Managing Limited Access Highways for High Performance: Costs, Benefits, and Revenues

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Abstract

Managed lanes are a set of lanes where highway operations strategies are actively applied in response to changing conditions. High-Occupancy/Toll (HOT) and Express Toll lanes are examples of managed lanes. The transportation operations concept discussed in this article involves conversion of existing freeways (all lanes) into premium-service free-flowing highways that provide fast, frequent, and inexpensive express bus service and charge all private vehicles a variable toll—except for authorized buses and certified ridesharing vehicles. The toll would vary by level of demand and would be set high enough to guarantee that excessive demand will not cause a breakdown of traffic flow. This article discusses the advantages of this concept. It introduces a new sketch-planning tool that provides estimates of costs, benefits, and revenues from applying the concept on a highway network in a prototypical large metropolitan area. The estimates suggest that implementing the concept can provide significant net social benefits. It may also generate sufficient new toll revenue to pay for all costs for implementation and operation, including new express bus and park-and-ride services that would complement the pricing scheme.

The views expressed in this article are those of the author and not necessarily those of the U.S. Department of Transportation or the Federal Highway Administration.

Introduction

Growing congestion on metropolitan highway networks poses a substantial threat to the U.S. economy and to the quality of life of millions of Americans. In the short term, congestion pricing—also known as value pricing—can relieve traffic congestion and reduce the waste associated with it. In the United States, several congestion pricing projects have been implemented involving separated lanes on freeways called High-Occupancy/Toll (HOT) lanes, in which demand is managed using variable tolls. Congestion pricing involves "open-road" tolling, or no toll booths. All tolls are collected electronically at highway speeds.

This article introduces a comprehensive pricing concept termed "Super HOT" transportation. It discusses the Super HOT concept, its advantages, the benefits and revenues from establishing a Super HOT transportation network in a prototypical major metropolitan area, and its costs and financial feasibility.

The Super HOT Transportation Concept

Role of Congestion Pricing

Once freeway traffic exceeds a certain threshold level (measured in terms of flow of vehicles per lane per hour, or in terms of density of vehicles per mile), both vehicle speed and vehicle throughput drop precipitously. Data show that maximum vehicle throughput occurs at speeds of about 45 mph to 55 mph (Chen and Varaiya 2002). When severe congestion sets in, the number of vehicles that get through per hour can drop by as much as 50 percent, while speeds drop to "crawl" speeds of 15 to 20 mph (Chen and Varaiya 2002). At high vehicle densities, traffic bogs down due to traffic demand exceeding the supply of road space. Traffic flow is kept in this condition of "collapse" for several hours after the rush of commuters has stopped. This causes further delay for motorists who arrive later in the day.

With peak-period highway pricing, a variable toll dissuades some motorists from using limited access highways (generally freeways) at critical locations where traffic demand is high, and where surges in demand may push the highway over the threshold at which traffic flow collapses. Pricing prevents a breakdown of traffic flow in the first instance, and thus maintains a high level of vehicle speed and throughput throughout the rush hours. Collapse of traffic flow from overcrowding is avoided. Not only are *more* motorists able get to their destinations during each hour—they also get there *faster*. Each priced lane in the median of State Route 91 in Orange County, California (on which traffic flow is managed using variable tolls) carries twice as many vehicles per lane as the adjacent toll-free lanes during the hour with heaviest traffic (U.S. Department of Transportation 2005). Management of traffic flow through pricing has allowed twice as many vehicles to be served per lane at three to four times the speed on the free lanes.

Currently, U.S. freeway systems use congestion delay as a way to ration scarce road space during rush hours. Delay imposes huge social costs on the traveling public and on the economy, and is an extremely wasteful way to allocate scarce road space. If freeway road space were instead rationed using variable tolls, the revenue generated would simply be a transfer of resources from motorists to the highway operator, and would not be a waste. The revenue could be used to generate further benefits for commuters or to reduce taxes. Unlike taxes, the toll revenue would be obtained from travelers willing to pay to get a direct benefit in return—the reduced waste of their time. By reliably preventing traffic flow breakdown and thereby ensuring a predictable trip travel time, freeway pricing would also reduce the "buffer" time that commuters must otherwise plan into their schedules. It would reduce fuel consumption and emissions, and reduce diversion of traffic to alternate routes where they may cause further congestion.

It might appear counterintuitive that imposing a new toll on a currently free road can actually reduce traffic on parallel facilities. Figure 1 and Table 1 attempt to demonstrate how this may happen. Figure 1 shows the magnitude of the waste of time and vehicle capacity that occurs when traffic flow breaks down on the four eastbound lanes of I-66 outside the Capital Beltway in Northern Virginia, inbound toward Washington, D.C. Traffic flows freely up to 7am. In the one-hour period between 6 and 7am, 8,000 vehicles are carried at an average speed of 55 mph. Traffic flow breaks down between 7 and 8am, with speeds dropping to 30 mph and vehicle throughput dropping to 7,000 vehicles. From 8 to 9am, throughput drops further to 6,000 vehicles, and average speed drops further to 25 mph. The reduced flow of 6,000 vehicles per hour continues between 9am and 10am, with speed increasing slightly to 30 mph. Table 1 provides estimates of time wasted, and the potential value of time savings on the freeway if free flow of traffic could be maintained. As much as $10 million annually could be saved on the 10-mile eastbound freeway segment with good traffic flow management in the morning peak period. Table 1 also shows that after accommodating the 19,000 existing users of the eastbound freeway who travel during the 7 to 10am period, there will be spare capacity of up to 5,000 vehicles available for use from 9 to 10am. This available capacity will draw drivers from alternative routes and from other times of the day (i.e., those who currently try to avoid congestion on the freeway). Thus, pricing the freeway to maximize throughput will reduce traffic levels on alternative routes and at other times of the day.

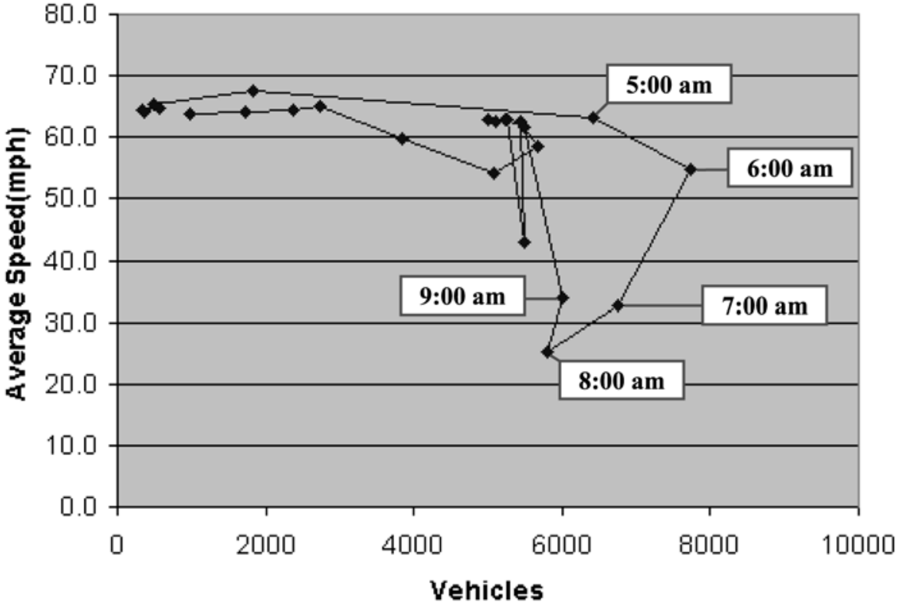
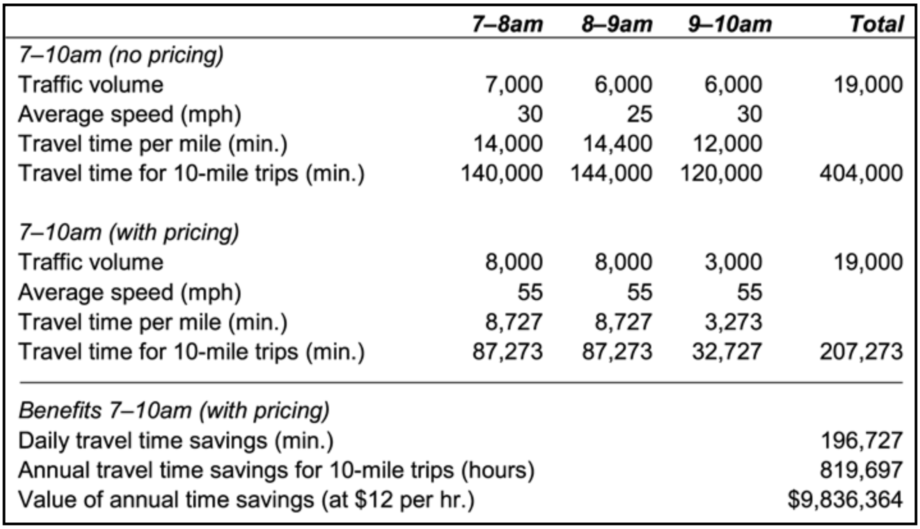


