off.

The presence of the HOTL creates two separate scheduling modification effects. First, those travelers who previously departed earlier in the morning peak to avoid congested conditions will enter the highway later than before because delay has been reduced. Second, SOVs who choose to pay for HOTL service can schedule their

departure times even later, since they can expect no queueing delays on the HOTL. Likewise, for evening work-to-home trips, the conversion of an HOVL to HOTL will create two scheduling modification effects. Some travelers will depart earlier than previously in response to delay reductions on GPLs. The reduced delay also induces additional trips that would otherwise have been forsaken.

Second-order Effects and Long-Run Equilibrium

The marginal shifts from other times of day and routes, coupled with additional trips and stimulated by the reduction in peak highway delay, will gradually increase peak highway volumes, thereby offsetting some of the delay reductions caused by extending express lane service to toll-paying SOVs. These effects will interact, evolving toward an equilibrium in which the relative cost of HOTL and mixed flow lane travel is no longer sufficient to motivate additional shifts from HOV to LOV and delay stabilized to the point where additional shifts to and from other times and other routes are no longer induced.

3.2.4 Converting HOVL to General Purpose Use (GPL)

The comparative benefits of reverting an HOVL back to GPL use depends on the extent to which the HOVL underperforms or performs poorly overall. A case can be made for converting HOVLs to general purpose use if (a) HOVLs are grossly underperforming, or (b) the initial proportion of people in HOVLs is greater than the amount of HOVL capacity as a proportion of overall highway corridor capacity. In both instances, converting an HOVL to general purpose use can reduce overall delays to a greater degree than leaving the HOVL as is. As noted earlier, the political implications of

such a reversion are highway charged.

Converting Underperforming HOVLs to GPL

The biggest differences between adding an HOVL and adding a GPL is that a GPL addition provides no incentives to shift to HOV and provides increased capacity for LOVs (Dahlgren 1994). In cases in which HOVLs are built along corridors with a low initial proportion of people traveling in HOVs, the presence of an HOVL is, by itself, unlikely to encourage large enough shifts from LOV to HOV to cause the HOVL to perform up to minimum design standards (Fuhs 1992; Dahlgren 1994). This might be characteristic of an area where few people use HOVs, either because transit service is non-existent or origins and destinations are so dispersed that opportunities to carpool are few and far between.

Here, an HOVL can be considered a misallocation of transportation resources, since – at a given initial proportion of people in HOVs – LOVs suffer travel delays on mixed flow lanes while a large proportion of peak HOVL capacity remains unused. Converting an HOVL to general purpose use will lower delays for LOVs by expanding capacity and maintain travel times for HOVs if the conversion of the HOVL to general purpose use eliminates queueing on the mixed flow lanes. If it reduces delays but does not entirely eliminate queueing, then converting an HOVL to general purpose use will cause delays for HOVs (who lose their HOVL-related time savings) but the overall vehicle delay for all travelers will be less than before conversion. The absolute change in person-delay, however, will depend on the average vehicle occupancy in the HOVL vis-a-vis the GPLs. The loss of the HOVL will result in a shift from HOV to LOV and the

magnitude of that shift depends largely on the initial proportion of people in HOVs and the travel time differential between the HOVL and GPLs prior to conversion. As in the case described in Section 3.2.1, shifts from other times and routes and induced demand effects will erode the initial reduction in travel delay caused by converting the HOVL to general purpose use. The net effect of converting an underutilized HOVL to general purpose use is in most cases a reduction in average person-delays (Dahlgren 1994).

3.2.5 Leaving an HOVL As Is

The decision to convert an HOVL to toll lane, HOTL or general purpose use is based on the performance of the HOVL, and the extent to which it meets HOVL performance standards. Fuhs (1990) argues that a minimum range that supports a public perception of adequate performance is 400 to 800 vehicles per hour for typical HOVL line-haul segments. This range is identified as appropriate because sufficient capacity must remain *unused* to accommodate future HOV growth without jeopardizing travel times (Fuhs 1990). If volumes are lower than this range, Fuhs (1990) suggests dropping minimum occupancy requirements from 3+/ $4+$ to 2+. If HOVL demand exceeds 1,600 vehicles per hour, HOV planners suggest raising the occupancy requirement from 2+ to 3+. Casting HOV2s back into mixed flow traffic however may cause increased delays on the highway, and anger both SOVs who must endure greater delays and HOV2s who lose their HOVL eligibility status.

3.3 ECONOMIC THEORY OF CONGESTION PRICING

An efficient highway finance system is one maximizes net social benefits, and produces benefits in excess of costs. Highway taxation and expenditure decisions

sometimes achieve the goal of allocating resources equitably but rarely maximize the benefits derived from the nation's highway system in the way just described. The direct costs arising out of highway use fall in four major categories:

- *Road damage costs*: wear and tear on the highway;
- *Congestion costs*: delays imposed on other road users;
- *Accident costs*: increased risks of accidents to others; and
- *Pollution costs*: noise, environment and air quality costs imposed on others, both on and off the road.

The most problematic consequences of a less-than-efficient highway taxation system are time costs borne by motorists stuck in traffic congestion (Small, Winston and Evans 1989; Downs 1992).

Because motorists are not required to pay for the delay they impose on other motorists, urban highways are subject to traffic congestion. The distinguishing features of traffic congestion are: 1) self-interested individuals acting rationally lead to an irrational collective outcome, and 2) there is no rational basis for individuals acting in their self-interest to cooperate to address this undesirable collective outcome. In this sense, this is the classical definition of a "commons" problem (Downs 1992).

3.3.1 Policy Responses to Traffic Congestion

Scarce roadway capacity and ever growing travel demand has long posed frustrating and seemingly intractable problems for transportation planners. Until the anti-freeway revolts of the 1960s and 1970s, the primary method of congestion management was to expand roadway capacity to accommodate demand. Small (1988) argues that providing sufficient capacity to accommodate peak traffic volumes has historically been the most expensive part of the public responsibility for roads in the United States.

Empirical evidence suggests that simply increasing roadway capacity to meet peak-period demand has not only been an ineffective policy remedy, in many instances it has actually induced higher levels of congestion than before (Downs, 1968, 1992; Small, 1988, 1994). In every metropolitan area, there is a large reservoir of *latent demanders* for whom the time costs imposed by congestion outweigh the benefit of the peak-period trip. They will forego making the peak trip until there is a sufficient decrease in the private cost (out-of-pocket costs + congestion-related time delays) of peak auto travel.

Simply increasing roadway capacity in the absence of pricing is an ineffective strategy because by lowering travel costs, the previously congested facility becomes more attractive to motorists (“latent demanders”) who would otherwise have avoided the peak-period trip, taken a shorter trip or used another mode. When time costs rise as peak volumes begin to exceed roadway capacity, congestion reappears. The “fundamental law of traffic congestion” suggests that new roadway investments designed to increase capacity, in effect, create their own demand (Downs 1992). While certain highway improvements can improve recurring bottlenecks and meet mobility objectives, adding highway capacity is generally not an effective congestion-relief strategy.

Under pressure to implement non-punitive policies that did not directly restrain automobility, policymakers in the 1960s and 1970s turned their attention to a number of command-and-control, systems management, and market-based strategies aimed at reducing single occupancy vehicle (SOV) travel. With the possible exception of parking cashing-out, non-pricing TDM and employer-based ridesharing programs have had a negligible effect on VMT (Shoup 1994). The failure of these strategies has recently

caused transportation planners to reevaluate the merits of roadway pricing strategies, and reconsider the prospects of incremental implementation.

3.3.2 Congestion Pricing and Estimated Effects

In its basic formulation, road pricing would require motorists using a highway to pay for the congestion they impose on other motorists. Since the goal of this section is to review the economic theory of road pricing as it relates to HOTL service, I will present a basic theory of road pricing derived from Pigou (1920), Knight (1924), Vickrey (1955), Mohring and Harwitz (1962), Small, Winston and Evans (1989), and Lau (1992) as it relates to short-run marginal and average user costs.

During off-peak hours, there is unused capacity on urban roads because traffic flow is below the highway's rated capacity. At low traffic volumes, the speed is not constrained by other vehicles. But as the number of drivers in a traffic stream increases, average delay increases, and traffic flow approaches the facility's rated capacity. The volume, q , which is defined as the number of vehicles passing a given point during a time interval (veh/hour), can be represented by

$$q = kv \tag{3.1}$$

which may rise or fall as vehicle density increases or decreases. The relationship between volume, q , and density, k , is often referred to as the *fundamental diagram of traffic flow*, and has the general shape of Figure 3.2.

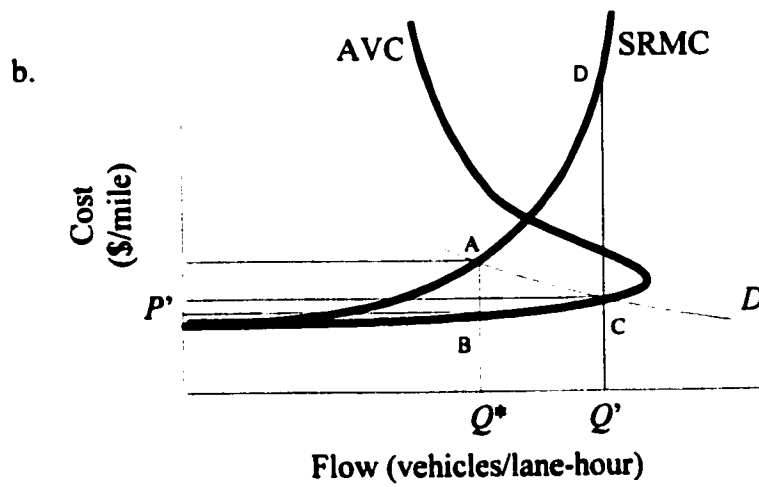
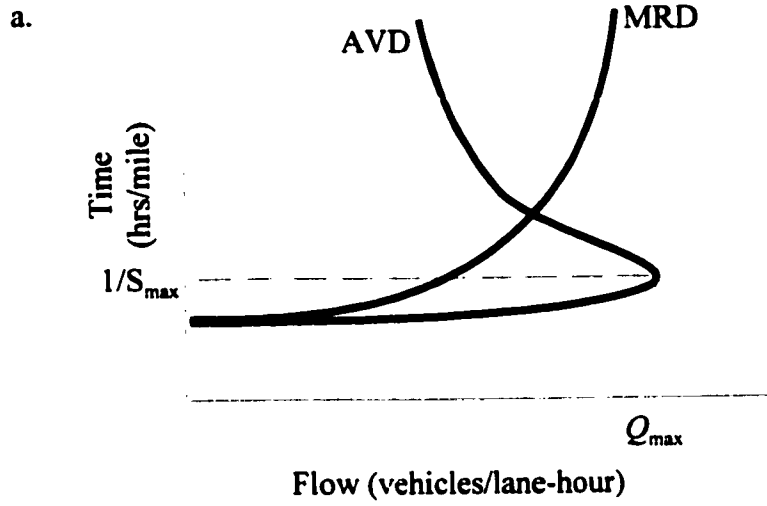
As volume, q , increases, so does the density, k , until the capacity of the highway is reached. When the number of vehicles attempting to use a highway exceeds capacity, the increase in k (veh/lane-mile), which causes vehicles to slow down to maintain a safe

cushion, results in a drop in the average speed, v , and eventually a reduction in volumes. The point of maximum flow (Q_{\max}) corresponds to the optimal density, k_0 . Beyond this point to the right, volume decreases as density increases. At jam density (k_j), the flow approaches zero.

Each additional car that enters the traffic stream imposes a marginal time cost (through a marginal decrease in travel speed) on all motorists upstream on the facility. Once capacity is reached, the entry of each additional motorists into the traffic stream causes the flow of vehicles per lane per unit of time to decrease, as seen in the backward-bending curve in Figure 3.4b.

Figure 3.5 illustrates the relationship between supply and demand for a typical unpriced highway facilities. The speed-flow curve shown in Figure 3.4b can be inverted from miles per hour (which measures speed) to hours per mile (which measures trip duration), thus yielding an average variable delay (AVD) and marginal delay (MD) curve, as shown in Figure 3.5a. By converting time to money, it is possible to transform AVD from a time per unit to a cost per unit variable (\$ per mile) by multiplying it by the average value of time as shown in Figure 3.5b. When vehicle operating costs are included, it becomes a short-run average variable cost (AVC). Likewise, MRD can be converted to a short-run marginal cost curve (SRMC). AVC is the total variable cost (TVC) per unit of volume at each level of traffic volume, Q , or (TVC/Q) and the SRMC is equal to the change in total variable costs with each change in traffic volume:

Figure 3.5 Marginal and Average Cost Curves



$$SRMC = \frac{TVC_1 - TVC_2}{q_1 - q_2} \quad (3.2)$$

Measurement of economic benefit requires a method of computing the traffic volume on a highway facility, which can only be determined by identifying the intersection of the relevant demand and supply curves. The volume of trips per time period is a function of trip costs, which are composed of tolls and travel times. The cost of a trip can be expressed

$$C = \text{Toll} + \text{Time Cost} = T(Q,S) + g(Q,S) \quad (3.3)$$

where S is a vector of highway capacity, and the toll, T , and the time cost function, g , increases with increases in q and with decreases in S (Mohring 1962). Short run benefit maximization involves determining the traffic volume and the toll that maximizes the difference between total benefits and total travel time costs, which can be expressed

$$NB_{SR} = \int_0^q F(x) dx - Qg(Q) \quad (3.4)$$

where $F(x)$ is the inverse of the demand function, $Q = f(c)$. Inverting this expression yields travel time costs as a function of traffic volume.

Mohring (1962) proves that the benefit-maximizing traffic volume can be determined by differentiating 3.4 with respect to q and setting the result equal to zero:

$$\frac{\partial(NB_{SR})}{\partial Q} = F(Q) - \frac{\partial(Qg(Q))}{\partial Q} = 0 \quad (3.5)$$

Here, the benefit-maximizing level of traffic, Q , is the volume at which marginal trip costs equal travel demand. The optimization condition can be expressed:

$$F(\hat{Q}) - g(\hat{Q}) = \hat{Q} \frac{\partial g}{\partial Q} \quad (3.6)$$

Benefits will be maximized if the difference between the costs corresponding to volume, Q , and the cost per trip associated with volume, Q , is set equal to the quantity Qdg/dQ (Mohring 1962). In Figure 3.5b, the quantity Qdg/dQ is the vertical distance AB between the intersection of the marginal cost curve and the demand curve and the average cost curve. This quantity is the change in AVC that results from an increase in volume, Q , multiplied by the number of drivers affected by the increased delay (Mohring 1962).

Because the average delay increases with flow, the marginal contribution of delay by each additional driver is increasing even more. This marginal delay is illustrated by the curve labeled SRMC in Figure 3.5b. The downward sloping demand curve, D , intersects the AVC curve at point C, thus yielding a flow level at Q' and an average price at P' . In the absence of an optimal congestion toll, travelers consider only the average per trip costs at time given time, resulting in Q' trips per hour (Small 1994). At any traffic volume beyond Q^* , travelers would be making trips with net values less than the marginal cost these trips impose on other travelers. This creates a deadweight loss as represented by the triangle, ACD. Absent a congestion toll, new motorists are largely unaware of the increased costs they impose on others, and consider only the average cost they experience (Downs 1992).

If the highway were optimally priced, a toll equal to the vertical distance between point A (the intersection of D and SRMC) and B would be charged to motorists entering the facility, thereby lowering traffic flow from Q' to Q^* . Only at a traffic volume of Q^*

would each traveler place a net value of her trip equal to or greater than the total costs imposed on other drivers (Mohring 1962).

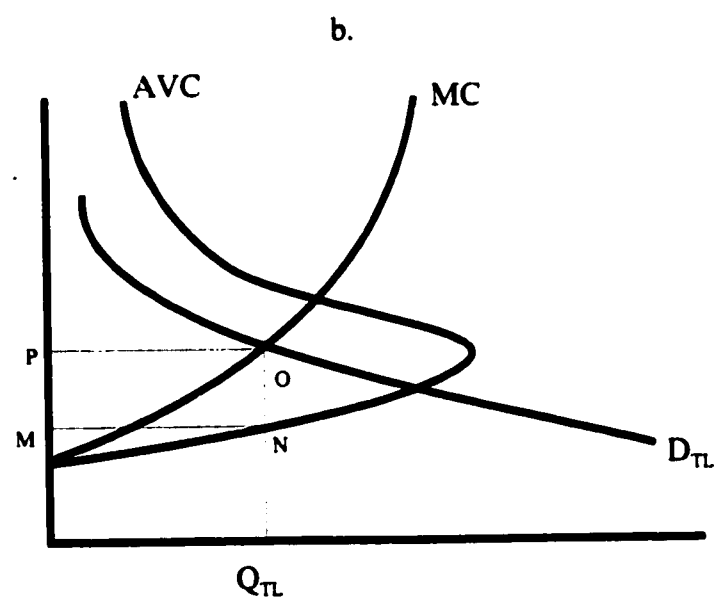
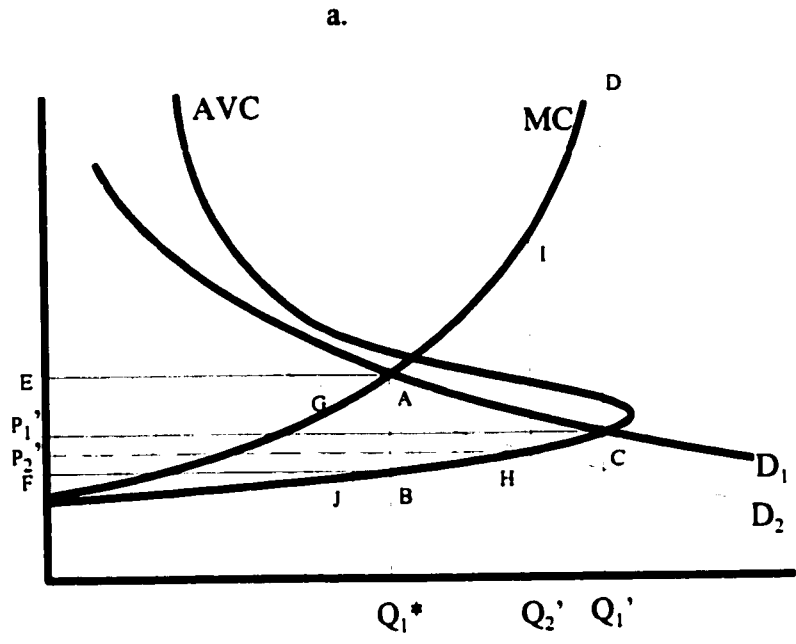
When faced with a toll, motorists for whom the toll exceeds the marginal value of the given peak-hour trip will opt to 1) take the trip during the off-peak period, 2) drive to another destination, 3) take a more circuitous unpriced route to their destination, 4) rideshare, 5) take an alternative form of transportation (public transit, bicycling, or walking), or 6) avoid taking the trip altogether. It is worth noting that congestion pricing induces shifts in travel by making what would otherwise be considered an inferior travel choice more attractive than peak-period roadway use at the advertised toll. If the roadway price diverted enough peak-period trips, congestion pricing could reduce congestion and save time for motorists for whom the value of their peak-period trip exceeds the congestion toll. On a toll lane, congestion pricing is used to manage peak demand on the subject facility, but will not be used to reduce congestion levels of adjacent GPLs.

3.3.3 User Benefits and Consumer Surplus

When a toll lane is retrofitted into an existing highway, there are several effects taking place simultaneously that alter both the quantity of non-priced highway service demanded and consumer surplus. The effects of adding a toll lane to an existing highway facility on consumer surplus is shown in Figure 3.6.

The first major effect is that overall capacity along the roadway corridor is increased, lowering the quantity demand for the unpriced highway from D_1 to D_2 , as shown in Figure 3.6a, as some peak motorists are diverted onto the toll lane. Demand for toll lane service equals highway demand before toll lane implementation subtracted by

Figure 3.6 Change in Producer and Consumer Surplus Resulting from a Toll Lane Addition



highway demand after toll lane implementation ($D_{TL} = D_1 - D_2$). Because a proportion of peak trips are diverted onto the toll lane, the size of deadweight loss decreases from the area represented by triangle ACD to triangle GHI. After vehicles are diverted onto the toll lane, main line volume falls from Q_1' to Q_2' with a corresponding drop in user cost from P_1' to P_2' .

Since the toll lane charges all vehicles a variable toll, there is a producer surplus shown by the rectangular region MNOP in Figure 3.6b. Contrary to what occurs on the unpriced highway, a variable toll equal to PM is charged to toll lane users, which makes each motorist to pay for the marginal cost their trip imposes on other toll lane users. Because some traffic diverts onto the toll lane, delays on the highway are reduced. Whether and to what extent latent demand effects wash out this reduction in peak travel costs is difficult to predict with any degree of accuracy, and is subject to numerous external factors.

While benefits resulting from a new transportation investment include an array of constituent elements that extend beyond the 'user,' in this dissertation the evaluation process will be confined to user benefits alone. The demand curve in Figure 3.7, which provides a measure of the willingness to pay for travel, depicts a situation in which either a GPL is added or an HOVL is converted to general purpose use (Stopher, Meyburg 1976). It represents this case better than Figure 3.5 because conversion to a GPL does not divert traffic onto a separate facility as in the toll lane case but merely expands fixed supply. At point Y, where the price is P_Y , the corresponding volume of travel will be Q_Y . Converting an HOVL to general purpose use will cause a drop in user cost from P_Y to P_Z

and corresponding increase in the travel volumes from Q_Y to Q_Z .

Lets assume that a traveler who is willing to pay P_Y to travel from point i to j . If the perceived price of travel fell to P_Z , the individual will take that trip and realize a “consumer surplus.” In Figure 3.7, the change in consumer surplus is represented by region WXYZ, defined as the difference between what an individual is willing to pay for travel and the actual travel price she incurs.⁴ The change in benefits resulting from an expansion of highway capacity can be expressed by:

$$\Delta B = Q_Z (P_Y - P_Z) \quad (3.7)$$

If an HOVL is underutilized, the conversion to general purpose will produce benefits equal to ΔB , as the removal of HOVL status lowers travel costs for LOVs and increases volumes.

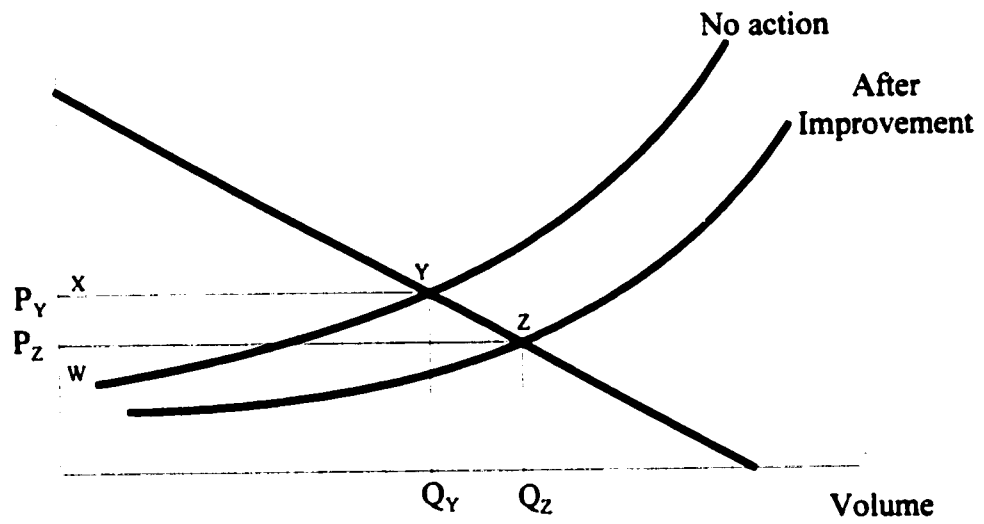
3.4 IDENTIFYING COSTS AND BENEFITS

Society is better off whenever (1) the benefits of an investment exceed its costs and (2) if the ratio of benefits to costs is higher than that of all other transportation improvements or policies (Lewis 1991). In project appraisal, one of the most important steps is the consideration of alternatives throughout the project cycle. Will a project create more net benefits to the regional economy than any other alternative for the use of the resources in question? The project design must be compared with various other

4

A basic assumption of the simple derivation of travel demand is that the demand curves of different individuals can be aggregated into a meaningful single demand curve, which is difficult to do empirically. In addition, it assumes that the entire demand curve can be determined and that it intersects the price axis at a finite perceived price of travel (Meyburg, Stopher 1976).

Figure 3.7 Highway Engineer's Definition of User Benefit



(Source: Stopher, Meyburg 1976)

designs involving differences in scale, the choice of beneficiaries, the types of output and services rendered, the production technology, location, starting date, and sequencing of components (OPR 1996). Also, the project should be compared with the alternative of not doing it at all.

This analysis will examine the difference between the availability of inputs and outputs with and without action to convert an HOVL to other uses. The with/without comparison depicted in Figure 3.8 measures the incremental benefits arising from the project.

3.4.1 Cost Functions

The production function, which defines the relationship between inputs and outputs, can be described mathematically:

$$F(q, x; \theta) = 0 \quad (3.8)$$

where q and x are vectors of outputs and inputs, respectively, and θ is a vector of parameters that represents service-quality descriptors (Small 1992). The cost function for a toll road concessionaire, for example, is the minimum cost of producing output vector q (peak travel time savings), given the production function and input costs. If all inputs are included in x , including those that can be varied over a long period of time, C is a long-run cost function. Likewise, if one or more inputs are fixed during the minimization, C is a short-run cost function (Small 1992). The subsequent cost function can be expressed

$$C(q, w; \theta) = \underset{x_n}{\text{Min}} \bar{C}(q, W; \theta, x_n). \quad (3.9)$$

The short-run cost function approaches a positive constant C^0 as the output q

approaches zero. C^0 is defined as the fixed cost. $C - C^0$ is the variable cost (Small 1992). The cost function also contains a fixed cost which includes the carrying cost of fixed capital ($w_n x_n$). The remainder of short-run costs consist of operating costs, which describe ongoing operations and maintenance. Average cost (AC) and marginal cost (MC) with respect to output, q , is C/q and dC/dq .

Returns to Scale

Returns to scale, which is defined as the degree to which a change in inputs causes a change in output, can be described as the inverse of the output-elasticity of cost:

$$s = \frac{AC}{MC} = \frac{C}{q(\partial C / \partial q)}. \quad (3.10)$$

Increasing returns to scale, defined formally here as a production function for which proportional changes inputs results a more than proportion increase in outputs, occurs when AC is greater MC ($S > 1$). Conversely, decreasing returns to scale, defined as a production function for which proportional changes inputs results a less than proportion increase in outputs, occurs when AC is less than MC ($S < 1$) (Small 1992). When a toll road concessionaire sells its peak travel time savings, q , at a price equal to its marginal cost, revenue is

$$R = q(\partial C / \partial q) = (1/s)C. \quad (3.11)$$

When there are increasing returns to scale, gross revenue will not equal total costs, resulting in a deficit. When there are decreasing returns to scale, gross revenues will

exceed total costs, resulting in a profit. In the case of constant returns to scale, gross revenues will just cover total costs, resulting in neither a deficit or a profit. Equation 3.11 holds under marginal cost pricing regimes like toll lanes.

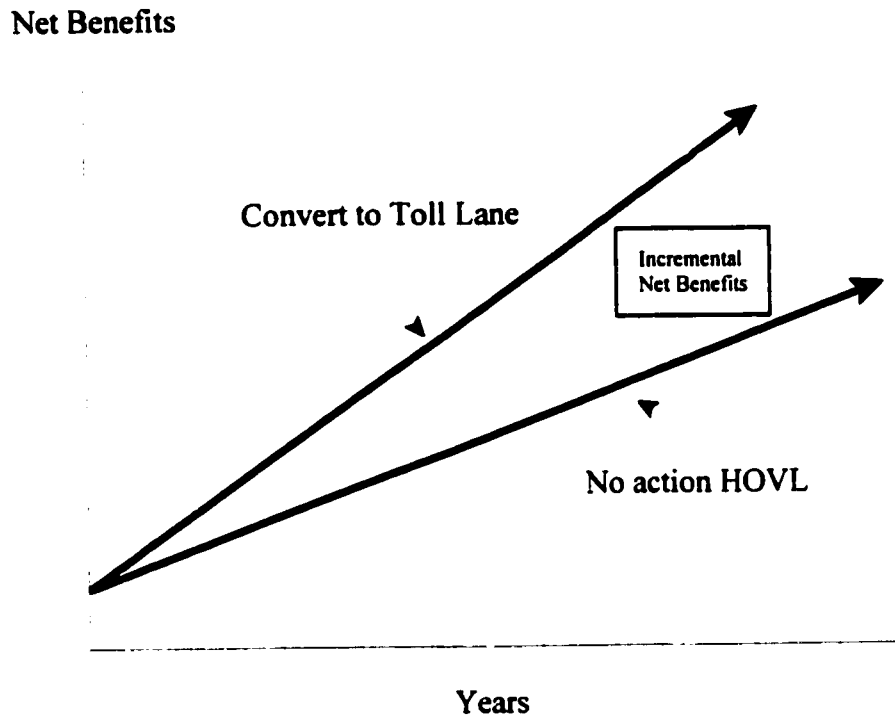
Construction, Operating and Maintenance Costs

Construction costs for toll lanes are higher than for HOVLs, primarily because toll lanes require the deployment of electronic toll equipment. The cost of electronic tolling equipment (electronic toll gantry, variable message signs, computer database and billing processing systems, etc.) can range between \$5 and \$20 million (Samuel 1998). In addition, toll lanes may require additional barriers, and separated on-ramps to prevent unauthorized use. Also, annual operating costs will be higher for toll lanes than HOVL because the toll operator will have to monitor the electronic toll collection system and market the service to the general public.

3.4.2 Intended Benefits of Toll Lanes

The primary objective of converting an HOVL to toll lane is to increase the highway's ability to move more people and lessen total facility-wide person-delay by selling express lane capacity to all motorists. Those who buy onto the toll lane are made better off, since they made the decision to exchange money for time savings. Those who remain in GPLs are also better off because the diversion of some trips onto the toll lane causes a reduction in overall peak delay. Converting an HOVL to toll lane is therefore intended to reduce overall person-delay by increasing the number of persons on the toll lane.

Figure 3.8 With/Without HOTL Comparison



Increased Travel Choice

Another benefit of toll lane service is that individuals can purchase express lane travel time savings without having to rideshare as a precondition. The option to bypass peak congestion does not necessarily mean that travelers will always choose to pay an express lane toll to avoid delay. Travelers will select express lane service for those trips that serve a high-value purpose and opt for uncontrolled highway travel for trips serving a lower-value purpose. While this toll buy-in feature might cause some HOVs to disband, the insurance against travel time uncertainty provided by the congestion-free toll service may encourage many HOVs to remain, and in some cases can increase ridesharing.

Toll Revenues and Cost Recovery

Another benefit of toll lanes is revenue. Unlike HOVLs and GPLs, a toll lane may generate enough revenues to retire bonds issued to finance up-front project costs, and pay for ongoing operating, maintenance, and depreciation costs throughout the project life. For HOTLs, this means that SOVs could provide a cross-subsidy to HOVs, which may mitigate public concerns about the equity of providing premium express lane service that is used more by higher income travelers than middle to lower income travelers. Policymakers have used the *double-benefit argument* to justify toll lanes (Fielding 1993). Travelers benefit by gaining access to travel time savings, and taxpayers benefit because toll lane projects have cost recovery potential.

Improved Performance

Congestion pricing is important operational breakthrough in highway technology insofar as it can allocate peak capacity precisely to travelers who place the highest value

on travel time savings while insuring free-flow conditions by adjusting prices to reflect travel conditions. An optimal pricing structure can optimize traffic flow throughout the peak, and encourage off-peak use by offering deep toll discounts. If there are secular or seasonal increases in traffic, tolls can be periodically raised to dampen peak demand. Without value pricing, a facility is subject to congested conditions and cannot maintain uncongested service during peak hours.

Non-User Benefits

Toll lanes also have the potential to provide non-user benefits in the form of reduced air pollution, reduced fuel consumption, and reduced vehicle operating costs.

3.4.3 Intended Benefits of GPLs

The conversion of an HOVL to general purpose use is primarily intended to reduce average person-delays. When an HOVL is underutilized, the conversion to general purpose use will allow LOVs to divert onto the previously underutilized HOVL, thereby creating a new equilibrium condition in which travel costs are equalized among all lanes and travel costs for all lanes decrease much the same way a new lane lowers travel costs. To the extent that lower vehicle emissions, reductions in greenhouse gases and lower vehicle operating costs result from a reduction in average person-delays, environmental benefits might be considered a secondary non-user benefit.

3.5 MEASUREMENT OF COSTS AND BENEFITS

User benefits are measured in changes in person-delay and vehicle-delay. What follows is a description of the benefits and costs for each class of travelers affected by the conversion of an HOVL to a toll lane or general purpose use.

3.5.1 Direct Benefits to Travelers

Travelers Who Do Not Shift Modes

The benefit or cost to travelers who continue to use the freeway and do not shift modes is simply the reduction or increase in their travel time in addition to any reduction and increase in vehicle operating costs resulting from the conversion of an HOVL to a toll lane.

Travelers Who Pay for Toll Lane Service

For travelers who remain SOV and pay for express lane toll service, the benefits or costs are straightforward. For a given peak trip, a traveler will benefit by taking the express lane if the toll is equal to or less than the value of travel time savings she expects to gain by using the toll lane. Costs include travel time, scheduling costs, tolls, and vehicle operating costs. While those who shift onto the toll lane incur an added cost in the form of a toll, they benefit because they gain a travel time savings that would otherwise have been unavailable. Arnott, DePalma and Lindsey (1991) point out that a toll lane can generate revenues equal to the queueing delay costs of an unpriced GPL, but travelers who shift onto the toll lane benefit or they wouldn't have made the choice to use toll lane service.

Travelers Who Shift from HOV to LOV

For travelers who shift from HOV to LOV, the benefits and costs are not quite as readily identifiable as in the previous case. Consider an individual who traveled via HOV, but was virtually indifferent between the two modes – that is, any reduction in LOV costs relative to HOV would induce her to shift to LOV. Costs include travel time,

tolls, vehicle operating expenses, and the psychological costs associated with each mode.

When an HOVL is converted to a toll lane, travel time for HOVs remain the same but travel time for LOVs decreases, both because delays on GPLs are reduced and SOVs now gain access to the toll lane. In Figure 3.9a, the two bars on the left graph represent the comparative costs via LOV and HOV prior to the conversion of HOVL to toll lane, which are roughly equal. After conversion, the two bars on the right graph represent the comparative LOV and HOV costs. In this scenario, LOVs costs decrease below HOV costs, which remain constant. This results in a shift from HOV to LOV.

In the case illustrated in Figure 3.9b, the two bars on the left graph illustrate that the cost of HOV travel is lower than the cost of LOV travel. After conversion to a toll lane, the two bars on the right graph illustrate that the person is virtually indifferent between the two modes. This person experiences no benefit from the conversion unless she opts for SOV travel, in which case her benefit will be a travel time reduction.

The two bars in the left graph of Figure 3.9c illustrate a case in which HOV costs are lower than LOV costs prior to conversion. When an HOVL is converted to toll lane, the reduction in LOV costs is substantial while HOV costs do not change, since HOVs experience no improvement in travel times as a result of the conversion, as shown in the two bars on the right side of the graph. In this instance, there will be a substantial shift from HOV to LOV. It is worth noting that the ultimate outcome of shifting between LOV and HOV depends on the distribution of HOVs who fall within the three cost scenarios described above, and the likelihood that the insurance against travel time uncertainty provided by the toll lanes encourages commuters to maintain carpools. If the insurance

Figure 3.9 Benefits to Travelers Shifting from HOV to LOV When an HOVL is Converted to Toll Lane

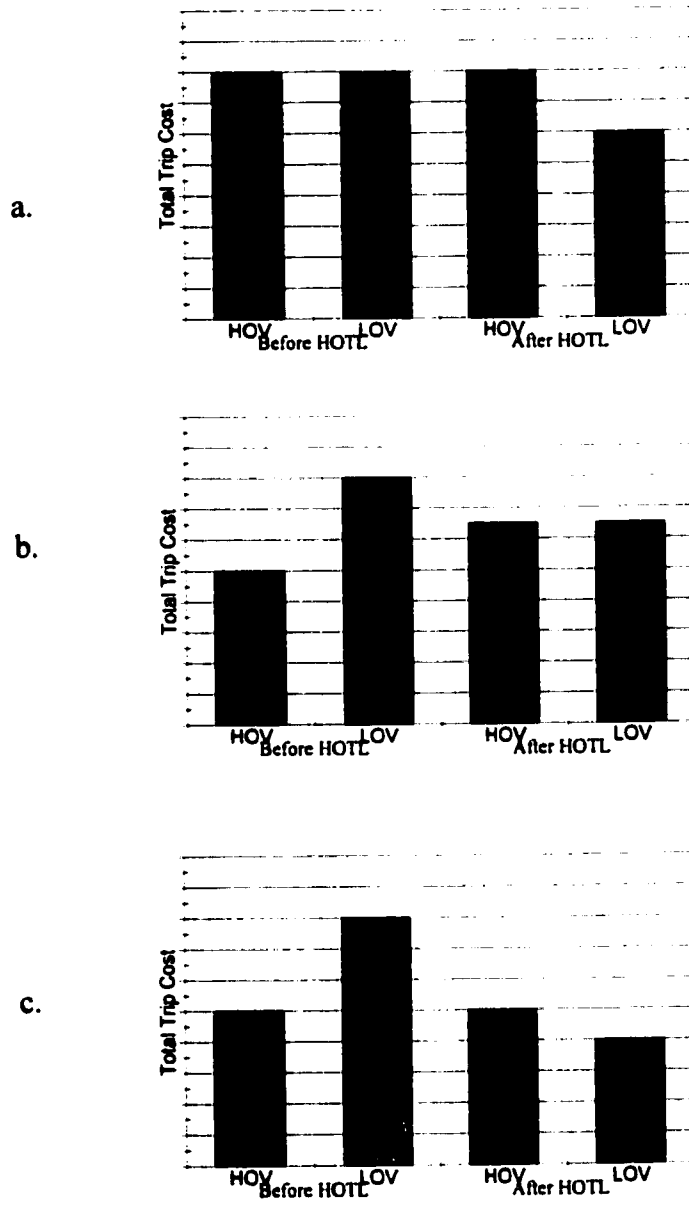
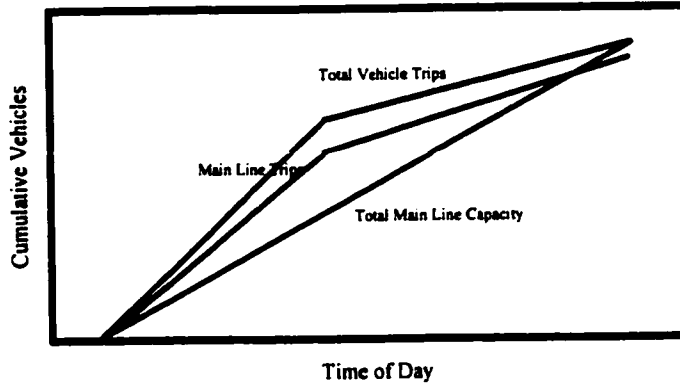
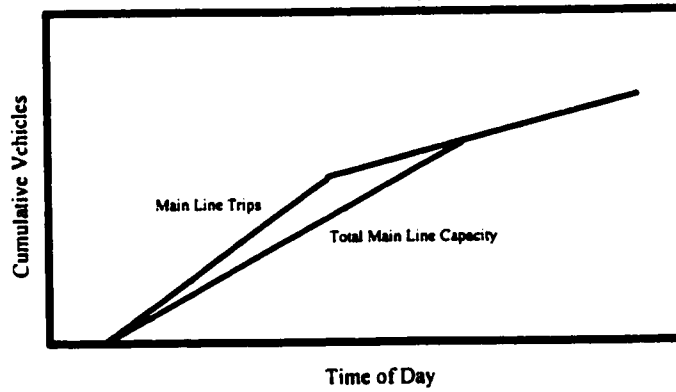


Figure 3.10 Scheduling Modifications and Queuing Delay When an HOVL is Converted to Toll Lane

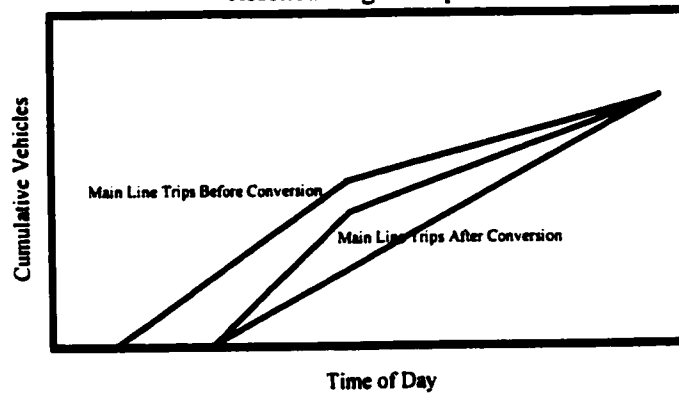
a. Before Conversion to Toll Lane



b. After Conversion to Toll Lane Without Rescheduling of Trip Starts



c. After Conversion to Toll Lane with Rescheduling of Trip Starts



effect outweighs the shifting caused by comparative changes in travel costs in favor of SOV, then ridesharing can in some instances withstand the tolling effect and actually increase with a new toll lane.

