Traffic Choices Study

–Final Report

DRAFT

Puget Sound Regional Council
PSRC
APRIL 2008

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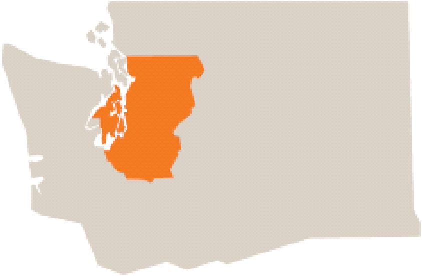
The region's natural setting includes snowcapped peaks, abundant waterways and shorelines and lush forests and greenery. The region rises from seawater tidelands to the crest of the Cascade mountain range and extends through the glacially sculpted lowland of the Olympic Peninsula. The region is made up of four large counties: King, Kitsap, Pierce and Snohomish, which encompass 6,290 square miles and contain 82 cities and towns. The five major cities are Seattle and Bellevue in King County, Tacoma in Pierce County, Everett in Snohomish County and Bremerton in Kitsap County.



Traffic Choices Study – *Final Report*

A Global Positioning System Based Pricing Pilot Project: Evaluating Traveler Response to Variable Road Tolling Through a Sample of Volunteer Participants

prepared by.........**Puget Sound Regional Council**

for the.........**Value Pricing Pilot Program**
.........**Federal Highway Administration**
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Overview

Technical studies and popular opinion agree: congestion in urban areas is getting worse. The standard approaches, such as building more roads, urban mass transit systems, even better land use planning, are not doing enough to solve the problem. Citizens in the greater Seattle metropolitan area face significant traffic congestion problems[1]; they spend 40 percent more time traveling by automobile during peak periods than they would spend if congestion were not present. Estimates of the cost of congestion, to residents and businesses in the central Puget Sound region, range from between $1.5 billion to $2 billion annually. These costs are primarily in the form of lost time that cannot ever be recovered. Many look to state, regional and local agencies for improvements.

But the region's topography and existing development patterns make the construction of new transportation capacity expensive. Planners are concluding that adding to transportation supply (whether highways, transit lines and vehicles, bike lanes, or sidewalks) is only part of the solution, and that public policy must pay more attention to improving the effectiveness of existing systems and managing the demand for travel.

Congestion-based road tolling attempts to make more efficient use of roads by charging the people who use them. Flat rate tolls are one form of charging for the use of roads. But the major transportation problem in urban areas is congestion, which occurs when too many people want to use the same route at the same time. Thus, roadway pricing is based on charging a variable toll: one that is higher on congested routes at congested times, offering a lower cost option when demand is less.

The few existing variable road-tolling projects have demonstrated that pricing can increase the efficiency of a transportation system. Instead of rationing space on the highway by wasting time in a queue, it gets rationed through payments. Those payments mean that the public sector gains revenues that it can use to further improve the transportation system, address issues of fairness (e.g., by finding ways to compensate travelers made worse off by the toll) or offset other existing taxes and fees.

In 2002, the Puget Sound Regional Council (PSRC) received a grant from the Federal Highway Administration to conduct a pilot project to see how travelers change their travel behavior (number, mode, route, and time of vehicle trips) in response to variable charges for road use (variable or congestion-based tolling). The project, called the Traffic Choices Study, placed Global Positioning System (GPS) tolling meters in the vehicles of about 275 volunteer households. The project observed driving patterns before and after hypothetical tolls were charged for the use of all the major freeways and arterials in the Seattle metropolitan area.

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[1] The Texas Transportation Institute's Urban Mobility Report (2007).

The primary aims of the Traffic Choices Study were to (1) accurately describe the behavioral response to the congestion-tolling of roadways, (2) better understand issues of policy related to the implementation of road network tolling, and (3) test an integrated system of technical solutions to the problem of tolling a large network of roads without deploying substantial physical hardware on the roadside. The study has met these goals and is the most comprehensive study of demand response to network tolls in existence. Primary conclusions from the study include:

1. Observed response of drivers to tolls suggests there is a dramatic opportunity to significantly reduce traffic congestion and raise revenues for investment.