Figure 1. Traffic Volumes and Speeds on I-66 Eastbound in Northern Virginia (Four Lanes, Morning Peak Period)

It takes only a small reduction in traffic demand at critical times during the peak period to restore free flow. Motorists in Washington, D.C. experience free-flowing traffic during rush hours in August, with only a small fraction of workers away on vacation and less than a 10 percent drop in peak-period traffic volumes. Similar experiences are reported in metropolitan areas in California on state holidays, when only state employees are off work. So the key is to shift a few rush-hour travelers to other modes or to other times of travel. Estimates of transit price cross-elasticity with respect to driving demand range from 0.025 to 0.056 (Glaister and Lewis 1978). Long-term elasticities tend to be much higher (Lee 2000) due to the ability of travelers to respond through changes in job or residential location in the longer term. This suggests that a 5 percent reduction in driving could be achieved by a combination of reductions in transit fares and travel time. With free-flowing

Table 1. Potential Impacts of Congestion Pricing on I-66 Eastbound



	7–8am	*8–9am*	*9–10am*	*Total*
7–10am (no pricing)				
Traffic volume	7,000	6,000	6,000	19,000
Average speed (mph)	30	25	30	
Travel time per mile (min.)	14,000	14,400	12,000	
Travel time for 10-mile trips (min.)	140,000	144,000	120,000	404,000
7–10am (with pricing)				
Traffic volume	8,000	8,000	3,000	19,000
Average speed (mph)	55	55	55	
Travel time per mile (min.)	8,727	8,727	3,273	
Travel time for 10-mile trips (min.)	87,273	87,273	32,727	207,273
Benefits 7–10am (with pricing)				
Daily travel time savings (min.)				196,727
Annual travel time savings for 10-mile trips (hours)				819,697
Value of annual time savings (at $12 per hr.)				$9,836,364

freeways, the entire freeway network could serve as a transit “fixed guideway,” providing travel time advantages for express bus services.

Additional reductions could be achieved through an increase in carpooling, vanpooling, flextime, and telecommuting. If freeways were free flowing, the entire freeway network could serve as a virtual HOV network that provides toll-free service to vanpools and carpools certified by employers or the metropolitan ridesharing agency. (Certification of ridesharing vehicles avoids the need for on-highway enforcement of occupancy requirements, which can be difficult to accomplish and may disrupt the flow of traffic). HOVs would have a time advantage, providing an inducement for mode shifts to HOVs. Based on before and after data from 10 HOV lane projects implemented in the United States, Richard H. Pratt, Consultant, Inc. et al. (2000) estimate that HOV lanes result in an increase of 14 percent in average vehicle occupancy for autos, carpools, and vanpools over *all* lanes of the freeway. This is equivalent to a 12.3 percent reduction in driving.

It is also important that area employees have flexibility to travel at less busy times or to telecommute. Employers could be encouraged to provide such flexibility for their employees, perhaps by setting target levels for the share of flextime and telecommuting employees for employer-certified carpools to get toll exemptions. Other motivations, such as tax incentives, may also be used.

Preserving Motorist Choice

A pricing strategy would need to address two key issues:

1. The public is opposed to having no choice but to pay for a service that they have been getting for free. So a pricing scheme may need to preserve the motorist's choice not to pay. A toll-free choice, with the same amount of motorist delay as before (or less), will be desirable, similar to the free lanes adjacent to HOT lanes.

2. The toll price will need to be high enough that the total user-borne cost to drive on a priced highway (i.e., time cost plus toll cost) will not be lower than the user-borne cost to drive prior to pricing (i.e., time cost only). If the perceived user-borne cost were lower after implementing pricing, the inducement to drive could increase, endangering the free flow of traffic. To counter this effect, increased inducements would then need to be provided for other modes to compete effectively with driving.

In the priced lane projects implemented in the United States to date, motorists have a choice not to pay tolls and suffer congestion delays in the adjacent toll-free lanes. The advantage of this approach is that no driver is made worse off. The limitation is the huge waste of time that continues on the free lanes when traffic flow breaks down.

Economics Nobel Prize winner William Vickrey suggested a way to preserve the motorist's choice *not* to pay on a priced highway by creating a toll-free bypass around toll gantries placed across all existing lanes of the roadway. Motorists who choose to do so can wait in a queue in the toll-bypass lane and pay a "time" price equivalent to their previous congestion delay time. This solution by itself will not work, because releasing queued vehicles after they have waited in line for the required time period would cause traffic flow to break down. It would simply delay the onset of congestion by a few minutes. But if the required reduction in driving demand during the critical period is achieved by mode shifts or shifts in time of travel, all remaining vehicles could be accommodated at free flow. Thus, to begin with the queue delay in the bypass lane might be zero. But this would not last long. As drivers notice the shortness of the queue delay, they would shift to the toll-bypass lane, until the time delay in the queue would be equivalent to the value of the (dynamically varying) toll in effect at the time. The two would be in equilibrium.

The length of the toll-bypass lane would depend on the toll rate and corresponding "time" price in effect, and the queue discharge rate. For example, if the toll were \$1 and the value of time of freeway travelers were 20 cents per minute (i.e., \$12 per hour), the "time" price in the toll-bypass lane would be 5 minutes. If the queue discharge rate were 15 vehicles per minute, the total number of vehicles to be accommodated in the toll-bypass lane would be 75 vehicles.

System Operation

Super HOT system operation would involve conversion of *all* lanes on existing freeways into premium-service free-flowing freeways that provide fast, frequent, and inexpensive express bus service. All vehicles, except authorized buses and certified ridesharing vehicles, would be charged a variable toll set high enough to guarantee that high demand will not cause a breakdown of traffic flow. Tolls would be charged during congested periods only.

A peak-period commuter would have several options:

- Pay a relatively low toll for the convenience of driving alone in free-flowing traffic on the Super HOT highway system.
- Join a carpool or vanpool and enjoy a fast trip on the Super HOT highway system for an even lower price by sharing the cost of the toll, or drive for free in an employer-certified or ridesharing agency-certified carpool or vanpool.
- Use newly expanded, faster and more convenient transit services provided by express buses that run on the Super HOT highway system.
- Drive alone for free, either on the arterial street system (which would be enhanced with advanced traffic signal optimization), or on the freeway by using toll-bypass lanes constructed in advance of toll gantries. The toll-bypass lanes would allow motorists to pay a "time" price in lieu of a toll, by waiting in the toll-free queue.