Travelers Who Shift Routes

Benefits to travelers who return to the freeway from other routes as a result of delay reduction are similar to those who shift modes from HOV to LOV. The benefit can be thought of as the difference between highway travel time reduction and the travel time reduction necessary to induce the traveler to shift back to the freeway (Dahlgren 1994). This takes two forms: (1) [(travel time on alternative route) – (travel time on highway mixed flow lanes)], and (2) [(travel time on alternative route) – (travel time on toll lane + toll)]. In both cases, the benefit falls somewhere between the highway travel time savings (plus associated tolls) and zero.

Travelers Who Shift Departure Times

Reduced delay on the highway will induce some travelers to adjust the scheduling of their departures on both home-to-work and work-to-home trips. Figures 3.8 provide representations of the possible effects of converting an HOVL to toll lane on the scheduling of departures. In Figure 3.10a, the number of arrivals is greater than the highway capacity, causing queueing delays equal to the region between the arrival and departure curves (it is assumed that all HOVs have already diverted onto the HOVL and delay on the highway persists).

After an HOVL is converted to toll lane, the diversion of some LOVs onto the toll lane causes a reduction in queueing delays on the highway, since the number of

departures has decreased. Figure 3.10b illustrates the reduction in delay, which is shown by the smaller area between the arrival and departure curves.

Figure 3.10c illustrates a case in which travelers arrival at the highway later than before in response to the reduced delays resulting from the conversion of the HOVL to toll lane. The magnitude of the delay reduction depends on the distribution of travelers who choose to arrive at the highway later than before. If travelers suffer a lateness penalty and all travelers wish to arrive at their worksite destination at the same time, then all travelers will arrive at the highway bottleneck later, resulting in no reduction in queueing delays at the peak hour. Although peak hour LOV delay has not been reduced, LOVs have benefitted by arriving at the highway later than before (Dahlgren 1994). The presence of toll lane service also provides a benefit to travelers who choose to avoid the highway bottleneck entirely. These travelers can depart for work even later than those travelers who chose to arrive at the highway bottleneck later than before, since they suffer no delays.

Induced Trips

The reduction in travel delay will induce trips that had previously been avoided because the perceived disutility of peak congested conditions. These travelers benefit, since the reduction in travel costs encourages persons who had previously been avoided travel to make a peak trip. How these induced peak trips are divided between GPLs and toll lane is uncertain. Even in case in which a toll lane does not reduce person-delays on main line lanes, the presence of the toll lane will induce trips that were previously avoided.

3.5.2 External Benefits and Costs

Mobile-source emissions consist primarily of three types of pollution: (1) hydrocarbons (HC), (2) carbon monoxide (CO), and (3) nitrogen oxides (NO_x). To the extent that converting an HOVL to toll lane produces a reduction in vehicle-delay and improved average peak speeds, there may be an emissions reduction associated with this action. California Air Resources Board (1991) reports that driving in congested, stop-and-go conditions results in hydrocarbon emissions that are roughly 3.5 times greater than the amount of emissions produced during free-flow conditions.

Emissions depend on vehicle trips, vehicle miles of travel, and vehicle delay (CARB 1999). Because congested trips, on average, require more driving time than uninterrupted free-flow trips, emissions are greater. If the conversion of an HOVL to a toll lane results in a reduction in travel, the investment will lower total emissions. Likewise, if it lowers delay to a greater extent than converting an HOVL to general purpose use and causes a lesser increase in vehicle miles of travel, converting an HOVL to a toll lane is more beneficial than converting an HOVL to GPL.

3.5.3 Data Requirements

An evaluation of the user and non-user effects of converting an HOVL to toll lane requires an analysis of changes in average vehicle-delay, average person-delay, vehicle trips, person trips and vehicle miles of travel. In the next chapter, I present a nested logit model that simulates a range of congested conditions using standard queueing theory. I estimate the effect of several different investment choices and compare these effects to the baseline case of no-action.

3.6 COST-BENEFIT ANALYSIS

The principal objective of good economic project analysis should be to design, select, and implement investments that contribute most to increased labor productivity, and facilitate sustained economic growth both within the region and nationally (Lewis 1991). Because the transportation sector is a critical part of the nation's capital stock, capital investments that meet the criteria for "good" project evaluation can generate time savings and reductions in private operating costs that yield productivity gains greatly in excess of their capital costs. A National Cooperative Highway Research Program (NCHRP) study on transportation and economic development reports:

. . . Recent studies of industrial logistics show how retail businesses and many other sectors of industry and commerce explicitly incorporate transportation improvements into their production and distribution technology, often "substituting" the transportation system for expensive storage facilities and heavy inventories to reduce overheads and improve competitiveness (Lewis 1991, NCHRP 342, pg. 3)."

In contrast to the private sector, transportation analysts must pay special attention to making sure that infrastructure investments yield labor productivity gains and economic benefits that exceed the total capital and social cost of achieving these objectives. Additionally, analysts must insure that a given investment choice provides a higher ratio of benefits to costs than competing alternative projects (Lewis 1991).

Financial vs. Economic Analysis

Financial analysis looks at the project from the perspective of the implementing agency: it identifies the project's net money flows to the implementing agency and assesses the agency's ability to meet financial obligations and the finance future

investments. By contrast, economic analysis looks at the project from the perspective of society at large. *While some aspects of financial analysis will be incorporated into this dissertation, the empirical approach taken to evaluate the fiscal impact of toll lanes will rely principally on economic analysis.* This difference in analytical approach requires that the analyst emphasize differing factors and cost items, use different valuations of the cost items to be considered, and employ different rates to discount the stream of costs and benefits. Once the financial analysis is complete, the analyst must then adjust the flows and prices to reflect net benefits to society and its various stakeholders.

Why is this important? If a project diverts resources from other activities that produce goods and services, the value of what is given up represents the *opportunity cost* of the project to society. Projects like HOVLs, for example, involve economic costs that do not necessarily involve a corresponding money flow to the project's financial account. In the case of HOVLs, the principle benefit – travel time savings for HOVs – represents a social benefit that is difficult to quantify in monetary terms (given the complexity of value of travel time savings methodologies). Capital projects like these entail no money flows to the implementing agency, but such outputs must be taken into account in estimating the economic costs of projects – especially if the productivity effects of these investments are to be compared to future capital improvements like toll lane conversion.

4. ESTIMATING THE COMPARATIVE EFFECTS OF ADDING TOLL LANE SERVICE

The purpose of this chapter is to present a comprehensive behavioral model for estimating the comparative benefits of adding (1) an HOVL, (2) a toll lane, and (3) a GPL. The principal methodology used to estimate the comparative effects of adding capacity to an existing congested highway is drawn from Dahlgren (1994), who developed the model to estimate the relative benefits of two investment alternatives, HOVLs and GPL additions. This approach is similar to a nested logit methodology – originally developed by Chu (1993), and first applied to HOTLs by McDonald and Noland (1999) – to estimate the initial proportion of HOVs in the toll lane alternative (without HOV toll exemption). McDonald and Noland (1999) used the nested logit model to compare the travel impacts of adding GPLs versus lanes designated as either HOVL or toll lanes, using coefficients estimated from prior studies on mode choice. I take a similar methodological approach, but modify the three-step nested logit model structure used by McDonald and Noland (1999) by (a) assuming a time-varying toll in the lane-choice nest, and (b) linking HOV and LOV travel time differentials directly to mode choice probabilities in the mode choice nest. In section 4.2.2, I modify the deterministic model to estimate scheduling decisions by incorporating the trade-off between scheduling delay and travel time costs.

4.1 ESTIMATING THE DEMAND FOR PEAK HOTL SERVICE

4.1.1 Rational Choice Behavior Theory

The theoretical origins of travel demand estimation can be traced to consumer

choice theory, which governs the selection of variables to be included in the empirical analysis of travel demand. The theoretical parameters of consumer choice as it pertains to travel behavior consists to two components: (1) the development of a derived demand model for urban transport in which the choice of travel alternatives is determined by the consumption activities of the individual, and (2) the possibility of deriving useful restrictions by factoring the demand function into component parts. (Domencich and McFadden 1975).

In the 1970s, Domencich and McFadden (1975) published the comprehensive treatment of the additive random-utility model, which represented the first time consumer choice theory was formally applied to the measurement of urban travel demand. Researchers have since favored the use of *disaggregate* travel demand models (over traditional *aggregate* travel demand models) because *discrete choice* models rely on individual survey data and have foundations rooted in microeconomic theories of rational consumer choice behavior (McFadden and Talvitie 1981; Ben-Akiva and Lerman 1979; Hensher and Johnson 1981; Small 1992).

Instead of developing a disaggregate travel demand model relying on individual survey data to estimate coefficients, I will use coefficients estimated in prior travel demand studies to determine choice probabilities using a synthetic sample of peak travelers. The nested logit model used to estimate the impact of toll lane conversion on the initial proportion of HOVs is based on empirical studies by Small (1982), Chu (1993), Chu & Fielding (1994), Noland (1999), and Noland & McDonald (1999). In subsequent

sections, I will discuss specific statistical procedures, the parameters of which are set by the trade-off between theoretical plausibility and the convenience of available estimation procedures, and present the overall structure of the *nested* logit model. In addition, I present a discussion of the limitations of using coefficients estimated from travel data taken in local contexts at a specific point in time, the statistical reliability of the coefficients are calibrated over the range of independent variables, and the methodological risks associated with estimating statistically valid comparative outputs for competing alternatives that are significantly smaller than the error terms in the nested logit model sequence.

4.1.2 Discrete Choice Models in Transportation

Rational choice behavior theory asserts that an individual can rank possible alternatives in order of preference, and will choose the most desirable of available alternatives, given relevant budgetary constraints (i.e. income or value of time) and personal tastes. Applied to transportation, the consumer is assumed to have a utility function defined on both consumption and transportation attributes.

The set of alternatives available to the individual is determined by: (1) the individual's budget constraint, (2) 'household' technology for accomplishing work and consumption activities at various locations and (3) the attributes of transportation modes at these locations (Domencich and McFadden 1975). Transportation demand modelers are principally interested in 'trips,' classified by mode, time of day, origin, destination, and purpose, as well as the socioeconomic characteristics of the traveler. Total demand

for a given trip can be defined as the number of journeys with these specifications taken by the subject urban subpopulation over a given time period.

The individual has a utility function

$$u = U(x, s; \varepsilon) \quad (4.1)$$

representing preferences, where x is a vector of observed attributes of an alternative, s is a vector of observed socioeconomic characteristics (i.e. income, sex, education, age, etc.) and ε is a vector of unobserved attributes such as experience, intelligence, and other difficult to quantify factors influencing preferences. ε is also known as the additive random element (Richards and Ben-Akiva 1975). The utility function is maximized subject to a 'budget constraint' $x \in B$ at a value x given by a system of demand functions,

$$x = h(B, s; \varepsilon) \quad (4.2)$$

In the case in which the set of alternatives is finite, the demand equation predicts a single chosen x when preferences and unobserved attributes of alternatives are assumed to be uniform across the population (Domencich and McFadden 1975).

Suppose an individual can choose from among J alternatives, indexed $J = 1, 2, \dots, J$, where the J^{th} alternatives represents travel along a particular link by a particular mode at a particular time. Each alternative has a vector of observed attributes x_j . The budget constraint, B , is composed of these vectors, $\mathbf{B} = \{x_1, x_2, \dots, x_j\}$. The observed socioeconomic characteristics of the individual is represented by vector s . The individual the travel alternative that maximizes her utility as expressed by

$$U_{jn} = V(x_{jn}, s_n; \varepsilon_{jn}) \quad (4.3)$$

where V is a function known as the systematic utility, x_{jn} is a vector of observed attributes of the alternative, s_n is a vector of socioeconomic characteristics of the individual, and ε_{jn} is a vector of unobservable attributes that captures the dispersion of choices made by observationally identical decisionmakers (McFadden 1973; Small 1992). The individual will choose option J if this travel alternative maximizes her utility:

$$V(x_{jn}, s_n) > V(x_{in}, s_n) \text{ for all } j \neq i, j = 1, \dots, J. \quad (4.4)$$

Since these utility values are stochastic, the event that the condition in equation (4.4) holds will occur with some probability, which we denote by

$$\begin{aligned} P_i &= H(B, s, i) \\ &= \text{Prob} [U(x_{jn}, s_n) > U(x_{in}, s_n) \text{ for all } j \neq i, j = 1, \dots, J]. \end{aligned} \quad (4.5)$$

The stochastic utility function $U(x_{jn}, s_n)$ can be written in the form

$$U(x_{jn}, s_n) = V(x_{jn}, s_n) + \eta(x_{jn}, s_n) \quad (4.6)$$

where V is non-stochastic and reflects the 'preferences' of the sample population, and η is the stochastic variable reflecting individual quirks and unobserved attributes for alternatives in B . Equation (4.5) can be rewritten

$$P_{IN} = \text{Prob}[\eta(x_{jn}, s_n) - \eta(x_{in}, s_n) < V(x_{jn}, s_n) - V(x_{in}, s_n) \text{ for } j \neq i, j = 1, \dots, J] \quad (4.7)$$

This expression implies that the mathematical form of the choice model depends on the joint distribution of the random elements (Richard and Ben-Akiva 1975). Let $\psi(t_1, \dots, t_j)$ represent the cumulative joint distribution function of $(\eta(x_{1n}, s_n), \dots, \eta(x_{jn}, s_n))$. Let ψ_i represent the first derivation of ψ with respect to its i^{th} argument, and let $V_{ij} = V(x_{jn}, s_n)$. Equation (4.7) can then be expressed

$$P_{1N} = \int \Psi_i (\varepsilon_{in} + V_{in} - V_{1n}, \dots, \varepsilon_{in} + V_{in} - V_{jn}) d\varepsilon_{in} \quad (4.8)$$

Assuming that the random elements are *independent* and *identically* distributed with a reciprocal exponential distribution, it can be shown that the choice model takes the functional form of a multinomial *logit* model (Richards and Ben-Akiva 1975; Ben-Akiva and Lerman 1985; Train 1986).

4.1.3 Probability Functions for Binary Choices

The simplest case one in which an individual chooses between two alternatives (indexed $j = 1, 2$), with vectors of attributes x_{1n} and x_{2n} , respectively. In a simple hypothetical case, let x_{1n} represent an individual's choice to use a highway during the afternoon work-to-home trip and let x_{2n} represent the individual's choice to use an express lane for an afternoon work-to-home trip. The choice probability here can be expressed

$$P_{1n} = \int \Psi_1 [\varepsilon_{1n}, \varepsilon_{1n} + V(x_{1n}, s_n) - V(x_{2n}, s_n)] d\varepsilon_{1n} \quad (4.9)$$

where Ψ is the cumulative joint distribution function of the random components $\eta(x_{2n}, s_n)$ and $\eta(x_{1n}, s_n)$ of the stochastic utility function. By introducing G as the cumulative distribution function of the difference of the random components, $\eta(x_{2n}, s_n) - \eta(x_{1n}, s_n)$, we can express the probability as

$$P_{1n} = G(V(x_{1n}, s) - V(x_{2n}, s)) \quad (4.10)$$

V will have the general form

$$V(x_{in}, s) = Z^1(x_{in}, s)\beta_1 + \dots + Z^k(x_{in}, s)\beta_k \quad (4.11)$$

where $Z^k(x_{in}, s)$ are empirical functions with no known parameters, $Z' = (Z^1, \dots, Z^k)$ is a row vector of these functions, and $\beta = (\beta_1, \dots, \beta_k)'$ is a column vector of unknown

parameters (Domencich and McFadden 1975).

These variables can be defined to include either generic or non-generic attributes of alternatives. In our simple case, because *in-vehicle travel time* is an attribute of each alternative (express lane vs. GPL highway lanes), the *in-vehicle travel time* variable can be introduced generically by setting $Z^1(x_{in}, s)$ equal to *in-vehicle travel time* on both alternatives $j = 1, 2$. β_1 would then be the generic weight for *in-vehicle travel time* on the first alternative (Domencich and McFadden 1975).

The cumulative distribution function G is an increasing function of one variable which translates the range of V into the probability scale with a value between zero and one. If the distribution function G is linear over the entire range of V , then

$$P_{in} = (Z(x_{1n}, s) - Z(x_{2n}, s))' \beta \quad (4.12)$$

is defined as the linear probability function. In our case, P_{in} is the probability that a SOV will choose to pay for toll lane service when faced with a binary choice between toll lane or GPLs with the following independent variables: $Z^1 =$ toll lane travel time (T_{TL}), $Z^2 =$ GPL travel time (T_{GPL}), $Z^3 =$ income (I) for the toll lane choice and zero for the GPL choice, $Z^4 =$ one for having a pre-existing toll lane account and zero for no pre-existing toll lane account. Equation 4.12 then becomes

$$P_{in} = \beta_1 T_{TL} - \beta_2 T_{GPL} + \beta_3 I + \beta_4 \quad (4.13)$$

The β 's measure the effect on the probability of toll lane choice of a one minute change in either TL or GPL travel time ($\beta_1, \beta_2 < 0$) or a one dollar change in income. The constant term β_4 is the coefficient of an "TL-account" dummy variable, while β_3 is the

coefficient of an interaction variable formed by the product of income and an “TL-account” dummy variable.

The logistic distribution gives the probability function

$$P_{in} = \frac{1}{1 + \exp[\beta' Z(x_{1n}, s) - \beta' Z(x_{2n}, s)]} \quad (4.14)$$

defined as the binary logit probability model. Instead of linear function, P_{in} is specified as an ogive¹, which fits the real line into an interval between zero and one, as shown in Figure 4.1 (McFadden and Domencich 1975). Letting P_{in} be the probability of choosing TL service, the inverse transformation of the cumulative logistic distribution can be rewritten as

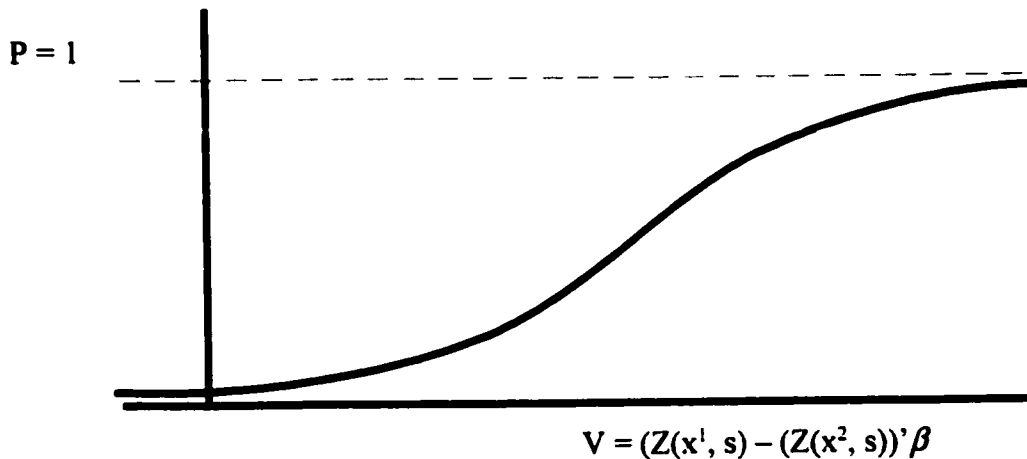
$$\log \left[\frac{P_{in}}{1 - P_{in}} \right] = \beta_1 T_{TL} - \beta_2 T_{GPL} + \beta_3 I + \beta_4 \quad (4.15)$$

Since P_{in} is the probability of choosing TL service, and $(1 - P_{in})$ is the probability of not choosing it, the ratio $P_{in}/(1 - P_{in})$ is known as the odds ratio. The logit model specification is useful in estimating travel demand because the log of the odds ratio (i.e. the probability of choosing alternative J) is a linear function of independent variables (Gujarati 1992). However, it can be made non-linear in any set of independent variables by specifying new variables equal to non-linear functions of the original ones (Small 1992). By substituting the ratio of wage w_n to travel cost c_m for income (I_n) and

¹

A logistic ogive function is used to estimate the binary mode choice probability between toll lane and GPL.

**Figure 4.1 Cumulative Probability Distribution
Giving a Two-tailed Ogive Curve**



transforming T_{TL} to a non-linear variable, for example, the linear-in-parameters specification in equation (4.15) can be modified to be non-linear:

$$V_{in} = \beta_1(c_{in}w_n) + \beta_1 T_{TL} - \beta_2 T_{GPL} + \beta_3 T_{TL}^2 + \beta_4 \quad (4.16)$$

Z_{in} can then be redefined as a vector of all such combinations of the original variables Z_{in} and s_n ,

$$V_{in} = \beta Z_{in} \quad (4.17)$$

For a logit model, data on actual choices can be used to estimate the unknown parameter vector β . Parameters are usually estimated through the maximum log-likelihood (MLL) function:

$$L(\beta) = \sum_{n=1}^N \sum_{j=1}^J d_{jn} \log P_{in}(\beta) \quad (4.18)$$

where N is the sample size, and d_{jn} is the choice variable equal to 1 if individual n chooses alternative j and 0 if she chooses otherwise. The choice of d_{jn} measures *revealed preferences* reflected in actual choices (rather than stated preferences which reflect hypothetical decisions). A major advantage of the logit model is the computational simplicity of the maximum log-likelihood method (Small 1991).

4.1.4 Conditional Probabilities in the Nested Logit Model

In the previous section, we considered an individual with a choice between two alternatives, indexed $j = 1, 2$, with vector of attributes x_{1n} and x_{2n} , respectively. The choice probability for the first alternative is given by equation (4.12). The “independence of irrelevant alternatives” axiom states that the relative odds of two options being chosen are independent of the presence or absence of non-chosen third alternatives (Luce 1959). The function $e^{V(x_i, s)}$ in the equation

$$P_{in} = \frac{e^{V(x_i, s)}}{\sum_{i=1}^J e^{V(x_i, s)}} \quad (4.19)$$

is known as a “strict utility function.” The probability of an alternative being chosen is proportional to its strict utility, with the proportion being determined by the condition that exactly one alternative must be chosen. In other words, the probabilities P_j must sum to one over the available alternatives (Richards and Ben-Akiva 1976). A mutually exclusive

and exhaustive set of alternatives is defined as a function in which the probability that an individual will choose a given alternative equals the probability that the utility of that alternative is equal to or greater than the utility of other alternatives. The model is deterministic because it compares all alternatives available, and selects the alternative with the highest utility (Luce 1959; CRA 1972; Richards and Ben-Akiva 1976).

Suppose data is available on two mode choice options, SOV ($j = 1$) and HOV ($j = 2$), each alternative described by a vector of attributes, x_1 and x_2 , respectively. Given the fitted functions $V(x^j, s)$ for $j = 1, 2$, we have the probability function

$$P_i = \frac{e^{V(x^i, s)}}{e^{V(x^1, s)} + e^{V(x^2, s)}} \quad \text{for } i = 1, 2. \quad (4.20)$$

The probability function estimates the frequency with which the population chooses either SOV or HOV. When there is a choice between two lane alternatives, GPL and toll lane, the mode choice probability is conditioned upon the probability that the individual will choose either GPL use or express lane. In this case,

$$P_n(ml) = P_n(m|l) P_n(l) \quad (4.21)$$

where $P_n(ml)$ represents the mode choice probability, m , given lane choice (Chu 1993; McDonald and Noland 1999). In both nests, $e^{V(x_j, s)}$ is a strict utility function involving a binary choice between two alternatives, indexed $j = 1, 2$, with vector of attributes x_{1n} and x_{2n} . The nested logit model must specify a logsum (LS) term, defined here as the natural logarithm of the sum of the utility of a given nest:

$$LS = \ln \sum_{i=1}^j \exp(V(x_i, s)) \quad (4.22)$$

where $V(x_i, s)$ is the utility for a given nest summed over all the j choices within the nest (Hensher and Johnson 1981). The conditional probability of an upper nest given LS coefficients determined in the lower nest can be defined:

$$P(c|b) = \frac{e^{(V(x', s) + \beta LS)}}{\sum_j e^{(V(x', s) + \beta LS)}} \quad (4.23)$$

where LS is the logsum of the lower nest, β is the coefficient of the logsum, and $V(x', s)$ is the strict utility function of the lower nest (Chu 1993; McDonald and Noland 1999). In the following section, I present a three-step nested logit model that predicts the effect of converting an HOVL to toll lane on the initial proportion of HOVs.

4.2 NESTED LOGIT MODEL FOR ESTIMATING THE EFFECTS OF ADDING HOTL SERVICE TO AN EXISTING HIGHWAY

The probability that a peak traveler will use a toll lane is a function of many attributes: (1) income, (2) toll price, (3) trip purpose, (4) schedule flexibility, (5) travel delay on GPLs, and (6) the HOV trip. The conversion of an HOVL to toll lane causes simultaneous mode shifting from SOV to HOV and from HOV to SOV, and may result in a positive or negation change in carpooling rates depending on (a) the incidence and magnitude of generalized travel cost changes (time + money) arising from the presence of a toll alternative, and (b) the value travelers assign to the hedge against travel time uncertainty provided by congestion-free toll lane service. Most SOVs will remain in

GPLs, but a proportion of SOV drivers with a high value of time use the toll lane. Travel demand analysis of toll lanes therefore must incorporate a nested feature in which mode choice probabilities are conditional upon lane choice decisions, which in turn are based on scheduling choice probabilities and value-of-travel-time-savings assumptions.

4.2.1 Dynamic Interaction and Queueing Behind a Bottleneck

Freeway congestion can be defined as a queue that gradually builds up at a bottleneck and dissipates throughout the remainder of the peak period. In the formal theoretical presentation, vehicles arrive at a some rate higher than capacity until the point of maximum queue length and then arrive at a lower constant rate until the queue eventually dissipates (Homberger and Kell 1992). Current models that estimate the effects of increases in highway capacity rely on instantaneous speed-flow, flow-density and speed-density relationships, described in great detail in the Highway Capacity Manual (TRB 1985). It is hypothesized that there is a linear relationship between speed (mph), v , on an uninterrupted highway segment and traffic density (vehicles/lane-mile), k , that can be represented by

$$v = A - Bk \quad (4.24)$$

where A and B are empirically determined parameters. Because the volume, q , is the product of density, k , and speed, v ,

$$q = kv = AK - Bk^2 \quad (4.25)$$

$$q = kv = (v - A)v/B = Av/B - v^2/B \quad (4.26)$$

When density is near zero, the average speed equals A, and at almost zero speed,

the jam density = A/B (Khisty and Lall 1998). The relationship between volume, q , and density, k , is often referred to as the *fundamental diagram of traffic flow*, and has the general shape of Figure 4.2c. As flow increases, so does the density, until the capacity of the highway is reached. When the number of vehicles attempting to use a highway exceeds capacity, the increase in k (veh/lane-mile), which causes vehicles to slow down to maintain a safe cushion, results in a drop in the average speed and eventually a reduction in traffic volumes. The point of maximum flow (q_{max}) corresponds to the optimal density, k_0 . Beyond this point to the right, volume decreases as density increases. At jam density (k_j), the flow approaches zero. The volume, q , which is defined as the number of vehicles passing a given point during a time interval (veh/hour), can be represented by

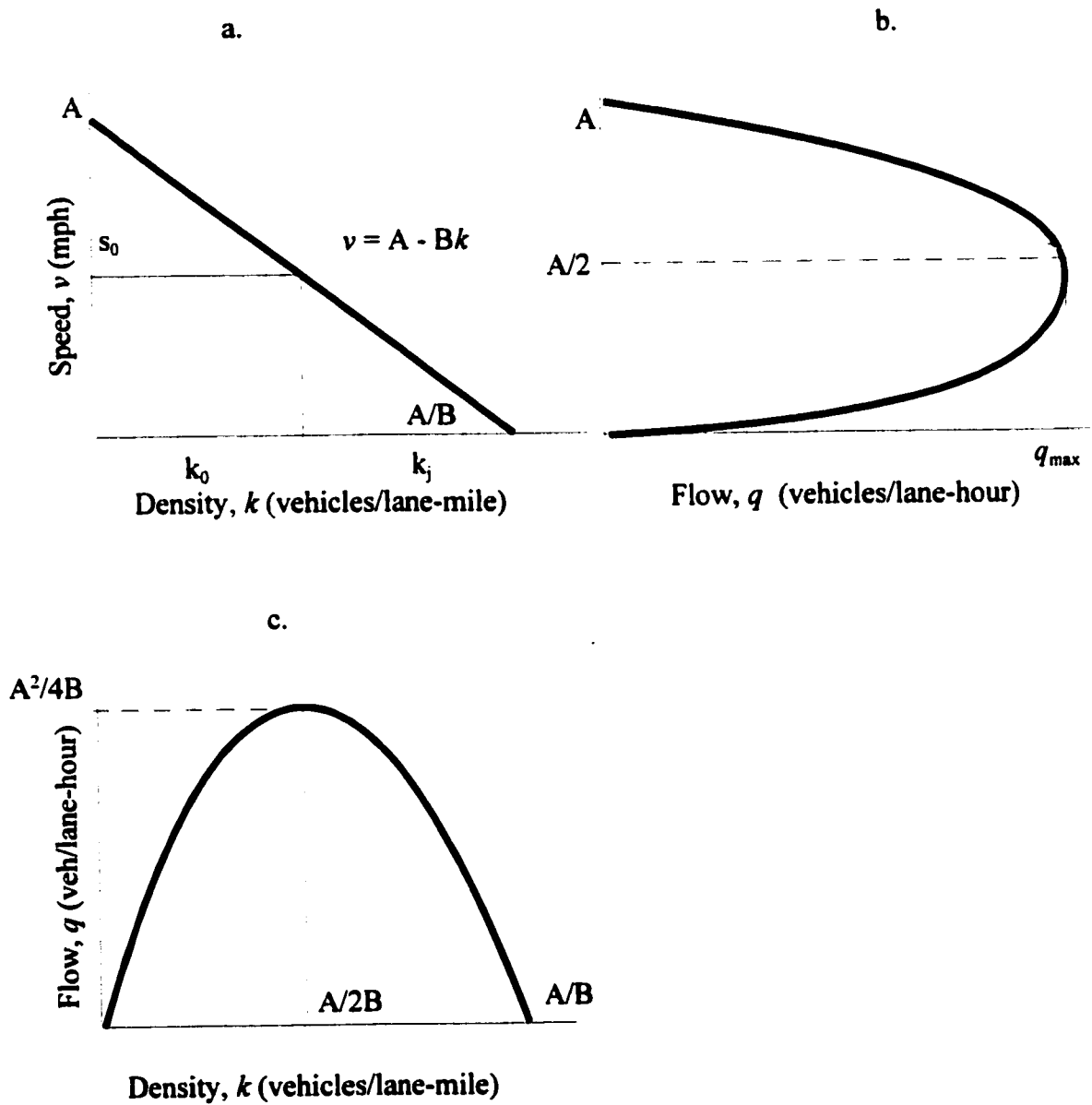
$$q = kv \tag{4.27}$$

which may rise or fall as density increases or decreases.

Empirical Studies of Traffic Delay on Uninterrupted Highways

Researchers have taken field measurements of speed, volume and density and fitted these traffic flow curves to actual data points through multivariate regression analysis, and raised doubts about the true shape of the flow-density curves in Figure 4.2. Hurdle and Soloman (1986) observed volumes and travel times on the Queen Elizabeth Way in Ontario and on five Bay Area freeway and found that travel times remained constant for volumes up to 1800 - 2000 vehicles per lane per hour, at which point a queue formed. In a study of highways in Ontario, Canada, Hall and Hall (1990) report that the

Figure 4.2 Speed-Flow-Density Curves



(Source: TRB 1985)

backward bending portion of the HCM speed-flow curve may be the result downstream bottlenecks that limit both capacity and speed.

Part of the problem with fitted speed-flow curves is their inability to describe how the demand for travel differs from average volume (Small 1992b). In other words, a speed-flow curve with a maximum flow cannot yield information on what happens when demand exceeds that volume (at the rated design capacity). Additionally, there are some disagreements over the nature of hypercongestion, a term used to describe the backward bending portion of the speed-flow curve where density, k , is such that flow decreases. Given the lack of empirical data available to illustrate hypercongestion, Ross (1988) provides a mathematical proof demonstrating that 'hypercongestion' is often confused with heavy vehicle flows in a queue resulting from some downstream bottleneck.

Traffic studies on the Riverside freeway prior to the opening of the Express Lanes reveal peak traffic conditions that closely resemble hypercongestion. Whether such conditions can be attributed to traffic density or the formation of queues behind a bottleneck is difficult to ascertain. Small (1992b) argues that in the absence of empirical evidence showing that hypercongestion describes a unique characteristics of traffic flow in the queue, researchers should model bottlenecks in terms of the queueing delays it causes. In the following sections, I will present a dynamic model that goes beyond the standard economic analyses of congestion used in static models described earlier. The approach is to incorporate user time directly as a cost, thereby making congestion technology a fundamental component of the cost function.

In this analysis, I construct several realistic arrival curves to simulate the behavior of a synthetic sample of commuters in a hypothetical 4-lane highway corridor to model a range of queueing patterns. A queue forming behind a bottleneck can be constructed with the following information: the length of the congested period, the maximum delay, the time at which maximum delay occurs, and freeway capacity (Khisty and Lall 1998).

The queue can be represented in a diagram, as shown in Figure 4.3. The function $A(t)$ represents the cumulative number of arrivals at the bottleneck facility at time t . The derivative of $A(t)$ is the rate at which workers arrive at the bottleneck facility as a function of time, denoted $m(t)$. The cumulative number of departures from the queue at the bottleneck is denoted $D(t)$; its derivative is the service rate g . The congested period extends from 0 to t_E , with maximum delay occurring at t_{MAX} . Let $Q(t)$ be the number of vehicles stored in the queue. The capacity condition implies that

$$D(t) = \begin{cases} A(t) & \text{if } A(t) \leq c \text{ and } w(t) = 0 \\ V_k & \text{otherwise} \end{cases} \quad (4.28)$$

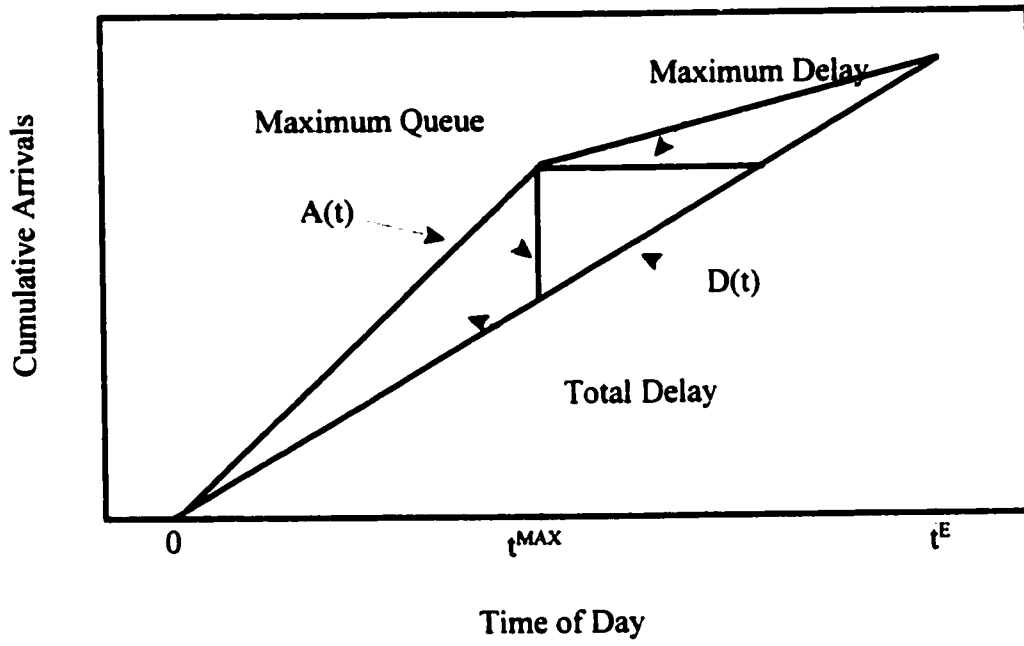
The number of vehicles waiting to pass through at time t is

$$Q(t) = A(t) - D(t) \quad (4.29)$$

Let t_0 be the start of the peak period at which point $A(t)$ first exceeds $D(t)$. For $t \leq t_0$, $w(t) = 0$ and has a right derivative at t_0 given by $A(t_0) - c$. Queue length is the area between $A(t)$ and $D(t)$,

$$Q(t_0) = \int_0^{t_0} [A(t) - D(t)] dt = 0 \quad (4.30)$$

Figure 4.3 An Idealized Queue



Each vehicle entering the queue at time t must wait for $Q(t)$ vehicles to pass through the bottleneck before it can pass through. The delay for a vehicle arriving at time t is

$$W(t) = \frac{Q(t)}{c} = \int_0^t \left[\frac{A(t')}{c} - 1 \right] dt', t_0 \leq t \leq t_E. \quad (4.31)$$

Average travel delay can be expressed

$$\begin{aligned} \bar{W} &= \frac{1}{t_p - t_p'} \int_{t_p'}^{t_p} W(t) dt \\ &= \begin{cases} 0 & \text{if } A(t) \leq c \\ \frac{1}{2}(t_p - t_p') \left(\frac{A(t)}{c} - 1 \right) & \text{if } A(t) \geq c \end{cases} \end{aligned} \quad (4.32)$$

This idealized queue, which is represented for a hypothetical highway and an additional lane, can be used to analyze how converting an HOVL into a toll lane affects peak highway delay.

4.2.2 Scheduling Choice

To estimate the full effect of a traveler's decision to enter a highway at a particular time, the dynamic interaction caused by queueing behind a bottleneck can be modeled with *deterministic queueing* behind a single bottleneck, which offers an effective way of incorporating the behavioral trade-off between congestion and endogenous trip-scheduling (Hendrickson and Kocur 1981; Small 1982b). The basic premise is that commuters minimize travel costs, which include travel time, scheduling delay (i.e. arriving early or late), and a discrete penalty for arriving late to work. Small (1982b)

estimated the following utility function

$$U_i = \alpha T + \beta SDE + \chi SDL + \delta D_L \quad (4.33)$$

where T is queue waiting time, SDE is schedule delay early, SDL is schedule delay late, and D_L is a penalty term equal to one if the individual arrives later than the desired work start time.

The dynamic model presented here, adapted from Hendrickson and Kocur (1981) and Arnott *et al.* (1990), considers endogenous trip-scheduling, which allows congestion and scheduling decisions to interact to determine the queue-entry rate $A(t)$ for morning home-to-work trips.