    1.1. Motorists made small-scale adjustments in travel that, in aggregate, would have a major effect on transportation system performance.
    1.2. When approached systematically, variable road tolling, with investments of toll revenues, could make excessive reoccurring congestion a thing of the past.
    1.3. The scale of the revenues confirms the theoretical expectation that "optimal" tolls would support expanding transportation supply when and where it is needed most.
    1.4. While most revenues are generated on a small portion of the toll roads, the secondary road network (arterials) should not be ignored, as diversion causes real problems with revenue loss and displaced traffic.
    1.5. Users demonstrating a willingness to pay for high value roadways could expect that improvements would be forthcoming.
    1.6. Done right, network tolling could provide broad benefit, including lower vehicle emissions, fewer accidents, travel time savings, improved roadway performance reliability, and lower operating costs.
    1.7. A conservative analysis of the benefits of network tolling in the Puget Sound region indicates that the present value of net benefits could exceed $28 billion over a 30-year period.

2. Not all aspects of a road network tolling system have been fully demonstrated yet. But the core technology for satellite-based (and whole road network) toll systems is mature and reliable.

    2.1. The tolling system performed as expected, and met basic system operating requirements. Further work on system refinement and design of enforcement and billing systems would be required prior to any full system deployment.
    2.2. Tolling of dense road networks with facilities that have only minimal access controls requires special attention to issues of GPS accuracy, and the overall approach to facility use determination.
    2.3. The approach to processing road use information (within the on-board device or in the toll system back office) has implications for user privacy, system stability, and data communications costs.
    2.4. Enforcement would require other facility use verification approaches (DSRC, video capture, mobile enforcement) in addition to the GPS-tolling technology.
    2.5. Installing in-vehicle tolling devices is a costly logistical challenge, but relying on equipment to come standard with new automobiles won't be practical if it doesn't represent a trusted platform for road tolling.
    2.6. The costs for GPS-based tolling systems are dominated by the initial investment in in-vehicle tolling equipment, and the communication of data during operations. Over the last few years, costs have declined dramatically and are expected to continue to come down.

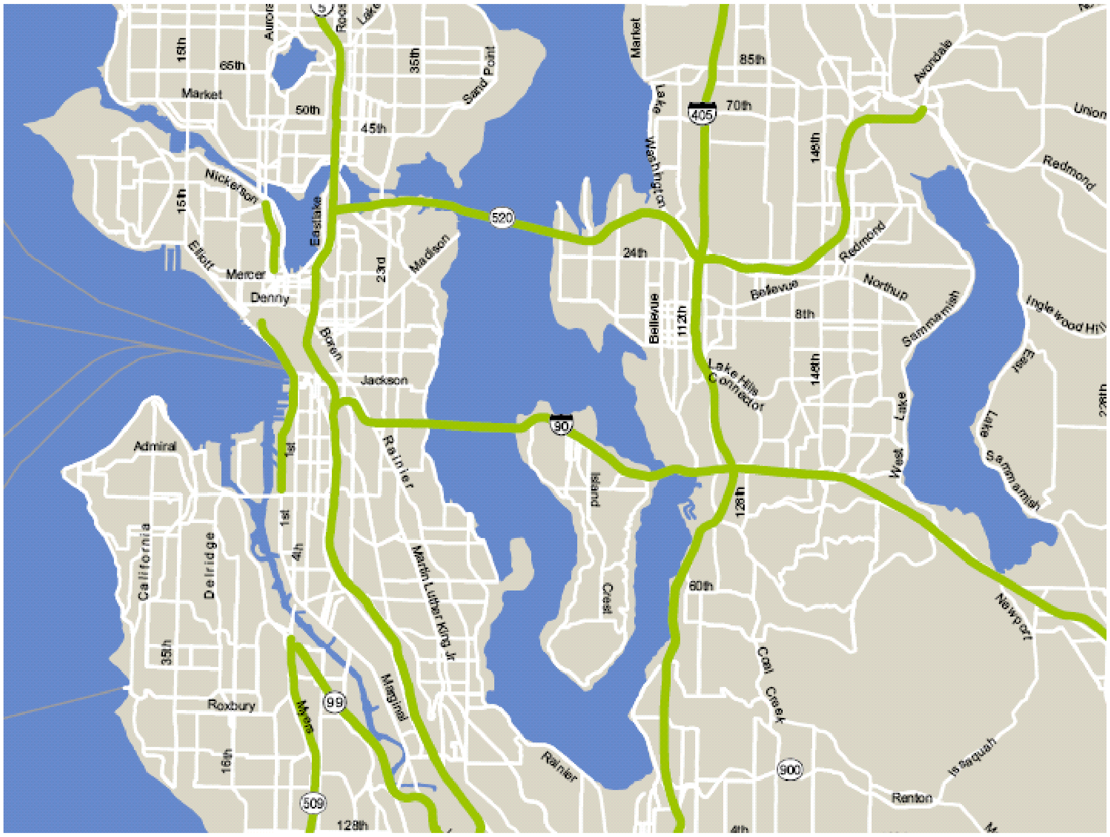
3. A large-scale U.S. deployment of a GPS-based road tolling program will depend on proven systems, a viable business model, and public acceptance of underlying concepts.