Licensed drivers in the area covered by the priced network, on request, could be issued an inexpensive electronic transponder (e.g., a "sticker" tag) free of charge, along with a transportation account. Nonresidents could purchase the tags at retail outlets such as 7-Elevens, or from ATM-like machines at welcome stations located at approaches to the metropolitan area. Those not having transponders could be "video-tolled," meaning that cameras would take pictures of their license plates, and the vehicle owner would be billed for the toll plus a small administrative charge to cover the extra costs. For example, on November 1, 2006, the

Florida Turnpike Enterprise, in conjunction with the Tampa Hillsborough County Expressway Authority, launched a "Pay-by-Plate" system, the first video-toll account system in the United States. Customers who are occasional users of the Lee Roy Selmon Crosstown Expressway (between Tampa and Brandon, Florida), and do not have a transponder, can call a toll-free number to open an account. They pay a toll of $1.25 (instead of $1.00 for those with transponders) to cover costs to process the license plate images.

Ramp meters could be used on freeway entrance ramps to ensure that merging of incoming traffic does not break down mainline traffic flow, and to discourage short trips on the freeway on sections where there may not be a toll gantry.

To ensure premium service for buses and carpools when lane blockages occur as a result of an incident, overhead lane controls would be installed. The lane controls would provide priority for buses and certified HOVs during incidents. A clear lane would be designated for use only by buses and certified HOVs. If there is spare capacity available in the lane, it could be opened up to other vehicles for a premium toll set high enough to ensure that the traffic in the lane continues to flow freely. Vehicles in other lanes that do not get service at the guaranteed speed, due to the incident, would get an automatic refund on tolls paid.

Addressing Traffic Diversion Concerns

When toll rates are raised on existing tollways, some drivers divert to toll-free arterials or surface streets to avoid paying the higher tolls. However, unlike conventional tollways, priced highways provide many more travel options. A Super HOT system would have several differences relative to tollways. These differences would reduce the potential for traffic diversion to parallel toll-free facilities.

First, variable tolls would provide options to motorists to reduce or eliminate their costs for new tolls by shifting their time of travel. In the case of tollways with flat tolls all day, drivers cannot escape tolls or avail themselves of a lower toll rate simply by traveling at a different time.

Second, introduction of variable tolls during congested periods would be accompanied by high-quality transit services and expanded availability of enhanced carpool and vanpool options on free-flowing "virtual" HOV networks, so that some solo drivers would shift to using transit, vanpools, or carpools, rather than diverting to parallel toll-free roadways.

Third, those who are not willing to pay the toll would have an option to wait in a toll-bypass lane and get a high-speed, predictable trip time for free. Wait times on the toll-bypass lanes can be expected to be lower than delays on alternative routes. Thus, there would be no incentive to divert from the freeway.

Fourth, when pricing is introduced on previously congested highways, some motorists who had been deterred by freeway congestion and had diverted to parallel arterials may shift back to the free-flowing priced highways, which would accommodate higher rush-hour traffic volumes in a shorter period of time, as explained previously with the I-66 example. Despite this shift from arterials, however, as long as parallel arterials remain toll free, new motorists (e.g., those who shift from other less convenient times of travel) can be expected to take the place of any traffic that shifts from the arterials to the priced highways. Thus, while total hourly vehicle and person trip throughput in the corridor may increase, severity of arterial congestion cannot be expected to improve significantly during key congested periods. However, the *duration* of congestion (i.e., the length of the congested period) can be expected to be shortened. For example, the availability of spare capacity on I-66 from 9am to 10am will draw traffic from parallel arterials, reducing congestion on the arterials during that hour.

Finally, if toll revenues are used to pay for optimizing traffic signal controls on parallel arterials (in cases where they may not currently be optimized), this could help to further improve traffic flow on them.

Advantages of a Super HOT Transportation System

An entire metropolitan Super HOT network can be put in place in a relatively short period of time. Time-consuming and lengthy environmental review processes generally associated with freeway widening projects will not delay implementation. Some new investment will be needed for the initial shoulder bus lanes, toll-bypass lanes, management and operation of the freeway and arterial networks, new express bus and vanpool services, and new park-and-ride facilities. However, these will not require the extent of environmental review normally necessary for road-widening projects.

The Super HOT concept has several advantages over the managed lane approach. Since all lanes would be priced, there would be no need for additional rights-of-way and pavement for barrier or buffer separation between priced lanes and toll-free general-purpose lanes. Neither would expensive connector ramps be needed for efficient movement of priced vehicles through busy freeway interchanges. All lanes would be available for use by all vehicles. This would maximize motorists' freedom to switch lanes and consequently maximize highway capacity. A slower moving vehicle in a separated single lane causes a gap to build up in front of it, reducing vehicle throughput. Additionally, vehicle throughput *per lane* is lower when fewer adjacent lanes are available for use by all traffic, since drivers of faster vehicles find it more difficult to switch lanes and overtake slower vehicles to occupy large gaps between vehicles.

Super HOT highways would allow direct access to premium service lanes from *all* existing freeway entrance ramps. They would avoid the need for traffic to merge into and out of priced lanes from adjacent general-purpose lanes. Such weaving movements are inconvenient for buses and for motorists, and reduce safety and highway capacity on the free lanes.

With Super HOT highways, much more premium service capacity would be available on multiple lanes. Therefore, relatively lower toll rates would be sufficient to ensure that traffic demand does not rise above available capacity. This would make use of the highway more affordable to a larger population of middle- and lower-income motorists. And those who cannot afford the toll nor shift their mode or time of travel would be no worse off than before, since they could choose a toll-bypass lane and pay a "time" price no higher than their previous delay time, to get free-flowing service on the freeway in return.

Finally, with a Super HOT system, *all* lanes are congestion free.

Benefits and Revenues

A sketch-planning tool, Tool for Rush-hour User Charge Evaluation (TRUCE), was developed by the author to assist in the estimation of the potential impacts of a Super HOT transportation facility or network, in particular the costs, benefits, and revenues.

Two scenarios were assessed, representing a range of congestion levels on freeway networks in major metropolitan areas in the United States. These scenarios were evaluated for a prototypical area (either an entire metropolitan area or a significant portion of a major metropolitan area) with approximately 1.0 million drivers and an existing 100-mile freeway network comprising a total of 600 lane miles (i.e., freeways with an average of 6 lanes; 3 lanes in each direction). The scenarios are as follow:

1. *A moderately congested freeway network*, with an average peak-period speed of 40 mph and a total of 4 hours of congestion per day (i.e., about 2 hours in the morning and about 2 hours in the afternoon). Note that the "average" speed of 40 mph represents a composite of quite high traffic speeds on some segments of the network and much lower speeds on other segments. For example, if half of all vehicles travel at a speed of 60 mph (i.e., 1 minute to travel 1 mile) and the other half travel at a speed of 30 mph (i.e., 2 minutes to travel 1 mile), the average speed of all vehicles would be 40 mph (i.e., 1.5 minutes to travel 1 mile). Assuming a free-flow freeway speed of 60 mph, this scenario represents a peak-period "travel time index" of 1.5 (i.e., ratio of average peak-period travel time to free-flow travel time; Texas Transportation Institute 2005).
2. *An extremely congested freeway network*, with average peak-period speeds of 30 mph and a total of 6 hours of congestion per day (i.e., about 2.5 hours in the morning and about 3.5 hours in the afternoon). For example, if half of all vehicles travel at a speed of 60 mph (i.e., 1 minute to travel 1 mile) and the other half travel at a speed of 20 mph (i.e., 3 minutes to travel 1 mile), the average speed of all vehicles would be 30 mph (i.e., 2 minutes to travel 1 mile). This scenario represents a peak-period "travel time index" of 2.0.