In the basic deterministic cost model, we assume all commuters travel to the same work-site destination via a highway suffering from recurring congestion behind a fixed bottleneck (Hendrickson and Kocur 1981). In order to simplify the presentation, the total number of vehicles, Q , is held constant, and each traveler attempts to minimize her own travel cost, expressed as a linear combination of queueing time in the bottleneck facility, w , schedule delay, s , lateness in arrival at work, m , and any tolls, f , each of which are functions of the user's arrival time at the bottleneck:

$$UC(t) = a_0 + a_1 w(t) + a_2 s(t) + a_3 m(t) + a_4 f(t) \quad (4.34)$$

where a_0 , a_1 , a_2 , a_3 and a_4 are constant parameters (Hendrickson and Kocur 1981). In subsequent analyses, I test a range of initial mode splits between SOV and HOV in the baseline case, and hold the commuter population constant in evaluating the effect of

competing investments on ridesharing.

Suppose all trips are taken via automobile, all workers must arrive at work at time B , and the bottleneck can serve a constant number of travelers, $D(t)$. Travelers arriving early incur only a schedule delay cost, $s(t)$, and travelers arriving late incur only a lateness penalty, $m(t)$

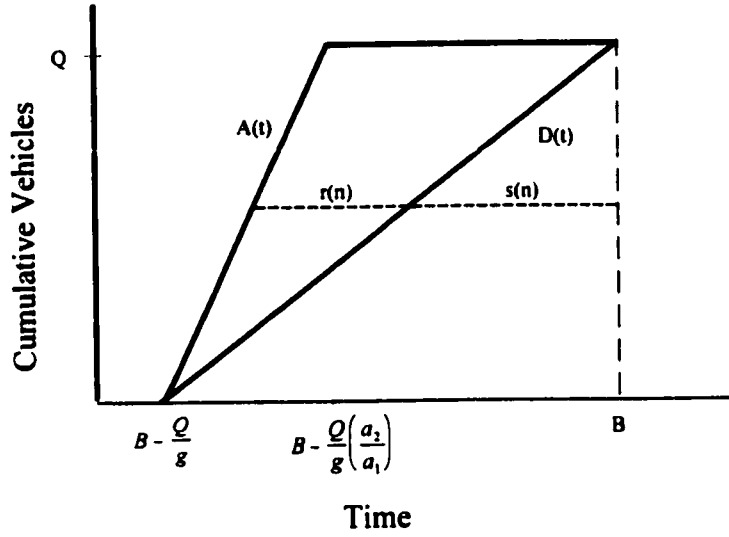
$$\begin{aligned}
 s(t) &= \begin{cases} B - t_w, & \text{if } t_w < B \\ 0, & \text{otherwise} \end{cases} \\
 m(t) &= \begin{cases} t_w - B, & \text{if } t_w > B \\ 0, & \text{otherwise} \end{cases}
 \end{aligned} \tag{4.35}$$

where t_w is the time commuters arrive at the work-site destination minus the time commuters first arrived at the bottleneck (Small 1982; McDonald and Noland 1999). The first derivation of $A(t)$ is the *rate* at which commuters arrive at the bottleneck as a function of time, denoted $a(t)$. The cumulative number of departures from the bottleneck is denoted by the constant, g .

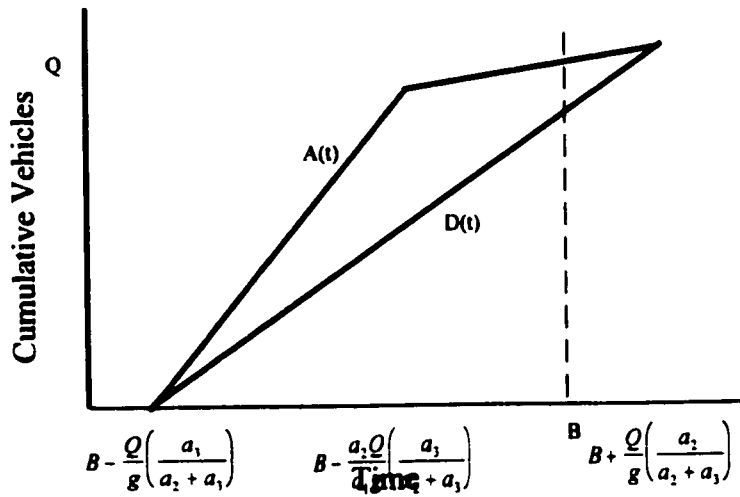
In cases in which $A(t) \leq D(t)$, there is no queueing cost, $w(t)$, and no schedule delay costs, $s(t)$, incurred because commuters can arrange their departure times to arrive at work precisely at the fixed work start time. When $A(t) \geq D(t)$, commuters are forced to trade off queueing delay against schedule delay in deciding on their desired queue-entry time. We expect that a minute spent at the workplace prior to start time, B , is less onerous than a minute spent waiting in the queue ($a_1 > a_2$), resulting in a stable equilibrium. In Figure 4.4a, the vertical distance $q(n)$ represents the length of the queue, the horizontal distance

Figure 4.4

a. Equilibrium Arrival Pattern Without Late Arrivals and Without Tolls



b. Equilibrium Arrival Pattern With Late Arrivals Permitted and Without Tolls



$w(n)$ represents the waiting time in the queue, and the horizontal distance $s(n)$ represents the schedule delay incurred. The waiting time in the queue at any arrival time t is

$$w(t) = 1/g \int_{t_0}^t (m(y) - g) dy \quad (4.36)$$

Schedule delay at time t , $s(t)$, equals $(B - t - w(t))$, resulting in a user cost that can be expressed

$$\begin{aligned} UC(t) &= a_0 + a_1 w(t) + a_2 (B - t - r(t)) \\ &= a_0 + (a_1 + a_2) w(t) + a_2 (B - t) \end{aligned} \quad (4.37)$$

Taking the first derivative and setting it equal to zero

$$\begin{aligned} \partial UC / \partial t &= (a_1 - a_2) (\partial w(t) / \partial t) - a_2 \\ &= (a_1 - a_2) ((m(t) - g) / g) - a_2 \end{aligned} \quad (4.38)$$

which reduces to

$$m(t) = \frac{g a_1}{a_1 - a_2} \quad (4.39)$$

The arrival rate, $m(t)$, shown above is a constant and represents a stable equilibrium.

While there is no incentive for a commuter to arrive at the bottleneck earlier, the last traveler can reduce her travel cost by arriving later. The average user cost of travel here is $a_0 + a_2 Q/g$, of which half is the time spent in the queue and half is the cost of schedule delay (Hendrickson and Kocur 1981).

System Equilibrium with Toll Addition

An important case through which to evaluate the pattern of arrivals resulting in a

minimum average user cost is a congestion toll lane. Optimal pricing in a dynamic model can be determined by deriving the optimal pattern of departures, then finding a time-varying price schedule that makes the optimal pattern an equilibrium one (Hendrickson and Kocur 1981). The 91 Express Lanes has implemented a pricing schedule that closely resembles the technique described here, although technically it is not a truly dynamic pricing system since the toll schedule is published periodically and modified in response to gradual increases in peak volumes. What follows is a presentation of a pattern of arrivals resulting in a minimum average user cost corresponding to a system optimum equilibrium. The parameter values used for this example are derived from a case in which late arrivals to work are permitted (with penalty).

Since the aim of congestion pricing is to modify traveler behavior, the marginal decision is to travel at a particular time of the day. The congestion fee on the express lane is a *Pareto* optimal toll. As shown in Figure 4.5, the arrival rate, $m(t)$, equals the bottleneck service rate, g , resulting in free-flow conditions where no queue forms ($m(t) = g$).

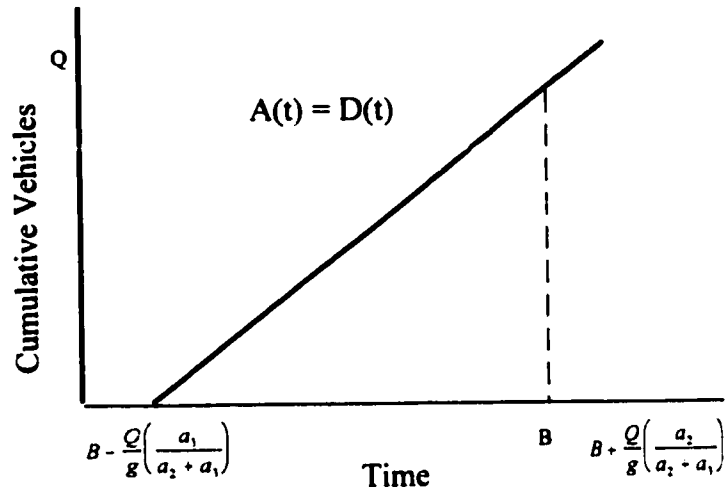
Total cost is the integral of schedule delay and lateness costs over all travelers, Q :

$$TC = \frac{a_2 g x^2}{2} + \frac{a_3 g (Q/g - x)^2}{2} \quad (4.40)$$

where x is the schedule delay incurred by the first arrival (at time $B - x$). Differentiating with respect to x :

$$\partial TC / \partial x = a_2 g x - a_3 g (Q/g - x) \quad (4.41)$$

**Figure 4.5 Equilibrium Arrival Pattern
on HOTL With Optimal Tolls**



which corresponds to an average user cost of

$$a_0 = a_2 a_3 Q / 2g(a_2 + a_3) \quad (4.42)$$

To achieve a system optimal flow pattern, a set of tolls must be established to create equal user cost for each arrival:

$$UC(t) = a_0 + a_2 a_3 Q / g(a_2 + a_3) \quad (4.43)$$

For early arrivals, schedule delay is decreasing with time, so tolls must increase at a rate of a_2 cents per minute to a maximum of $a_2 a_3 Q / g(a_2 + a_3)$, which is the toll charged to the traveler who arrives right at time B . After time B tolls should decline at a constant rate of a_3 cents per minute until they reach zero (Cosslett 1977; Hendrickson and Kocur 1981).

Sequential Mode Choice Decision Process: The Toll Lane Case

When an express lane is added to a highway corridor, the overall model structure of can be expressed:

$$P(mlt) = P_n(m|lt)P_n(l|t)P_n(t) \quad (4.44)$$

where $P_n(mlt)$ represents the probability of choosing mode, m , given lane choice, l , given departure time, t . The choice probability is defined in Equation 4.22. The commuter determines a departure time by minimizing travel cost while still arriving at work by a some preferred start time (Chu 1993). HOVs benefit when an express lane is present because vehicle travel time, T , is lower than for SOVs, who cannot avoid the highway bottleneck and must wait to pass through the queue. HOVs therefore can depart later than

SOVs.

If the SOV traveler's value of time savings is equal to or greater than the express lane toll, the commuter will choose an express lane and depart later. If the commuter's value of *time savings* is less than the express lane toll the commuter will depart earlier and must wait to pass through the queue. The lane choice decision is determined only after the utility of departure time has been ranked. The mode choice decision is determined only after the utility of lane choice has been ranked.

Vickrey (1959) stresses that a congestion toll makes each traveler precisely as well off as in the case of unpriced equilibrium. In other words, the welfare of a traveler who pays a congestion fee on a express lane is identical to the welfare of a traveler who enters a queue behind a bottleneck on the unpriced highway:

$$\begin{aligned} UC^x(t) &= a^x_0 + a^x_1 w(t) + a^x_2 s(t) + a^x_3 m(t) + a^x_4 f(t) = \\ UC^y(t) &= a^y_0 + a^y_1 w(t) + a^y_2 s(t) + a^y_3 m(t) \end{aligned} \quad (4.45)$$

Applying this to the toll lane case, the welfare of a traveler paying the congestion toll on the express lane is equal to the welfare of a traveler who opts not to use the express lane and enters the unpriced GPL queue. In equation 4.45, the user costs of two hypothetical travelers, one using an express lane and the other using the GPL, are equal because the toll price, $f(t)$, captures the monetized cost of waiting time, $w(t)$, and schedule delay, $s(t)$, which effectively is zero for the express lane user. The traveler who chooses the unpriced highway pays no toll but experiences a waiting time, $w(t)$, and a schedule delay cost, $s(t)$,

that equals $f(t)$ in the toll lane case. Thus a congestion toll produces no internal benefits.

Adding Toll Lane Capacity to An Existing Highway: A Hypothetical Case

Suppose there are 25,600 vehicles that must arrive at work by 8:00am over a four lane highway facility with a capacity of 1,600 vehicles per lane per hour (6,400 vehicle/hour). For the sake of simplicity, we assume that the travel time from the bottleneck to the worksite is negligible. The average value of travel time is \$9 per hour and schedule delay cost is \$3 per hour. For the unpriced highway, the waiting time in the queue, $w(t)$, is the horizontal distance between $A(t)$ and $D(t)$ and the length of the queue is the vertical distance between $A(t)$ and $D(t)$. The baseline case presented here (i.e. before toll lane capacity is added) can be analyzed under two separate scenarios: (1) late arrivals are not permitted, and (2) late arrivals are permitted.

Late Arrivals Not Permitted

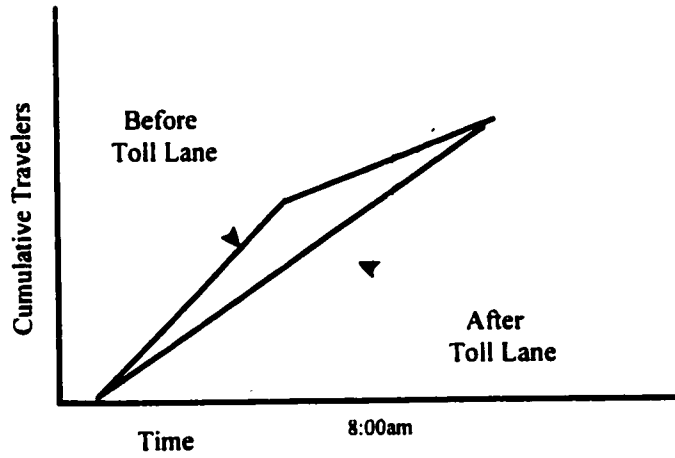
The first worker arrives at 7:00am and experiences no queue but must endure a one hour schedule delay cost for arriving one hour before the official work start time. The last worker arrives at the bottleneck at 7:15am, has a 45-minute wait in the queue, but arrives precisely at the work start time B . The maximum queue length of 4,800 vehicles occurs at 7:15am and the maximum delay is 45 minutes. Suppose two toll lanes with a capacity of 1,600 vehicles per lane per hour (3,200 vehicles per hour) were added to the highway. Of the 25,600 vehicles using the highway to get to work, 3,200 vehicles would divert onto the toll lanes and 22,400 vehicles would enter the queue behind the highway bottleneck.

Assuming that the toll lane implements dynamic pricing to prevent a queue from forming, the arrival rate, $a(t)$, never exceeds the bottleneck service rate, g . The toll rises to a maximum of \$1.50 at 7:37am and decreases at a constant rate of \$.05 per minute until it drops to zero. On the adjacent highway, the addition of the toll lanes, which captures 12.5 percent of the commuting market, causes the first worker to arrive at the bottleneck at 7:20am instead of 7:00am, but a queue still exists from 7:20am to 8:00am, reaching a maximum queue length of 3,657 vehicles at 7:37am.

Late Arrivals Permitted

When late arrivals are permitted, the first commuter does not arrive until 7:15am and the last commuter arrives at 8:15am, 15 minutes later than the work start time of B . The maximum queue length of 1,600 vehicles occurs at 7:45am with a 15 minute maximum wait. When toll lane capacity of 3,200 vehicle per hour is added, the first commuter arrives at work at 7:30am instead of 7:15am, and the last commuter arrives at 8:10am instead of 8:15am. A queue still exists from 7:30am to 8:10am, reaching a maximum queue length of 1,600 (identical to the base case) at 7:50am. As shown in Figure 4.6, the presence of a toll lane does not prevent queuing on the uncontrolled highway lanes but it does reduce the average waiting time and the duration of the queue, since departure times have adjusted to the new equilibrium conditions caused by the added capacity.

Figure 4.6 Equilibrium Arrival Pattern Before and After the Addition of a HOTL With Late Arrivals Permitted



Empirical Coefficient Estimates of the Scheduling Choice Utility Function

Small (1982a) estimated coefficients for the following utility functions for SOV and HOV modes using data collected in the San Francisco Bay Area:

$$U_t = -0.106T - 0.065SDE - 0.254SDL - 0.58DL \quad (4.46)$$

$$U_t = -0.045T - 0.054SDE - 0.362SDL - 1.14DL$$

The differences in coefficients show that arriving late to work has higher costs for HOVs, arriving early has lower costs, and in-vehicle travel time is less onerous for HOVs (Small 1982b). These coefficients are used to determine scheduling choice in the time-of-day nest of the model.

4.2.2. Lane Choice for SOVs

Once scheduling choice probabilities and logsum values are estimated, the probability that a SOV will choose a given lane (GPL vs. toll lane) is determined in the second nest. For simulations that involve a toll lane, all highway travelers face a choice between general purpose and toll lane. This nest incorporates a variable peak toll that corresponds to time savings differentials between the GPL and express lanes. Because the variable toll is a function of queueing delay, while the toll price varies, the toll per minute saved is assumed to be constant throughout the peak period.

Value of Travel Time Savings

$w_{GPL}(t)$ can be converted into a monetary toll cost by multiplying queue time (in minutes) by the value of travel time savings (\$/min). Pricing travel time savings correctly is an important component of travel demand analysis, especially as it relates to express

lanes because travel demand elasticities yield information about how volumes change in response to changes in tolls. Because time-of-day tolls vary as a function of queueing delay, the task of estimating demand can become quite complicated. However, if tolls are indexed to travel time savings, the average toll price per minute saved at time t is constant throughout the peak period. There is a wealth of theoretical and empirical literature on the topic of valuation of travel time savings, the full breadth of which is beyond the scope of this dissertation (Hensher 1978; Hensher 1989).

The biggest methodological problem with setting a value of travel time savings measure is theory does not specify how this value ought to be measured (Stopher 1976). One approach has been to derive values of travel time based on trade-offs between two alternatives, such as a toll road-free road choice. The value of travel time can be defined

$$V = \frac{O\Delta m}{\Delta t} \quad (4.47)$$

where

V = value of travel time
 O = operating costs per mile
 Δm = additional distance required to save time
 Δt = time saving of the faster alternative

When the faster alternative is an express lane, the equation can be modified to

$$V = \frac{f + O\Delta m}{\Delta t} \quad (4.48)$$

where f = toll price (Stopher and Meyburg 1976).

More recent measurements of the value of travel time are based on discrete choice models that predict travel choices based on a given set of individual and travel attributes.

In a simple binary choice model, the traveler must choose between alternatives 1 and 2, as shown in equation (4.19):

$$P_{in} = \frac{e^{V(x_i, s)}}{\sum_{i=1}^J e^{V(x_i, s)}} \quad (4.49)$$

where P_{in} = probability that individual n will choose alternative 1
 $V(x^j, s) = \alpha_0 + \sum \alpha_j x^j$
 x^j = attributes of alternative j
 $\alpha_0, \alpha_1, \text{ etc.}$ = coefficients of revealed behavior

Equation (4.18) can be rewritten when the travel choice is limited to 2 alternatives:

$$P_{HOTL} = \frac{1}{1 + \gamma e^{\beta[w(t)]}} \quad (4.50)$$

In the case in which $\beta[w(t)]$ is defined in terms of travel time and travel cost alone, the term $\beta[w(t)]$ can be expressed

$$\beta[w(t)] = \alpha_0 + \alpha_1(t_i - t_j) + \alpha_2(c_1 - c_2) \quad (4.51)$$

The ratio of the coefficients of time and cost indicates the comparative importance of cost and time in revealed preference surveys. The ratio, α_1 / α_2 , can be interpreted as the "value of travel time." (Stopher and Meyburg 1976) While the coefficients, α_1 and α_2 , may be normally distributed, the ratio of the two variables is not necessarily normally distributed, precluding some forms of statistical testing. Given the absence of empirical data to implement the methodological procedures described above, I use an empirically

derived value of travel time of \$12 per hour.²

Coefficients for Lane Choice Utility Function

Chu and Fielding (1994) estimate a toll coefficient of -0.532 using stated preference data from a sample of SR-91 corridor commuters, indicating that a 10 percent decrease in tolls would result in a 5.32 percent increase in toll lane use. In a more recent demand elasticity study, Dahlgren (1999) estimates a much smaller toll coefficient of -0.09, suggesting that volumes are insensitive to changes in toll price. To verify Chu and Fielding's and Dahlgren's coefficient estimate, I used 91 Express Lane volume, travel speed, and total corridor travel volume data (obtained from ARDFA) to estimate toll coefficients. The estimate was obtained with a linear regression of the logarithm of the toll lane volume on the logarithm of cost per minute saved, average total corridor volume. The regression results are summarized in Table 5.3 in section 5.4.3.

The low P-values suggest that there is a small probability that the variables included in the regression model are not significant. The coefficient for ln (toll per minute saved) is -.292, and the values of -.374 and -.210 in the Lower 95 percent and Upper 95 percent respectively indicate that there is a 90 percent probability that the actual value falls somewhere in between this range. Since the coefficient, ln (toll per minutes saved), represents the elasticity with respect to the dependent variable, toll lane

²

The value of travel time savings estimate is taken from ARDFA's travel impact study of the 91 Express Lanes and is based on main line and Express Lanes travel time run and toll data collected on the 91 Express Lanes in 1996 and 1997.

volume, it can be inferred that a 10 percent increase in tolls would result in a 2.1 percent to 3.74 percent decrease in Express Lane volumes, which suggests that toll lane demand is not very sensitive to toll price.

Given the variability of toll coefficients published in the literature, I use a toll coefficient of -0.292 based on the regression analysis conducted in Chapter 5. Because there are very few studies that report logsum coefficients for toll lanes (based on the time-of-day nest), McDonald and Noland (1999) borrow logsum coefficients used by Parsons Brinckerhoff (1999), who estimate a logsum coefficient of 0.65 for GPLs and 0.1 for the toll lane in their study of the Route 101 corridor. The following utility function captures the binary lane choice decision:

$$U_i = C_i + \tau T_i + \phi LS_{i,j} \quad (4.52)$$

C_i is an alternative specific constant for the choice of lane, calibrated to -2 for toll lane. T_i is the toll divided by time savings, ϕ is the logsum coefficient, and $LS_{i,j}$ is the logsum from the time-of-day choice. In simulations that involve only GPLs, this nest is not included (McDonald and Noland 1999).

4.2.3. Mode Choice for HOVs

The third nest in this three-tier logit model determines the probability that an individual will be an SOV or HOV. The mode choice probability distribution estimated in this nest establishes the initial proportion of people in HOVs. In this simple model, HOVs are restricted to 2 persons per vehicle. When a GPL is added, the proportion of

HOVs will likely decrease if SOV travel times fall enough to undermine incentives to continue ridesharing. When an HOVL is added, HOVs experience a travel time advantage over SOVs, and the proportion of HOVs increases and decreases as a function of the travel time differential between GPLs and the HOVL. When a toll lane is added, HOVs who choose to remain on the toll lane will share capacity with SOV toll buy-ins, who receive travel time savings previously reserved for HOVs. Those HOVs for whom the cost of continuing ridesharing is greater than the cost associated with SOV toll buy-in will disband in favor of SOV express lane use. Likewise, HOV travelers for whom the value of the insurance against SOV travel time uncertainty is greater than the travel cost reduction will remain in HOVs.

Chu's (1993) mode choice nest assigns an HOV delay penalty representing the time cost associated with arranging HOVs. Carpooling studies estimate that commuters assess delays associated with carpooling at 40 times that of in-vehicle travel time, which implies a very high delay penalty (Small 1982; Dahlgren 1994). McDonald and Noland (1999) use an HOV delay coefficient of -2.04 to estimate initial HOV mode share. The lane choice nest must be conditional upon the mode choice nest because the remaining express lane capacity must be known before it can be sold to SOV buy-ins.

Based on nested logit model using a 1972 sample of San Francisco Bay Area commuters, Chu (1993) estimated logsum coefficients of 0.6842 for SOVs and 0.2242 for HOVs. Using these coefficients, it is possible to calibrate the model to an initial HOV mode split of 15 percent using the following utility function in the upper nest:

$$U_m = C_m + \theta D_m + \omega_m LS_{l,m} \quad (4.53)$$

where C_m is the alternative specific constant, D_m is the delay associated with HOVs, ω_m is the logsum from the lane choice nest (Chu 1993).

Relationship between Delay and Mode Split

Based on empirical observations on the Katy freeway in Houston, the El Monte busway in Los Angeles county, and the SR-55 HOVLs in Orange county, the proportion of HOVs using an express lane corresponds roughly with the queueing delay on GPLs (Kain 1992; Turnbull 1992; Dahlgren 1994). In the baseline case (4 GPLs) presented here, the proportion of HOVs throughout the peak period can be represented by a simple logit model:

$$P_{HOV} = \frac{1}{1 + \gamma e^{\beta[w(t)]}} \quad (4.54)$$

where β_i are the travel time coefficients of the attributes, and

$$w(t) = \frac{Q(t)}{c} = \frac{A(t) - D(t)}{c} = \frac{A(t)}{c} \quad (4.55)$$

When either an HOVL or toll lane is added to the baseline scenario, the only attribute that changes is $w(t)$. Consequently, all other attributes can be expressed as a constant, τ , which represents the *initial maximum delay* behind the bottleneck. The exponent of e , $\beta_i[w(t)]$, can be thought of as the difference in travel time on GPLs and the toll lanes from the point-of-entry, since the service flow on the designated toll lane is assumed to be free-flow (Dahlgren 1994; 1999). To calculate travel time differentials, $A(t)$ is defined as the

cumulative person arrivals at the freeway, $P(t)$ represents cumulative person arrivals in HOVs, L and H represent LOV and HOV average occupancies, and C_{GPL} and C_{HOVL} represent capacities on the GPL and HOVLs, respectively. The congested period begins at time $t = 0$; congestion on the HOVLs begin at time t_H (Dahlgren 1998). Delay for travelers entering the uncontrolled highway at time t is

$$w_{UGPL}(t) = \max \left\{ \frac{\frac{A(t) - P(t)}{L} - tC_{UGPL}}{C_{UGPL}}, 0 \right\} = \max \left\{ \frac{A(t) - P(t)}{LC_{UGPL}} - t, 0 \right\} \quad (4.56)$$

and for HOVs is

$$w_{HOV}(t) = \max \left\{ \frac{P(t) - P(t_H)}{HC_H} - (t - t_H), 0 \right\} \quad (4.57)$$

$P(t)$, the cumulative HOVs at time t , depends on the travel time differential $L_i - H_i$ at time t , which equals $w_L(x) - w_H(x)$.

$$P(t) = \int_0^t [a(x) P_{HOV}(x)] dx = \int_0^t a(x) \frac{1}{1 + \gamma e^{\beta_i [w_L(x) - w_H(x)]}} dx \quad (4.58)$$

where

$$a(x) = \frac{dA(x)}{dx} \quad (4.59)$$

Because the only attributes that change are the travel times for the two lanes, all other

attributes can their coefficients can be captured in the term, γ (Dahlgren 1999). The travel time differential, $w_L(x) - w_H(x)$, is calculated for each minute and used to calculate $P(t)$ for the subsequent minute interval (Dahlgren 1994). Total person-delay, vehicle-delay, and vehicle-trips can be calculated for travelers entering the highway during each time interval. These estimates can be summed to obtain total person-delay, vehicle-delay, and vehicle-trips for the entire peak period.

4.2.5 Model Validity in a Simulated Logit Analysis Using Borrowed Coefficients

Parameters of a behavioral travel demand model are calibrated for a random sample of travelers through revealed preference household surveys, which quantify actual choices made and alternatives available but not chosen. Mode, lane and departure choice decisions are based on a set of attributes that are subject to both non-stochastic representative preferences and stochastic idiosyncracies in individual taste. In the simply binary choice case for each nested sequence, a logit model which transforms the function into a zero-one interval of linear-in-parameters functions is selected.

For individual i ,

$$P_{1i} = G(V_{1i} - V_{2i}) \quad (4.60)$$

and

$$V_{ji} = v(x^{ji}, s^i) = \sum_{k=1}^V \beta_k Z^k(x^{ji}, s^i) = \beta' Z(x^{ji}, s^i) \quad (4.61)$$

where G is the cumulative distribution function mapping points on the real line into the

unit interval, β' is a vector of unknown parameters, z^k is a numerical function of x^{ji} and s^i , and z^{ji} is a vector of these numerical functions (Domencich and McFadden 1975). The linear probability model can then be used to predict the behavior of an individual selected randomly from the population. The sampling data is assumed to have observations that are statistically independent across all individuals. The parameters, β , in the linear probability model can be proven to be best, linear unbiased estimators.

The model can be expressed:

$$P_{li} = \begin{cases} 0 & \text{if } \beta' z^i \leq 0 \\ \beta' z^i & \text{if } 0 \leq \beta' z^i < 1, \\ 1 & \text{if } 1 < \beta' z^i. \end{cases} \quad (4.62)$$

In the conventional estimate procedure, all data yield responses in the interval, $\beta' z_i$, and apply ordinary least squares to the regression equation

$$f_{li} = \beta' z^i + \varepsilon_i \quad (4.63)$$

The estimates can then be expressed

$$\beta' = \left[\sum_{i=1}^l z^i z^{i'} \right]^{-1} \left[\sum_{i=1}^l z^i f_{li} \right] \quad (4.64)$$

The estimates are proven to be unbiased because the average of the estimates calculated from repeated samples equals the true parameter (Domencich and McFadden 1975).

The additive random element, η , is heteroskedastic, with $E(\eta) = P_{li} (1 - P_{li})$.

If the distribution of the additive random element, η , is not independently and identically

distributed, the choice model may lack statistical validity in the binomial logit form since the utility, V , is not a 'strict utility'

$$P_i = \text{prob}[\eta(x^j, s) - \eta(x^i, s) \geq V(x^i, s) - V(x^j, s)] \quad (4.65)$$

since the underlying stochastic variables are non-independent. This expression implies that the form of the discrete choice model may not be determined by the joint distribution of the random elements, which may have implausible implications in multiple choice applications.

In the binary choice case ($j = 1, 2$) with vectors of attributes x^1 and x^2 , the choice probability for the first alternative is

$$P_1 = \int_{-\infty}^{+\infty} \psi(t, t + V(x^1, s) - V(x^2, s)) dt \quad (4.66)$$

where Ψ is the cumulative joint distribution function of the additive random elements. By defining G as the cumulative distribution function of the difference of the additive random elements, we get

$$P_1 = G(V(x^1, s) - V(x^2, s)). \quad (4.67)$$

G , the cumulative distribution function, in Equation 4.67 is an increasing function of one variable which translates the range of V into the probability scale (between 0 and 1) (Domencich and McFadden 1975). While there is a general assumption that G is independent of x^1 , x^2 , and s , variations in taste due to unmeasured socioeconomic characteristics may cause the mean of G to shift with s , which will greatly influence

specification validity (Domencich and McFadden 1975).

The three-tier nested logit model described here in Section 4.2 is introduced as a formal technique for estimating the change in HOV mode share after the conversion of an HOVL to toll lane. The nested logit structure defines a logsum (LS) term that is the logarithm of the sum of the utilities of a given nest:

$$LS = \ln \sum_{i=1}^J \exp(V(x^j, s) + \eta(x^j, s)) \quad (4.68)$$

To the extent that systematic preferences are not correlated with observed socioeconomic characteristics in random samples of two different populations (i.e. in different regions), borrowing coefficients from various empirical studies may pose no validity problems. However, if G is not independent of vector and socioeconomic attributes in one or more studies, specification error in the LS coefficient may contribute to biased estimates in the utility function of the upper nest. Such specification errors can be compounded when applying parameter estimates that have been calibrated in several different empirical studies to discrete utility functions within a multi-tiered nested logit model. A travel survey of a sample of a subject highway's population, which yields information on binary decisions within each nested utility function over the range of variables presented here in Section 4.2, is the ideal way of insuring statistical validity. Such an empirical analysis would be a logical extension of the synthetic logit analysis that is the basis for estimating comparative travel-delay benefits associated with investment alternatives described in the beginning of Chapter 4.

Borrowing coefficients from prior studies, McDonald and Noland (1999) used a three-step nested logit model to estimate the effect of converting an HOVL to HOTL on vehicle miles of travel, and found that conversion to HOTL resulted in a decrease in HOV mode share from 27 percent to 20 percent. While theory suggests that conversion of an HOVL to toll lane may result in a decrease in the HOV mode split, preliminary empirical evidence on carpooling rates on the I-15 Express Lanes in San Diego County suggests that tolling on HOVLs may have a beneficial effect on carpooling.

Because the three-step nested logit model presented in this chapter is best suited for an empirical study that produces numerical estimates of model parameters for each variables within each nested sequence, I will not use the nested logit sequence to estimate the effect of conversion strategies on mode split in this synthetic logit analysis. While it is often necessary to borrow coefficients from other studies, the danger of compounding specification error in the multi-tiered nested logit sequence is significant enough to undermine the potential validity of the comparative estimates in what is fundamentally theoretical model that attempts – so far as it is possible – to replicate real-world conditions. To avoid this methodological dilemma, I choose to analyze a range of initial conditions (while holding all other factors constant) to test the sensitivity of the synthetic logit model to changes in key assumptions rather than incorporate the mode share outputs of the nested logit sequence directly into the simulated corridor analysis. The range of initial conditions is presented in section 5.1. Instead of incorporating the three-step logit model (using parameter estimates borrowed from prior empirical studies) in the synthetic

logit analysis, I will simply test a range of possible mode share outcomes for each comparative analysis holding all other factors constant.

Travel time coefficients are taken from the literature, which provides a wide range of possible values. McFadden (1973) reports a coefficient of -0.05 based on survey data on shopping trips in southwestern Pennsylvania in 1967. McFadden and Talvitie (1977) estimated coefficients based on a survey of commuters in the San Francisco Bay Area and found in-vehicle travel time coefficients to range between -0.02 and -0.03, depending on the model specification. Due to the scarcity of empirical studies, I will use the range of -0.01 to -0.04 to derive a reasonable range of average person-delay estimates.

4.3 INDUCED GROWTH AND OTHER EFFECTS OF ADDING CAPACITY

Adding capacity to a congested highway will reduce individual travel delay costs, inducing a host of secondary adjustments: routes changes, new trips, rescheduling, and growth. These effects will vary depending on how much traffic the additional capacity of competing investments can handle without themselves becoming congested. An improvement that attracts the most vehicles and facilitates the most efficient vehicle throughput will produce the largest effects. While none of the following effects are explicitly incorporated into the model, they are presented to provide some context for interpreting the results presented in Chapter 5 and 6. To the extent that these effects arise whenever highway capacity is added, the results presented here overstate delay reduction benefits, especially as they are projected into the future. To capture some of these effects, in Chapter 6 I assume a linear growth trend in benefits projections based on a realistic set

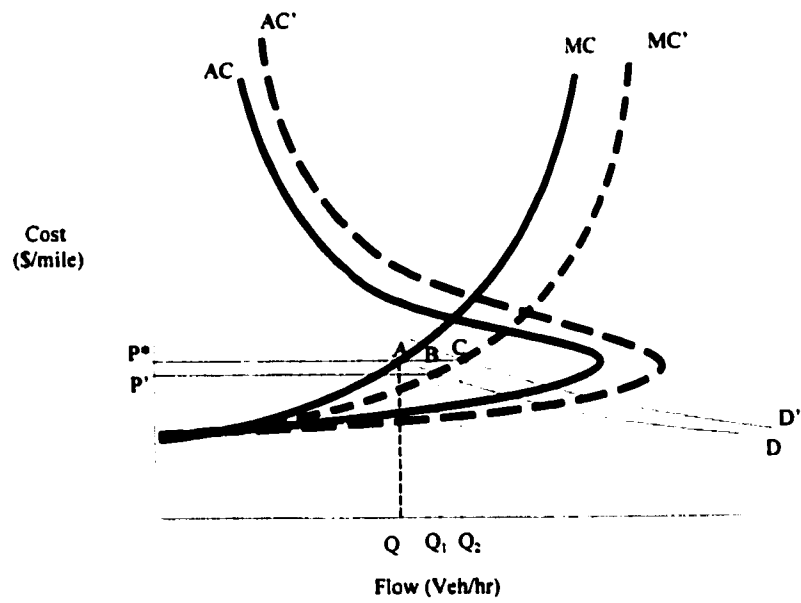
of initial conditions and assumptions.

4.3.1 Induced Growth

Adding new highway capacity reduces individual travel delay costs, which in turn generate more demand for travel by shifting the average variable and marginal cost curves to a higher point on the demand curve. Figure 4.7 illustrates the induced demand effect of adding new highway capacity. After a highway lane is added, the marginal and average cost curves shift outward and to the right (as shown in MC' and AC'), causing a reduction in individual travel costs from P to P' . In response to the one-time travel cost decrease, demand gradually increases from D to D' to a point where the individual travel cost equilibrates back to P^* , the individual travel cost prior to the lane addition. Over the long term, lower individual travel costs may induce new development in areas where property values appreciate as a result of greater travel mobility to outlying areas and residents decide to trade off lower travel costs for better housing and longer commutes. Increased development attracts firms and jobs from other areas, which creates more traffic and eventually washes out the travel delay reduction benefits of added highway capacity. Because this process occurs over many years and is very difficult to predict, its effects are difficult to capture explicitly in the behavioral model presented here.

Researchers investigating induced growth effects have identified a strong relationship between freeway capacity and traffic growth. Gillen, Hansen, Huang, and Puvanthingal (1993) conducted a panel data regression on 30 urban counties in California from 1973 to 1990 and found that every 10 percent increase in new lane-miles to existing

Figure 4.7 The Effect of Latent Demand After Highway Capacity is Added



highways generated a 9 percent increase in VMT beyond what can be attributed to other factors. They report VMT elasticities with respect to new lane-miles added of 0.3-0.4 after 10 years, 0.4-0.7 after 20 years and 0.5-0.6 in 6 to 9 years in urban areas (Gillen, Hansen, Huang, and Puvanthingal 1993).

4.3.2 Scheduling of Departure Times

The trade off between travel and scheduling delay costs are discussed at length in section 4.2.2. The model used to estimate the comparative effects of competing investments incorporates scheduling choice considerations in Section 5.3.

4.3.3 Route Shifts

To evaluate the extent to which travelers on arterial routes benefit from adding a toll lane, let $a(t)$ be the sum of $a_1(t)$ and $a_2(t)$, the number of vehicles arriving at worksite destination via the highway and arterial route, respectively, at time t . The total number of arrivals at time t is

$$A_1(t) + A_2(t) = A(t) = \int_0^t a(x) dx \quad (4.69)$$

At Waldrobian equilibrium, travel costs on the two routes will be equal (Newell 1982).

The initial delay at time t can be expressed

$$w_1(t) = \frac{A_1(t)}{c_1} - t = w_2(t) = \frac{A_2(t)}{c_2} - t \quad (4.70)$$

which can be simplified to

$$a_2 = \frac{c_2}{c_1} a_1(t) \quad (4.71)$$

By expanding highway capacity by adding a toll lane, the reduction in delay on the highway has motivated people who previously shifted to the arterial route back to the highway. An equilibrium between the arterial route, the highway, and the toll lane is reached

$$w'(t) = \frac{A(t)}{c_1 + c_2 + c_3} - t = \frac{A_1(t)(c_1 + c_2)}{c_1(c_1 + c_2 + c_3)} - t \quad (4.72)$$

where c_3 is new capacity on the toll lane. Since the lane charges a toll, the Waldropian equilibrium assumes that the toll lane travel cost + toll equals the monetized cost of delay on the highway and arterial routes. After a toll lane is added, there is a delay reduction because highway capacity is expanded and users have diverted on the toll lane. There is also a delay reduction on arterial routes because travelers have shifted back to the highway. The key is to calculate how the change in total delay with route shifting compares to the change in total delay without any shifting. The ratio of total delay reduction with route shifting to total delay reduction without route shifting can be expressed

$$\frac{c_1 + c_2}{c_1} \cdot \frac{c_1 + c_3}{(c_1 + c_2 + c_3)} \quad (4.73)$$

If this value is greater than one, total delay will be reduced more with a shift than without (Newell 1982). In Chapter 2 of the 91 Express Lanes Final Report entitled "Evaluating

the Impacts of the SR 91 Variable-Toll Express Lane Facility,” the authors report 21 percent of the growth in weekday ADT in the first full year after the opening of the Express Lanes can be attributed to trips diverted from arterial routes. In the six months after the opening, they also observed a slight improvement in travel times along Santa Ana Canyon Road, the most heavily used arterial route in the area (Sullivan et al. 1998).