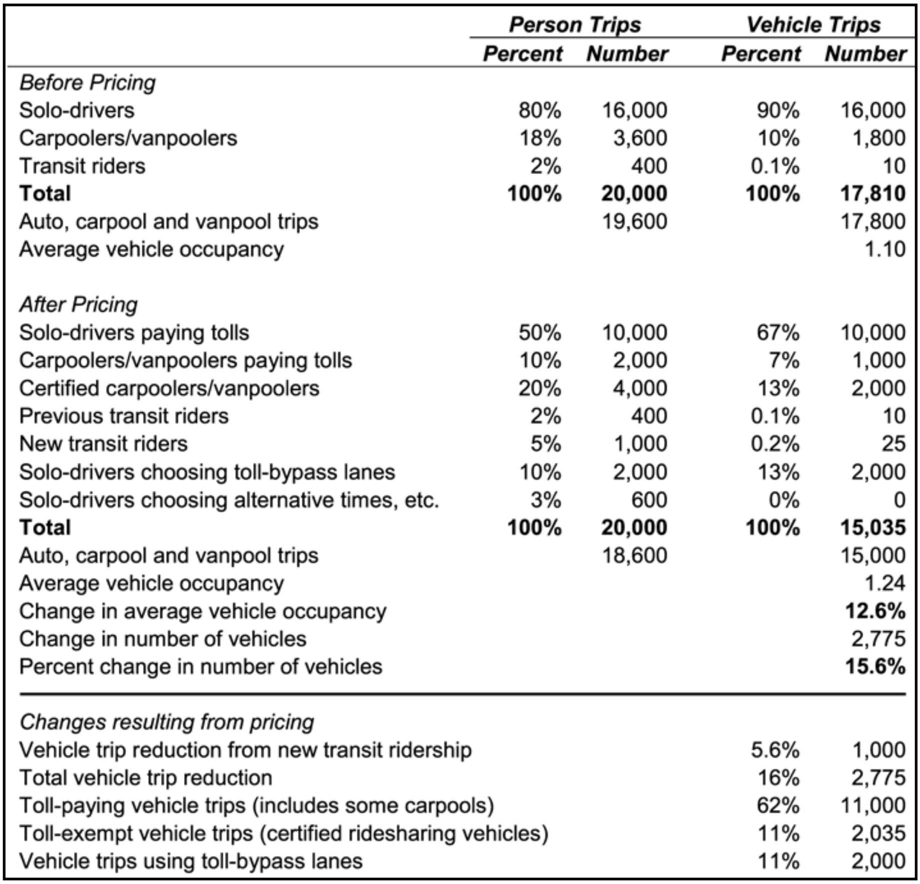
For comparison, in 2003, the average daily congested travel period in major U.S. metropolitan areas amounted to about 6.5 hours (Texas Transportation Institute 2005). By using relatively fewer hours of congestion in this analysis, we ensure a conservative estimate of toll revenue and benefits from travel time savings.

Estimates of Travel Impacts

The analysis assumes that flextime, telecommuting arrangements, transit, and ridesharing will in aggregate attract about 16 percent of motorists from driving alone on the priced highways during critical times during the congested periods. (The basis of this assumption is discussed later in this article). A drop of 16 percent in traffic volume will also result in a very significant reduction in delay. Under normal circumstances, the reduced "time" cost would induce additional drivers to use the facility, causing congestion to recur. With pricing, however, variable tolls would be set high enough to ensure free flow of traffic. The toll rates would therefore be equivalent to the value of time that is saved, so that total user-borne cost to use the facility stays roughly the same. Consequently, additional travel would not be induced. There may, of course, be a change in the demographic composition of users. Those with higher values of time would perceive a reduction in their costs, and would increase their use of the priced highway. This will be balanced by a reduction in use by those with a lower value of time, who will perceive an increase in their costs.

To simplify the analytical process, we make several assumptions. Table 2 presents an analysis of what these assumptions mean in terms of the various categories of freeway travelers. It uses as an example an existing "base" peak-period freeway throughput of 20,000 person trips. This existing travel is carried in a little less than 18,000 vehicles. Assumptions and their plausibility are demonstrated through the example in Table 2, and are explained below.

Table 2. An Example of Redistribution of Mode of Travel with Congestion Pricing



	Person Trips		*Vehicle Trips*	
	Percent	***Number***	***Percent***	***Number***
Before Pricing				
Solo-drivers	80%	16,000	90%	16,000
Carpoolers/vanpoolers	18%	3,600	10%	1,800
Transit riders	2%	400	0.1%	10
Total	**100%**	**20,000**	**100%**	**17,810**
Auto, carpool and vanpool trips		19,600		17,800
Average vehicle occupancy				1.10
After Pricing				
Solo-drivers paying tolls	50%	10,000	67%	10,000
Carpoolers/vanpoolers paying tolls	10%	2,000	7%	1,000
Certified carpoolers/vanpoolers	20%	4,000	13%	2,000
Previous transit riders	2%	400	0.1%	10
New transit riders	5%	1,000	0.2%	25
Solo-drivers choosing toll-bypass lanes	10%	2,000	13%	2,000
Solo-drivers choosing alternative times, etc.	3%	600	0%	0
Total	**100%**	**20,000**	**100%**	**15,035**
Auto, carpool and vanpool trips		18,600		15,000
Average vehicle occupancy				1.24
Change in average vehicle occupancy				**12.6%**
Change in number of vehicles				2,775
Percent change in number of vehicles				**15.6%**
Changes resulting from pricing				
Vehicle trip reduction from new transit ridership			5.6%	1,000
Total vehicle trip reduction			16%	2,775
Toll-paying vehicle trips (includes some carpools)			62%	11,000
Toll-exempt vehicle trips (certified ridesharing vehicles)			11%	2,035
Vehicle trips using toll-bypass lanes			11%	2,000

Due to reductions in transit travel time and fares, it is assumed that approximately a third of diverted travelers (i.e., 5% of total existing peak-period users) will shift to use of express buses. This is consistent with the cross-elasticity estimates discussed earlier.

It is assumed that ridesharing will increase from an existing level of 18 percent of person trips (or 10% of existing vehicle volume) to about 30 percent of person trips. This assumption amounts to a 12.5 percent increase in average vehicle occupancy (AVO) for autos, carpools, and vanpools, from 1.10 to 1.24, as indicated in the example provided in Table 2. This 12.5 percent increase in AVO is less than the average AVO increase of 14 percent observed for 10 HOV lane projects implemented in the United States (Richard H. Pratt, Consultant, Inc. et al. 2000).

It is assumed that an additional 3 percent of drivers will choose to telecommute or travel at other times. Given the potential of teleworking, and National Household Travel Survey data indicating that 10 to 23 percent of peak-period trips are made solely to shop (U.S. Department of Transportation 2004), this is a plausible assumption.

It is assumed that half of all travelers would continue to drive solo, paying the full toll. It is plausible that 50 percent of travelers would have a value of time that exceeds the average value of time, based on which the toll rate is estimated. They would value the time savings more than the toll. It is assumed that an additional 10 percent of travelers would pay half the going toll rate by sharing the toll with another person in a noncertified carpool.

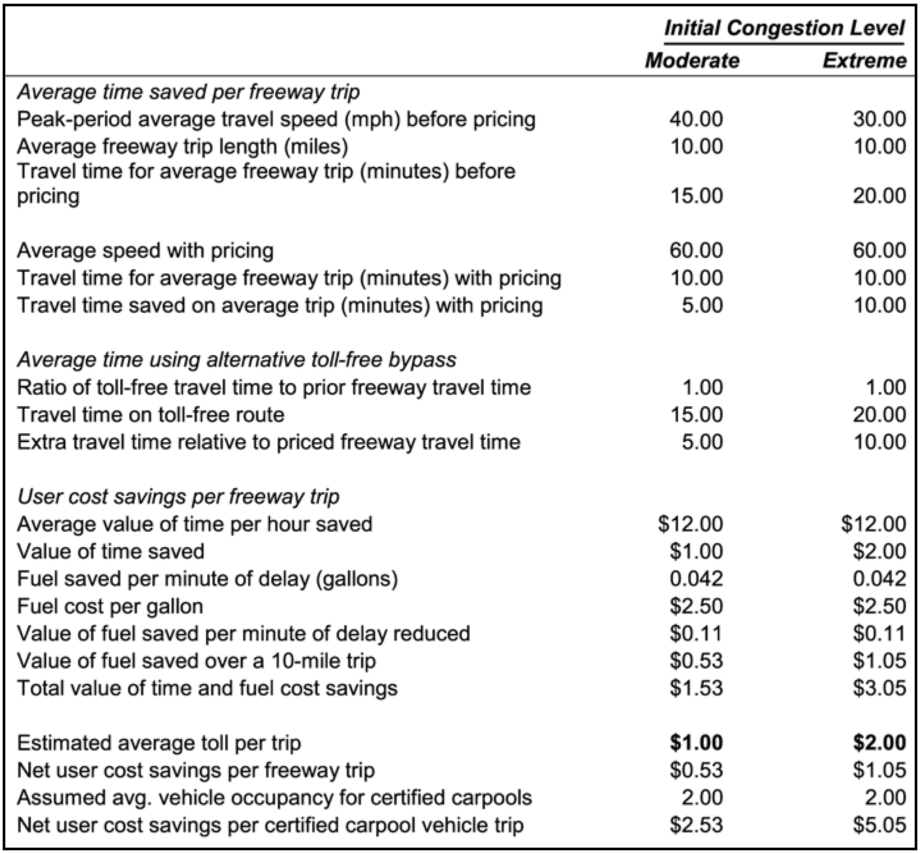
Finally, it is assumed that the balance of 10 percent of travelers (11% of existing drivers) will choose to use the toll-bypass lanes.

Overall, these assumptions translate to about 16 percent of total peak-period vehicle traffic demand shifting to other modes, to other times of travel, or to telecommuting. While anecdotal evidence suggests that a 10 percent shift would be adequate, the higher percentage shift provides a factor of safety.

Estimates of Highway User Benefits

As shown in Table 3, TRUCE begins with estimation of average travel time that would be saved on a trip that uses a 10-mile segment of the freeway network. These savings are converted into monetary values, based on the inflation-adjusted average value of time per hour per person recommended by U.S. DOT (U.S. Department of Transportation 2002). Although generally not perceived by motorists, delay reductions also result in significant fuel consumption savings, due to fewer accelerations and braking events. To be conservative in estimating benefits, estimates of fuel consumption savings are based on estimates of fuel saved by a *small* car per minute of delay reduced, as documented in the American Association of State Highway and Transportation Official's (AASHTO's) *User Benefit Analysis for Highways Manual* (ECONorthwest et al. 2003).

Table 3. Benefits to Toll-Paying Motorists



	Initial Congestion Level	
	Moderate	***Extreme***
Average time saved per freeway trip		
Peak-period average travel speed (mph) before pricing	40.00	30.00
Average freeway trip length (miles)	10.00	10.00
Travel time for average freeway trip (minutes) before pricing	15.00	20.00
Average speed with pricing	60.00	60.00
Travel time for average freeway trip (minutes) with pricing	10.00	10.00
Travel time saved on average trip (minutes) with pricing	5.00	10.00
Average time using alternative toll-free bypass		
Ratio of toll-free travel time to prior freeway travel time	1.00	1.00
Travel time on toll-free route	15.00	20.00
Extra travel time relative to priced freeway travel time	5.00	10.00
User cost savings per freeway trip		
Average value of time per hour saved	$12.00	$12.00
Value of time saved	$1.00	$2.00
Fuel saved per minute of delay (gallons)	0.042	0.042
Fuel cost per gallon	$2.50	$2.50
Value of fuel saved per minute of delay reduced	$0.11	$0.11
Value of fuel saved over a 10-mile trip	$0.53	$1.05
Total value of time and fuel cost savings	$1.53	$3.05
Estimated average toll per trip	**$1.00**	**$2.00**
Net user cost savings per freeway trip	$0.53	$1.05
Assumed avg. vehicle occupancy for certified carpools	2.00	2.00
Net user cost savings per certified carpool vehicle trip	$2.53	$5.05

Table 3 presents user cost savings per freeway trip for those paying the toll. Net user cost savings per freeway trip are estimated by subtracting the toll cost from the monetary value of time and fuel cost savings. For certified carpools, travel time savings are multiplied by auto occupancy to get total time savings. For informal carpools that pay tolls, it is assumed that the total time savings of occupants will be equal to the value of the toll paid. Net user cost savings are thus equal to the value of fuel savings, as they are for solo drivers. While average values of time are useful in estimating aggregate benefits for all motorists, motorists' values of time are actually distributed over a range. Motorists with higher values of time will perceive proportionally higher benefits. Motorists with lower values of time would perceive disbenefits if they had to pay a toll, and would respond to new congestion tolls by choosing the toll-free bypass lane, or by diverting to other modes, routes, or times of the day. Their disbenefits (i.e., "consumer surplus" losses) are accounted for in aggregate highway benefit estimates provided in Table 4.

For the purpose of estimating the average peak-period toll rate, we assume that:

- In deciding whether to pay the toll, motorists would consider how much delay they would incur in the toll-bypass lane and compare the equivalent monetary cost of that delay to the going toll rate.
- A current freeway motorist who wants to avoid the toll by waiting in the toll-bypass lane would face a travel time equal to the "base" congested travel time on the freeway (i.e., prior to introduction of pricing). If this delay were lower than before, additional travel would be induced. If it were higher, diversion to alternative routes could occur.
- Of those motorists who decide to pay the toll (i.e., 50% of all travelers), the solo driver who values his or her time the least would have a value of time equal to the average value of time for all travelers (i.e., $12 per hour). This value, along with the queue delay time, determines the toll rate. The two would be in equilibrium.

Based on a value of time of $12 per hour, the average peak-period toll for a 10-mile freeway trip is estimated to range from about $1 to $2 for passenger cars. It is assumed that trucks would pay toll rates that reflect their relative passenger car equivalents. Since a heavy truck on average consumes two to three times the lane capacity of a passenger car in free-flowing traffic, toll rates for trucks would average about 2.5 times the toll rates for passenger cars.

Table 4 provides estimates of highway benefits and toll revenues for the two scenarios. Existing peak-period demand for freeway use is estimated to be equal to the total vehicle volume that currently uses the freeway during the congested peak period. Over all lanes in both directions of the freeway, existing hourly peak-period traffic volume is assumed to be 1,800 vehicles per lane. This accounts for both lost throughput in the heavy traffic direction, as well as vehicle volumes in the reverse direction.

Table 4. Highway User Benefits and Toll Revenues

Vehicle trips on 10-mile freeway		
Average prior peak-period traffic volume per hour per lane	1,800	1,800
Average number of lanes (both directions)	6	6
Average number of hours of congestion daily	4	6
Average prior peak period traffic volume daily	43,200	64,800
Percent traffic volume reduction with pricing (from Table 2)	16.00%	16.00%
Average traffic volume with pricing	36,288	54,432
Number of vehicles diverted	6,912	10,368
Percent of vehicles exempt from tolls (from Table 2)	11.00%	11.00%
Number of vehicles exempt from tolls	4,752	7,128
Percent of vehicles choosing to pay "time" price	11.00%	11.00%
Number of vehicles choosing to pay "time" price	4,752	7,128
Number of priced vehicles	26,784	40,176
Daily benefits on 10-mile freeway		
User cost savings to exempt vehicles (carpools)	$11,999	$35,996
User cost savings to motorists choosing "time" price	$0	$0
User cost savings to priced motorists	$14,062	$42,185
Estimated average value of time of diverted motorists	$9.00	$9.00
Consumer surplus change for diverted motorists	-$864	-$2,592
Toll revenues	$26,784	$80,352
Change in fuel tax receipts	-$2,649	-$7,947
Total benefits	$49,331	$147,994
Annual benefits and toll revenue for managed network		
Number of weekdays per year	250	250
Annual tolled vehicle trips for 10-mile highway	6,696,000	10,044,000
Annual benefits for 10-mile highway	$12,332,844	$36,998,532
Number of miles of priced highway network	100	100
Annual tolled vehicle trips for 100-mile network	66,960,000	100,440,000
Annual benefits for priced highway network	**$123,328,440**	**$369,985,320**
Annual toll revenues for 10-mile managed highway	$6,696,000	$20,088,000
Annual toll revenues for managed highway network	**$66,960,000**	**$200,880,000**

Social benefits of the network are estimated by accounting for:

1. *Net user cost savings* on the priced freeway. Benefits to those who continue to travel on the freeway are estimated based on the benefits per vehicle trip calculated in Table 3. *Losses of consumer surplus* by motorists who shift from driving alone on the freeway are estimated based on the rule of half. It is calculated as the number of deterred motorists times half the difference between (1) monetary value of motorists' travel time plus toll cost on priced freeways and (2) monetary value of motorists' travel time cost prior to pricing. Given typical observed distributions of values of time of motorists (Steimetz and Brownstone 2004), it is reasonable to assume that the 16 percent of all motorists who shift from driving alone in the peak periods on the freeway would have a value of time equal to about 75 percent of the average value of time (i.e., $9).
2. *Toll revenue* "transfers" from motorists to the system operator. (Tolls paid by motorists are subtracted in computing net user cost savings under item 1 above.)
3. *Reductions in government fuel tax receipts* due to reduced fuel consumption estimated at 40 cents per gallon for state and federal taxes combined. (Fuel taxes are included in fuel cost savings estimated to compute user cost savings under item 1 above.)