In the next chapter, I present a simulated logit analysis that does not explicitly incorporate route shifting in comparative estimates of alternatives under consideration. Without adequate empirical data on route shifting effects, and a real traffic network through which routing effects can be estimated, route shifting considerations in a simulated setting would be inappropriate to attempt to predict. The theoretical context for the logit analysis presented in Chapter 5 is a single highway bottleneck, which is insufficient for predicting route shifting effects without (a) empirical travel data, and (b) a fully developed street network. Following the conclusion of the simulated corridor analysis, I will discuss empirical observations of route shifting effects on the 91 Express Lanes highway corridor.

5. A COMPARATIVE ANALYSIS OF THE BENEFITS OF HOVLS, TOLL LANES, AND GPLs

In this chapter, I present the results of a simulated logit analysis used to estimate the comparative effects of adding (1) an HOVL (2) a toll lane, and (3) a GPL. My analytical approach is to present a baseline case in which the performance of an HOVL, the initial proportion of people in HOVs and highway delays reflect a range of realistic, real-world conditions. I then run simulations that compare the baseline case to the investment alternatives described above. In the toll lane case, special attention is paid to estimating the price elasticity of demand. In section 5.5, I present an evaluation of the impact of the 91 Express Lanes on travel demand with an emphasis on main line volume, travel delay, and ridesharing trends.

The analysis suggest that a toll lane always provides comparatively larger vehicle and person-delay reductions than the “no action” HOVL case *and* induces lower increases in vehicle-miles of travel than GPLs. In all but a few exceptional cases, a GPL addition provides greater person-delay reductions than an HOVL. Although charging a toll to HOVs who had previously enjoyed express HOVL service may result in minor shifts from HOV to LOV, tolling indirectly preserves economic incentives to rideshare by (a) spreading tolls over more than one passenger, and (b) providing insurance against travel time uncertainty in the event that a carpool participant unexpectedly cancels. If converting an HOVL to toll lane results in a large shift from HOV to LOV, an HOTL may provide greater travel delay reductions than a toll lane. If converting an HOVL to toll lane results in no significant reduction in HOV mode share, however, a toll lane provides

as much travel delay reduction benefit as HOTLs, with two important financial advantages: (a) lower debt service (due to lower capital and operating costs), and (b) higher annual revenues.¹ These financial considerations will be discussed at length in Chapter 6. Environmental impacts under competing investment scenarios are also presented in Chapter 6.

5.1 BASELINE CONDITIONS AND ASSUMPTIONS

Because this is a simulated analysis, a number of simplifying assumptions must be made in order to present a transparent and flexible procedure for estimating the effect of capacity expansion on the proportion of travelers likely to change behavioral decisions based on generalized travel cost changes. The first and most important assumption is that all travelers have the same probability of forming an HOV. Since the causes of carpool formation are stochastic, any attempt to estimate the cumulative distribution of initial HOV mode share would not improve model validity (Dahlgren 1994).

In the baseline simulation with four GPLs and an HOVL, the proportion of HOVs throughout the peak period can be represented by a simple logit model. The expected proportion of people in HOVs is equal to the individual probability of using an HOV:

$$P_{HOV} = \frac{1}{1 + \gamma e^{\beta[w(t)]}} \quad (5.1)$$

1

HOTLs require higher capital and operating costs than regular toll lanes because the tolling authority must (a) develop an electronic billing system that exempts pre-existing HOV account holders from the toll, (b) integrate visual inspection facilities into the design and layout of the toll project, and (c) hire persons to visually enforce the HOV toll exemption for eligible vehicles.

where β_i are the travel time coefficients of the attributes, and

$$w(t) = \frac{Q(t)}{c} = \frac{A(t) - D(t)}{c} = \frac{A(t)}{c} \quad (5.2)$$

$w(t)$, valued at 0 at the start of the peak period, is the peak travel time differential between GPLs and HOVL. γ is the initial proportion of HOVs. When either an HOVL or toll lane is added to a congested highway, the only attribute that changes is $w(t)$. Consequently, all other attributes can be expressed as a constant, τ , which represents the *initial maximum delay* behind the bottleneck. The constant, τ , varies from location to location, and is a function of unique socioeconomic, demographic and travel cost attributes. The exponent of e , $\beta_i[w(t)]$, the difference in peak travel time on GPLs and the toll lane beginning from the point-of-entry multiplied by some in-vehicle travel time coefficient, captures the sensitivity of HOV formation as a function of peak travel time savings. A discussion of empirical estimates of β is presented in Section 5.1.4.

The service flow on the designated HOVL or toll lane is assumed to be free-flow throughout the peak period. To calculate travel time differentials, $A(t)$ is defined as the cumulative person arrivals at the highway bottleneck, $P(t)$ represents cumulative person arrivals in HOVs, L and H represent LOV and HOV average occupancies, and C_{GPL} and C_{HOVL} represent capacities on GPLs and lane alternative (HOVL or toll lane), respectively. To calculate travel time differentials for the lane addition, $A(t)$ is defined as the cumulative person arrivals at the freeway, $P(t)$ represents cumulative alternative lane person arrivals, L and H represent GPL and HOVL or toll lane average occupancies, and C_{GPL} , C_{HOVL} , and C_{TL} represent capacities on the general purpose,

HOVL and toll lanes, respectively. The congested period begins at time $t = 0$; congestion on the lane alternative begins at time t_H (Dahlgren 1998). Delay for travelers entering the uncontrolled highway at time t is

$$w_{GPL}(t) = \max \left\{ \frac{\frac{A(t) - P(t)}{L} - tC_{GPL}}{C_{GPL}}, 0 \right\} = \max \left\{ \frac{A(t) - P(t)}{LC_{GPL}} - t, 0 \right\} \quad (5.3)$$

and for HOVs is

$$w_{HOV}(t) = \max \left\{ \frac{P(t) - P(t_H)}{HC_H} - (t - t_H), 0 \right\} \quad (5.4)$$

$P(t)$, the cumulative HOVs at time t , depends on the travel time differential $L_i - H_i$ at time t , which equals $w_L(x) - w_H(x)$.

$$P(t) = \int_0^t [a(x) P_{HOV}(x)] dx = \int_0^t a(x) \frac{1}{1 + \gamma e^{\beta_t [w_L(x) - w_H(x)]}} dx \quad (5.5)$$

where

$$a(x) = \frac{dA(x)}{dx} \quad (5.6)$$

Because the only attributes that change are the travel times for the two lanes, all other attributes can their coefficients can be captured in the term, γ (Dahlgren 1999). The travel time differential, $w_L(x) - w_H(x)$, is calculated for each minute and used to calculate $P(t)$ for the subsequent minute interval (Dahlgren 1994). Total person-delay, vehicle-delay, and vehicle-trips can be calculated for travelers entering the highway during each

time interval. These estimates can be summed to obtain total person-delay, vehicle-delay, and vehicle-trips for the entire peak period. The model outputs for each of the sensitivity analyses presented in Sections 5.1.2, 5.1.3 and 5.1.4 are provided in the Appendices.

An assessment of the comparative benefits requires a set of assumptions with respect to:

1. *HOVL occupancy requirements*

2. *Initial Conditions*

- * Proportion of people in HOVs
- * Average occupancies for LOVs and HOVs
- * Length of peak period
- * Maximum delay
- * Number of lanes
- * Lane capacity

3. *Behavioral Assumptions*

- * In-vehicle travel time coefficient
- * Toll coefficient
- * Value of Travel Time Savings

In the analysis to follow, the simulated highway corridor has four GPLs and one HOVL, each with a capacity of 1,600 vehicles per hour. The peak period is three hours long, maximum delays occurs half way through the peak. Holding other factors constant, this analysis will estimate average person-delays over a range of initial conditions: (1) initial proportion of HOVs ranging from 0 to 20 percent, (2) maximum waiting times of 10, 15, 20, 25, 30, 35, and 45 minutes, and (3) travel time coefficients from -0.01 to -0.04. The objective in testing a range of initial conditions is to allow a sensitivity testing of model outputs. In testing a range of plausible values for each set of initial conditions

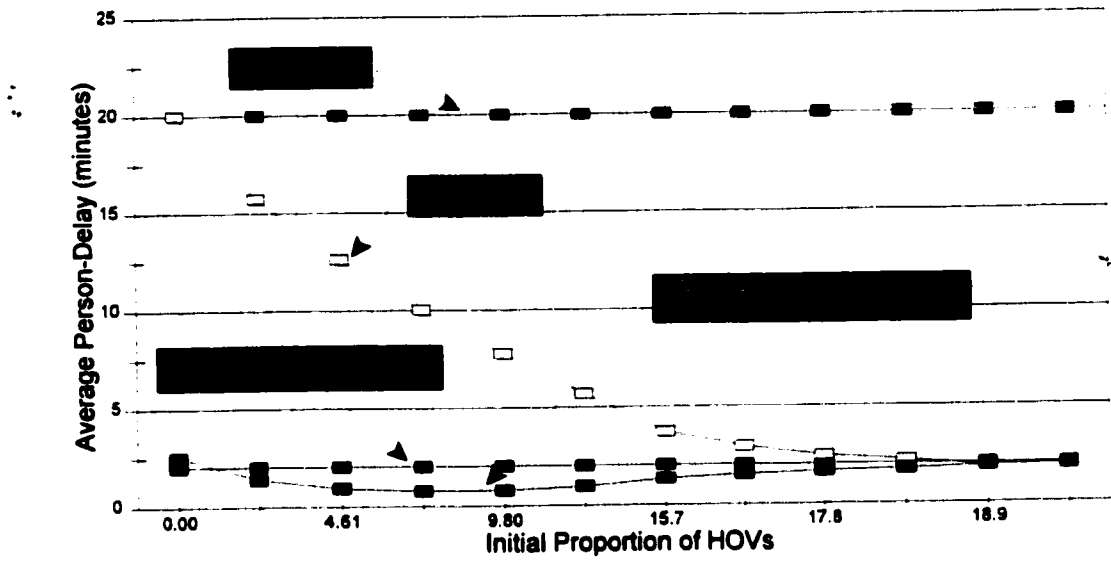
described above, the goal is to establish whether any values within a specified range significantly alter the findings. If it can be shown that outputs do not significantly change over the range of values for a set of initial conditions, in order to simplify the analysis I will choose a default value in testing the sensitivity of subsequent coefficients. The average vehicle occupancy for LOVs is 1.0 and the average vehicle occupancy for HOVs is 2.3.

5.1.1 Initial Proportion of People in HOVs

Because the HOV mode share varies from place to place, it is important to understand how the initial proportion of HOVs affects the comparative travel delay reduction benefits are associated with competing investments. A comparison of how the initial proportion of people in HOVs influences average person-delays under the investment choices described earlier is shown in Figure 5.1. The initial proportion of people in HOVs is shown on the horizontal axis and the average-person delay on the vertical axis. The baseline assumptions in this analysis represent a range of possible conditions: (1) 4 GPLs, each with a capacity of 1,600 vehicles per hour, (2) a lane addition with a capacity of 1,600 vehicles per hour, (3) a 3 hour period, (4) a maximum delay of 30 minutes, which occurs half-way through the peak, (5) an average HOV occupancy of 2.3, and (6) a travel time coefficient of -0.02. Model outputs for each of the alternatives shown in Figure 5.1 are provided in Appendix B.

In the baseline case with no lane addition, the average person-delay over the range of initial proportion of HOVs is 20 minutes. When a GPL is added, average person-delays fall from 20 minutes to 2 minutes. In other words, the expansion of the highway

Figure 5.1 The Relationship Between the Initial Proportion of People in HOVs and Average Person-Delay



from four to five lanes almost entirely eliminates queueing delays, assuming the initial conditions described above. Because adding a GPL does not encourage ridesharing, a GPL addition will provide the same average person-delays irrespective of the initial HOV mode share. When an HOVL is added, Figure 5.1 shows that highways with a higher initial proportion of HOVs produce larger average person-delay reduction benefits than highways with a low initial proportion of HOVs. The curvature of the “Add HOVL” curve reflect two countervailing effects: (a) the diversion of HOVs to the new HOVL, which reduces delay for HOVs, and (b) the increase in capacity for LOVs on the existing GPLs, which lowers delays for LOVs. When there are few HOVs and most people are traveling via LOV, an HOVL addition will be poorly utilized and be unable to reduce average person-delays to a greater degree than the pre-HOVL ‘no action’ case. In the extreme case in which there are no HOVs, an HOVL addition will result in no reduction in average person-delays over the baseline “no action” case. As the proportion of HOV increases, the reduction in average person-delays gradually decreases, approaching the average person--delays provided by the “Add GPL” case. Over the range of initial proportion of HOVs from zero to when the proportion of HOVs equals the proportion of HOVL capacity to total highway capacity, simply adding a GPL provides greater average person-delay reductions than adding an HOVL. When the proportion of HOVs exceeds the proportion of HOVL capacity to total capacity, there is no difference in average person-delay between the “Add GPL” and “Add HOVL” case because delays on the HOVL erode the travel time differential between the HOVL and GPLs, ultimately inducing an equilibration of HOV and LOV travel times and no further shifts from LOV

to HOV.

In estimating the change in average person-delays in the toll lane case, I make the simplifying assumption that the initial proportion of HOVs for a given highway remains constant after highway capacity is expanded. Although this may not be entirely realistic insofar as an expansion of highway capacity may result in a decrease in SOV travel costs (and a corresponding shift to from SOV to HOV), it provides the upper limit of potential average person-delay reductions over the baseline case. In section 5.1.2, I relax this assumption to test how a reduction in the initial proportion of HOVs caused by the conversion of an HOVL to toll lane may affect comparative average-person delays. Figure 5.1 shows that converting an HOVL to toll lane results in the largest comparative reduction in average person-delays of the three investments under consideration. Compared to an HOVL, a toll lane provides the largest comparative average person-delay reductions when the initial proportion of HOVs is between the range of 4 and 10 percent, and unused capacity is sold to SOV travelers previously restricted from the HOVL. As the initial proportion of HOVs increases and the amount of lane capacity that can be sold to SOVs decreases, the difference in average person-delays between the “Add HOVL” curve and the “Convert HOVL to Toll Lane” diminishes until they converge at a point where the initial proportion of HOVs approximately equals the proportion of capacity devoted to the toll lane. This occurs because the amount of capacity that can be sold to travelers who had previously been restricted from express lane service decreases as a function of the increase in the initial proportion of HOVs. The singular advantage of toll lane service over existing HOVL treatments is that lane performance is not constrained by

unexpected or secular increases in the initial proportion of HOVs.

On highways with high carpooling rates, the conversion of an HOVL to toll lane will not reduce carpooling rates as much as it will redistribute carpools between congested GPLs and the toll lane. The split of HOVs between the congested highway and the toll lane is subject to local conditions, and is best determined through a nested logit model with parameter estimates calibrated using travel survey data.

Delays reductions on a highway with a low initial proportion of HOVs is slightly larger in the “Convert to Toll Lane” case than the “Convert to GPL” case. Over the range of initial proportion of HOVLs from 5 percent to the point at which the initial proportion of HOVs equal the proportion of capacity devoted to the toll lane, converting an HOVL to toll lane provides greater average person-delay reductions than a GPL. The singular advantage of toll lane over GPL is that in cases where the initial proportion of HOVs is high, the diversion of HOVs onto a congestion-free lane will provide a greater level of average-person delay benefits than a GPL addition that – while being able to reduce overall average-person delay – does not create a free-flow alternative that allowing multi-person vehicles to avoid queuing delays. The higher the proportion of HOVs a toll lane is able to attract, the greater the comparative average-person delay benefits over GPL additions. On a highway with a high initial proportion of HOVs equal to or greater than the proportion of toll lane capacity, the “Add HOVL” and “Convert HOVL to Toll Lane” curves converge with the “Add GPL” curve.

One major advantage of toll lane service over HOTL service is that the decision to convert a candidate HOVL is not necessarily limited to cases in which the HOV mode

share is low, and the HOVL is clearly underperforming.. In the HOTL context, peak lane capacity in excess of capacity reserved for HOVs can be sold to the public. In areas where the pre-existing HOV mode share is high and the HOVL is well utilized (800 – 1000 vph), the HOTL operator can only sell peak travel time savings to 600 to 800 SOVs per hour. If demand for travel time savings is high (due to large peak highway delays), then tolls would have to be set very high in order to maintain free-flow conditions and reserve enough capacity for eligible HOVs. On toll lanes without HOV toll exemption, peak travel time savings can be sold to 1,600 vehicles per hour. Although the travel cost for HOVs has increased slightly (by now charging a toll), the incentive to rideshare remains intact. The toll operator benefits by gaining toll revenue from HOVs that would otherwise have been foregone in the HOTL case.

5.1.2 How Changes in the Initial Proportion of HOVs after Converting an HOVL to Toll Lane Affects Delay Reduction Benefits

There is much debate over the ability of HOVLs to encourage ridesharing. Despite over two decades of unwavering federal and state support in the belief that HOVLs can increase new carpooling, a recent California Legislative Accounting Office (LAO) study found that “the average number of vehicles using any given segments of the HOV network does not necessarily increase over time.” (Orski 2000, pg. 1) While noting that the statewide impact of HOVLs on ridesharing is difficult to determine, “surveys have found that many carpoolers would ride together regardless of whether or not the HOV lane existed.” (LAO 2000) In other words, adding an HOVL diverted HOVs that would already have been formed even if the HOVL had not been built.

While theory suggests that allowing toll buy-ins on HOVLs (via HOTLs) may result in a decrease in carpooling rates, a recent SANDAG study of the I-15 Express Lanes found that since the conversion of the reversible-flow HOVL to Express Lane service, carpooling rates during peak hours have increased slightly over pre-Express Lanes levels (SANDAG 1999). One possible explanation is that the provision of peak free-flow service for SOVs (via the Express Lanes) provides insurance against the risk of travel time uncertainty in cases where a stable HOV partner unexpectedly cancels the morning of the day's carpool commute. In the event that a carpooling trip falls through, the carpooler who must now drive as an SOV has the option to gain travel time certainty by paying for express toll service. This option is worthwhile as long as the lateness penalty associated with late arrival to work is greater than the SOV toll. Had the SOV toll buy-in option not been available, the commuter who lost her carpool partner for the day would be subject to travel time variability that could result in a lateness penalty at work. Because the SOV toll buy-in option provides a long-term hedge against the penalty associated with unexpected carpool partners dropping out, carpooling may be more stable over time. This effect is manifested in two forms: (1) new carpools, and (2) more stable long-term carpooling.

Except for Sullivan et al.'s study of the 91 Express Lanes, there are no empirical studies of the effect of converting an HOVL to toll lane on carpooling rates. The 91 Express Lanes opened as a classic HOTL by exempting HOV3+s from tolls. In January 1998, CPTC began charging a half-toll to HOV3+ occupants. The effect of charging HOV3+s a toll was immediate and dramatic; the proportion of peak HOV3+s dropped

from 20 percent to 14 percent (see Figure 5.14).

In comparing the delay reduction benefits of alternatives to an HOVL, I will test three different ridesharing outcomes: (1) converting an HOVL to toll lane results in a 25 percent decrease in carpooling, (2) converting an HOVL to toll lane results in no change in carpooling, and (3) converting an HOVL to toll lane results in a 25 percent increase in carpooling. This range of outcomes provides a sufficient context for analyzing the comparative effects of HOVL versus toll lane treatments given possible changes in ridesharing levels.

The following are initial conditions: (a) four GPLs and one HOVL, (b) peak period of 3 hours, (c) a maximum delay of 30 minutes (occurring at 1 hour 30 minutes), (d) a travel time coefficient of -0.02. In this simulation, the initial proportion of HOVs is 20 percent before and after the HOVL is added.

Table 5.1 The Comparative Effects of Converting an HOVL to Toll Lane Over a Range of Possible Changes in the Initial Proportion of HOVs

	HOVL 20% HOVs	Toll Lane 15% HOVs	Toll Lane 20% HOVs	Toll Lane 25% HOVs
Average person-delay (min)	7.8	.77	.79	.96
Length of peak period (min)	141	105	105	106
Maximum queueing delay (min)	11.1	.93	.94	1.11

Table 5.1 summarizes the results of a logit analysis testing the comparative of effects of changes in the initial proportion of HOVs resulting from the conversion of an HOVL to toll lane. Before the HOVL is added, average person-delay is approximately 20

minutes. This estimate is obtained by dividing total queuing delay by total passengers. After the HOVL is added, average person-delays fall from 20 minutes to 7.8 minutes, the length of the peak period falls from 3 hours to 2 hours 21 minutes, and the maximum delay of 30 minutes at 1 hour 30 minutes falls to 11.1 minutes at 1 hour 45 minutes.

In cases where the conversion of an HOVL to toll lane results in a 25 percent decrease in the initial proportion of HOVs, the initial proportion falls from 20 percent in the HOVL case to 15 percent in the toll lane case. The simulated logit model indicates that in spite of a reduction in carpooling by 25 percent, the increased lane utilization on the toll lane caused by the diversion of SOVs reduces average person-delay from 7.8 minutes to .77 minutes. The peak period falls from a length of 2 hours 21 minutes in the HOVL case to 1 hour 45 minutes, and the maximum delay falls from 11.1 minutes at 1 hour 45 minutes to .9 minutes at 56 minutes.

On highways where the conversion of an HOVL to toll lane results in no change in the initial proportion of HOVs, average person delays fall from 7.8 minutes in the HOVL case to .79 minutes. On highways where conversion to toll lane results in an increase in the initial proportion of HOVs from 20 percent to 25 percent, average person-delays fall from 7.8 minutes to .96 minutes. Based on the simulated logit analysis presented here, it appears that a toll lane will provide a substantially larger delay reduction benefit over HOVLs regardless of whether the conversion to toll lane results in a significantly increase or decrease in the initial proportion of HOVs. To the extent that HOTLs offer free service to eligible HOVs, HOTLs may be able to preserve ridesharing to a greater degree than toll lanes in comparison to the baseline HOVL case. But the

evidence clearly suggests that even in the extreme case that an HOTL results in a 25 percent increase in carpooling and a toll lane results in a 25 percent decrease in ridesharing, the comparative difference in average person-delays, length of the peak period and maximum queueing delays are quite marginal over the initial conditions described above.

While Dahlgren (1994) argues that the travel time coefficient should be the same for all mode, I use a travel time coefficient on -0.02 in the “Add HOVL” scenario and a travel time coefficient of -0.01 for the “Convert HOVL to HOTL” scenario instead of using the lower initial proportion of HOVs predicted in the nested logit analysis. The logic of using a lower travel time coefficient for HOTLs is that the motivation of shift to HOVs as a function of the travel time differential is slightly dampened by the choice to remain SOV and pay the peak toll.

5.1.3 Initial Maximum Delay

Congestion arises whenever the rate of vehicle arrivals exceeds capacity, or the bottleneck service rate, g , described in Chapter 4. Using a time-space diagram to represent a highway bottleneck, it possible to calculate an arrival rate based on the length of the peak period, the time of maximum delay, the number of lanes, the capacity of each lane, and the length of maximum delay. The arrival rate is greater when the peak period is shortened, the time of maximum delay is earlier, there are more lanes, or the maximum delay is longer. Consequently, the sensitivity of freeway performance to any one of these initial conditions is similar to the sensitivity of the initial maximum delay (Dahlgren 1994). Testing average person-delays as a function of initial maximum delays is intended

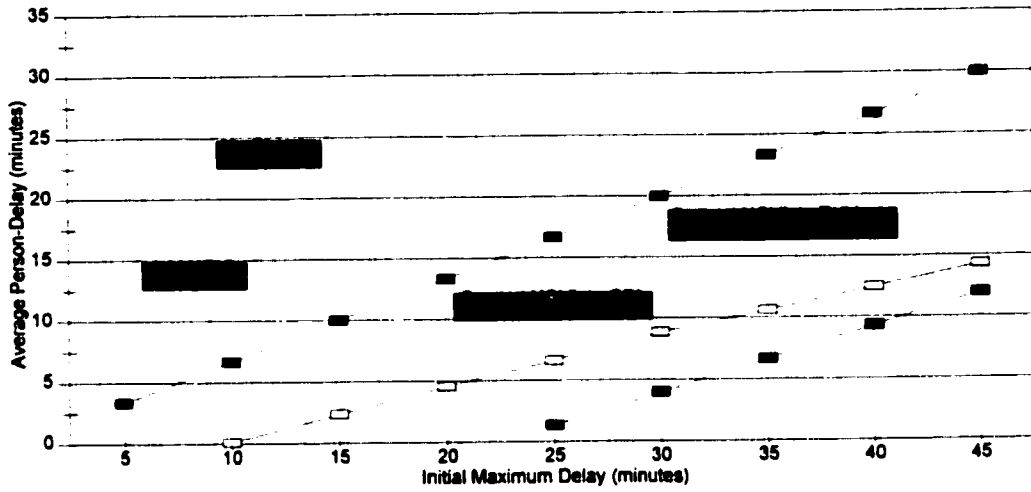
to provide a basis for estimating the comparative effects of competing investment choices over a range of peak congested conditions.

Figure 5.2 illustrates the relationship between average person-delay and the initial maximum prior to the addition of new capacity. The initial conditions are similar to those in Figure 5.1, except that the initial proportion of HOVs is fixed at 9 percent and the maximum queuing delays vary from a low of 5 minutes to a maximum of 45 minutes. The travel time coefficient is fixed at -0.02.

When a GPL is added to a congested highway, queuing delays is eliminated if the total highway capacity at each peak interval exceeds the arrival rate. Table 5.2 shows that a GPL addition will eliminate congestion over a range of initial maximum delays from 5 minutes to 24 minutes. Over this range, the new capacity, which consists of five GPLs each with a capacity of 1,600 vehicles per hour, is greater than the maximum arrival rate. Similarly, there is no delay when an HOVL is added if the LOV arrival rate is less than the capacity of the four GPLs, which occurs when the initial maximum delay is less than 10 minutes. In other words, the HOVL addition is able to divert enough HOVs that the volume of LOVs throughout the peak period never exceeds highway capacity.

The "Add HOVL" curve has a lesser slope than the "Add GPL" curve because the magnitude of the shift from LOV to HOV depends on the travel time differential. While the slope of the "Add Toll Lane" and "Add GPL" curves are equal, at every level of initial maximum delay the "Add Toll Lane" curve has a slightly lower average person-delay than the "Add GPL" curve because the optimization of the toll lane throughout the peak limits total queuing delays to four highway lanes instead of five. Total queuing

Figure 5.2 The Relationship Between the Initial Maximum Delay and Average Person-Delay



delay divided by highway travelers in the “Add GPL” case is slightly larger than the total queueing delay divided by highway travelers in the “Add Toll Lane” case. When an HOVL is converted to a toll lane, person-delays first arise when the initial maximum delay is 150 percent greater than the baseline HOVL case. The model outputs for this analysis are located in Appendix C.

5.1.4 Travel Time Coefficients

Travel time coefficients are taken from the literature, which provides a wide range of possible values. Small (1972) found a coefficient of -0.02 per minute of round-trip on-vehicle time based on a sample of San Francisco Bay Area commuters in 1972. McFadden (1973) reports a coefficient of -0.05 based on survey data on shopping trips in southwestern Pennsylvania in 1967. McFadden and Talvitie (1977) estimated coefficients based on a survey of commuters in the San Francisco Bay Area and found in-vehicle travel time coefficients to range between -0.02 and -0.03, depending on the model specification. Due the scarcity of empirical studies, I will use the range of -0.01 to -0.04 to derive a reasonable range of average person-delay estimates. Koppelman (1983) cites estimates from ranging from -0.0082 in a Chicago Area Transportation Study (CATS) and -0.056 in the Peak, Marwick, and Mitchell study of travel demand in San Diego. In a disaggregate study of San Francisco Bay Area commuters developed at the Metropolitan Transportation Commission, Kollo (1986) estimated coefficients for in-vehicle round trip travel times of -0.012 and -0.016 per minute for three mode and four mode models, respectively.

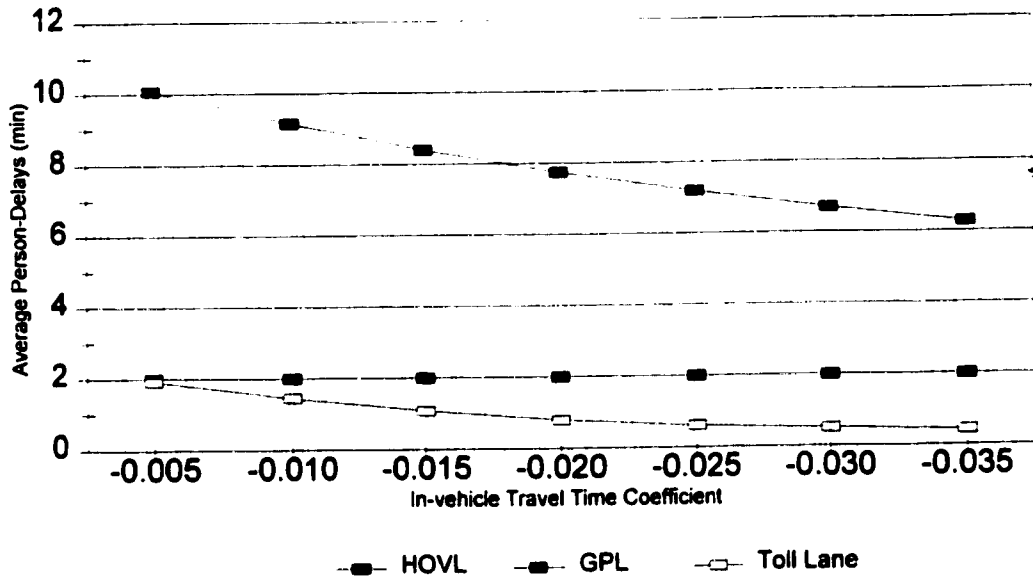
Based on the wide range of in-vehicle travel time coefficients, I will test a the

following range of coefficients: -0.005, -0.01, -0.015, -0.020, -0.025, -0.030 and -0.035. While the literature generally finds that in-vehicle travel time has a weak effect on mode choice, it is worthwhile to evaluate a range of in-vehicle travel time coefficients to identify whether instances in which there is a strong mode choice effect influence the comparative benefits of alternative lane treatments.

Figure 5.3 summarizes the results of a simulation analysis which shows the relationship between in vehicle travel time coefficient, β , and average person-delay for each of the major investment alternatives under consideration. The first major point of observation is that both HOVLs and toll lanes, average person-delay is negatively correlated with in-vehicle travel time coefficient. In the HOVL case, as the propensity to shift to HOVs increases, an increasing proportion of HOVs per peak interval shifts onto the HOVL, leaving more capacity to be shared by fewer SOVs. Thus, average person-delay decreases from 10.1 minutes with a travel time coefficient of -0.005 to 6.3 minutes with a travel time coefficient of .035. In the toll lane case, the same general relationship between average person-delay and travel time coefficient is observed. Average person-delay fall from 1.9 minutes with a travel time coefficient of -0.005 to .4 minutes with a travel time coefficient of -0.035.

Figure 5.3 also shows that at each level of travel time coefficient a toll lane provides substantially larger average person-delay reductions than an HOVL. It is worth noting that the difference in average person-delay between the HOVL and toll lane case decreases from 8.2 minutes to 5.9 minutes as the travel time coefficient increases from -0.005 to -0.035. As the propensity to shift to HOV increases as a function of travel time

Figure 5.3 The Relationship between Average Person-Delay and Travel Time Coefficient



differential, less peak lane capacity is available for SOVs. While increasing travel time coefficients result in improved peak lane utilization in the HOVL case, it results in marginal decrease in the capacity available to SOVs in the toll lane case.

One scenario worth considering is a situation in which the conversion of an HOVL to toll lane results in a decrease in the in-vehicle HOV travel time coefficient. It is not unreasonable after all to expect that the imposition of a toll on HOVs to dampen the probability of shifting to HOVs as a function of the travel time differential between congested highway lanes and the toll lane. Consider the extreme case presented in Figure 5.3 where the conversion of an HOVL to toll lane results in a decrease in travel time coefficient from -0.035 (pre-toll lane) to -0.005 (after-toll lane). Assuming no change in the initial proportion of HOVs, the increase in peak lane utilization on the toll lane over the baseline HOVL case – caused primarily by the attraction of SOV toll buy-ins – results in a substantial decrease in average person-delay from 6.3 minutes to 1.9 minutes.

This analysis clearly shows that the welfare benefits associated with converting an HOVL to toll lane are present over a wide range of travel time coefficients, which reflect empirically derived coefficient estimates drawn from a number of different travel demand studies. The model outputs for this analysis are located in Appendix D.

5.2 COMPARING THE EFFECTS OF GPLs, HOVLs AND TOLL LANES

As noted in Chapter 4, because induced demand effects – manifested in new trips and secondary shifts from other times and routes – are not explicitly modeled, the analytical approach used here only estimates the *comparative* benefits of competing investment choices and may therefore overstate actual benefits. The analysis presented in

Sections 5.1.2 to 5.1.4 demonstrate that over a wide range of initial conditions with respect to the initial proportion of the HOVs, initial maximum delays and travel time coefficients comparative effects HOVLs and toll lanes are stable. In this section, I estimate the benefits of converting an HOVL to toll lane and GPL with the no-action “HOVL” baseline case using the following set of real-world conditions:

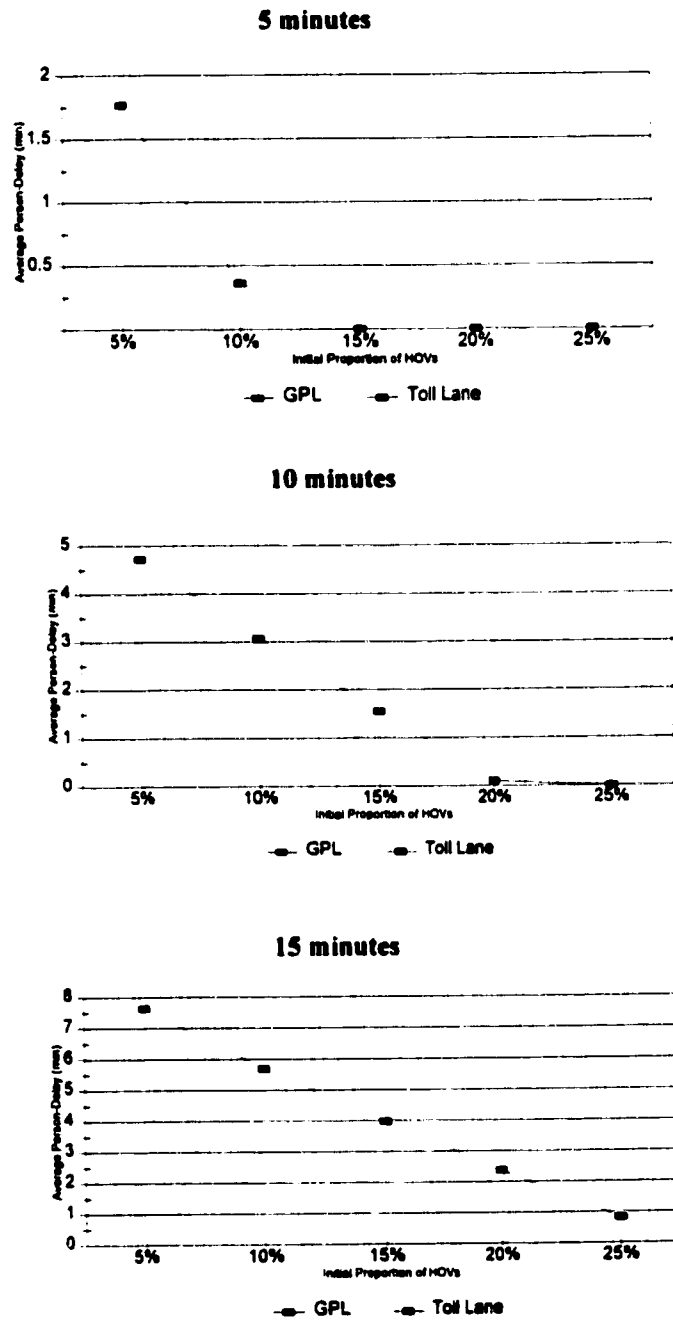
- **Initial proportion of HOVs: 5%, 10%, 15%, 20% and 25%**
- **Initial Maximum Delay: 5 minutes, 10 minutes, 15 minutes, 20 minutes, 25 minutes, 30 minutes, 35 minutes, 40 minutes and 45 minutes.**
- **Travel time coefficient: -0.02 for HOVLs, -0.01 for toll lanes**
- **Average HOV Occupancy: 2.3 persons**

Average Person-Delay

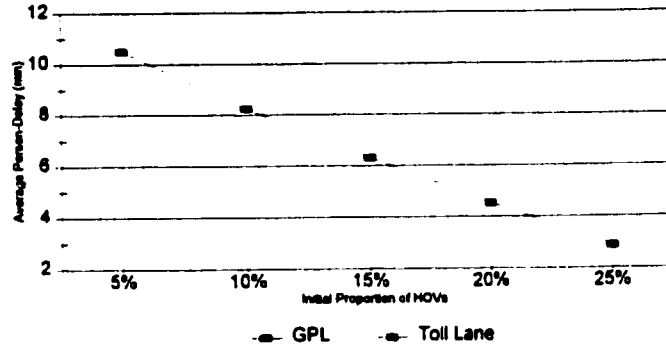
Figure 5.4 illustrates the difference in average person-delay for the three alternatives under consideration: (1) HOVL, (2) toll lane, and (3) GPL. When initial maximum delay is between 5 and 20 minutes, there is no difference in average person-delay reductions between the three investment alternatives because the capacity increase is sufficient to eliminate highway delays. Within this range, any of the three alternatives would produce the same level of welfare gains.