Several components of social benefits are not included in the above social benefit calculations:

1. *Benefits from an increase in trip time reliability*. With more predictable trip times, travelers will be able to reduce the "buffer" time that they build into their schedules. Surveys of travelers who use priced lanes in San Diego and in Orange County, California, suggest that travelers perceive that they save almost twice the amount of time that they actually save. This may simply reflect a reduction in the amount of "buffer" time that they allocate for their trips, due to the reliability of their trip times.
2. *Environmental and safety benefits*, such as reductions in air pollution, noise, and greenhouse gas emissions, and accident cost reductions. Environmental benefits are expected to be positive, since mode shifts will reduce vehicle traffic, and higher traffic speeds will reduce most emissions. Shortening of response times for emergency personnel may save lives. With reduced traffic, the number of accidents would also be reduced; however, severity

of accidents would increase due to higher speeds, raising the average cost per accident.

3. *Impacts of traffic diversion on congestion levels on parallel toll-free routes.* As discussed earlier, modal and time of travel choices and the availability of the toll-bypass lane are expected to limit traffic diversion, so any negative impacts are expected to be minor, and positive impacts may occur due to increased vehicle and person throughput in the freeway corridor.
4. *Benefits to businesses and the economy,* including productivity benefits from reduced freight delays and increased reliability of deliveries.
5. *Increase in energy security* due to reduced fuel consumption.
6. *Increased opportunities for civic participation.*
7. *Reduced distortions in the housing market.*

Based on the above analysis, annual benefits are estimated to range from $123 million to $370 million. Toll revenues are estimated to range from $67 million to $200 million annually.

Transit Benefits

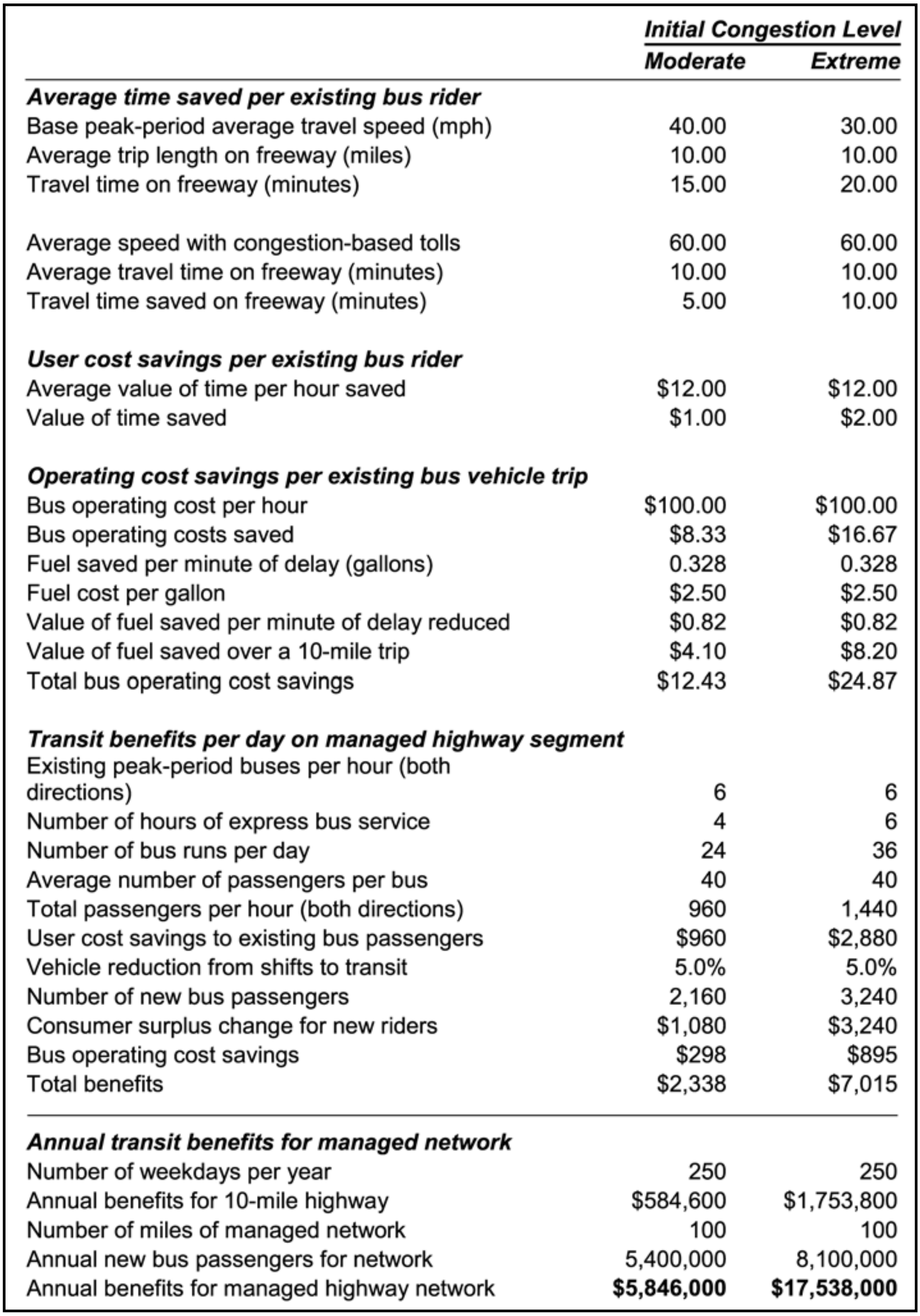
Table 5 presents estimates of transit benefits. Travel time savings for existing bus passengers are assumed to be equivalent to those accruing to motorists. Operating cost savings for existing bus services are computed by combining driver time savings and bus fuel cost savings. Fuel cost savings are based on AASHTO estimates of fuel consumption per minute of delay for a single-unit truck (ECONorthwest 2003).

Existing bus service is estimated at 6 buses per hour, with 40 passengers per bus, resulting in an estimated 240 riders per rush hour in each freeway corridor. This amounts to 2 percent of travelers on a 6-lane freeway carrying 12,000 people per rush hour (i.e., 2,000 people per lane, based on 1,800 vehicles per lane per hour and an average vehicle occupancy of about 1.10).

As discussed earlier, our analysis assumes that 5 percent of freeway drivers (i.e., a third of the 16% diverted rush-hour solo drivers) will use transit. Benefits to new transit riders are estimated based on the rule of half (i.e., half of the change in travel time costs, times the estimated number of new riders).

Table 5 indicates that annual transit benefits would range from $6 million to $17.5 million. Total highway and transit benefits combined would range from $129 million to $388 million.

Table 5. Transit Benefits



	Initial Congestion Level	
	Moderate	***Extreme***
Average time saved per existing bus rider		
Base peak-period average travel speed (mph)	40.00	30.00
Average trip length on freeway (miles)	10.00	10.00
Travel time on freeway (minutes)	15.00	20.00
Average speed with congestion-based tolls	60.00	60.00
Average travel time on freeway (minutes)	10.00	10.00
Travel time saved on freeway (minutes)	5.00	10.00
User cost savings per existing bus rider		
Average value of time per hour saved	$12.00	$12.00
Value of time saved	$1.00	$2.00
Operating cost savings per existing bus vehicle trip		
Bus operating cost per hour	$100.00	$100.00
Bus operating costs saved	$8.33	$16.67
Fuel saved per minute of delay (gallons)	0.328	0.328
Fuel cost per gallon	$2.50	$2.50
Value of fuel saved per minute of delay reduced	$0.82	$0.82
Value of fuel saved over a 10-mile trip	$4.10	$8.20
Total bus operating cost savings	$12.43	$24.87
Transit benefits per day on managed highway segment		
Existing peak-period buses per hour (both directions)	6	6
Number of hours of express bus service	4	6
Number of bus runs per day	24	36
Average number of passengers per bus	40	40
Total passengers per hour (both directions)	960	1,440
User cost savings to existing bus passengers	$960	$2,880
Vehicle reduction from shifts to transit	5.0%	5.0%
Number of new bus passengers	2,160	3,240
Consumer surplus change for new riders	$1,080	$3,240
Bus operating cost savings	$298	$895
Total benefits	$2,338	$7,015
Annual transit benefits for managed network		
Number of weekdays per year	250	250
Annual benefits for 10-mile highway	$584,600	$1,753,800
Number of miles of managed network	100	100
Annual new bus passengers for network	5,400,000	8,100,000
Annual benefits for managed highway network	**$5,846,000**	**$17,538,000**

Costs

Highway Operating Costs

To estimate capital costs for toll collection, an open-road electronic toll collection system was assumed, with toll gantries installed at 5-mile intervals, and at the boundaries of the priced network. Unit capital cost estimates were provided by Mitretek (personal communication from Paul Gonzalez, September 2006). Total capital costs were annualized based on a 7 percent discount rate and 30-year life.

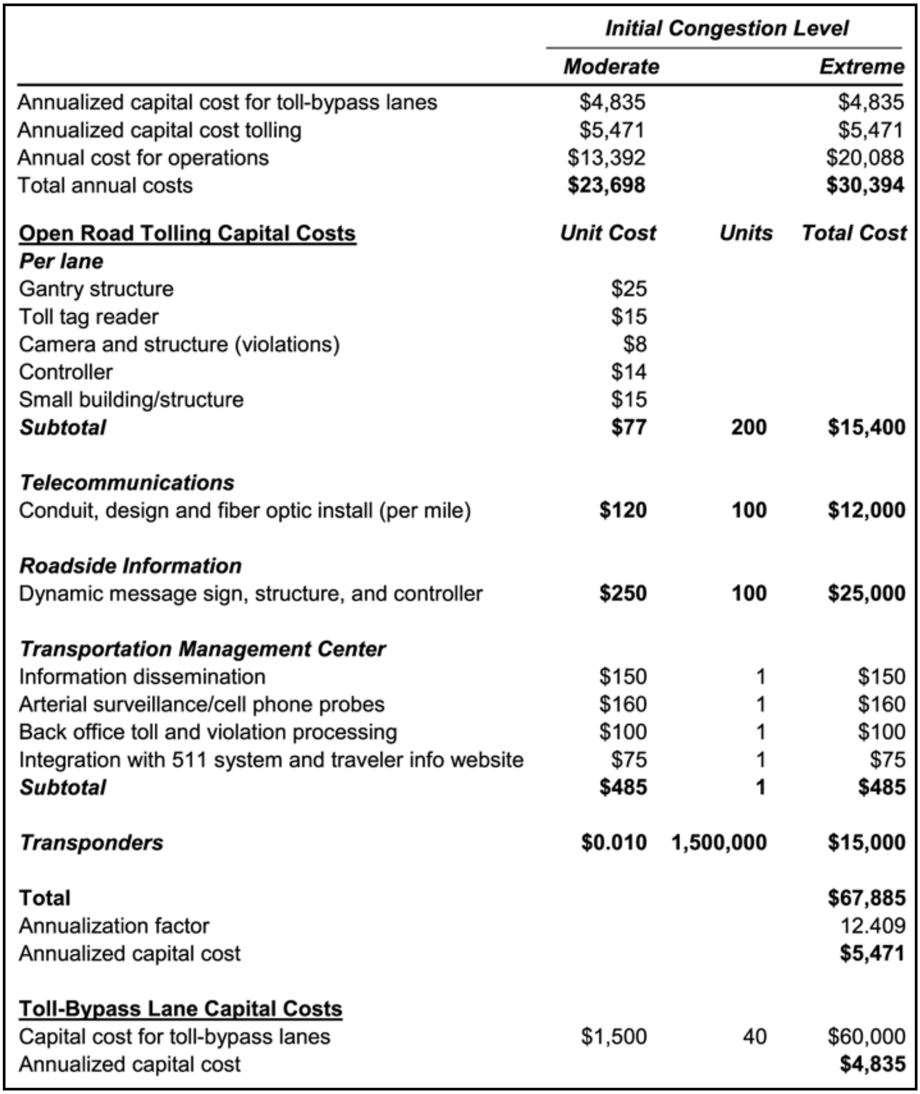
Average operating costs for toll collection are estimated at 8.5 cents per trip, based on an estimate of 5 to 10 cents per trip by ITS Decision, Service and Technologies (2005). Since toll collection costs will decrease with large-scale implementation, this is a conservative estimate.

In addition to toll collection costs, highway operations will involve costs for traffic management, such as operation of variable message signs, traffic monitoring equipment, and communications. Data from the I-15 FasTrak budget and expenditure data for FY 2005 indicate that annual costs for *both* traffic management and toll collection on the dynamically priced I-15 HOT facility in San Diego were about $0.7 million in fiscal year 2005. The facility carried about 5 million vehicles during that year, about 75 percent of them nontolled HOVs. The remaining 25 percent were tolled vehicles. Subtracting costs for tolling (at 10 cents per trip), traffic management costs for the year are estimated at $575,000, or 11.5 cents per vehicle served. Based on these cost estimates, a total cost of 20 cents per vehicle trip was estimated for tolling and traffic management combined.

As shown in Table 6, total annual operating costs for toll collection and traffic management would range from $13 to $20 million, with the higher costs associated with a longer congested period in areas with high existing congestion levels. Capital costs would be $68 million, or annualized costs of $5.5 million. Additional capital costs would be incurred for construction of toll-bypass lanes. It is estimated that a total of 20 lane-miles of new pavement (i.e., 40 half-mile sections) would need to be constructed, and that existing rights-of-way would be adequate. At an average cost of $3 million per lane mile, capital costs for toll-bypass lanes are estimated at $60 million, or annualized costs of $4.8 million.

Total annualized highway system costs would range from $23 to $30 million.