When the initial maximum delay is greater than 20 minutes, the difference in average person-delay reductions associated with each investment diverges. In most cases, the average person-delay reduction associated with converting an HOVL to GPL is slightly larger than the average person-delay reductions associated with conversion toll lane when the initial maximum delay is equal to or greater than 30 minutes. The

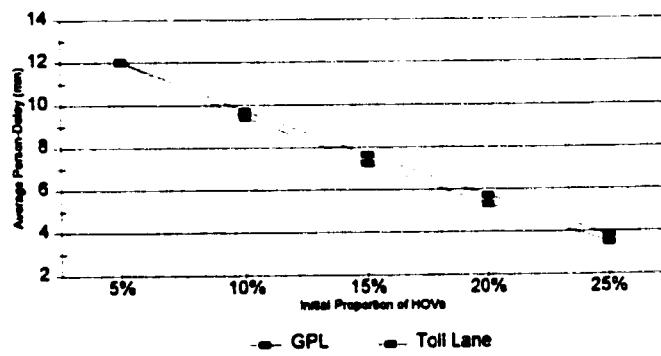
Figures 5.4 Difference in Average Person-Delay Between the 'No Action' HOVL Baseline Case and Competing Alternatives



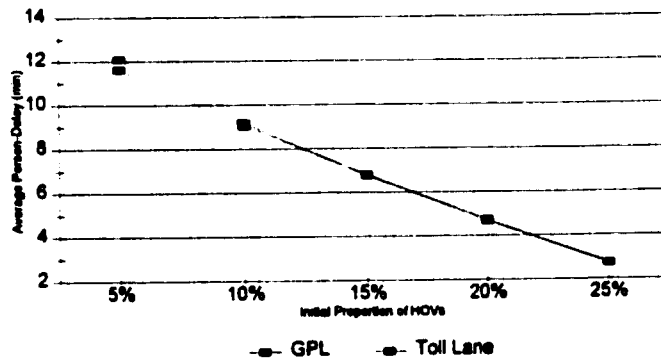
20 minutes



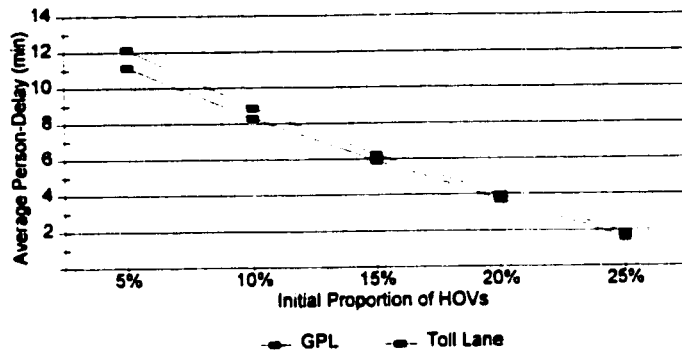
25 minutes



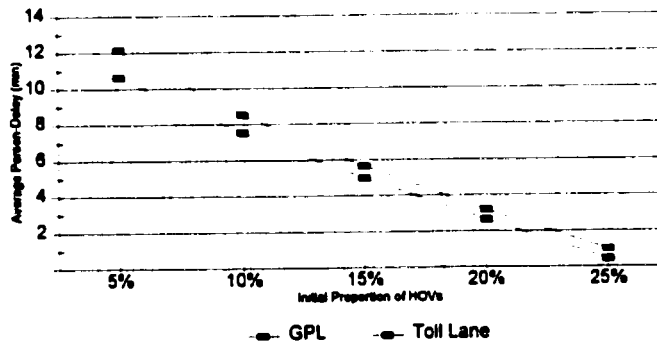
30 minutes



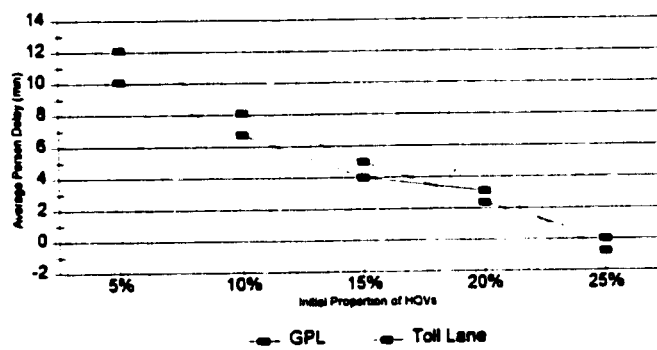
35 minutes



40 minutes



45 minutes



**Table 5.2 Peak Hour Average Person-Delays
Under Competing Investment Alternatives**

INITIAL CONDITIONS						AVERAGE PERSON-DELAY (minutes)			
Number of Lanes	Initial Maximum Delay	Average HOV Occupancy	Initial Proportion in HOVs	HOVL Travel Time Coefficient	Toll Lane Travel Time Coefficient	Before HOVL Addition	Add HOVL	Convert HOVL to GPL	Convert HOVL to Toll Lane
4	5	2.3	5%	-0.02	-0.01	3.3	1.8	0.0	0.0
4	5	2.3	10%	-0.02	-0.01	3.3	0.4	0.0	0.0
4	5	2.3	15%	-0.02	-0.01	3.3	0.0	0.0	0.0
4	5	2.3	20%	-0.02	-0.01	3.3	0.0	0.0	0.0
4	5	2.3	25%	-0.02	-0.01	3.3	0.0	0.0	0.0
4	10	2.3	5%	-0.02	-0.01	6.7	4.7	0.0	0.0
4	10	2.3	10%	-0.02	-0.01	6.7	3.1	0.0	0.0
4	10	2.3	15%	-0.02	-0.01	6.7	1.5	0.0	0.0
4	10	2.3	20%	-0.02	-0.01	6.7	0.1	0.0	0.0
4	10	2.3	25%	-0.02	-0.01	6.7	0.0	0.0	0.0
4	15	2.3	5%	-0.02	-0.01	10.0	7.6	0.0	0.0
4	15	2.3	10%	-0.02	-0.01	10.0	5.7	0.0	0.0
4	15	2.3	15%	-0.02	-0.01	10.0	4.0	0.0	0.0
4	15	2.3	20%	-0.02	-0.01	10.0	2.4	0.0	0.0
4	15	2.3	25%	-0.02	-0.01	10.0	0.8	0.0	0.0
4	20	2.3	5%	-0.02	-0.01	13.3	10.5	0.0	0.0
4	20	2.3	10%	-0.02	-0.01	13.3	8.2	0.0	0.0
4	20	2.3	15%	-0.02	-0.01	13.3	6.3	0.0	0.0
4	20	2.3	20%	-0.02	-0.01	13.3	4.5	0.0	0.0
4	20	2.3	25%	-0.02	-0.01	13.3	2.9	0.0	0.0
4	25	2.3	5%	-0.02	-0.01	16.7	13.3	1.3	1.3
4	25	2.3	10%	-0.02	-0.01	16.7	10.7	1.3	1.0
4	25	2.3	15%	-0.02	-0.01	16.7	8.6	1.3	0.9
4	25	2.3	20%	-0.02	-0.01	16.7	6.6	1.3	0.9
4	25	2.3	25%	-0.02	-0.01	16.7	4.8	1.3	1.0
4	30	2.3	5%	-0.02	-0.01	20.0	16.1	4.0	4.5
4	30	2.3	10%	-0.02	-0.01	20.0	13.2	4.0	4.1
4	30	2.3	15%	-0.02	-0.01	20.0	10.8	4.0	4.0
4	30	2.3	20%	-0.02	-0.01	20.0	8.7	4.0	3.9
4	30	2.3	25%	-0.02	-0.01	20.0	6.7	4.0	4.0
4	35	2.3	5%	-0.02	-0.01	23.3	18.8	6.7	7.7
4	35	2.3	10%	-0.02	-0.01	23.3	15.5	6.7	7.2
4	35	2.3	15%	-0.02	-0.01	23.3	12.9	6.7	7.0
4	35	2.3	20%	-0.02	-0.01	23.3	10.6	6.7	6.9
4	35	2.3	25%	-0.02	-0.01	23.3	8.5	6.7	6.9
4	40	2.3	5%	-0.02	-0.01	26.7	21.5	9.3	10.8
4	40	2.3	10%	-0.02	-0.01	26.7	17.9	9.3	10.3
4	40	2.3	15%	-0.02	-0.01	26.7	15.0	9.3	10.0
4	40	2.3	20%	-0.02	-0.01	26.7	12.5	9.3	9.9
4	40	2.3	25%	-0.02	-0.01	26.7	10.3	9.3	9.9
4	45	2.3	5%	-0.02	-0.01	30.0	24.1	12.0	14.0
4	45	2.3	10%	-0.02	-0.01	30.0	20.1	12.0	13.4
4	45	2.3	15%	-0.02	-0.01	30.0	17.0	12.0	13.0
4	45	2.3	20%	-0.02	-0.01	30.0	14.3	12.0	11.2
4	45	2.3	25%	-0.02	-0.01	30.0	12.0	12.0	12.8

difference in average person-delay reductions is greatest when the initial maximum delay is largest. Each investment alternative will be discussed in turn.

Converting an HOVL to GPL

Column C in Table 5.2 shows the change in average person-delays resulting from the conversion of an HOVL to general purpose use. In all cases, the conversion results in average person-delay reductions greater than the baseline “no-action” HOVL case. The average person-delay reduction is a linear function of the initial maximum delay and is the same irrespective of the initial proportion of HOVs. Person-delay is eliminated for initial maximum delays between 5 and 20 minutes, and rises from 1.3 minutes at an initial maximum delay of 25 minutes to 12 minutes at an initial maximum delay of 45 minutes.

Converting an HOVL to Toll Lane

Column D in Table 5.2 indicates the change in average person-delay resulting from the conversion of an HOVL to a toll lane. Similar to the conversion of an HOVL to GPL, the conversion of an HOVL to toll lane eliminates delays up to an initial maximum delay of 20 minutes. At an initial maximum delay of 25 minutes, the average person-delays over the range of initial proportion in HOVs from .05 to .25 is lower than the average person-delays associated with the conversion of an HOVL to GPL. At an initial maximum delay of greater than 25 minutes, the average person-delays resulting from the conversion of an HOVL to toll lane is greater than the average person-delays resulting from the conversion of an HOVL to GPL.

With the exception of the 25 minute initial maximum delay case, average person-delays are slightly higher in the “Convert HOVL to Toll Lane” case than in the “Convert

HOVL to GPL” case. This is because the increase change in the travel time coefficient from -0.02 in the “Add HOVL” case to -0.01 in the “Convert to Toll Lane” case results in a slight decrease in the propensity of HOVs to shift on the toll lane as a function of peak travel time differentials. The assumption that the conversion of an HOVL to toll lane causes a decrease in travel time coefficient results in marginally higher average person-delays over the range of initial proportion of HOVs from 5 percent to 25 percent in comparison to a GPL. This observation holds true for all initial proportion of HOVs over the range of initial maximum delays greater than 20 minutes.

Note in Table 5.2 that at a given initial maximum delay person-delay is inversely related to the initial proportion of people in HOVs. As the initial proportion of people in HOVs falls, the percentage change in non-toll lane travelers is less than corresponding change in total delay, resulting in a slight increase in average person-delays as the initial proportion of people in HOVs falls.

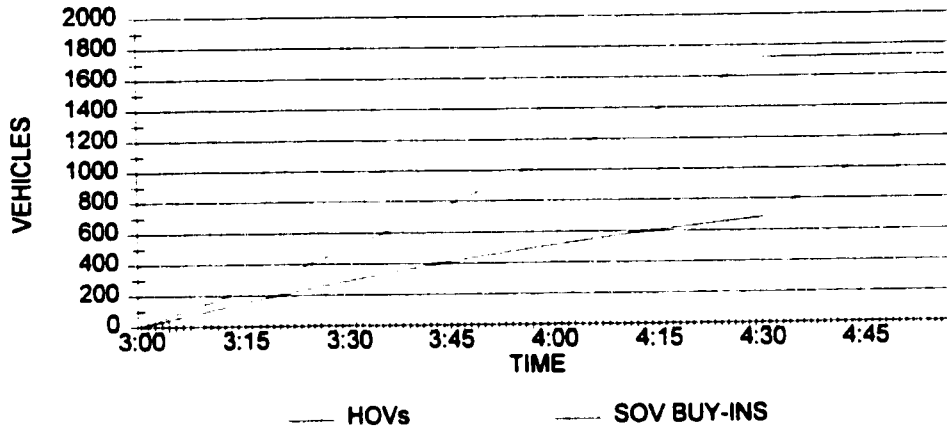
Figure 5.5 illustrates volumes on a toll lane with an initial maximum delay of 45 minutes and an initial proportion in HOVs of 20 percent. The SOV toll buy-in volumes are calculated by subtracting the total lane capacity from the number of HOV toll buy-in volumes at every time slice within the peak period. While these volumes represent a hypothetical maximum condition, it gives a clear indication of the amount of capacity that can be made available to SOVs under a congestion pricing system.

5.3 SCHEDULING CHOICE

5.3.1 On-Time Arrivals Required

When late arrivals at work are not permitted, commuters must arrive at a fixed

**Figure 5.5 HOV and SOV Buy-In Volumes on a HOTL
with an Initial Maximum Delay of 45 minutes**



start time, B, which in this case is set at 9:00am. The condition for user equilibrium is that user costs for all travelers are equal:

$$UC(t) = a_0 + a_1r(t) + a_2s(t) = c_1 \quad \text{for all } t \quad (5.7)$$

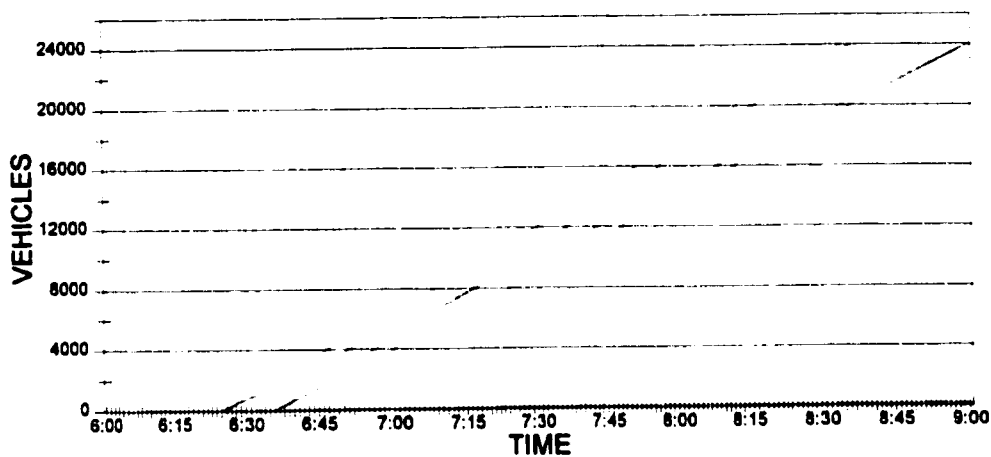
where c_1 is a constant. Because no equilibrium condition arises if time is spent at the workplace early is more onerous than time spent waiting in a queue, coefficient a_1 (user cost of waiting time, cents/min) is greater than a_2 (user cost of schedule delay, cents/min) (Hendrickson and Kocur 1981).

Converting an HOVL to GPL

Figure 5.6 shows what occurs when an HOVL is converted to GPL. In this example, I assume an initial proportion in HOVs of 5 percent, an initial maximum delay of 30 minutes and an initial peak period of 3 hours. When an HOVL is added, the reduction in delay caused by the diversion of HOVs to the HOVL allows non-HOVL travelers to adjust the scheduling of their trip without incurring increased user costs. After an HOVL is added, there is no incentive to arrive at the bottleneck any sooner than 6:25am. The queue length increases linearly to a maximum of 4,026 vehicles at 8:34am and decreases to zero at 9:00am, the fixed work start time.

When an HOVL is converted to GPL, the extent to which departure times are pushed back is a function of how well the HOVL was utilized before it was converted to GPL. In Figure 5.6, I assume an initial proportion in HOVs of 15 percent, which translates into an average peak HOVL volume-to-capacity ratio of .36. Under this condition, converting an HOVL to general purpose use greatly reduces delay on the

Figure 5.6 Queuing Before and After an HOVL is Converted to General Purpose Use with Endogenous Trip-Scheduling and On Time Arrival at Work Required



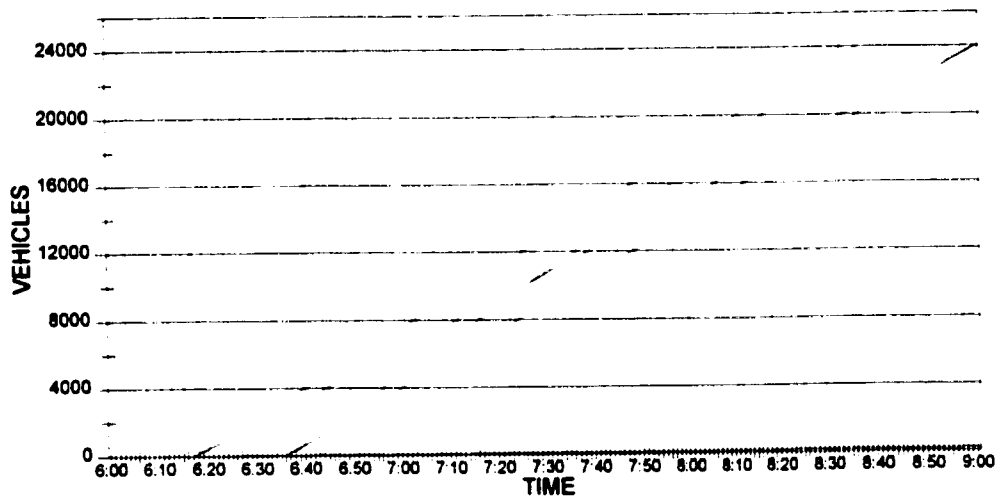
remaining GPLs, causing the first commuter to shift her departure start time from 6:25am to 6:36am. The queue length increases linearly to a maximum of 4,000 vehicles at 8:36am and decreases to zero at 9:00am, the fixed work start time. The maximum queue falls from 25.7 minutes in the HOVL case to 24 minutes in the GPL case. Average person-delay falls from 17.1 minutes to 16 minutes.

In cases in which an HOVL is well utilized and the initial proportion of HOVs is roughly equal to the proportion of lane capacity reserved for the HOVL, the conversion of an HOVL to GPL will not result in any shifts in the timing of departures and reductions in person-delay.

When an HOVL is Converted to Toll Lane

In Figure 5.7, the conversion of an HOVL to toll lane reduces delays slightly, causing a modification in the equilibrium arrival pattern. Figure 5.7 illustrates how converting an HOVL to toll lane affects the scheduling of morning home-to-work trips, and changes overall person-delays. The shift in departure times observed in this case is not unlike the case depicted in Figure 5.6. The magnitude of the shift in departure times is similar to the "Convert HOVL to GPL" case because the toll lane provides a comparable reduction in person-delay to a GPL, since both conversion strategies entirely eliminate delays without endogenous trip-scheduling. SOV travelers who departed at the highway bottleneck at 6:17am in the HOVL case can improve their welfare by arriving at the highway bottleneck 19 minutes later at 6:36am after the HOVL is converted to a toll lane. The rescheduling of departure times for non-toll lane travelers is made possible by the reduction in queuing delays brought about by diversion of peak vehicles onto the an

Figure 5.7 Queueing Before and After an HOVL is Converted to Toll Lane with Endogenous Trip-Scheduling and On Time Arrivals at Work Required



HOVL that had been underutilized prior to its conversion to toll lane. In other words, converting an HOVL to toll lane produces a similar result as adding lane capacity.

5.3.2 Late Arrivals Permitted

The condition for user equilibrium is that user costs for all travelers are equal:

$$UC(t) = a_0 + a_1r(t) + a_2s(t) + a_3p(t) = c_1 \quad \text{for all } t \quad (5.8)$$

where c_1 is a constant. Since late arrivals are permitted, $a_3 > 0$ and $a_1 > a_2 > 0$.

(Hendrickson and Kocur 1981).

In this analysis, I present a situation in which 16,000 people must arrive at work by 8:00am over a four lane highway with a capacity of 2,000 vehicles per lane per hour. Time spent in the queue and late arrival time are assumed to be valued by travelers at an average of \$12 per hour and schedule delay is valued at \$6 per hour. In the baseline case, the first worker arrives at 6:40am, experiences no queue, and has an 80 minute schedule delay. The last worker arrives at 8:40am, 40 minutes late. The maximum queue length of 5,333 vehicles occurs at 7:20 with a maximum wait of 40 minutes.

When an HOVL is Converted to General Purpose Use

The addition of an HOVL to a four lane highway under the assumptions stated above will produce delay reduction benefits that vary according to the initial proportion in HOVs and the motivation to shift to HOV as a result of the travel time differential between the GPLs and the HOVL. I assume here an initial proportion in HOVs of 10 percent, and a travel time coefficient of -0.02.

When an HOVL is added to a four lane highway under conditions described

above, the diversion of HOVs onto the HOVL does not substantially reduce average person-delays with endogenous trip-scheduling and late arrivals permitted. Average person delays fall from 26.7 minutes in the baseline pre-HOVL case to 25.3 minutes in the “Add HOVL” case. The reduction in delays resulting from the diversion of HOVs onto the HOVL causes the first worker to arrive at the highway at 6:44am, 4 minutes after the first worker arrived in the baseline case. The last worker arrives at 8:38am, two minutes earlier than the arrival of the last worker in the baseline case.

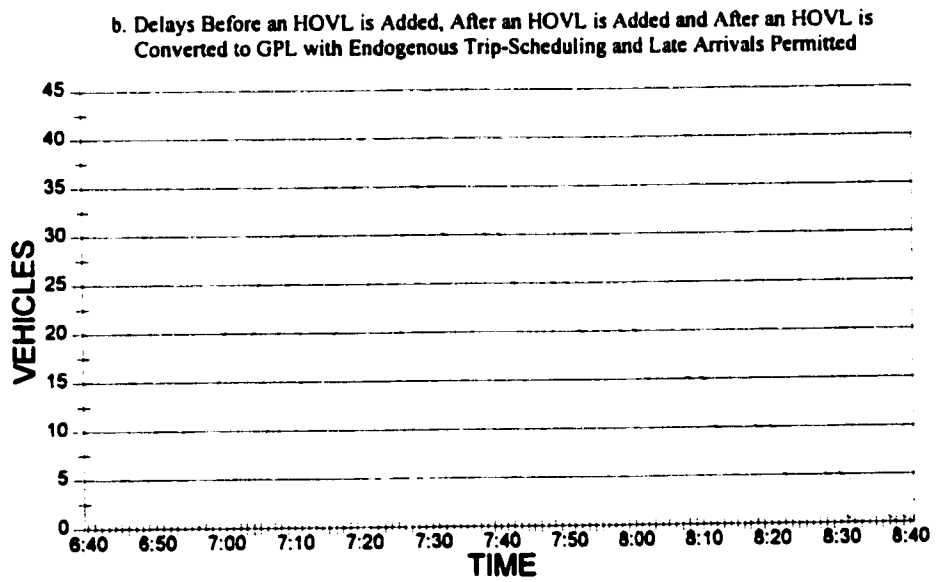
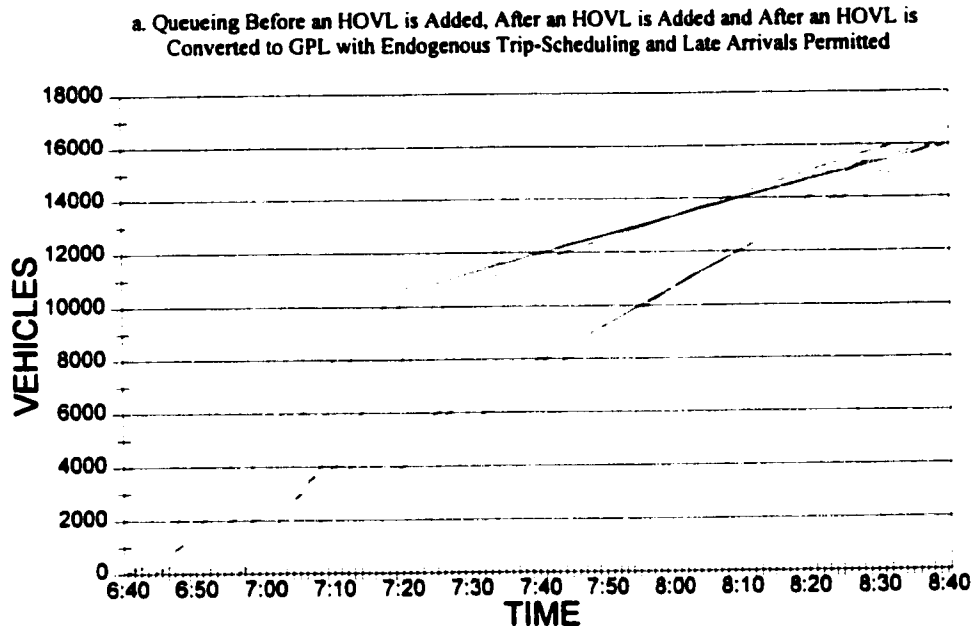
When an HOVL is converted to GPL, there is a substantial reduction in overall person-delay because the proportion of vehicles using the HOVL rises from 4.5 percent in the “Add HOVL” case to exactly 20 percent in the “Convert HOVL to GPL” case.

Figure 5.8 illustrates the timing and change in waiting time before an HOVL is added, after an HOVL is added, and after an HOVL is converted to GPL. After an HOVL is converted to GPL, the length of the peak period shortens by 18 minutes because there is no incentive for any individual to arrive at the bottleneck earlier than 6:56am, 12 minutes after the first worker arrived before the HOVL was converted to general purpose use. The maximum delay falls from 38 minutes at 7:22am to 32 minutes at 7:28am. Average person-delay falls from 25.3 minutes to 21.3 minutes.

When an HOVL is Converted to Toll Lane

When the delay reductions associated with converting an HOVL to toll lane are similar to those of converting an HOVL to a GPL, the shift, distribution and timing of arrivals will be comparable to the case described in Figure 5.8a. There are however cases in which converting an HOVL to toll lane may provide greater person-delay

Figure 5.8



reduction benefits than the “Convert HOVL to GPL” case. Dynamic pricing on the toll lane allows the facility operator to achieve an arrival pattern resulting in minimum user cost, corresponding to a system optimum equilibrium. Depending on the initial proportion in HOVs and total highway corridor volumes, a toll lane may in some cases provide a higher degree of external benefits than a GPL.

5.4 ESTIMATING THE ELASTICITY OF HOTL DEMAND

Throughout this analysis, I make the assumption that HOTL tolls can be set to preserve enough capacity for HOVs and optimize express lane utilization. For example, if there is a secular increase in HOV volumes, tolls can be raised to dampen LOV toll buy-in volumes in order to maintain free-flow conditions. However how much tolls need to be raised in order to lower toll lane volumes is not well known. Likewise, how much tolls should be discounted at the shoulder of the peak to optimize toll lane usage is not well known either, since there are only a few HOTL projects currently in operation for which volume and toll structure data are being collected (Sullivan et al. 1998; SANDAG 1998). Knowing the price elasticity of demand enables one to estimate how demand changes as a function of changes in price.

Price elasticity of demand is formally defined here as the percentage change in the quantity demanded of a good that results from a one percent change in its price (Frank 1991). If we let P be the current price of a good, and Q be the quantity demanded at that price, ΔQ is the change in the quantity demanded occurring in response to a change in price, ΔP . Mathematically, the price elasticity of demand at a given quantity and price can be expressed

$$\eta = \frac{\Delta Q/Q}{\Delta P/P} \quad (5.2)$$

Empirical attempts to measure price elasticity of demand are extremely difficult because demand is a function of a multitude of factors in addition to price: the availability and price of complementary and substitute goods, income, and changes in tastes (Dahlgren 1999). Since toll lane demand is made up of travelers purchasing peak time savings, the demand for toll lane service can be thought of as the market for peak travel time savings along a highway corridor where delay-free toll service exists.

Estimating price elasticity is critical because the extent to which an increase in the price of peak time savings induces a small or large change in peak toll lane volumes yields important information about the feasibility of converting candidate underutilized HOVLS to toll lane or adding toll lanes to highway with recurring bottleneck problems. When queuing behind a highway bottleneck begins, the growing travel time differential between the GPLs and the toll lane (over a fixed distance) induces an increasingly large proportion of travelers to purchase travel time savings – until the queue dissipates, resulting in a decline in the demand for peak travel time savings. In order to allocate congestion-free toll lane service efficiently, the operator must therefore charge a variable toll.

5.4.1 Description of Data

To estimate toll elasticities in a regression analysis of toll lane travel demand, I obtained SR-91 traffic volume, SR-91 and 91 Express Lane travel time and toll data from the Applied Research and Development Facilities and Activities (ARDF) at California

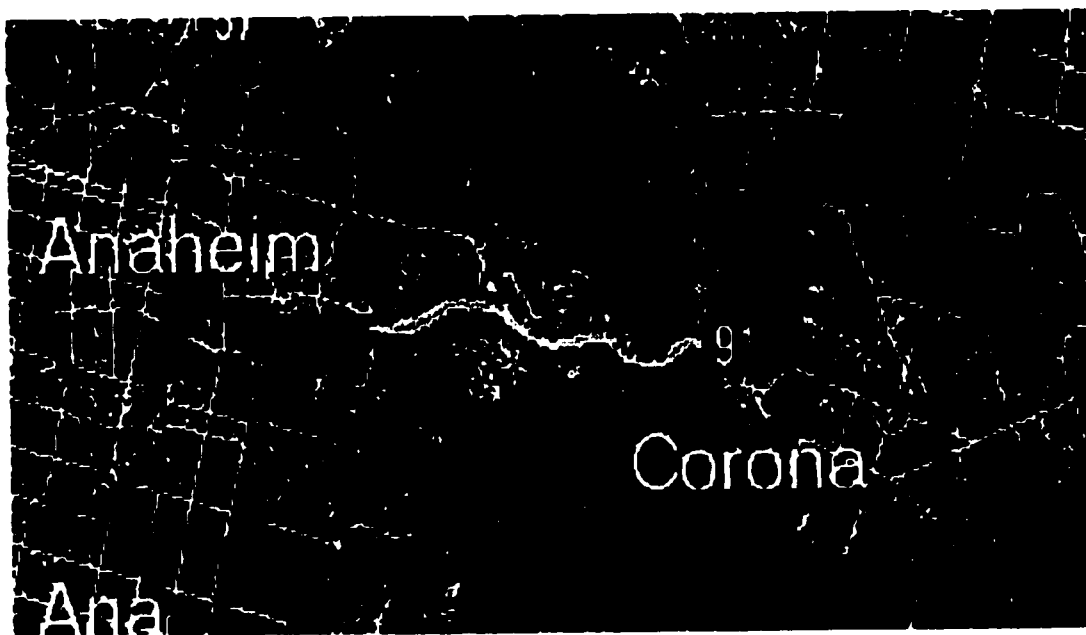
Polytechnic Institute at San Luis Obispo. Travel time and volume data cover one week in February, 1996, June 1996, February 1997, and June 1997. Although five minute interval data were available for SR-91 highway lanes and 15 minute interval data were available for toll lane volumes, only hourly data were available for travel times. Consequently, SR-91 mainline highway volume and toll lane volume data had to be aggregated to 60 minute intervals, which to some extent compromised the model's ability to capture the toll elasticity variation within the peak periods.

Mainline highway volume data tend to understate travel demand because it does not capture reduced flow resulting directly from high traffic densities (vehicles/lane-mile), which is represented theoretically as the backward-bending portion of the speed-flow curves presented in Chapter 4. Consequently, this analysis will utilize average flows for a particular week, time and year. Also, travel times on the mainline highway lanes were estimated from average hourly speed runs conducted on successive Tuesdays, Wednesdays, and Thursdays during the observation months mentioned above corresponding to the weeks in which toll volume and main line volume data were collected. Travel time runs were conducted at the start of each hour between 2:00pm and 11:00pm in the eastbound direction between Magnolia Boulevard and Coal Canyon.² Travel time run data were available for only the eastbound direction, so the analysis is limited to the PM peak period.

²

Speed data were collected at the following highway on-ramps between the intersection of SR-91 and SR-55 and the Orange/Riverside County border (from west to east): Magnolia, Gibert Brookhurst, Euclid, Harbor, Lemon, La Palma, Glassell, Imperial, Weir, Gypsum Canyon, and Coal Canyon.

Figure 5.9 Map of the SR-91 AFDFA Study Area



For February 1996 and 1997, 5-minute interval speed data were obtained from loop detectors at Weir Road, Gypsum Canyon Road, and Coal Canyon Road. Speed data at each loop detector were averaged at each 5-minute interval, and then averaged to the hour. This average speed estimate was then converted to travel times assuming a distance of 9.8 miles. For each hour, the travel time estimate was subtracted from the optimal travel time through the corridor (assuming an optimal highway speed of 50 mph).

5.4.2 Analytical Approach

A simple linear regression model is used to estimate the elasticity of demand for peak travel time savings. I estimated a toll coefficient by regressing the natural logarithm of 91 Express Lane volume on the logarithms of toll cost per minute of travel time saved (the toll divided by the delay) and total corridor travel demand. The analysis covers the month June in 1995, 1996, and 1997.

The basic premise of this analysis is that toll lane volumes depend on travel time differentials, total corridor volumes and toll price. The elasticity of Express Lanes demand is estimated by regressing Express Lanes hourly volume on toll per minute of travel time saved, and total travel demand. Several regression specifications were tested and the best fitting model specification was a linear regression of the natural logarithm of Express Lanes volume on the natural logarithms of toll per minute saved and average main line volume, which resulted in a constant price elasticity.

$$\ln(vol_{91,X}) = f[\ln(\$ / \text{min saved}), \ln(vol_{SR91})] \quad (5.9)$$

To the extent that there is some correlation between tolls and total highway volume and

travel time savings, the statistical reliability of the coefficients in this regression analysis must be interpreted with caution. While theory suggests that there should be a negative correlation between toll cost per minute saved and volume, the effects of volume may be obscured by toll cost effects.

5.4.3 Findings and Results

Table 5.3 yields the results of the regression model described above. The ANOVA test shows a high F value (313.2) with 43 degrees of freedom and a low probability (.000), indicating that we can reject the null hypothesis that the independent variables, \ln (toll per minute saved) and \ln (average main line volume), have no impact on the dependent variable, \ln (Express Lane volume). The log-log model specification therefore appears to be a good fit. The low P-values (significance) indicate that we can reject the null hypothesis that the explanatory variables are not statistically significant, since the t-values are higher than the critical t-values for 43 degrees of freedom at the 5 percent level of significance. The coefficient for \ln (toll per minute saved) is -.292, and the values of -.374 and -.210 in the Lower 95 percent and Upper 95 percent respectively indicate that there is a 90 percent probability that the actual value falls somewhere in between this range. In other words, a 10 percent increase in tolls would result in a 2.1 percent to 3.74 percent decrease in Express Lanes volumes, which suggests that toll lane demand is relatively insensitive to toll price. For example, a 100 percent increase in toll price from \$1.50 to \$3.00 would result in a 21 percent to 34 percent decrease in Express Lanes usage.

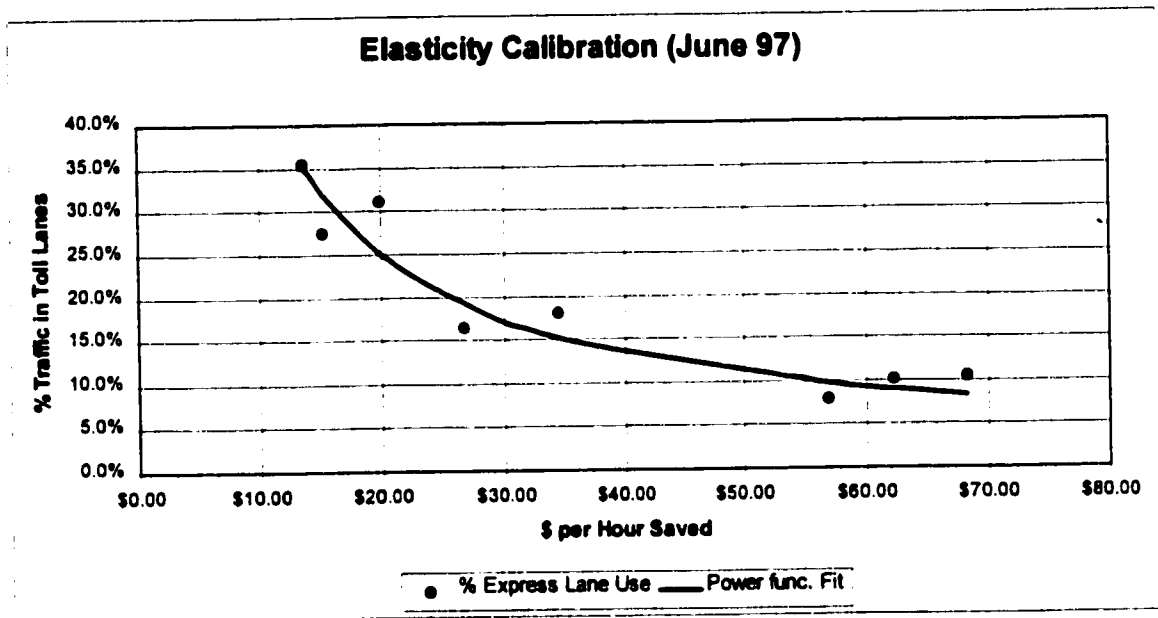
Table 5.3 Linear Regression of the Natural Logarithm of Express Lane Volumes on the Natural Logarithms of Toll Per Minute Saved and Average Main line Volumes – Eastbound SR-91

REGRESSION OUTPUT						
<i>Model Summary</i>						
Observations			44			
R			0.969			
R Square			0.939			
Adjusted R Square			0.936			
Std. Error			0.3675			
ANOVA						
	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance F	
Regression	84.614	2	42.307	313.217	0.000	
Residual	5.538	41	0.135			
Total	90.152	43				
	Coefficient B	Standard Error	t	Significance	Lower 95%	Upper 95%
Constant	-13.593	1.390	-9.780	0.000	-16.400	-10.786
ln (toll/minute saved)	-0.292	0.041	-7.203	0.000	-0.374	2.210
ln (average mainline volume)	2.324	0.161	14.454	0.000	1.999	2.648

Figure 5.10 shows data on the relationship between the percentage of toll lane traffic and toll per time savings, which is fitted to a negative exponential function with the specification, $Y = 370X^{-0.9}$. Based on data collected in June 1997, the percentage of toll lane traffic gradually falls as the toll per time savings increases, which is consistent with theory.

How applicable estimates of price elasticity of toll lane demand using data collected on the 91 Express Lanes are to other locations is uncertain, given that origins and destinations, income, traffic patterns, and travel choices differ from region to region and may influence how sensitive travelers are to changes in tolls.

Figure 5.10



5.5 EMPIRICAL FINDINGS ON TRAVEL IMPACTS OF NEW TOLL LANES: 91 Express Lanes

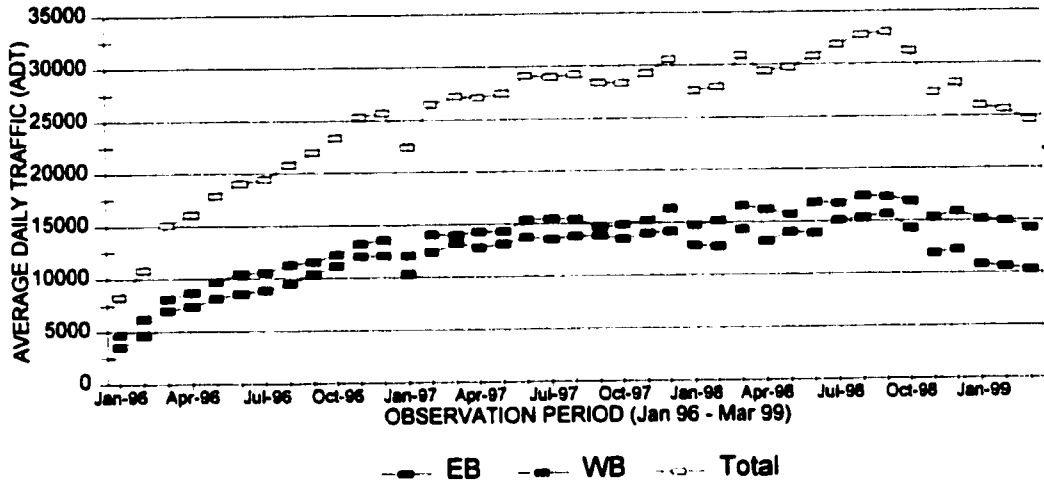
In December 1995, California Private Transportation Corporation (CTPC) opened the nation's first fully automated electronic toll lanes in Orange County, California, a 4-lane, 10-mile Express Lane located in between the westbound and eastbound Riverside freeway main lines. Sullivan et al. (1998) report on the conditions before and after the opening of the 91 Express Lanes. The traffic impact findings presented here are not necessarily intended to verify or refute the hypotheses tested in the simulated corridor analysis discussed in the first several sections of this chapter. Rather, the findings on the travel impacts of the 91 Express Lanes are intended to provide the reader with the first comprehensive empirical analysis of the behavioral effects of building a new toll lane along a congested highway, a congestion mitigation investment consideration that has only been the subject of serious policy consideration.

5.5.1 91 Express Lane Volume Trends

Since December 1995, the 91 Express Lanes have attracted a substantial share of total SR-91 highway traffic, which steadily grew over the first two years in operation. Figure 5.11 shows the weekday average daily traffic (ADT) trend on the 91 Express Lanes for a 38 month period following its opening. The 12 percent dip in ADT in January 1997 can best be attributed to two factors: (a) a toll increase effective January 1, 1997, and (b) the winter holiday season.

Given the reappearance of a slight dip in ADT the following January, at least part of the variation in vehicle travel appears due to seasonal travel fluctuations. Despite the

Figure 5.11 Trend in Daily Weekday Traffic on the Express Lanes

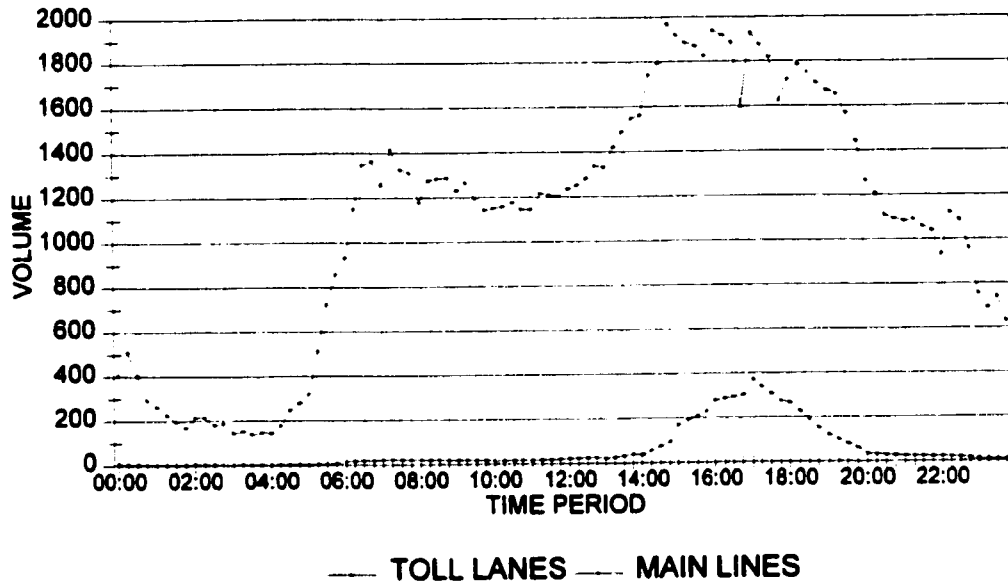


toll increase, the overall ADT growth trend resumed in February 1997. Increasing kurtosis of the afternoon peak caused CPTC to change its toll schedule in September 1997, which increased the maximum toll for the peak one-hour period. From April to September 1998, ADT increased 5,420 vehicles to an all-time high of 32,997. In the following six month period, ADT fell from an average of 8,391 to 24,606 vehicles. The gradual decrease in Express Lanes ADT coincided with the opening of the Eastern Transportation Corridor (ETC), a competing perpendicular facility which eventually captured a sizeable share of the travel market from Riverside/San Bernardino counties to central and south Orange County.

AM and PM trends mirrored each other closely, with ADT consistently heavier in the eastbound direction. Figure 5.12 shows the 24-hour trend of average westbound and eastbound volumes for the Tuesday, Wednesday, and Thursday of the week of February 6, 1996. The sharp AM peak westbound and PM peak eastbound reflected the extreme peak-directional nature of travel along the SR-91 travel corridor. AM Express Lane volumes increased steeply beginning at 3:45am, when vanpools originating from San Bernardino and eastern Riverside counties represent a significant proportion of early morning traffic, to a maximum of 306 vehicles per 15-minute interval at 7:00am when the toll was \$2.95.

From 7:00am to 10:00am 15-minute volumes fell steeply from 306 vehicles to 30 vehicles. Westbound volumes rose slightly in the PM peak, but never exceeds 45 vehicles per 15-minute interval. In the eastbound direction, volumes rose sharply once the PM peak period begins at approximately 2:30pm to a maximum 15-minute volume of

Figure 5.12 24-hour Trend of SR-91 and Express Lane Eastbound Volumes for the Week of February 6, 1996



373 at 5:00pm when the toll increased from \$2.85 to \$2.95. After 5:00pm, 15-minute volumes decrease sharply to 34 vehicles 8:00pm, the end of the evening peak when tolls fall from \$1.60 to \$1.10.

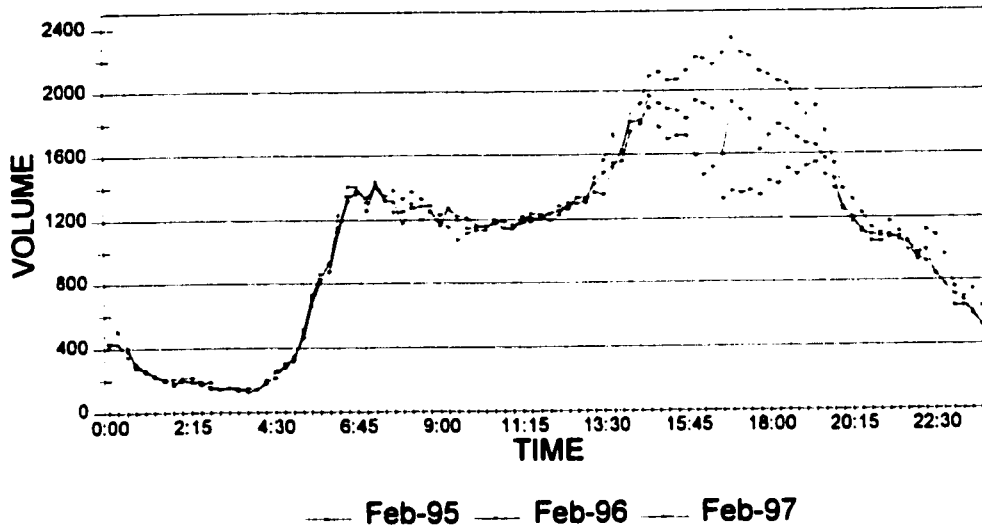
Assuming a maximum 15-minute capacity of 800 vehicles (1,600 vehicles per lane per hour; 2 lanes per direction), at its heaviest peak 15-minute interval westbound traffic took up 38 percent of total capacity, while eastbound traffic in the heaviest peak 15-minute interval takes up a 46 percent of total capacity. The fact that the peak 15-minute Express Lanes volumes were below 50 percent of total capacity suggests that either (a) peak tolls are well above optimal levels, or (b) CPTC deliberately erred on the side of caution, and setting aside capacity for future growth.

5.5.2 SR-91 Main line Volumes Before and After 91X

The addition of the 91 Express Lanes had a beneficial impact on SR-91 main line highway traffic conditions, providing short-run benefits comparable to those described in Section 5.2.1. Figure 5.13 shows a 24-hour profile of average eastbound volumes in February 1995, February 1996, and February 1997. The 24-hour volume profile for February 1995, 10 months prior to the opening of the Express Lanes, shows what appears to be hypercongestion in the afternoon peak between 3:00pm and 7:15pm, a phenomenon in which traffic flow declines sharply as a result of the extreme metering effect caused by downstream congestion.

Two months after the opening of the Express Lanes in February 1996, the hypercongested travel conditions observed in February 1995 disappeared. While much of

Figure 5.13 24-hour Profile of Average SR-91 Main Line Volumes, Eastbound, February 1995, February 1996, and February 1997



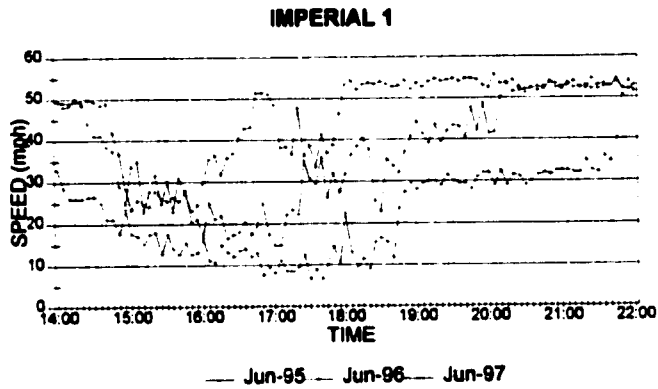
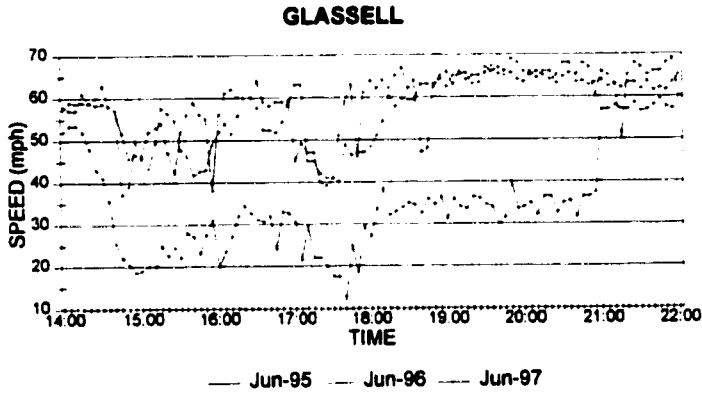
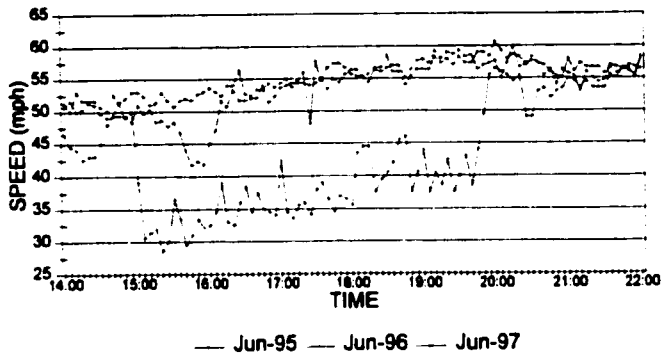
the reduction in PM traffic congestion can be attributed to the expansion of highway capacity, Sullivan et al. (1998) argue that by February 1996, travelers had not yet fully adjusted their trip-making patterns to the new, improved travel conditions along the SR-91 highway corridor. By February 1997, the full effect of the Express Lanes addition on travel conditions came to focus, as travelers adapted to the new corridor travel conditions. The February 1997 volume profile shows the reemergence of a sharp peak period. It is worth noting that after long-term adjustments to improved travel conditions on the SR-91 corridor, hypercongested conditions have not reappeared to the degree observed prior to the Express Lanes opening.

5.5.3 Main Line Speeds and Travel Times Before and After 91 Express Lanes

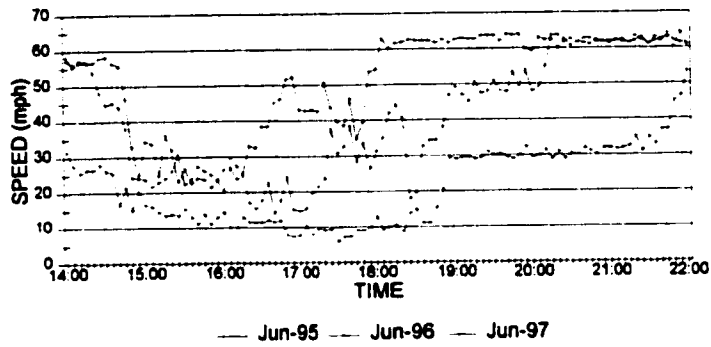
Travel Speeds

Figures 5.14 show average 5-minute interval travel speeds on SR-91 main line highway lanes taken in June 1995, June 1996, and June 1997 at six interchange locations, two (Lemon St. & Glassell Ave.) west of the Express Lanes and four (Imperial 1,2 & Weir 1,2) along the Express Lanes segment. At the Lemon interchange in June 1995 (five months before the Express Lane opening) extreme congestion in eastbound main lines was evidenced by a sudden reduction in average speeds at 3:00pm from roughly 50 mph to 20 mph. Throughout the peak-of-the-peak (4:30pm to 6:30pm) the average main line speeds ranged between 32mph to 41mph, and returned to free-flow at 7:45pm. The Glassell Avenue cordon shows a similar general pattern, except that there was a noticeable dip in average speeds between 5:00pm and 5:40pm with a low of 12mph at 5:40pm. The Imperial and Weir interchanges also showed the same general patterns as

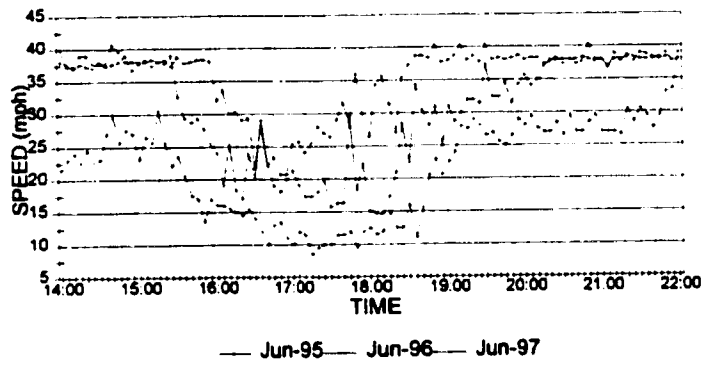
**Figure 5.14 Average 5-minute Travel Speeds on SR-91 Main Lines,
June 1995, June 1996, and June 1997**



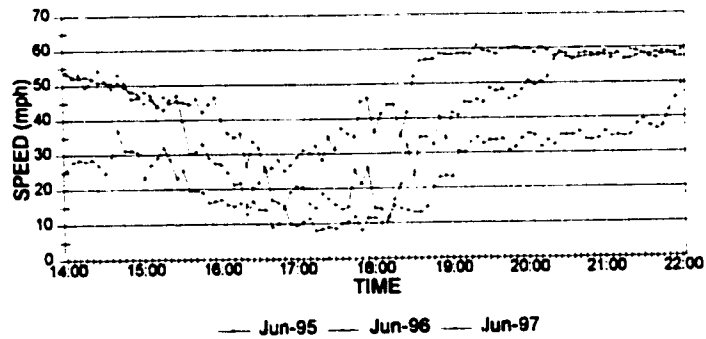
IMPERIAL 2



WEIR 1



WEIR 2



Lemon St. and Glassell Ave.

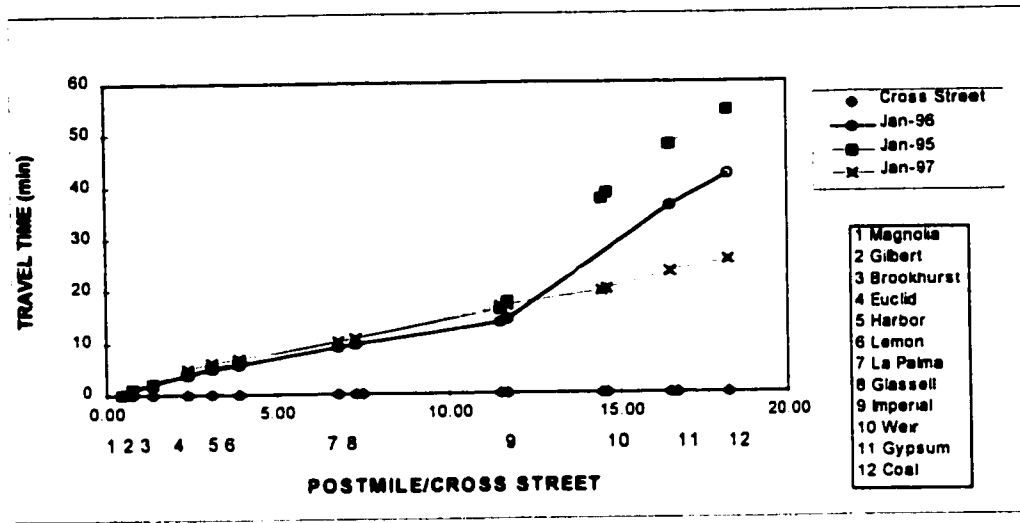
In June 1996, there was a noticeable range of average travel speed improvements at each of the intersection locations, with free-flow throughout the peak at the Lemon St. interchange. While travel delay reductions can definitely be attributed to the diversion of traffic onto the Express Lanes, secular growth trends and induced demand effects have appeared to wash out some but not all of the delay reduction improvements caused by the Express Lane addition. In June 1997, Imperial Hwy and Weir Canyon Rd. cordons show a slight worsening of travel speeds since June 1996, a phenomenon attributable to new trips and induced trips from other times and routes. Sullivan et al. (1998) report an increase of roughly 28,000 vehicles per day in the first year following the Express Lanes opening, a 14 percent increase in ADT. Of the total ADT increase, they estimate that 21 percent are trips from other routes, 20 percent are attributable to secular growth trends, and 59 percent represent new trips induced by improved travel conditions (Sullivan et al. 1998).

Travel Times

The data show that adding the Express Lanes resulted in dramatic improvement in travel times on SR-91 main line highway lanes. Thousands of vehicles per day diverted onto the Express Lanes immediately after its opening, and diverted the greatest number of vehicles during times of day when congestion was at its most extreme, and produced an immediate short-term improvement in travel times through the corridor.

Figure 5.15 presents a time-space diagram of eastbound travel at 5:00pm from Magnolia to Coal Canyon. From January 1995 to January 1996, PM eastbound travel

Figure 5.15 Travel Plot of SR-91EB, 5:00pm



time through the corridor fell 12.5 minutes from 54.5 to 42 minutes, and fell again from January 1996 to January 1997 16.3 minutes from 42 to 25.7 minutes. The dramatic improvements in travel time were preserved even though “the amount of daily traffic diverted from the free lanes to the express lane during the first year closely matched the increase in total SR 91 ADT during the same period.” (Sullivan et al. 1998, p. 30)

5.5.4 Ridesharing Trends

After the opening of the Express Lanes, peak period HOV3+ vehicles and vanpools increased 40 percent, most of which can be reasonably attributed to the ridesharing incentive manifested in the HOV3+ toll exemption. Average 1994-1995 PM peak counts of HOV3+ vehicles increased from 496 vehicles to 725 vehicles in 1995-1996. Figure 5.16a shows the trend in average “Full Toll” and “HOV3+” volumes for eastbound and westbound Express Lanes from January 1996 to March 1999. The graph

reveals that HOV3+ volumes between January 1996 and December 1997 – during which HOV3+ vehicles were toll exempt – there was a slight growth trend in HOV3+ vehicles. After CPTC required HOV3+ to pay a half-toll effective January 1998, the number of HOV3+ vehicles dropped. In the six months prior to change, HOV3+ counts averaged 16,974 vehicles. In the six months after the HOV3+ half-toll was implemented, HOV3+ counts averaged 12,732 vehicles. The change is statistically significant at the 99 percent confidence interval (Sullivan et al. 1998).

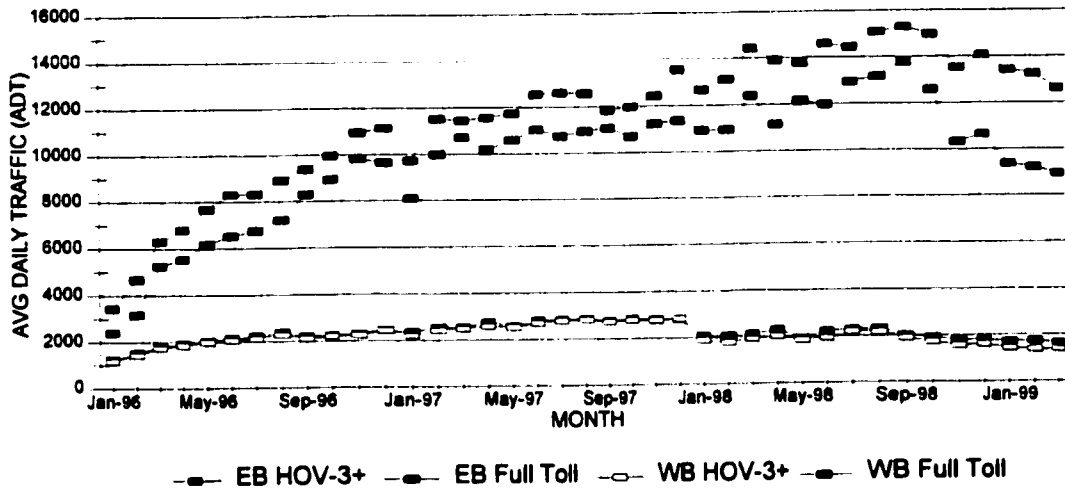
Figure 5.16b shows the eastbound and westbound trend in the proportion of HOV3+ to total Express Lanes volumes between January 1996 and March 1999. In both directions, the proportion of HOV3+ vehicles to total Express Lanes traffic appears to be declining over time largely because the growth in SOV Express Lanes vehicles has outpaced the growth in HOV3+ vehicles, which remained relatively stable both before and after the January 1999 HOV3+ half-toll was charged. In the six months after the Express Lanes opened, there was an overall drop in weekday peak AVO along the SR-91 highway corridor because the large increase in SOV travel overwhelmed the modest increase in both HOV2+ and HOV3+ travel.

5.6 SUMMARY

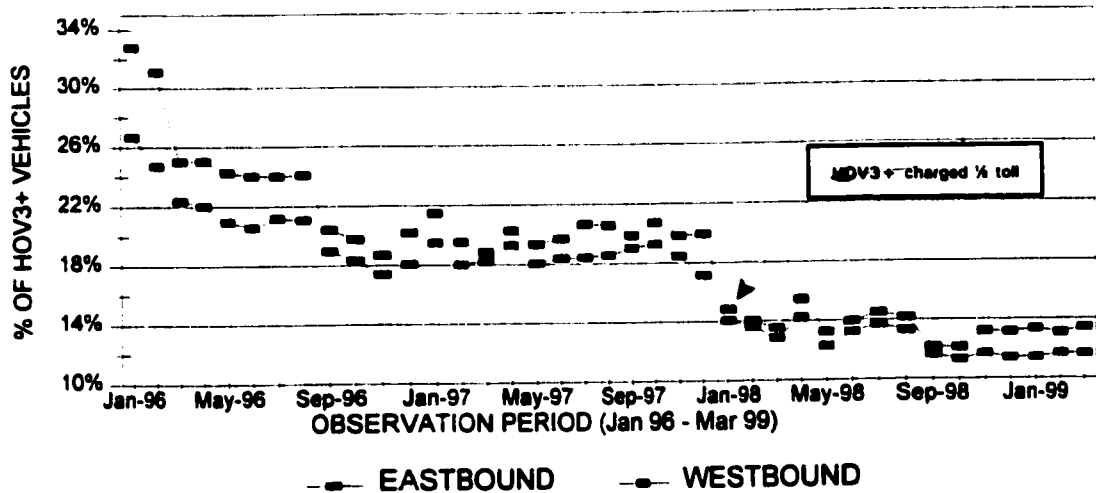
Based on the simulated logit analysis presented here in Chapter 5, the results of repeated simulations – using a range of initial mode share, maximum delay, and travel time coefficient conditions designed to reflect plausible congested highway conditions – suggest that conversion of HOVLs to toll lanes will in almost every case provide a greater average person-delay reduction benefits than the baseline “no action” HOVL case. While

Figure 5.16

a. Eastbound and Westbound Trend of Average HOV3+ Volumes on Express Lanes, January 1996 to March 1999



b. Eastbound and Westbound Trend of the Proportion of HOV3+ Vehicles on Express Lanes, January 1996 to



the analysis in Section 5.2 indicates that in cases where the conversion of an HOVL to toll lane results in lower HOV travel time coefficient GPLs provide slightly higher average person-delays reduction benefits than toll lanes, the relative difference in average person-delays between toll lanes and GPLs are minimal. Assuming no substantive difference in person-delay reductions, the option to convert to GPL instead of toll lane results in an opportunity cost equal to the toll revenue foregone in the “Convert to GPL” case. A full accounting of the present value of toll revenues over a 20 year project life is presented in Section 6.3.2.

The travel impacts of the 91 Express Lanes appear to reinforce some of the theoretical findings presented earlier in this chapter. The data must be interpreted with caution, however, insofar as the validation of theoretical findings based on simulated corridor analyses are best left to a disaggregate behavioral model using data from a sample of urban travelers. While there is no way to directly compare the delay reduction effects of the 91 Express Lanes to a hypothetical HOVL, the empirical data presented in Section 5.5 indicates that the 91 Express Lanes have caused a substantial improvements in SR-91 highway main line traffic, as evidenced by both improved peak hour volumes (and the disappearance of hypercongested conditions) and sustained improvements in peak travel speeds. Moreover, the improvements in SR-91 main line highway traffic conditions has been stable over the first three years of the 91 Express Lanes opening, lending support for the argument that toll lanes offer qualitatively unique congestion-relieving attributes unattainable via GPLs and HOVLs. More research however needs to be conducted in this area.

In the following chapter, I build on the behavioral model presented in this chapter by incorporating it into a cost-benefit framework that allows the decisionmaker to rank the social opportunity cost associated with competing investments over the span of a 20 year service life. Special attention to paid to the methodological advantages and disadvantages of alternative cost accounting procedures. While I acknowledge the potential danger of predicting induced demand effects over the long-term, the cost-benefit model presented in the Chapter 6 attempts to incorporate realistic traffic growth trends. In the second part of Chapter 6, I present an emissions factor model that allows for a evaluation of the emissions impacts under competing alternatives.

6. THE SOCIAL AND ENVIRONMENTAL COSTS OF HOVLS, TOLL LANES, AND GPLs

6.1 TECHNIQUES FOR EVALUATING SOCIAL COSTS

In this chapter, I develop a benefits assessment framework and apply these accounting techniques to measure the present value of future social and environmental impacts arising from the major investment alternatives analyzed in Chapter 5. First, I will review techniques for evaluating benefits and costs occurring at different times and utilize a theoretical approach to gain insight on the magnitude, timing, and present value of future costs and benefits for competing investment choices. Then in section 6.2, I apply benefit assessment techniques to estimate the present value of future benefits resulting from the conversion of an HOVL to toll lane and GPL, and compare these benefits to the “no action” HOVL case. The chapter concludes with a discussion of comparative costs, cost recovery, financial performance and environmental impacts.

6.1.1 Internal Rate of Return (IRR)

Because benefits and costs occur at different times, with up-front costs often exceeding benefits, evaluative techniques that discount future costs and benefit to a common basis of comparison must be applied. Discounting procedures allow economic assessments of the value of future benefits received at a given interest rate. At interest rate, ρ , the value today of a dollar received in year $t = 1 \div (1 + \rho)^t$. IRR allows the transportation analyst to evaluate whether capital investments are a worthwhile. IRR for a given project (ρ) is obtained by the solution to the following equation:

$$\sum_{t=0}^N \frac{B_t - C_t}{(1 + \rho)^t} = 0 \quad (6.1)$$

where B_t represents the benefits anticipated to accrue in year t of a project's life and C_t represents the costs anticipated to be incurred in year t . N is the length of the life of the project. Costs are defined formally here to include capital outlays, labor, materials, energy and transportation costs, and maintenance and repair expenditures. In evaluating transportation investments, Lewis (1991) argues that rate of return computations ought to include impacts beyond those of direct consequence to the executive's immediate area of fiscal responsibility¹:

. . . in addition to changes in the structural sufficiency of pavement expected to result from a proposed road improvement program, the highway executive needs to examine the proposal's monetary implications for vehicle operating costs and time savings, both in relation to the capital expense and future maintenance costs associated with the proposal. (Lewis 1991, pg. v)

In practice, the IRR method should be applied to establish both whether an investment proposal promotes economic growth and when the economically appropriate time to invest occurs (Harberger 1977). There are a few important caviats, however, to this general proposition.

For example, a project with capital cost of 100 in year 0 that yields a benefit of

¹

Lewis also argues that the impact of transportation investments on parties other than users should be taken into account, especially negative externalities like environmental and noise spillover: "Accounting for these negative 'spillovers' in social rate of return calculation ensures that transportation-related productivity and growth strategies are not at odds with the higher aim of improved living standards." (Lewis 1991, pg. vi)

120 in year 1 with an operating cost of 20 will have an IRR equal to zero, indicating that no more than capital recovery can be expected from this project. If the project were to have a benefit of 130 in year 1, with an operating cost of 20 in that year, its IRR would be 10 percent, indicating that the capital invested in the project will produce a yield of 10 percent after allowing for capital recovery (Harberger 1977).

The singular advantage of the IRR test is that it can be calculated based on project data alone. The calculation does not require information on the social opportunity cost of capital -- which is a critical component of any net present value appraisal. A project evaluator can simply develop independent internal rates of return for all the different investment projects to be appraised, and rank the IRR estimates as a basis for funding worthiness. Projects with higher IRR would be funded ahead of projects that exhibited lower IRR (OPR 1996).

In cases in which all projects are strictly independent, the IRR test will work well. In cases in which two projects are alternatives, the IRR test can potentially lead the decisionmaker to choose project A, even though project B might be preferable (Harberger 1977). Suppose for example that a state highway department was considering the alternative treatments of an underperforming HOVL. Based on individual project data alone, the agency determines that a GPL will have an IRR of 20 percent and a toll lane will have an IRR of 12 percent. Assuming a prevailing social opportunity cost of investible capital of 8 percent, it is possible to calculate the NPV of these alternative projects using an 8 percent discount rate (Harberger 1977).

Suppose the toll lane alternative produces a net benefit of \$2,400,000 per year in

perpetuity on a capital investment of \$20 million, while a GPL has a net benefit of \$640,000 per year in perpetuity on a capital investment of \$3,200,000. The NPV of the toll lane project's benefits, evaluated at an 8 percent discount rate, is \$30 million, while the project cost is \$20 million, yielding a net excess of benefits over costs of \$10 million. The present value of the GPL's benefits, evaluated at an 8 percent discount rate, is \$8,000,000, while the project cost is \$3,200,000, yielding a net excess of benefits over costs of \$4,800,000.

Despite the HOVLs' higher ratio of benefits to costs (5:2 vs. 3:2), the toll lane is preferable, since the best alternative use for the \$16,800,000 (\$20,000,000 - \$3,200,000) saved is a 'marginal' investment with an IRR of 8 percent on which the excess benefits over costs, evaluated at a discount rate of 8 percent, would be zero. In this example, even though the GPL has a higher IRR than a toll lane, a toll lane has a higher NPV, making the toll lane the preferred investment choice (Harberger 1977). In general, the IRR test is used to indicate the extent to which the expected return on investment exceeds or falls short of the minimum-required rate of return (the prevailing social opportunity cost of capital in the private sector) and thus provides insight into project risk (OPR 1996).

6.1.2 Net Present Value (NPV)

Discounting is a procedure under which the minimum-required rate of return (also referred to in the project evaluation literature as the *social opportunity cost of capital* in the private sector) is used to align all forecasts of costs and benefits to a common temporal basis of comparison. This is accomplished by computing the equivalent present-day values, a procedure designed to compensate for the fact that discrete

investment choices produce costs and benefits at different rates over their services lives. The general form of the net present value (NPV) criteria for a project of N years duration, is

$$NPV = \sum_{t=0}^T \frac{B_t - C_t}{(1+r)^t} \quad (6.2)$$

If the NPV of a prospective investment is greater than zero, it may be considered a worthwhile contribution to productivity and worthy of project funding. If NPV of a prospective investment is less than zero, it may be considered less worthy of project funding than alternatives with higher NPV and may be recommended for deferral.

Table 6.1 summarizes the three primary measures used in cost-benefits analyses of transportation investments. As measures of economic productivity, each measure has unique methodological parameters that limit applicability to appropriate analytical contexts. For example, contrary to the IRR criteria, NPV permits decisionmakers to rank alternative investments in order of relative merit. Investment alternatives with higher NPV promote more productivity and growth than those with lower results. Because the IRR test encounters some mathematical difficulties as an investment criterion in the ranking of project alternatives (see previous discussion), the cost-benefits analysis of converting an HOVL to GPL or toll lane should be presented in terms of their NPV. While the IRR analysis can be conducted based on project data alone, it cannot effectively reveal the social opportunity cost of choosing one investment over another. Because the decisionmaker must understand how changes in peak travel influence the productivity of TSM investments in comparison to the baseline “no action” HOVL case, an NPV

Table 6.1 Key Measures of Productivity and Economic Growth		
MEASURES OF WORTH	DEFINITION	INTERPRETATION
Net Present Value	Present-day value of benefits minus present-day value of costs	NPV greater than 0 means project is economically efficient. (Projects are ranked according to NPV.)
Internal Rate of Return	The discount rate at which Net Present Value (NPV) = 0	Rate of Return should exceed pre-set hurdle rate to qualify for consideration
Cost-Effectiveness	Cost per unit of Output (e.g. capital cost per peak HOV trip)	Because there is no absolute cost-effectiveness standard, cost-effectiveness measures can only provide relative comparisons within the same investment classification.
MEASURES OF TIMING		
First-Year Benefit	Benefits in Year 1 after construction divided by costs to date including interest paid during construction, expressed as a percent.	A ratio equal to the threshold rate means the project is optimally timed. A ratio below the threshold rate means the project is premature. A ratio above the threshold rate means the project is overdue.
Pay-Back Period	Number of years until capital is recouped through the flow of benefits	A short pay-back period means less risk.

Source: Lewis 1991

framework will be developed to evaluate the relative benefits of converting an HOVL to alternative uses.

6.1.3 Cost-Effectiveness

Although the cost-effectiveness criterion is often cited as the least dependable method of determining the economic viability of competing investment alternative, it can yield important information about the cost of producing a given output in cases where market prices are not used to allocate public services. In the case of HOVLs, for example, peak HOVL capacity is not allocated through a price mechanism (which normally yields information about the value of HOV travel time savings) but through eligibility restrictions. When not used as a criterion for investment selection, cost-effectiveness measures such as capital cost per peak HOV passenger can yield useful information about the relative performance within a given classification of highway investment, but such measures often cannot quantify performance during off-peak hours. The biggest deficiency with cost-effectiveness measures however is that it is ineffective as an evaluative technique when competing investments use pricing to allocate services to market and the baseline case does not. Consequently, there is a potential danger in misinterpreting the significance of measures such as capital cost per peak HOV passenger over all competing investment alternatives. Although the capital cost per peak HOV passenger may be lower in the baseline HOVL case than other alternatives, it does not effectively capture the full social opportunity cost of not choosing competing alternatives.

6.2 Growth Effects and Valuing User and Non-User Benefits

The worth of any transportation investment is assessed on the basis of future costs

and benefits, both of which arise from expectations regarding economic growth, population trends, increased development, and corresponding changes in travel patterns. As annual travel demand grows, the relative benefits of converting an HOVL to GPL, converting an HOVL to toll lane, or “no action” will vary slightly. A robust comparison of the stream of benefits and costs associated with the “no action” baseline case with other investment alternatives requires the analyst to make realistic assumptions about travel growth.

6.2.1 Assumptions About Travel Growth

Adding transportation capacity is socially beneficial to the extent that it increases regional mobility and spatial connectedness between consumers and businesses. However there is an emerging policy debate focusing on the impact of highway capacity expansion on vehicle miles of travel (VMT) growth that identifies concern over (a) the benefits of adding roadway capacity to relieve peak traffic congestion, and (b) the environmental costs of increased VMT. In light of research suggesting that adding new highway lane-miles induces travel growth that washes out the short-term delay reduction benefits of added capacity, policymakers have reevaluated the merits of simply adding highway lane-miles to reduce traffic congestion. These empirical findings provide a significant cornerstone in the canon of federal air quality regulations prohibiting states from constructing of new highway lanes in non-attainment urban areas. Because many non-attainment areas are also those that suffer from the nation’s worst traffic problems, however, there is a political tension between the desire to meet federal air quality standards and the pressure to fund highway improvements that lower congested

conditions, how ever short those benefits may be. This research is intended to provide decisionmakers with a context for identifying transportation investments that meet these conflicting objectives without challenging the empirical basis for federal intervention in state and regional transportation planning efforts.

In this analysis, I assume growth projections throughout of the project life of 1 percent per year, which encompasses both secular and induced growth considerations. Furthermore, I assume a social opportunity cost of capital of 4 percent, a standard often used in the project evaluation literature (Harberger 1977). Estimates of vehicle operating costs and user travel time costs require information on both toll lane and highway main line volumes, which have traditionally been calculated in terms of ADT over the project life (HCM 1997). Instead of using Highway Capacity Manual's approach, I will use a slightly modified method in which I estimate total annual delays based an annual 1 percent increase in peak traffic. This approach assumes that because non-peak traffic volumes are constant irrespective of investment scenario, changes in delay (and corresponding costs and benefits) can be estimated on the basis of peak hour projections alone. To the extent that secular growth trends increase non-peak travel, this analysis will understate the future impacts.

6.2.2 Estimating the Present Value of User Benefits

Table 6.2 shows the input assumptions in the traffic projection model used to estimate the comparative benefits of the investment alternatives described earlier, which reflects the performance of a typical HOVL, and compares the effects of competing

**Table 6.2 Effects of Adding an HOV and Converting
an HOVL to GPL and Toll Lane**

ASSUMPTIONS

Initial Number of Lanes (4 GPL + 1 HOVL)	5
Capacity (vehicles per lane per hour)	2000
Length of Peak Period (hr)	3
Time Maximum Delay Begins (hr)	1.5
Initial Maximum Delay (min)	40
HOVL Average Occupancy	2.3
Initial Proportion of HOVs	10%
Annual Growth Rate	0.01
HOVL In-Vehicle Travel Time Coefficient	-0.02
HOTL In-Vehicle Travel Time Coefficient	-0.01
Proportion of HOVs Using HOVL	0.80

OUTPUT	PRE- HOVL	NO ACTION (HOVL)	CONVERT TO GPL	CONVERT TO TOLL LANE
Average Annual Peak Delay (millions of hours)	6474.1	1637.1	1277.9	985.0
Total Delay Over 20 Years (millions of hours)	135957.0	34378.7	26835.9	20685.3
Present Value of Total Delay (discounted at 4%) (millions of 1998 constant dollars)	\$17,611.5	\$4,426.6	\$3,281.4	\$2,521.6
Maximum Peak Period Delay (minutes)	66	35.4	34.8	35.9

investments. In the baseline “HOVL” case, there are 5 highway lanes (4 GPL and 1 HOVL). The peak period is 3 hours long, the initial proportion of HOVs is 10 percent, and the average HOV occupancy is 2.3. Because I assume that conversion is unlikely to be considered for HOVLs that have a high initial proportion of HOVs and good utilization (see Section 5.2), the 10 percent figure is deliberately intended to represent the mid-range of realistic initial proportions of HOVs. As discussed in Section 5.2, the magnitude of delay reduction benefits diminishes as the proportion of HOVs approaches the proportion of HOVL capacity to total highway capacity.

In Table 6.2, I compare four cases. The first case represents a 4 lane highway in which no lane addition is made. The second case, which reflects the baseline “no action” case in my analysis, involves the addition of an HOVL in year 0. The third case represents a situation in which an existing HOVL is converted to a GPL. And the fourth case represent a situation in which an existing HOVL is converted to a toll lane.