Table 6. Annualized Highway System Costs (Thousands of Dollars)

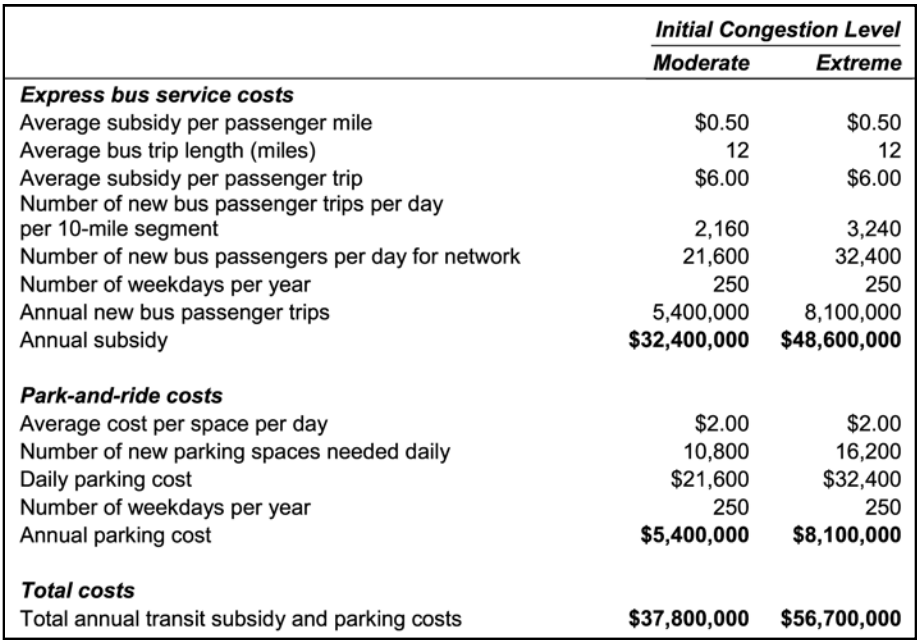


	Initial Congestion Level		
	Moderate		***Extreme***
Annualized capital cost for toll-bypass lanes	$4,835		$4,835
Annualized capital cost tolling	$5,471		$5,471
Annual cost for operations	$13,392		$20,088
Total annual costs	**$23,698**		**$30,394**
Open Road Tolling Capital Costs	***Unit Cost***	***Units***	***Total Cost***
Per lane			
Gantry structure	$25		
Toll tag reader	$15		
Camera and structure (violations)	$8		
Controller	$14		
Small building/structure	$15		
Subtotal	**$77**	**200**	**$15,400**
Telecommunications			
Conduit, design and fiber optic install (per mile)	**$120**	**100**	**$12,000**
Roadside Information			
Dynamic message sign, structure, and controller	**$250**	**100**	**$25,000**
Transportation Management Center			
Information dissemination	$150	1	$150
Arterial surveillance/cell phone probes	$160	1	$160
Back office toll and violation processing	$100	1	$100
Integration with 511 system and traveler info website	$75	1	$75
Subtotal	**$485**	**1**	**$485**
Transponders	**$0.010**	**1,500,000**	**$15,000**
Total			**$67,885**
Annualization factor			12.409
Annualized capital cost			**$5,471**
Toll-Bypass Lane Capital Costs			
Capital cost for toll-bypass lanes	$1,500	40	$60,000
Annualized capital cost			**$4,835**

Transit and Park-and-Ride Costs

The express bus system would need to carry all travelers who would shift from driving on the freeway to transit (i.e., 5% of peak-period freeway demand that is expected to shift to transit), as discussed earlier. As indicated in Table 7, depending on existing levels of congestion, new daily ridership is estimated to range from 22,000 to 32,000, or 5 million to 8 million annually.

Table 7. Transit and Park-and-Ride Costs



	Initial Congestion Level	
	Moderate	***Extreme***
Express bus service costs		
Average subsidy per passenger mile	$0.50	$0.50
Average bus trip length (miles)	12	12
Average subsidy per passenger trip	$6.00	$6.00
Number of new bus passenger trips per day per 10-mile segment	2,160	3,240
Number of new bus passengers per day for network	21,600	32,400
Number of weekdays per year	250	250
Annual new bus passenger trips	5,400,000	8,100,000
Annual subsidy	**$32,400,000**	**$48,600,000**
Park-and-ride costs		
Average cost per space per day	$2.00	$2.00
Number of new parking spaces needed daily	10,800	16,200
Daily parking cost	$21,600	$32,400
Number of weekdays per year	250	250
Annual parking cost	**$5,400,000**	**$8,100,000**
Total costs		
Total annual transit subsidy and parking costs	**$37,800,000**	**$56,700,000**

Transit subsidy needs were estimated at 50 cents per passenger mile, based on nationwide subsidies of $23.5 billion supporting 50 billion passenger miles annually (Taylor and VanDoren 2002). An average bus passenger trip was estimated at 12 miles, based on work trip length data (U.S. Department of Transportation 2004). Total annual transit subsidy costs are estimated to range from $32 million to $48 million.

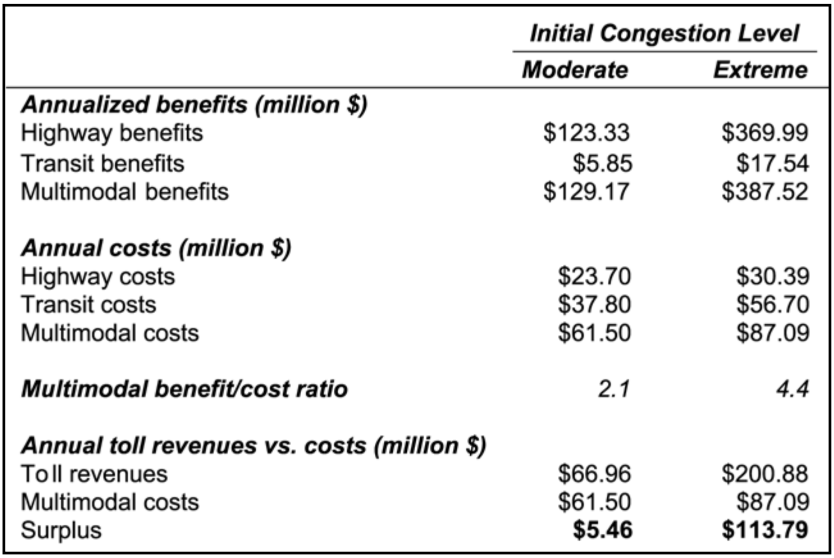
Most of the new park-and-ride spaces will be needed in exurban or suburban locations. At these locations, it is more likely that a public agency will own land within existing rights-of-way near interchanges or along the freeway. It may therefore be possible to build new park-and-ride facilities on surface lots, adjacent to express bus stations. Also, it may be possible to use existing parking spaces at shopping centers near the freeway, reducing new construction costs. Parking costs are estimated at $2.00 per parking space per day, based on annualized costs for construction and maintenance of surface parking spaces in outer suburbs (U.S. Department of Transportation 1992), adjusted for inflation. Total annual costs for providing parking are estimated at $5 million to $8 million, with the high-end costs associated with higher transit use in more congested areas.

Total combined annual costs for transit subsidies and parking at park-and-ride lots are estimated to range from $38 million to $57 million.

Financial Feasibility

Table 8 summarizes estimates of toll revenues, benefits, and costs of the multimodal pricing package. Benefit/cost ratios would range from 2.1 to 4.4, depending on the severity of existing levels of congestion. Because of the conservative assumptions used to estimate benefits in the analysis, these estimates are conservative. The results suggest that the multimodal pricing package would be financially self-sufficient. Surplus revenue would be much higher in more severely congested areas, because of higher toll rates as well as longer congested periods during which tolls would be charged. Annual toll revenue surpluses would range from $5 million to $114 million.

Table 8. Benefits, Costs, and Financial Feasibility



	Initial Congestion Level	
	Moderate	***Extreme***
Annualized benefits (million $)		
Highway benefits	$123.33	$369.99
Transit benefits	$5.85	$17.54
Multimodal benefits	$129.17	$387.52
Annual costs (million $)		
Highway costs	$23.70	$30.39
Transit costs	$37.80	$56.70
Multimodal costs	$61.50	$87.09
Multimodal benefit/cost ratio	*2.1*	*4.4*
Annual toll revenues vs. costs (million $)		
Toll revenues	$66.96	$200.88
Multimodal costs	$61.50	$87.09
Surplus	**$5.46**	**$113.79**

Conclusions

A Super HOT transportation network in a large metropolitan area could provide social benefits that far exceed multimodal investment and operating costs. Revenues from tolls would be sufficient to pay for all costs, including new express bus services and park-and-ride services that would complement the pricing scheme. The multimodal pricing package would be financially self-sufficient, with annual toll revenue surpluses depending on the severity of congestion. A limited short-term "trial" demonstrating the concept in a congested corridor may help show if the concept will work, and lead to public acceptance of larger-scale implementation.

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