6.2.3 Comparing Benefits

Table 6.2 shows that the addition of an HOVL to a congested highway provides a substantial delay reduction over the length of the 20 year service life. Assuming an annual increase in peak hour traffic of 1 percent per year, the average person-delay increases from 14.7 minutes in year 0 to 24.5 minutes in year 20. The following equation is used to estimate annual peak delay:

$$\text{Annual Delay}_i = \text{Peak Delay}_i^j * 250 \quad (6.1)$$

where peak delay during year *i* on day *j* multiplied by the number of working days per

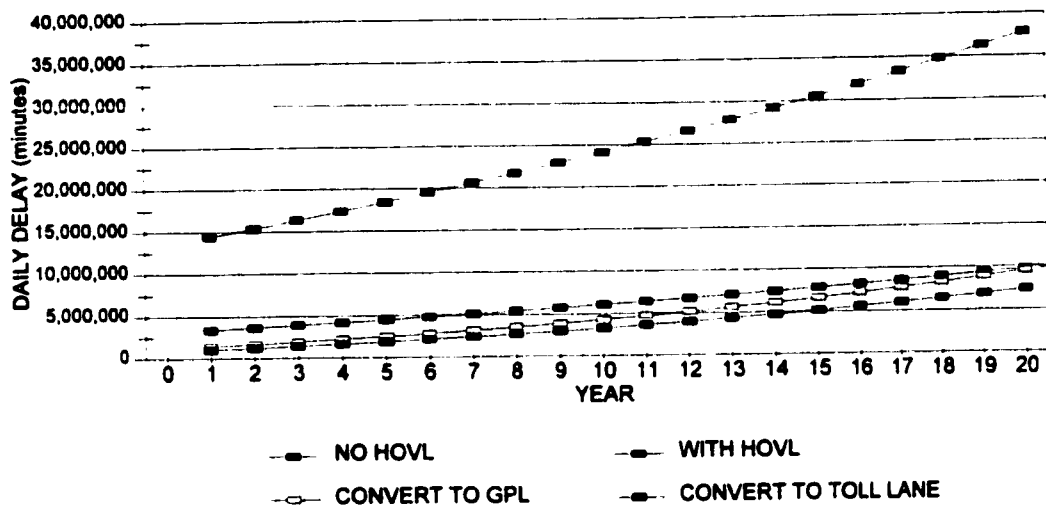
calendar year, 250, equals the total annual delay per year. Average annual peak delay falls from 6.5 billion hours to 1.6 billion hours, which represents a present value of \$13.2 billion in travel time savings over the 20 year project life.

Delay Reductions

Figure 6.1 shows the trend in average daily person-delay for the four cases described above (See Appendix F for model outputs). Over the 20 year period, the “Convert HOVL to Toll Lane” case provides the largest person-delay reductions, with the three investment cases appearing to converge at year 20. Total peak delay in the “HOVL” case increases linearly from 3.39 million minutes in year 0 to 10.17 million minutes in year 20. Total peak delay in the “Convert to GPL” case increases linearly from 1.41 million minutes in year 0 to 10.18 million minutes in year 20. Stated another way, converting an HOVL to GPL in year 0 will provide no peak delay reduction benefits by year 20. Of the three alternatives, the total peak delay trend line is lowest for the “Convert to Toll Lane” case – with the “HOVL” and “Convert to GPL” alternatives converging at year 20. In the “Convert to Toll Lane” case, total peak delay increases linearly from 1.03 million minutes in year 0 to 7.93 million minutes in year 20.

The reason that a toll lane provides a consistently greater reduction in total peak delay in spite of annual increases in peak vehicles is that the toll lane is able to provide optimal, free-flow service (via dynamic pricing) and divert a fixed amount of vehicles per peak period, thereby limiting queueing delays to the four main line highway lanes and a smaller number of peak passengers. While an HOVL can effectively remove HOVs from congested highway lanes, often there remains unused peak capacity on the HOVL

Figure 6.1 Total Peak Period Delay By Year



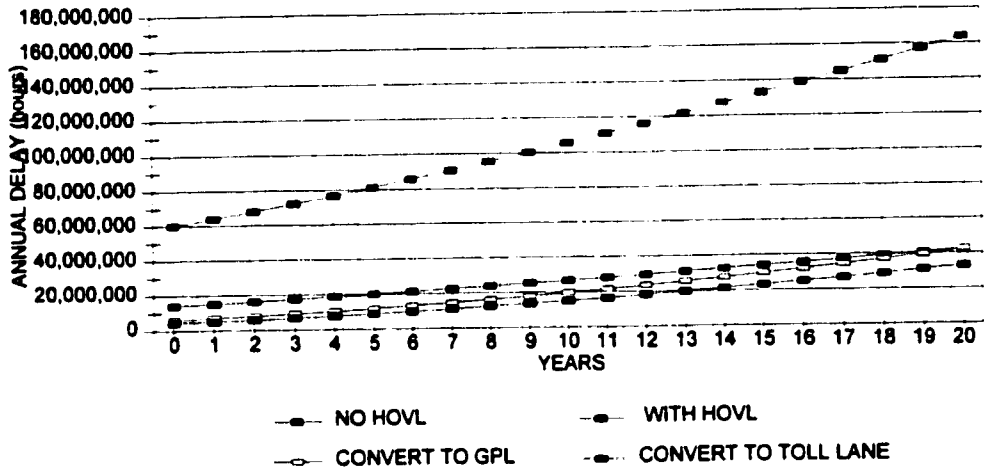
throughout the peak period despite annual increases in the number of peak HOVs. Consequently, suboptimal peak HOVL utilization results in greater queueing delays in comparison to the toll lane case, which can more effectively attract peak vehicles through pricing.

Figure 6.2a, which shows the total annual delay trend line for the four cases summarized in Table 6.2. indicates that the “Convert to Toll Lane” case produces the lowest total delay of the three investment alternatives. Over the 20 year period, the “Convert to Toll Lane” case produces a stable annual delay trend that is consistently lower than the “no action” HOVL case. In year 0, the “Convert to Toll Lane” case provides a delay reduction of 9.8 million hours. The delay reduction increases to a maximum of 11.6 million hours in year 14 and diminishes slightly to 9.3 million hours in year 20, as shown in Figure 6.2b. The “Convert to Toll Lane” peak time-savings curve has a convex shape primarily because the rate of peak HOVL underutilization in the “no action” case through year 14 diminishes as the peak vehicle grow from year to year, resulting in a marginally smaller differences in average person-delays between the HOVL and toll lane alternatives. After year 14, improvement in peak HOVL utilization due directly to annual growth in peak traffic contributes to a marginal decrease in the difference between the HOVL and toll lane alternative. Stated another way, as annual HOVs increase the amount of HOVL capacity remaining unused diminishes, resulting in a decreasing difference between HOVLs and toll lanes in later years.

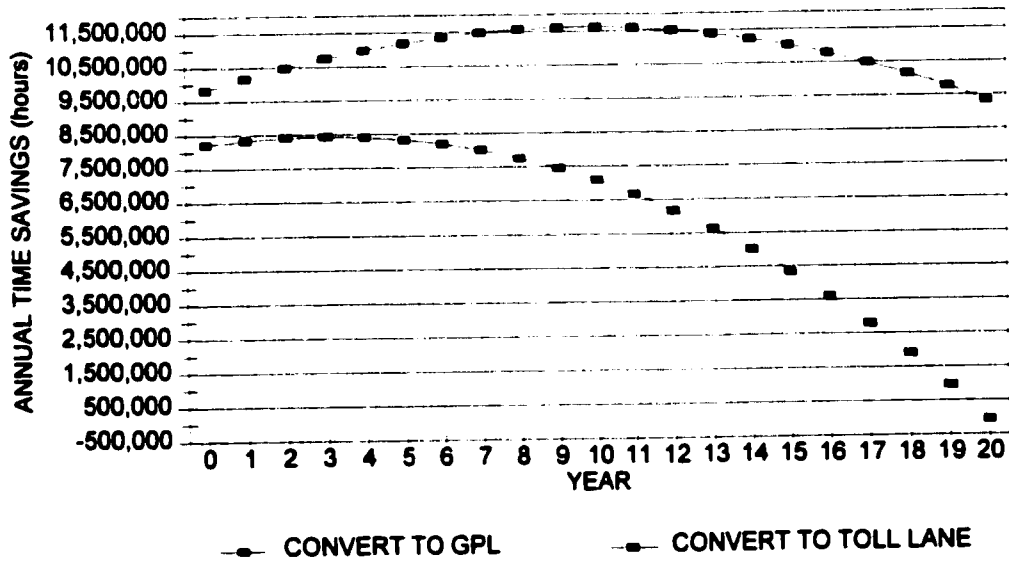
By contrast, the difference in peak delay between the “Convert to GPL” case and the baseline HOVL case gradually diminishes from year 0 to year 20, at which point the

Figure 6.2

a. Total Annual Delay By Year



b. Annual Time Savings in Comparison with No Action HOVL Case



pro

“Convert to GPL” case produces slightly greater delays than the baseline no action HOVL case. In year 0, conversion to GPL provides the largest difference in peak delays primarily because the rate of peak HOVL underutilization is highest early in the 20 year period. Converting to GPL will produce an immediate and largest delay reduction benefit by providing peak SOVs with five instead of four GPLs. In every subsequent year, the difference in peak delay between the two alternatives gradually diminishes as the peak performance of the HOVL improves. By year 20, the amount of delay on the four main line highway lanes in the no action HOVL case roughly equals the peak delays on the five main line highway lanes in the “Convert to GPL” case. Figure 6.2b shows that delay reductions over the baseline “no action” HOVL case rises from 8.2 million hours in year 0 to a maximum of 8.4 million hours in year 4 and subsequently falls to 959,935 hours in year 19, after which point there is greater delay in the “Convert to GPL” case than the no action HOVL case.

Value of Travel Time Savings

Monetizing the travel time savings associated with each investment alternatives requires a value of travel time savings measure and discount rate. There is a vast literature on the valuation of travel time savings, the full breadth of which is beyond the scope of this dissertation. Stopher and Meyburg (1976) present an overview of methodologies estimating the value of travel time, and report that there are conflicting theories on the valuation of travel time savings incurred outside working hours. One viewpoint holds that leisure time, which cannot be traded for goods or services, has little or no economic value. The opposing viewpoint argues that overtime pay implies that

leisure time has considerable value to the individual, possibly at values higher than the hourly wage (Hensher 1972; de Donnea 1974; Stopher and Meyburg 1976).

de Donnea (1974) provided the first major theoretical exposition of the value of travel time savings for nonworking time. Consumer utility, for the joint product of an activity and its travel costs, is defined

$$U = V\left[A_i, G(t_i, X_{ij})\right] \text{ where } i = 1, \dots, I; j = 1, \dots, J \quad (6.2)$$

where

A_i = level of i th activity ($i = 1, \dots, I$)

X_{ij} = the quantity of good or service k used in the production of activity i ($k = 1, \dots, J$)

t_i = time spent in activity i

$G(\)$ = individual utility as a function of attributes X_{ij} and t_i

The utility function above is subject to a budget constraint expressed in Equations 6.3, 6.4, and 6.5:

$$Y = \sum_{j=1}^J \sum_{i=1}^I p_j X_{ji} \quad (6.3)$$

where

Y = income

p_j = market price of good or service j

X_{ji} = quantity of good or service j required for activity i

$$T_c = \sum_{i=1}^I t_i \quad (6.4)$$

where T_c = total consumption of time in a given period

$$T_c = T - T_w \quad (6.5)$$

where T = total time in a given period

T_w = total work time in a given period

Given these budget constraints, the strict utility can be solved using a Lagrange multiplier method:

$$V = U\left[A_i, G(t_i, X_{ij})\right] + \lambda \left[Y - \sum_j \sum_i p_k X_{ji} \right] + \mu \left[T_c - \sum_i t_i \right] \quad (6.6)$$

where λ and μ are the Lagrange multipliers. The first order conditions of Equation 6.6 with respect to t_i and X_{ji} , set equal to zero for maximization, are shown as:

$$\frac{\partial}{\partial A_i} \frac{\partial A_i}{\partial X_{ji}} + \frac{\partial U}{\partial G} \frac{\partial G}{\partial X_{ji}} - \lambda p_j = 0 \quad (6.7)$$

$$\frac{\partial U}{\partial A_i} \frac{\partial A_i}{\partial t_i} + \frac{\partial U}{\partial G} \frac{\partial G}{\partial t_i} - \mu = 0 \quad (6.8)$$

These two equations represent a system of equations for all i and all j (de Donnea 1974; Stopher and Meyburg 1976; Kmenta 1986). In Equation 6.8, the total marginal utility of a good k used in the production of activity i is equal to its price p_k , multiplied by the marginal utility of money. Similarly, in Equation 6.8, μ is the marginal utility of time.

Letting

$$\frac{\partial U}{\partial G} \frac{\partial G}{\partial X_{ji}} = g_{ji} \quad (6.9)$$

and

$$\frac{\partial U}{\partial G} \frac{\partial G}{\partial t_i} = g_{ji} \quad (6.10)$$

Rewriting equations 6.9 and 6.10, we get

$$\frac{\partial U}{\partial A_i} \frac{\partial A_i}{\partial X_{ji}} = \lambda p_k - g_{ji} \quad (6.11)$$

$$\frac{\partial U}{\partial A_i} \frac{\partial A_i}{\partial t_i} = \lambda - g_{ii} \quad (6.12)$$

Dividing Equation 6.11 by 6.12 provides the rate of substitution of time and a given input k used in the production of activity i :

$$-\frac{dt_i}{dX_{ji}} = \frac{\lambda p_k - g_{ji}}{\lambda - g_{ii}} \quad (6.13)$$

Ignoring the purpose under which time is spent, the marginal value of time can be defined as

$$\frac{\mu - l_i}{\lambda} = -\frac{dx_{ji}}{dt_i} p_k \quad (6.14)$$

Numerous studies have been based on the utility maximization problem shown here.

While utility maximization theory provides a framework for estimating the value of nonworking time, there is no clear rule of thumb governing how best the measure

should be valued. Stopher and Meyburg (1976) report that value of travel time should be based on willingness to pay. Applying a procedure determining how much money an individual is willing to pay to save time at the margin, Hensher (1972) designed a survey which asked people how much of a change in the cost of current and alternative travel modes would be necessary to induce a shift in mode choice. In theory, this should yield estimates of the marginal value of time for each individual.

In the absence of a travel demand survey, I adopt an empirically derived VTTS estimate taken from ARDFA's travel impact study of the 91 Express Lanes, which employs a methodology similar to Hensher's procedure (Sullivan et al. 1998). They calculate work travel time savings by taking the difference between the actual freeway trip time for a particular time of day and the fastest estimated trip time through the section. In Spring 1997, they report a 12 minute time savings during the peak 4:30 - 5:30 pm period during which the toll is \$2.75, implying a value of travel time savings of \$13-14 per hour. Because there is evidence to suggest that commuters tend to overvalue their true time savings by assuming a greater level of time savings than actually received, empirically derived estimates should be used with caution (Hensher 1978; Sullivan et al. 1998). In this analysis, I assume a value of travel time savings of \$12 per hour in 1998 constant dollars (Sullivan et al. 1998).

Present Value of Total Annual Delay

In the travel demand literature, several studies have reported that travel time savings constitutes the major portion of the benefits computed in conventional cost-benefit evaluations of roadway projects (Stopher and Meyburg 1976). Hensher (1972)

estimated that 25 percent of all economic benefit from urban roads in Australia were attributable to private travel time savings. In the United States, between 72 and 81 percent of the benefits of the interstate highway system have been estimated to be derived from travel time savings (Fallon 1970). In Great Britain, Foster and Beesley estimated travel time savings to comprise 48 percent of the benefits of the Victoria Line in London. The significance of estimating travel time savings in project evaluation is the major theme underscoring the analysis presented in this chapter.

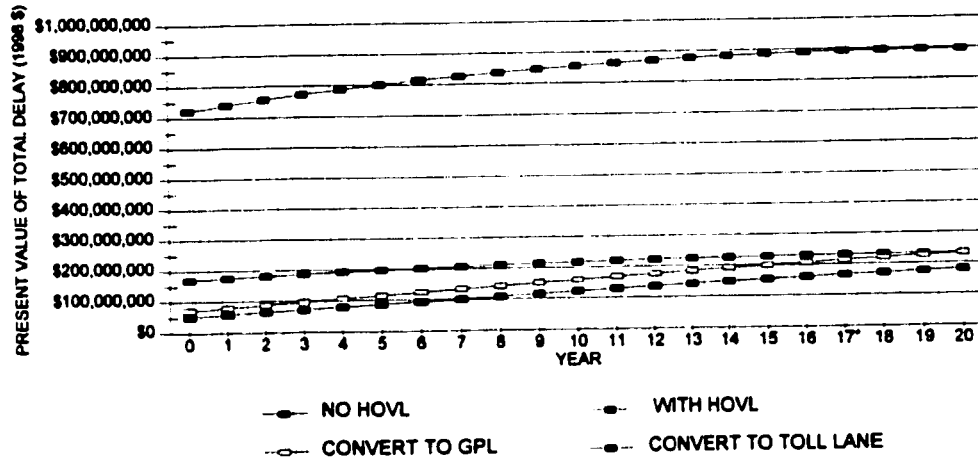
The difference in total annual delay between the no action HOVL case and competing investment choices can be thought of as time savings foregone had no action been taken. Figure 6.3 shows the trend lines for the present value of total annual delay under the investment scenarios described earlier, and the present value of time savings benefits corresponding to the two major competing investment scenarios, “Convert to GPL” and “Convert to Toll Lane.”

Table 6.3 summarizes the present value of total annual delay associated with each investment alternative. Adding an HOVL will produce a NPV of \$13.2 billion in main-line user time savings benefits over the “no action” case. By comparison, the “Convert to GPL” scenario provides an additional NPV of \$1.14 billion in user time savings benefits – although by year 20 total annual delay in the “Convert to GPL” case exceeds the baseline HOVL case.

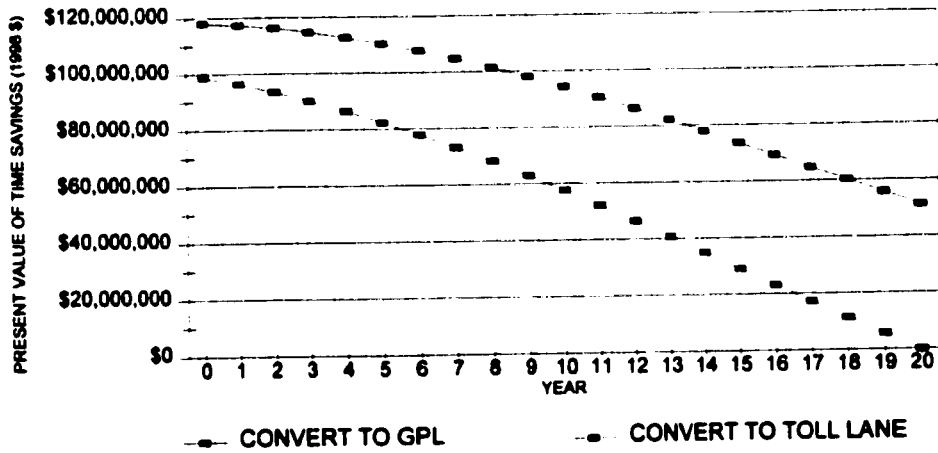
The “Convert to Toll Lane” scenario produces an additional NPV of \$1.90 billion in main line highway user time savings benefits beyond the baseline case, which represents approximately a present value of \$759 million in time savings benefits in

Figure 6.3

a. Present Value of Total Delay by Year



b. Present Value of Time Savings Over the No Action HOVL Case



**Table 6.3 Net Present Value of Annual Delays of
Converting an HOVL to GPL versus Toll Lane**

YEAR	DISCOUNT		NPV CONVERT TO GPL	NPV CONVERT TO TOLL LANE
	RATE	(1+i) ⁿ		
0	0.04	1.0000	\$98,661,232	\$117,931,863
1	0.04	1.0400	\$96,265,462	\$117,290,751
2	0.04	1.0816	\$93,381,610	\$116,171,415
3	0.04	1.1249	\$90,047,292	\$114,605,657
4	0.04	1.1699	\$86,298,837	\$112,623,770
5	0.04	1.2167	\$82,192,017	\$110,279,309
6	0.04	1.2653	\$77,759,498	\$107,599,414
7	0.04	1.3159	\$73,031,765	\$104,608,940
8	0.04	1.3686	\$68,059,650	\$101,357,641
9	0.04	1.4233	\$62,871,809	\$97,869,116
10	0.04	1.4802	\$57,493,615	\$94,163,605
11	0.04	1.5395	\$51,970,189	\$90,286,363
12	0.04	1.6010	\$46,323,306	\$86,254,583
13	0.04	1.6651	\$40,577,351	\$82,088,030
14	0.04	1.7317	\$34,766,951	\$77,822,488
15	0.04	1.8009	\$28,912,198	\$73,473,821
16	0.04	1.8730	\$23,031,310	\$69,056,186
17	0.04	1.9479	\$17,153,638	\$64,601,259
18	0.04	2.0258	\$11,293,477	\$60,119,617
19	0.04	2.1068	\$5,467,516	\$55,623,949
20	0.04	2.1911	-\$303,870	\$51,137,904
			\$1,145,254,856	\$1,904,965,680

excess of the “Convert to GPL” case. In this analysis, time savings denotes the delay reduction benefits received by main line highway users as a result of capacity expansion. The NPV for the “Convert to Toll Lane” case does not include any time savings received by toll lane users, since technically any time savings benefits were received in exchange for a toll, which should be considered a part of user costs. However, toll revenues should be included as a social benefit insofar as toll revenues relieve the burden of having to finance debt service, operating and maintenance costs through general taxation.

6.3 Costs, Financial Performance and Equity Issues

The cost estimates carried out in any cost-benefit analysis are relatively straightforward, at least in comparison to the complexity of estimating project benefits. The capital, maintenance, and operating costs associated with toll lanes are not trivial, and are significantly higher those costs associated with HOVLs and GPL additions. The notation for various costs associated with transportation projects are similar to those used by Wohl and Martin (1962):

$CFC_{y,t}$ = capital costs for construction, etc.

$CFO_{y,t}$ = continuing costs of operation and maintenance

$CUT_{y,t}$ = costs for users of travel time (also discomfort and inconvenience, if a monetary equivalent for these is available)

$CVO_{y,t}$ = vehicle operating and maintenance costs

All these costs are for project y in year t . While vehicles operating and road maintenance costs are relatively easy to obtain, changes in the number and intensity of traffic accidents resulting directly from a toll lane addition are extremely difficult to estimate accurately.

There are also secondary impacts resulting from new traffic generated by some roadway investment and ripple effects on regional economic development, all of which bear consideration in benefits assessment but which are beyond the scope of this analysis.

6.3.1 Capital and Operating Costs for HOVL and GPL Additions

In cases in which lane capacity can be added to an existing highway by converting an unused median to a lane, the construction cost of adding a GPL is roughly comparable to that of adding an HOVL (or 'diamond lane'). Caltrans reported that the 8-mile SR-91 HOVL cost roughly \$215,000 and that the SR-55 HOVL cost \$400,000, most of which was spent on repaving, striping, and restriping of main line highway lanes. Kain et al. (1992) report that express busways, designed as grade-separated exclusive lanes planned with on-line stations, are significantly more expensive to construct than 'diamond lane'-version HOVLs. The El Monte busway is estimated to have cost \$109.6 million; the Shirley Highway is estimated to have cost \$127.2 million (in 1989 dollars).

In terms of cost-effectiveness, the total cost per round trip for 'diamond lanes' HOVLs is significantly lower than that of exclusive busways mainly because 'diamond lane' costs are significantly lower than typical busways. Kain et al. (1992) report a per-transit-round-trip cost of \$16,896 on the El Monte busway and \$9,215 on the Shirley Highway (in 1989 dollars). When sharing capital costs with non-transit vehicles, the per round trip cost decreased to \$5,195 on the El Monte busway and \$4,084 on the Shirley highway. Even though these busways eventually facilities opened service to non-transit HOVs and peak daily person trips on non-transit vehicles eventually surpassed that of transit vehicles, the cost per round trip on conventional 'diamond lanes' were much

cheaper. In 1989, the HOVLs on SR-91 and SR-55 had an average per HOVL round trip cost of \$24 and \$19 respectively (in 1989 constant dollars) (Kain et al. 1992).

6.3.2 Toll Lanes: Costs, Cost Recovery, and Financial Performance

Because there are so few urban toll lanes in operation, and the design, operation and implementation of these few projects differ greatly, there are few generalizations that can definitely be drawn about the cost profile of toll lanes in relation to those of HOVL to GPL additions. Based on the initial conditions and annual traffic growth assumptions presented in section 6.2.3, I will discuss revenue and cost recovery issues for a simulated highway corridor with a toll lane, and estimate the present value of toll revenue using a 4 percent social opportunity cost of capital. In the following two sections, I will then provide a financial profile of the two California HOTL projects in operation, the I-15 Express Lanes and the 91 Express Lanes discussed in Chapter 2. It is worth noting that the scale and design of toll lane facilities may be larger or more complex than those analyzed in Chapter 5 and in Section 6.2, since they bear a closer resemblance to express busways than the simpler, more cost-effective 'diamond lanes,' which are the subject of this analysis. Therefore interpretations concerning capital costs, depreciation and long-term cost recovery should be drawn with caution.

Toll Revenues and Cost Recovery

While the capital and operating costs associated with toll lanes are greater than those of HOVL and GPL additions, the revenue generating dimension of toll lanes creates a unique 'double-benefit' advantage that neither HOVL or GPL possess. Tolling creates welfare gains for both toll buy-in customers who benefit by purchasing peak time savings

and main-line highway travelers, and reduces social costs by placing the burden of project costs squarely on users who benefit most from the provision of the facility. To the extent that toll lanes more precisely manifest the user fee principle than the pay-at-the-pump gas tax, toll lanes (1) create a more tangible link between VMT and per-mile travel costs, and (2) compel travelers to consider the marginal cost of each given trip.

My analysis thus far has deliberately deemphasizes the “double-benefit” claim in order to present an analysis that allows an apples-to-apples comparison of competing investments. In any full-blown cost-benefit analysis, an accounting of toll revenues would lower the social opportunity cost of capital by displacing public funds that would have to be allocated to alternative unpriced highway alternatives. Without a full consideration of toll revenues, any economic analysis of these alternatives would result in an underestimation of the social benefits of conversion to toll lane. Assuming constant returns-to-scale, an optimally priced toll lane generate revenues that cover amortized capital, operating, and maintenance costs.

Table 6.4 summarizes the net present value of toll lane revenues over a 20 year project life. Assuming that tolls are optimally priced throughout the peak, there are a maximum of 33 vehicles per peak-minute interval. To account for the growth in toll lane demand over the 20 year service life, the average toll over the peak period increases by 5 percent each year, starting at an average peak toll of \$1.00 in year 0 and rising to average peak toll of \$2.00 in year 20.² In theory, the number of peak vehicles from year to year

²

In this analysis, I consider only peak hour toll lane volumes and calculate the annual toll

**Table 6.4 Net Present Value of Total Revenues
after an HOVL is Converted to HOTL**

YEAR	DISCOUNT RATE	(1+i) ⁿ	ANNUAL REVENUE	NPV OF ANNUAL REVENUE
0	0.04	1.0000	\$2,175,000.00	\$2,175,000.00
1	0.04	1.0400	\$2,283,750.00	\$2,195,913.46
2	0.04	1.0816	\$2,392,500.00	\$2,212,000.74
3	0.04	1.1249	\$2,501,250.00	\$2,223,602.14
4	0.04	1.1699	\$2,610,000.00	\$2,231,038.94
5	0.04	1.2167	\$2,718,750.00	\$2,234,614.32
6	0.04	1.2653	\$2,827,500.00	\$2,234,614.32
7	0.04	1.3159	\$2,936,250.00	\$2,231,308.68
8	0.04	1.3686	\$3,045,000.00	\$2,224,951.67
9	0.04	1.4233	\$3,153,750.00	\$2,215,782.92
10	0.04	1.4802	\$3,262,500.00	\$2,204,028.10
11	0.04	1.5395	\$3,371,250.00	\$2,189,899.72
12	0.04	1.6010	\$3,480,000.00	\$2,173,597.73
13	0.04	1.6651	\$3,588,750.00	\$2,155,310.25
14	0.04	1.7317	\$3,697,500.00	\$2,135,214.12
15	0.04	1.8009	\$3,806,250.00	\$2,113,475.51
16	0.04	1.8730	\$3,915,000.00	\$2,090,250.51
17	0.04	1.9479	\$4,023,750.00	\$2,065,685.60
18	0.04	2.0258	\$4,132,500.00	\$2,039,918.21
19	0.04	2.1068	\$4,241,250.00	\$2,013,077.18
20	0.04	2.1911	\$4,350,000.00	\$1,985,283.22
				\$45,344,567.34

revenue by multiplying the total number of peak passengers by the number of peak periods per day, (2), then multiplying the product by 250, the number of workday per year. The decision to consider only peak toll lane volumes is deliberately done to provide a conservative estimate of the revenue potential of converting one HOVL to toll lane. To the extent that non-peak toll lane volumes are not considered, this analysis is likely to understate annual toll revenues.

should remain constant, since an optimal pricing system will align demand with toll lane capacity. In reality, this may not be realistic, however, since a variable pricing system is implemented on a trial-and-error basis, and toll operators have an incentive to err on the side of caution early in the project life. The NPV estimate of \$45,344,567 can be thought in two ways: (a) the present value of toll lane travel time savings over the 20 year period, and (b) the financial opportunity cost associated with not converting an HOVL to toll lane.

Expenditure of Revenue

From an equity perspective, the singular advantage of toll lanes is that the incidence of user costs is directly proportional to frequency of usage. In other words, those who use toll lane service most pay the most in user fees and, by extension, shoulder the most in project costs. To the extent that high income travelers use toll lane service more frequently than lower income groups, they pay a higher proportion of project costs for a facility that provides time savings benefits to all groups irrespective of income.

If a toll lane is publicly owned and cost recovery is only one of multiple project objectives, revenues generated in excess of operating costs can be used to address equity concerns through a number of means: improving transit service along the corridor, offsetting highway depreciation and maintenance costs, or direct transfer payments to low-income travelers. The advantage of publicly owned facilities is that public concerns over fairness can be addressed by setting revenue aside to resolve specific equity concerns. On the I-15 Express Lanes, for example, SANDAG has spent \$650,000 in federal funds and revenue surplus on Inland Breeze, a new express bus service that runs

along the Express Lanes during its line-haul portion (Samuel 1999). Moreover, since its opening, the publicly operated I-15 Express Lanes has suffered none of the negative publicity surrounding the 91 Express Lanes, a facility whose poor bond rating and disappointing profits have greatly disappointed investors.

I-15 Express Lanes

The I-15 Express Lanes, originally opened in October 1988 as a reversible HOVL, was estimated to have a capital cost of roughly \$15.6 million (SANDAG 1999). The cost of TransCore's ETC system, which included an electronic gantry to house an overhead transponder reader, a lighting system, video cameras, in-lane loop detectors, variable message signs, and restriping for enforcement purposes, came to approximately \$1.8 million (SANDAG 1997). SANDAG currently subcontracts operation of the customer service center to TransCore at an annual cost of \$393,000, pays the California Highway Patrol (CHP) \$100,000 per year to enforce the program, and spends approximately \$71,000 in annual warranty and maintenance costs, bringing annual operating costs \$564,000 per year (SANDAG 1999).

Since the beginning of Phase II, ADT on the I-15 Express Lanes increased by 29 percent from 11,700 vehicles per day in March 1998 to 15,078 vehicles per day in November 1999. The average daily volume of SOV toll buy-ins increased 287 percent from 910 users in March 1998 to 3,523 in November 1999 (SANDAG 1999). In 1999, SANDAG reported an annual revenue of \$1 million, which is well below Wilbur Smith Associates' (WSA) estimate that \$4 to \$6 million of toll revenues would be collected over the three-year demonstration study period. In its traffic forecasting study, WSA

predicted an increase from 2,000 to 4,000 in daily toll trips in the project's first year and a sustainable volume of 4,500 toll trips per day in year 2, producing in an average annual revenue of \$2 million.

From the start of Phase II in March 1998, revenues have increased gradually from \$66,000 per month to a high of \$139,000 per month in October 1999. For the month of March 1999, SANDAG reported 3,122 daily Express Lane customers paying an average toll of \$2.02, resulting in a daily revenue of roughly \$6,300 (SANDAG 1999). These average daily ridership figures have since gradually increased throughout the remainder of the year. As of December 1999, SANDAG reported approximately revenues of approximately \$950,000 per year, which unfortunately is well short of WSA's forecasts (SANDAG 1999). Because no debt was incurred to finance the up-front project costs and the project has the potential to be self-financing, local representatives have sponsored a bill (SB252) to continue the toll buy-in project as a self-financing operation (Samuel 1999).

The fact that ridership and revenue figures are well below WSA's forecasting estimates has not raised serious financial concerns within SANDAG. First and foremost, actual ridership and revenue figures for all of California's toll lane projects – the 91 Express Lanes, the San Joaquin Hills Transportation Corridor and the I-15 Express Lanes – have been significantly lower than WSA's ridership forecasts and revenue projections. The reasons why toll road projections have been systematically overoptimistic are uncertain, thus raising troubling questions about forecasting of HOTLs. Unlike the 91 Express Lanes – where WSA's overly optimistic ridership growth projections lead

investors to downgrade 91X bonds to 'junk' status, prompting CPTC to initiate a sale of the 91 Express Lanes in September 1999 – the publicly owned I-15 Express Lanes which did not require a bond issuance is not subject to same financial pressures that came to bear on the privately owned 91 Express Lanes. Without any financial burden to investors, SANDAG has had more flexibility to evaluate I-15 Express Lanes performance without adopting revenue-enhancing tactics designed to improve quarter-to-quarter profitability.

One interesting new finding on the I-15 Express Lanes is that carpooling has increased in Phase II, which, on its face, defies conventional wisdom. Between March 1998 and November 1999 (Phase I), average daily carpools increased 6 percent from 10,790 to 11,424. Since October 1996 (the beginning of Phase I), carpooling on the I-15 Express Lanes has increased an astounding 49 percent from 7,685 average daily carpools to 11,424 average daily carpools in November 1999 (SANDAG 1999).

During a typical day, HOVs outnumber SOV toll buy-ins by a ratio of over 4:1 (SANDAG 1999). The fact that approximately 75 percent of total I-15 Express Lanes project consists of HOVs helps to explain why tolls have remained very high. SANDAG officials believe that ridesharing has increased since the opening of the I-15 Express Lanes because the toll alternative provides an insurance against travel time uncertainty in cases where a carpool partner cancels the morning before the carpool trips is pre-arranged. Whereas without the toll alternative long-term carpools are more likely to disband because one or the other carpool partner unexpectedly cancels, with a toll alternative that offers abandoned carpools peak travel time certainty long-term carpooling may be more stable. More research in this area needs to be conducted.

91 Express Lanes

Table 6.5, which summarizes capital costs through December 31, 1996, shows a total cost of \$133.9 million, approximately \$43 millions more than CPTC estimated in the original bid for rights to the private franchise. Capital improvements and equipment include toll road construction costs and the electronic toll and traffic management system, which identifies traffic statistics generated from 91 Express Lane travel. Development costs include those incurred in the preparation of construction contracts, and the subcontracting of traffic, demographic, economic, environmental and marketing studies. Financing costs are costs incurred to secure debt to the finance construction of the 91 Express Lanes. Start-up costs are those incurred in the preparation of facility operation (CPTC 1998).

Table 6.6 provides a statement of available cash flow for 1996, 1997, and 1998, assuming a base rate of return of 17 percent as stipulated in the Franchise agreement. Available cash flow is defined here as revenues less operating costs, taxes, debt service and depreciation. In its first full year in operation, CPTC earned \$7,074,972 in revenue against \$6,341,386 in operating costs, resulting in an operating income in \$733,586. After debt service \$12,667,068, CPTC reported a negative cash flow of \$11,933,482. With a base rate of return on investment of 17.11 percent, the present value of available negative cash flow was \$10,189,980 (CPTC 1999).³ At the end of year 2 (December 31,

³

The Base Rate of Return, as provided by the Franchise Agreement, is 17 percent adjusted by 20 percent of the increase in the average yield of five-year United States Treasury Bonds for a 30 year period.

**Table 6.5 Summary of 91 Express Lanes Construction Costs as of
December 31, 1996 (in 1996 dollars)**

ASSET CATEGORY	Cost as of December 31, 1996
Capital Improvement & Equipment	\$92,483,433
Development Costs	\$13,014,249
Financing Costs	\$8,454,811
Start-up Costs	\$2,740,880
Subtotal	\$116,693,373
Capitalized Interest	\$15,113,924
Total Capitalized Cost	\$131,807,297
Capital Costs at Completion	\$133,932,768

Source: 1996 CPTC Annual Report

**Table 6.6 Statement of Available Cash Flow for 91 Express Lanes,
1996, 1997, and 1998**

	1996	1997	1998
TOTAL REVENUE	\$7,074,972	\$13,883,246	\$20,117,842
OPERATING EXPENSES			
Facility Operations and Administration	3,984,383	5,787,221	5,720,238
Repair and Maintenance	205,431	263,887	237,620
Police Services	540,051	559,906	568,607
Professional Services	332,073	518,821	130,098
Technical Services	688,000	762,660	776,630
Property and Franchise Taxes	601,448	1,242,493	1,258,311
Total Operating Expenses	6,341,386	9,134,988	8,691,504
OPERATING INCOME	\$733,586	\$4,748,258	\$11,426,338
DEBT SERVICE	\$4,845,414	\$9,867,996	\$11,118,585
TOTAL VEHICLE TRIPS	5692725	8622346	9269883

Source: 1996, 1997 and 1998 CPTC
Annual Reports

1997), 91 Express Lanes revenues increased to \$13,883,246 against \$9,134,988 in operating expenses, resulting in an operating income of \$4,748,258. Minus additional capital expenses, CPTC reported a cash flow of \$3,133,746 in 1997, which equals a present value of \$2,287,313 at a base rate of return of 17.05 percent in year 2. Carrying over the negative cash flow from the previous year, the present value of negative cash flow as of December 31, 1997 was \$7,902,667. CPTC reported a net loss on taxable investment, and therefore paid no income taxes in 1997 (CPTC 1999). By year 3, CPTC's revenue stream increased to \$20,117,842 against \$8,691,504 in operating expenses, resulting in an operating income of \$11,426,338. After servicing a debt of \$11,118,585, CPTC reported break-even cash flow in 1998, with a profit of \$307,753. Total annual trips on the 91 Express Lanes have grown steadily from 5.69 million vehicles trips in 1996 to 8.62 million vehicle trips in 1997. In 1998, the 91 Express Lanes accommodated 9.27 million vehicle trips and carried approximately 13.5 million passengers (assuming an AVO of 1.46 passengers per vehicle) (CPTC 1999).

6.3.3 Equity Issues

Sullivan et al.'s 1996 Origin-Destination (O-D) survey found that frequent users of the Express Lanes have higher average incomes than commuters that use the Express Lanes infrequently or rarely. The highest income group (>\$100K/yr) in their stratified random sample of 350 home-to-work trips were twice as likely as the two lowest income groups (<\$25K/yr, \$25-\$40K/yr) to be frequent Express Lane users (Sullivan et al. 1998). They conclude that while there is a statistically significant income effect among frequent, infrequent and non-users of the Express Lanes, "many low income travelers use the toll

lanes frequently. . . [and] we believe it is incorrect to conclude that the express lanes primarily benefit high income travelers.” (Sullivan et al. 1998, pg. 73)

Although equity arguments raised against HOTLs based purely on income effect issues may have some merit – since higher income travelers use the 91 Express Lanes more frequently than medium to low-income travelers – long-term equity implications depend of the net outcome of usage based on income, cross-subsidies between HOTL users and HOVs, and the expenditure of HOTL revenue.

Cross-Subsidies Among 91 Express Lane Users

To the extent that toll exemptions and deep discounts are provided for HOVs as a method of encouraging ridesharing, there is a built-in cross-subsidy from LOV toll buy-ins to HOVs. On the 91 Express Lanes, HOV3+ vehicles were toll exempt for a 24 month period from December 1995 to December 1997, and were subsequently required to pay a half-toll after January 1, 1998.

Over the first 12-month period, Express Lane customers paid \$6,492,837 in tolls (in 1996 dollars) on 4.46 million trips and directly subsidized capital, debt service, depreciation and operating expenses for approximately 1.23 million free HOV3+ trips. Assuming an AVO of 1.2 for toll-paying LOVs and an AVO of 3.5 for HOV3+, 5.36 million passengers subsidized the facility costs of roughly 4.30 million additional travelers. In other words, 55 percent of total travelers covered the total cost of providing Express Lanes service in 1996. From a cost-benefit standpoint, offering toll exemption for multi-person vehicles would be worthwhile only if corresponding increases in ridesharing were above and beyond levels that would have been achieved had no toll

exemption been offered *and* the benefits associated with the elimination of vehicle trips equal or exceed the value of foregone revenue.

Given the absence of statistically valid HOV3+ toll coefficients, I do not estimate the number of eliminated trips or the value of foregone revenue. Though Sullivan et al. did observe a dramatic increase in HOV3+ traffic post-Express Lanes opening, the opening of the Express Lanes generated an immediate increase in HOV3+ traffic, the overall SR-91 corridor AVO declined slightly due to flat HOV2+ growth and substantial growth in SOV traffic (Sullivan et al. 1998).

From January 1 to December 31, 1997, Express Lane customers paid \$12,709,075 on 6.96 million trips and directly subsidized capital, debt service, depreciation and operating expenses for approximately 1.66 million free HOV3+ trips. Assuming an AVO of 1.2 for toll-paying LOVs and an AVO of 3.5 for HOV3+, 10.44 million passengers subsidized the facility costs of roughly 5.81 million additional travelers. In 1997, 64 percent of total travelers covered 100 percent of the total cost of providing Express Lanes service.

Pursuant to the terms of the Franchise agreement, CPTC began charging a half-toll to HOV3+ in an attempt to achieve a debt coverage ratio of 1.2 as of January 1, 1998 (California Department of Transportation 1990). The imposition of the half-toll had an immediate dampening effect on HOV3+ traffic. The proportion of HOV3+ to total ADT fell from 19 percent in 1997 to 13 percent in 1998, but the half-toll charge helped boost 1998 revenues to \$20,117,842.

Immediately after charging a half-toll for HOV3+, eastbound HOV3+ ADT fell 26

percent from 2,807 in December 1997 to 2,074 in January 1998 – suggesting a high elasticity of demand for HOV3+ travel. 8.03 million LOV passengers paid approximately \$16.7 million in tolls while 3.56 million HOV3+ passengers paid \$1.27 million in tolls. In other words, the 30 percent of total passengers in HOV3+ paid 7 percent of total 1998 project costs.

6.4 Environmental Impacts

The environmental benefits/costs associated with adding capacity to a congested highway are important considerations in the social cost inventory and influence the balance of benefits/costs in favor or against competing investment choices. Converting an HOVL to toll lane or GPL will affect emissions to the extent that conversion changes the number of vehicle trips and alters the length and severity of congested conditions. Those investments that best reduce vehicle delay will produce the greatest reduction in mobile-source emissions. In this section, I will present a comparison of emissions for the hypothetical cases described in Section 6.2 in relation to the three major mobile source emissions: Reactive Organic Gases (ROG), Nitrogen Oxide (NO_x), and Carbon Monoxide (CO).

6.4.1 Emission Factors

Two vehicle operation modes contribute most to exhaust emissions: the start mode and the stabilized running mode. The start mode occurs during the first 100 seconds after vehicle has been started. Because a vehicle takes time to achieve its optimal operating temperature, the emissions during starts are generally higher (CARB 1999). The stabilized running mode occurs when the engine is at normal operating

temperature. Emissions also result from a 'hot soak' during which time fuel vapors escape for about 60 minutes after the engine is turned off. These emissions are caused by high under-hood and fuel temperatures (CARB 1999).

The major sources of emissions are reactive organic gases (ROG), nitrogen oxides (NO_x), and carbon monoxide (CO) – each is which is emitted at different rates at varying speeds. During congested periods when vehicles must accelerate and decelerate within a range of low speeds, per mile emissions are high. As speeds increase to 60 mph, emission rates decrease (See Appendix B for a graphical comparison of EMFAC2000 and MVEI7G emissions rates).

In November 1999, the California Air Resources Board (CARB) staff sought Board approval of the inventory of pollutants from on-road mobile sources as calculated by EMFAC2000, the model which provides emission rates and inventories of exhaust and evaporative hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x) and particulate matter (PM) associated with exhaust, tire-wear and brake-wear (CARB 1999). Figure 6.4 shows the gram per mile comparison between EMFAC2000 and MVEI7G for ROG, NO_x and CO, respectively. In the previously used MVEI7G model, the basic emission rates were based on the Federal Test Procedure (FTP). To adjust for more contemporary driving habits, these rates were adjusted to a Unified Correction (UC) basis using cycle correction factors (CARB 1999).

Vehicle emissions are estimated using EMFAC2000 emission rates for trip end and running emissions for light-duty vehicles. Because the model outputs used here does not calculate variations in peak hour speeds, this analysis predicts emissions as a function

of the change in peak hour delay as a proxy for reduced congestion (and improved travel speeds). For example, insofar as an HOVL reduces vehicle running time, there will be a corresponding emissions reductions. Additionally, if conversion to toll lane reduces the length of the peak period and total peak delay, such action will result in emissions reductions. Table 6.7, which summarizes the factors used to estimate ROG, NOx, and CO emissions, assumes an average peak

Table 6.7 EMFAC 2000 Emission Factors

EMISSION	ROG	NOx	CO
Trip-end emissions (grams)	4.31	2.46	58.25
Running emissions (grams/veh-mile)	0.62	0.67	3.58
Emissions per veh-hour of delay (grams/veh-hr)	20.55		190.35

Source: California Air Resources Board, 1999

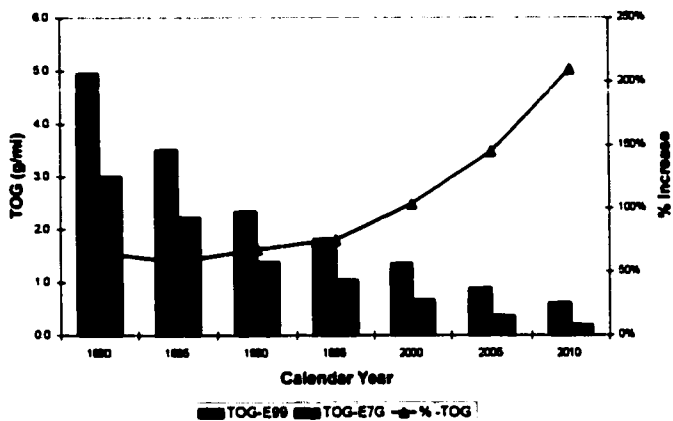
hour speed of 20mph (Dahlgren 1994). The average trip distance is assumed to be 20 miles.

6.4.2 Emissions Under Competing Investment Alternatives

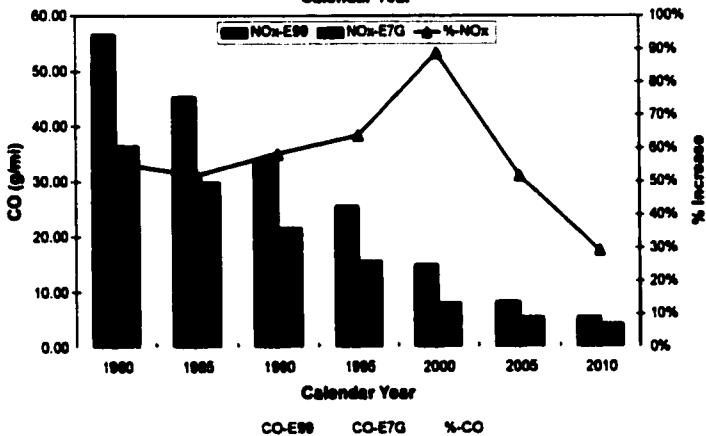
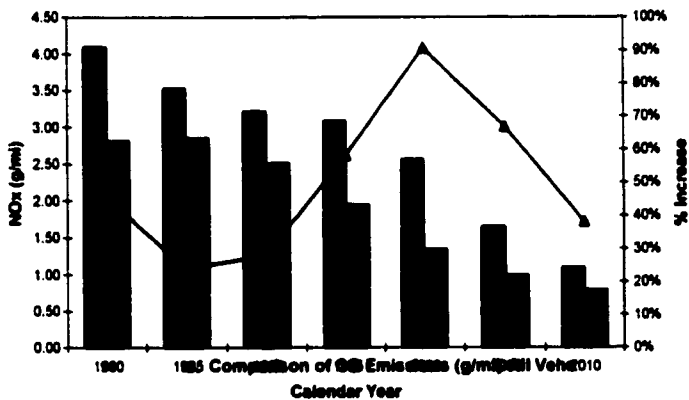
In terms of emissions, the baseline “no action” HOVL case produces a greater output of ROG, NOx and CO than converting to either GPL or toll lane. Of the two competing investment alternatives, converting to toll lane will provide greater reduction in ROG, NOx and CO than converting to general purpose use. In year 1, the baseline “no action” HOVL case produces 1.63 metric-tons of ROG per peak period. The “Convert to GPL” case produces 0.83 metric-tons of ROG per peak period. The “Convert to toll lane” case produces 0.74 metric-tons of ROG per peak period in the first year, a reduction of .89 metric-tons of ROG emissions per peak period over the baseline case. In terms of

Figure 6.4 Gram per Mile Comparison Between EMFAC2000 and MVEI7G for TOG, NOx and CO

a. Comparison of TOG (g/mi)-All Vehicles



b. Comparison of NOx-Exhaust (g/mi)-All Vehicles



NOx and CO, the “Convert to Toll Lane” also produces less metric-tons of emissions per peak period than the baseline case and the “Convert to GPL” case.

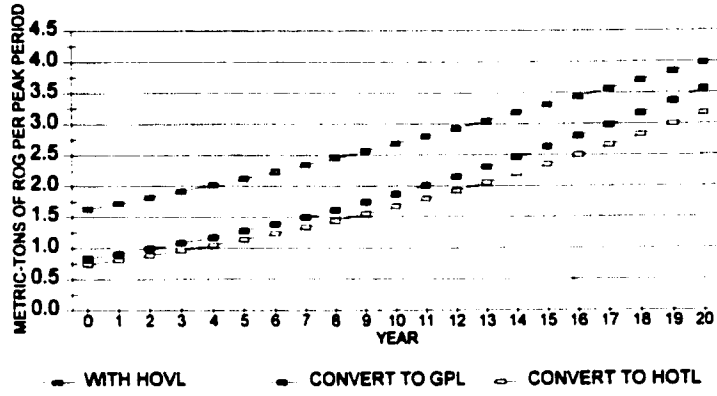
Figure 6.5 shows the trend in emissions per peak period for the cases described above from year 0 to year 20. To represent the most conservative of possible outcomes, I assume constant 2000 emissions factors throughout the 20 year period and make no attempt to predict improvements in light-duty tailpipe emissions based on light-duty vehicle fleet turnover, technology-forcing regulations, or overall improvements in automotive technology. The growth in traffic each year is assumed to be .01.

The graphs for ROG, NOx, and CO emissions per peak period show the same general trend with emissions lowest for the “Convert to Toll Lane” case and highest for the baseline “no action” HOVL case. With respect to ROG emissions, it takes until year 10 to produce emissions per peak period in the “Convert to Toll Lane” case equivalent to the emissions per peak period produce under the baseline “no action” HOVL case in year 0. Over this 10 year period, this represents approximately 2,673 metric-tons of eliminated ROG emissions. In terms of NOx, the “Convert to Toll Lane” case provides the lowest emissions per peak period of the three cases. Converting to toll lane in year 0 would result in the elimination of 271 metric-tons in NOx emissions by year 20. Converting to GPL in year 0 would result in the elimination of 210 metric-tons by year 20. This analysis may underestimate actual emissions because latent demand effects are not explicitly included in behavioral model.

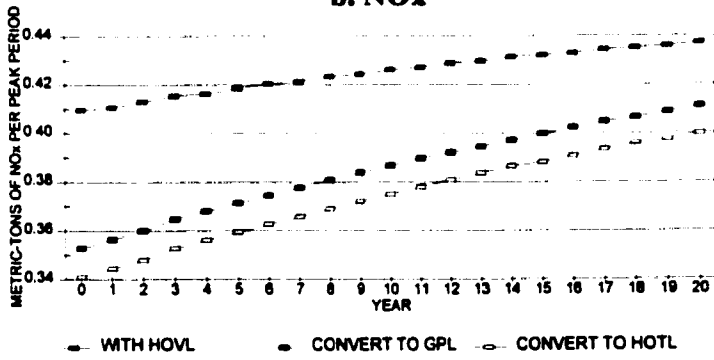
In terms of CO, it also takes until year 10 to produce emissions per peak period in the “Convert to Toll Lane” case equivalent to the emissions per peak period produce

Figure 6.5 Emission Output

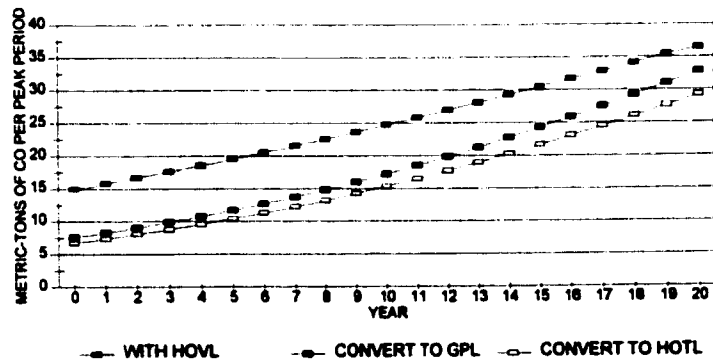
a. ROG



b. NOx



c. CO



under the baseline “no action” HOVL case in year 0. Over this 10 year period, this represents an elimination of 24,699 metric-tons of CO emissions if conversion took place in year 0.

An HOVL with low initial proportion of HOVs induce very marginal reductions in peak vehicle trips and is unable to reduce peak main line delays as effectively as simply adding another GPL. Consequently, the peak delay effects overwhelm any benefits corresponding to the elimination of vehicle trips due to increased ridesharing. When the delay effect predominates, adding a GPL will cause greater reductions in emissions than HOVL additions because it more effectively lessens the duration and intensity of the peak period.

A toll lane provides the largest emissions reductions because it eliminates some vehicle trips (like an HOVL) while reducing congested conditions more effectively than a GPL addition, and partially addresses the effects of latent demand. By optimizing peak lane utilization, a toll lane attracts enough LOVs to lessen congested conditions on the remaining four main line highway lanes without itself contributing to total delay. By contrast, a GPL is subject to queueing delays when maximum delays are large enough that adding a lane does not eliminate congestion. While adding capacity of any kind will reduce the length and intensity of the peak period, total delay is greater in the “Convert to GPL” case because total delay is composed of five main line highway lanes as opposed to the “Convert to Toll Lane” case in which delay is confined to the four pre-existing main line highway lanes. Because emissions are positively correlated with total delay, investments that provide the greatest delay reductions will produce the least amount of

emissions per peak period.

6.4.3 Conclusions

In cases in which there are substantial peak delays and a low initial proportion of HOVs, a toll lane provides greater benefits than a GPL and HOVL. The delay reduction benefits of converting to toll lane become smaller when there is a medium to high initial proportion of HOVs on the HOVL, and peak utilization is good. Over this range of scenarios tested here, converting an HOVL to either toll lane or GPL provides a greater reduction in ROG, NO_x, and CO than the “no action” case – although the difference between a toll lane and GPL is marginal. Even in cases in which toll lanes produce vehicle emissions comparable to HOVLs and GPLs, conversion to toll lane should be considered whenever expected toll revenues exceed annualized capital and operating costs. All other external cost consideration aside, the cost recovery dimension is the singular advantage toll lanes have over unpriced alternatives.

7. CONCLUDING REMARKS

7.1 COMPARATIVE BENEFITS

When an HOVL is added to a congested highway and attracts sufficient HOVs, overall peak delay is reduced because fewer vehicles share space on the highway GPLs. The magnitude of that overall delay reduction depends on the number of HOVs diverted and created, which in turn depends on the initial proportion of HOVs and the propensity of travelers to shift from LOV to HOV as a function of travel time savings. In cases when both the proportion of HOVs is small and the propensity to shift to HOVs is relatively low, adding an HOVL will not reduce overall person-delay as effectively as GPLs and toll lanes.

Certainly, there are instances in which an HOVL with a high initial proportion of HOVs can encourage increased ridesharing and attract as many vehicles as a GPL addition. However, the ability to sustain shifts from LOV to HOV depends on the travel-time differential, which can diminish when an HOVL attracts too many vehicles and peak level of service drops. In other words, there is a self-limiting threshold beyond which an HOVL cannot encourage more ridesharing and reduce overall delays. That threshold appears whenever the HOVL itself becomes congested.

The paradox of HOVLs is that they are best able to encourage ridesharing when there is a low initial proportion in HOVs and the overall delay reductions are comparatively smaller than when a GPL is added. They are least able to encourage ridesharing when there is a high initial proportion of HOVs and peak lane utilization

quickly approaches capacity – in which case overall delay reductions are comparable to a GPL addition (since both alternatives have roughly the same peak volumes). Eligibility based on vehicle occupancy is simply too blunt an instrument to assure optimal peak lane performance in the face of secular growth factors. Too often HOVLs are caught between the Scylla of the ‘empty lane’ lane syndrome and Charybdis of stop-and-go traffic. While there is a range between these two extreme cases in which HOVLs can induce shifts from LOV to SOV and produce substantial overall delay reductions, the overall benefits of trip elimination and delay reduction are almost always smaller than those produced by a toll lane.

One of my main findings is that over a wide range of initial conditions toll lanes using value pricing are inherently better suited to meeting congestion-relief objectives than HOVLs, which must rely on often arbitrary occupancy requirements that are too inflexible an instrument to ration peak lane capacity in the face of traffic growth. The analysis presented in Chapter 6 includes estimates of the present value of toll revenue and time savings benefits, and the cumulative social benefits arising from toll lane implementation are not trivial. The estimated net present value of toll revenue alone exceeds \$50 million over a 20 year project life. The present value of delay reductions for peak non-toll lane users is even larger. Although GPLs appear to provide comparable long-term time savings and emissions reductions benefits to toll lanes, the forfeiture of toll revenue greatly favors the conversion to toll lane from a cost-benefit standpoint.

7.1.1 Situations that Favor No Action

An HOVL will provide greater benefits than a GPL only if the benefits of trip

elimination (due to increased ridesharing) more than offsets the difference in overall delay reduction between a fully utilized GPL and the underutilized HOVL. For a four-lane highway, HOVL benefits are comparable to those of a GPL when initial maximum delay is greater than 30 minutes and the initial proportion of HOVs is between the 15 to 20 percent range. In this case, peak HOVL utilization is high because the initial proportion of HOVs is roughly equal to the amount of new HOVL capacity to total highway capacity. While the HOVL may be subject to periods of sudden stop-and-go conditions, overall it provides a comparable reduction in overall delays as a GPL, and comparable emissions. Such HOVLs should remain as is.

7.1.2 Situations that Favor Conversion

Conversion to General Purpose Use

An HOVL is less effective than a GPL if the benefits of trip elimination (due to increased ridesharing) are less than the difference in overall delay reduction between a fully utilized GPL and the HOVL. This will be the case when peak HOVL utilization is poor and the presence of the HOVL does little to increase ridesharing. Conversion to GPL will produce benefit delay reduction effects when peak flow is below 700 vehicles per hour, the initial proportion of HOVs is between 3 to 7 percent and maximum delays range between 10 to 20 minutes. Under these conditions, conversion will have a negligible adverse impact on ridesharing but produce substantial overall delay reduction benefits by more than doubling peak lane utilization. Conversion to GPL is especially beneficial if the diversion of additional vehicles onto the previously underutilized HOVL eliminates peak delays entirely.

Conversion to Congestion Toll Lane

Over a wide range of possible initial conditions, a congestion toll lane provides greater social benefits than an HOVL. Certainly for those HOVLs with high peak utilization, the delay reduction benefits of converting to toll lane may be negligible. However, for those HOVLs that chronically underperform, the conversion to toll lane will provide three substantial benefits: (1) reduced peak delays on the highway GPLs, (2) the choice to purchase peak time savings, (3) toll revenue. Even in cases when the conversion to toll lane causes a slight reduction in HOVs, dynamic pricing can increase peak lane utilization by optimizing the number of vehicle per peak hour, and by indirectly encouraging carpooling toll lanes can generate greater person throughput than a GPL. Conversion to toll lane is recommended for HOVLs with peak flows below 800 vehicles per lane per hour, an initial proportion of HOVs below 10 percent, and maximum delays ranging between 20 to 45 minutes.

Comparatively, GPLs and toll lanes of comparable size produce roughly the same overall delay reduction and environmental benefits. When considering long-term growth trends, however, the benefits of a toll lane may outweigh a GPL addition because congestion tolling can effectively preserve free-flow, premium service in the midst of worsening corridor traffic conditions. Depending on the severity of induced demand effects and secular growth trends, the short-term delay reduction benefits provided by adding a GPL can be washed out in the long run. Additionally, there is an opportunity cost of adding a GPL equal to the revenue that would have been generated over the service life of the toll lane.

Situations that Favor Conversion to HOTL

To a lesser extent, the same findings generally apply to HOTLs with a few notable cases. To the extent that HOTLs must reserve a proportion of peak lane capacity for HOVs, the net present value of HOTL revenues is lower than toll lane revenues. The magnitude of this difference is a function of the initial proportion of HOVs, and in turn how much peak lane capacity HOVs occupy. Two extreme cases are worth exploring. In the case in which the initial proportion of HOVs is low, the indirect benefits to main-line highway users and the toll revenues are comparable that of pure toll lanes. From a cost-benefit standpoint, HOVLs that are poorly utilized because the initial proportion of HOVs is very low is the best case for conversion to either HOTL or toll lane.

In the other extreme case in which the initial proportion of HOVs is relatively high and the HOVL has good (but still suboptimal) peak lane utilization, the financial benefits of converting to HOTL are significantly smaller than those arising from the conversion to toll lane. Assuming that the conversion to HOTL does not result in an decrease in the initial proportion of HOVs, the high volume of pre-existing HOVs on the HOVLs results a situation in which only a small proportion of peak lane capacity can be sold to LOVs. Were the HOVL converted to toll lane (without the toll exemption for HOVs), the revenue potential and the indirect time savings benefits to peak main-line highway users would be significantly greater than conversion to HOTL.

The case of the I-15 Express Lanes supports the hypothesis that the conversion of an underperforming HOVL to HOTL can result in improved facility performance and substantial revenue-generating potential. Prior to the conversion to HOTL, the I-15

HOVL had a substantial proportion of unused peak capacity. After the conversion to HOTL, there was a substantial increase in the volume of Express Lane passengers per peak hour, and a statistically significant increase in carpooling. If the I-15 carpool lanes were well utilized during the peak, there would have been less justification for converting to HOTL based solely on the fact that peak HOVL utilization is already high, and selling excess peak capacity would not appreciably improve peak performance and generate sufficient revenues. By contrast, the conversion of an HOVL to pure toll lane would generate a much larger revenue stream by charging all vehicles a peak toll. In other words, while not all HOVLs are ideal candidates for HOTLs, they are always viable candidates for toll lanes.

7.1.3 Design Issues

There are several operations issues that must be considered in project identification stage. Non-separated single “diamond lanes” with ingress/egress points located at every interchange are not as desirable toll lane conversion candidates as multi-lane grade-separated express HOVLs with limited ingress/egress points. Because single ‘diamond lanes’ are unable to handle beyond 20 percent of peak vehicles, they are subject to congested conditions when peak flows increase beyond capacity. Vehicles weaving in and out can trigger sudden bottlenecks at recurring interchange locations and affect vehicle flow both on GPLs and toll lane.

Minimum Design Requirements

To prevent toll lane service disruptions, the minimum design standards of a typical HOTL should include:

- at least two standard 12-ft wide highway lanes per direction
- a 6-8 ft wide shoulder
- a buffer separating the HOTL from main line lanes
- limited ingress/egress points
- a variable message sign and electronic toll meter at each ingress/egress point

Along highway corridors with highway directional traffic patterns, one possible approach to converting a single “diamond lane” (per direction) to toll lane service is to borrow the lane in the off-peak direction of the freeway for toll lane use in the peak direction. To minimize safety risks of opposing traffic operating adjacent to the contraflow toll lane, a physical concrete barrier or plastic pylons inserted into holes drilled into the pavement may have to be placed. The contraflow -HOTL concept is currently in use on the I-15 Express Lanes in San Diego County.

Another possibility is to convert an existing GPL and a “diamond lane” to toll lane service. While this scenario provides has the potential to provide a large overall delay reduction (see Section 5.2) and is not prohibited for Interstate projects approved under the value pricing program, the conversion of an existing GPL is highly controversial and is not recommended except in rare cases.

7.2 METHODOLOGICAL ISSUES: BRIDGING THE GAP BETWEEN THEORY & EMPIRICAL ANALYSIS

The validity of the interpretations and findings presented in this dissertation hinge on the assumption that the simple theoretical behavioral model presented in Chapter 4

and elaborated on in Chapter 5 is sufficiently capable of accurately capturing the complex interplay between individual behavioral decisions and shifting travel costs. To be intellectually honest, one must acknowledge the possibility of that the models used in this hypothetical analysis are simply too unwieldy and theoretically cumbersome to suggest a rational course of action based on subtle differences from one alternative to the next. Given the methodological complexity of this analysis, one should exercise caution in interpreting the findings presented herein. After all, these tools are simply not up to the tasks to which we apply them.

While the state-of-the-art in disaggregate travel demand modeling has made tremendous strides over the last thirty years in applying consumer utility theory to the question of travel behavior, in many respects the state-of-the-art fundamentally cannot allow decisionmakers to quantify all the social costs arising from a given investment alternative, given the multitude, subtlety and complexity of imperceptible behavioral adjustment of thousands of individual decisionmakers over a given roadway network. Discrete choice models can yield statistically valid parameter estimates of a range of variables, and estimate the probability of discrete outcomes for a given population, but these tools simply cannot allow the decisionmaker to peer into the future and inform good planning practice through the discovery of universal notions that have equal relevance in locations, and in all contexts.

The author makes no attempt to mollify such criticism, since that kernel of Cartesian doubt is at the very essence of this hypothetical theoretical exercise. Although I attempt to leaven its plausibility by sprinkling the analysis with empirical insights on the

few case studies that do exist, the findings must, in the end, rest squarely on the myriad of suppositions and assumptions that gird its theoretical foundation.

New traffic simulation models however are allowing researchers to model traffic networks of unprecedented complexity and scale. New models like TRANSIMS, currently being developed at Los Alamos National Laboratories as part of the U.S. Department of Transportation's Travel Model Improvement Program (TMIP), will allow analysts to evaluate the behavioral impacts of minor modifications to an existing transportation network on a scale much larger than a highway corridor. It is my hope that these state-of-the-art modeling tools can help decisionmakers to evaluate the impact of new investment choices like congestion toll lanes in regions where there is a political consensus in favor of exploring innovative solutions to age-old commons problems.

7.3 DIRECTIONS FOR FUTURE RESEARCH

There are several research frontiers that need further exploration. First and foremost, very little is known about the network effects of adding a congestion toll lane system within a metropolitan region. If congestion toll lanes provide substantial delay reduction benefits in a simulated corridor setting, the development of a toll lane network in highly congested regions like the Los Angeles metropolitan area with an extensive highway system could produce beneficial network effects. Modeling tools like TRANSIMS can analyze the equilibrium effects of building a congestion toll lane network within a larger highway system, and such models can readily consider latent demand effects, incorporate value-of-travel-time-savings (VTTS) estimates, and weigh project-specific cost functions to provide a comparative snapshots of competing

investment alternatives.

Second, preliminary evidence from the 91 Express Lanes suggests that the toll lanes have drastically improved traffic conditions on the adjacent highway lanes, and that there is a new equilibrium in which peak travel times on the main line highway lanes have remained stable in the face of consistent growth in SR-91 corridor ADT. This finding seems to suggest that congestion toll lanes are capable of alleviating conditions of latent demand and short-circuiting the reemergence of congestion conditions that accompany latent demand effects. More research needs to be conducted on this intriguing and important question.

Finally, new emissions models must be periodically modified and updated in order to provide more accurate emissions comparisons between congestion toll lanes and currently favored alternatives. These models are the analytical basis for assessing whether or not congestion toll lanes conform to the quantitative emissions reduction targets described in transportation implementation plans for federal air quality nonattainment areas. While this research provides some preliminary evidence suggesting that congestion toll lanes can meet emissions objectives by improving peak traffic conditions and lowering highway delays, its effects of long-term VMT are unknown and must be investigated using more sophisticated modeling techniques.

7.4 THE POLITICS OF TOLLING

In spite of access to the good analysis, decisionmakers who privately place great emphasis on sound analytical judgment must weigh support for new investment decisions, legal changes and new programs within the context of the political

environment within which the policy agenda is both formulated and prioritized. The historical failure of congestion pricing as a policy alternative to the existing system of federal and state highway finance is a testimony to this unassailable reality, which – depending on one’s perspective – is either a good or bad thing. From the voter’s perspective, it is a good thing that minor policy changes are adopted incrementally and within the context of a representative democracy that lends authenticity to those new programs and initiatives that produce clear benefits for all, and concentrates the economic hardship on the few. Fundamentally changing the way we price automobile travel is simply too radical a notion for most. From the technocrat’s perspective, collectively irrational outcomes are inevitable whenever interest group politics has the institutional power to undermine policy changes that offer the most effective means of aligning the collective good with individual self-interest, and solving commons problems that, by definition, do not have technical solutions.

My position is that the polemical debate over the social equity of toll lanes – whether they be implemented as part of a comprehensive congestion management strategy or as a last-ditch effort to finance new highway capacity – will continue to overwhelm the merits of toll lanes justified on efficiency grounds. In the provision of public facilities, most people prefer the democratic vagaries of congestion-for-all to the tyranny of premium service-for-the-Lexus-driving-dot.com-elite. In other words, the collectively irrational outcome of traffic congestion is tolerable insofar as it is fairest of all possible worlds. In the 21st century, few new toll lane projects will be programmed, planned and built except under extraordinary conditions. By and large, Americans will

continue to object to the notion that the freedom to travel should in any way be encumbered by tolls, even if in exchange they might receive a precious few extra minutes each day. This is the conundrum within which congestion toll lane concept is tightly wrapped.

Another matter complicating toll lane implementation is the uncertainty surrounding public/private partnerships and possible abuses of the public trust. Prior to the botched sale attempt of the 91 Express Lanes in September 1999, state and local officials viewed the privatization model under AB680 as a potentially viable method of bridging the financial gap between the mobility needs of rapidly growing communities and lack of public funding. That optimism has since been shattered, perhaps irrevocably.

The controversy over the failed sale has highlighted several key problems areas: (a) the design of the franchise agreement, (b) the procedure governing transfer of sale, and (c) eligibility for bond finance through the state infrastructure bank.¹ CPTC's ability to exploit each of these unforeseen loopholes – which nearly resulted in a \$90 million windfall profit on an initial investment of \$10 million – ended up costing CPTC all the public goodwill it so diligently cultivated since 1995. The extent to which the public

1

Critics have assailed Caltrans for including a noncompetition clause in the franchise agreement allowing CPTC to veto any capital improvements to the adjacent SR-91 highway facility that CPTC believes threatens the profitability of the toll road. Since 1998, local residents have expressed increasing dissatisfaction with an alarming growth residential residential traffic around the SR-91 highway corridor, and are outraged that Caltrans agreed to forfeit the state's right to make improvements when threatened by a lawsuit CPTC initiated to pressure Caltrans into approving the sale (Kindy, Orange County Register, February 13, 2000).

backlash generated against roadway privatization has altered the public perception of congestion toll roads in general remains to be seen. The disappointing financial performance of the 91 Express Lanes may lend credence to the claim that privatization is not necessary the most appropriate program design for congestion toll lanes. As a roadway innovation, however, its significance in providing congestion relief can hardly be overstated. From a policy standpoint, the 91 Express Lanes have served an important policy function by demonstrating the efficiencies of automated toll road service and congestion pricing, and singlehandedly bridging the great divide between theory and practice. There is currently a strong interest among Riverside County in purchasing the 91 Express Lanes, and operating them through a joint-powers public agency whose governing board consists of locally elected officials – which suggests that the elected officials are voters are distinguishing the merits of congestion toll lane service from the institutional setting within which such projects are implemented. The goal of this dissertation is to provide a small but meaningful contribution to the debate over whether congestion toll lanes can overcome the shortcomings in HOVL performance. This is but a minor policy question within a larger, value-laden political context.

7.5 POLICY RECOMMENDATIONS

The federal regulatory regime under which states and localities plan, finance and implement resurfacing, restoring, rehabilitating and reconstructing (4R) interstate highways is composed of numerous programmatic guidelines making federal matching funds contingent on the adoption of congestion management plans that conform to air quality improvement goals. Under the Interstate Highway System Maintenance (IM)

program, for example, states with air quality non-attainment areas are prohibited from programming IM matching funds for GPL addition improvements [Section 119(d), Title 23, USC]. HOVLs have served as expedient alternatives to GPL additions because they simultaneously fulfill numerous regulatory, funding, and cost objectives, but continued public debate over the merits of continued HOVL expansion has caused policymakers to consider alternative treatments, in some instances in direct opposition to federal law. More research is needed to estimate the impact of converting an HOVL to toll lane on (1) vehicle miles of travel, and (2) emissions.

Under the Clean Air Act (CAA) of 1990 and its amendments in 1997, metropolitan planning organizations (MPOs) are required to develop and submit a transportation implementation plan (TIP) – which includes estimates of total emissions (based on recent population, employment, and travel forecasts) arising from new projects and programs – and must assure that the elements within the TIP conform to federal air quality standards for air quality nonattainment areas. CAA stipulates that the federal government may not provide financial assistance for planning activities that do not conform to the TIP, nor can MPOs approve plans that do not conform to the pre-approved TIP.

New projects however may be found to be in conformity with a pre-approved TIPs if the emissions expected from implementation of such plans are consistent with the emissions estimates and necessary emissions reductions already contained in the TIP. If an MPO can provide evidence that congestion toll lane projects meet the legal definition of a transportation control measure (TCM), congestion toll lanes can be included, and,

potentially replace HOVLs as an allowable project within a given transportation improvement plan. Already there is movement in this direction. The Southern California Association of Governments has included toll lane projects in its 1998 Regional Transportation Improvement Plan (RTIP). While CAA clearly provides legal room for states and regions to develop innovation plans that can be proven to conform with pre-existing implementation plans, it is the responsibility of MPOs to provide more empirical support for the belief that congestion toll lanes can further the goal of environmental improvement. More research and better models need to be developed to inform decisionmakers interested implementing toll lanes where few other highway alternatives are available.

Under the TEA-21, which provides states with greater flexibility in transferring apportionments between various programs than under ISTEA, the partial lifting of the federal ban on toll on interstate highways may provide an opportunity to program congestion-relief improvements that do not disqualify recipient states from receiving apportionments under the IM, Congestion Mitigation Air Quality (CMAQ) and Surface Transportation programs (STP). Unlike the case described above, efforts to toll HOVLs are eligible for federal support under the IM program and have received federal recognition as a legitimate approach to traffic management. The funding programs and provisions under TEA-21 allowing tolling on interstates are outlined below.

7.5.1 Interstate Tolling Under TEA-21

Before the passage of the landmark Transportation Efficiency Act for the 21st Century (TEA-21) in 1998, federal law prohibited states from applying tolls on interstate

highways. To assist local efforts to establish road pricing programs, Congress included a congestion pricing demonstration program in ISTEA that gave FHWA the authority to exempt interstate facilities identified in proposal accepted under the program. However, ISTEA continued the general ban on interstate tolling. Under ISTEA's demonstration program, FHWA funded ten projects and disbursed over \$30 million in support of project costs, administrative coordination and regional pricing workshops.

Under TEA-21, there is a provision that for the first time allows for reconstruction or rehabilitation of a free Interstate highway segment and its conversion to a toll highway for up to three pilot projects (FHWA 1998). While this is a relatively minor provision, it represents a fundamental shift in federal policy. The stated purpose of the provision is to facilitate improvements on Interstate highways where the costs exceed available funding and improvements cannot take place without the collection of tolls. States can accumulate toll revenue credits to be applied to the non-Federal share of eligible highway projects (FHWA 1998).

If the pilot projects demonstrate that conversion of urban Interstate highway to toll highway successfully achieves stated objectives, Congress should give serious consideration to expanding the number of pilot projects or simply assigning states the authority to determine whether it should convert Interstate highways to toll highways if such actions are (a) in conformance with existing implementation plans, and (b) tolling can facilitate immediate improvements where capital costs exceed existing available funding. Assuming the formula for apportioning IM funds to states does not change, granting states the authority to toll Interstate highways will not drastically affect the

annual apportionment of IM funds.² To the extent that tolling on Interstate highway may free up some IM funds, the provision allowing up to 50 percent apportionment of IM funds to transferred to NHS, STP, and CMAQ programs may provide increased funding for enhancements, congestion mitigation, and multimodal projects.

7.5.2 Expand Value Pricing Demonstration Program

The Value Pricing Pilot program under TEA-21 provides authorizations totaling \$51 million for FYs 1999-2003 for up to 15 new value pricing projects.³ A value pricing project under this program may involve tolling on Interstate highway segments and does not preclude the use of tolls on highway GPLs. In a direct reference to toll lane conversion efforts, the provision specifies that the implementing agency may permit vehicles with fewer than two occupants to operate in high occupancy vehicle lanes if the subject facility is part of a value pricing program (FWHA 1999).⁴

2

33.3% of IM funds are based on total Interstate lane miles in each State as a percentage of the total Interstate lane miles in all states. 33.3% is based on the total VMT on Interstate routes as a percentage of total VMT on all Interstate highways. 33.3% is based on the total of each State's annual contribution to the Highway Account of the Highway Trust Fund as a percentage of the total annual contribution in all states. During the term of a pilot Interstate toll project, IM funds cannot be used on the portion of Interstate route where tolls are being collected.

3

Funding is provided in support of pre-implementation costs, public participation costs, pre-project planning and the funding period lasts three years from the time the project is implemented.

4

The implementing agency is required to consider the equity impacts of value pricing projects on low-income traveler and develop mitigation measures to address adverse financial impacts on low-income travelers.

Awards are based on the following eligibility criteria:

- **the condition and usage of the existing Interstate facility**
- **interagency coordination with the local MPO**
- **evidence demonstrating that the Interstate facility cannot be maintained or improved with the use of tolls**
- **a comprehensive management and financial plan**

The Interstate highway that is part of the value pricing program is eligible for IM funds after the 10 year term limit.

There may be some justification for placing the value pricing demonstration program within the CMAQ program, and raising the cap from 15 to 30 projects nationally. Congestion toll lanes are arguably the most effective means of congestion mitigation currently available. Based on the research presented here, they offer the greatest potential for providing long-term congested mitigation, while offering comparable emissions impacts to HOVLS. Under the CMAQ program, states with air quality nonattainment areas could tap CMAQ funds cover the federal share of costs for new toll lane projects they would otherwise be ineligible to receive.

7.5.3 State and Local Regulations

With increased federal support for tolling initiatives, states and regions have taken inventory of highway improvement projects and begun to identify tolling projects where such efforts are best able to meet stated objectives and garner public support. In California, SCAG has identified the Antelope Valley (SR-14) freeway as a candidate toll lane projects in the 1998 RTIP for the Los Angeles metropolitan area. In Texas, Florida,

Minnesota and Washington, similar efforts are being undertaken in the development of transportation management plans. State legislatures must pass enabling legislation authorizing local MPOs and state DOTs to convert GPLs into toll lanes. Because tolling is controversial, a precondition to legislative support is strong local support. Where there is dissatisfaction with HOVL performance, state legislatures have turned to toll lanes as possible alternatives. Assuming MPOs can convince FHWA and EPA that congestion toll lanes facilitate conformance with existing regional improvements plans in air quality nonattainment areas, state legislatures may acquiesce to regions who can justify the need for innovative solutions to traffic problems.

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