    3.1. The public sector business case is based on the sizable social benefits of road tolling. There are ways to generate revenues that are less administratively burdensome, but these displace economic activity, and fail to address traffic congestion.
    3.2. A transition to road network tolling would be costly and complex. It must be seen to be worth the sizable upfront effort.
    3.3. Road tolling will be seen as unfair unless people understand that directly charging users addresses existing inequalities across users of the transportation system, and improves overall economic efficiency, leaving society with greater resources available to address remaining issues of fairness.
    3.4. 3.4 Concerns over user privacy depend on what data leaves the vehicle, and what safeguards are in place to limit its availability and use. A road tolling system can be developed such that user privacy is maintained. But like so many things, this would come at a price.
    3.5. 3.5 Some experience and familiarity with road tolling makes people more open to the concept, but all programs are unique and will succeed or fail on their own merits. Road users are particularly interested in the question of how revenues will be used.

This report describes the approach and results of the Traffic Choices Study. It has five sections in addition to this overview:

- **Chapter 1, Background**, describes (1) the problem the report addresses (increasing urban congestion and the difficulty of funding new transportation capacity that might reduce it); (2) the reasons the proposed solution (variable road pricing) might help reduce the problem; and (3) how variable pricing got implemented in this pilot project.
- **Chapter 2,** the **Experiment,** describes how the experiment was designed and implemented, and the kind of information it collected.
- **Chapter 3, Behavioral Analysis and Results,** describes data preparation, analytical techniques, and the results of the experiment.
- **Chapter 4, Road Network Implications**, goes beyond the results to suggest what they mean for the feasibility of future road pricing.

A set of **Technical Appendices** provide more detail about most of the topics covered in this report. For a shorter and less technical version of the material in this report there is also a summary document available under separate cover.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CHAPTER 1

BACKGROUND

CHAPTER OVERVIEW

Technical studies and popular opinion agree: congestion in urban areas is getting worse. The standard approaches, such as building more roads, urban mass transit systems, even better land use planning, are not doing enough to solve the problem. Citizens in the greater Seattle metropolitan area face significant traffic congestion problems1; they spend 40 percent more time traveling by automobile during peak periods than they would spend if congestion were not present. Estimates of the cost of congestion, to residents and businesses in the central Puget Sound region, range from between $1.5 billion to $2 billion annually. These costs are primarily in the form of lost time that cannot ever be recovered. Many look to state, regional and local agencies for improvements.

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The primary aims of the Traffic Choices Study were to (1) accurately describe the behavioral response to the congestion-tolling of roadways, (2) better understand issues of policy related to the implementation of road network tolling, and (3) test an integrated system of technical solutions to the problem of tolling a large network of roads without deploying substantial physical hardware on the roadside. The study has met these goals and is the most comprehensive study of demand response to network tolls in existence. This chapter describes the background for the experiment:

- *The problem it addresses (urban congestion and the difficulty of funding congestion relief)*
- *The solution it tests (variable pricing of the road network using GPS technology that tracks automobile trips)*
- *The specific implementation of that solution in the Seattle metropolitan area (the Traffic Options Study).*

1.1. THE AILMENTS: URBAN TRAFFIC CONGESTION AND LIMITED FUNDING

Metropolitan regions throughout the nation face increasing problems with urban congestion. Their citizens want better (or, at least, not deteriorating) mobility. The cost of providing each new unit of system capacity is increasing, the effectiveness of that capacity is debatable (How much and for how long does it relieve congestion?), and the public appetite for funding that capacity is waning.

Limited public financial capacity for transportation infrastructure investment has encouraged transportation professionals and regional policy makers to begin discussing the potential benefits associated with reforming the way society pays for and finances transportation. Business leaders, national experts, and state legislators are all coming to similar conclusions: traditional tax-based financing measures will not, by themselves, be sufficient to solve our transportation problems.

Most of the public revenue sources that help pay for the transportation system do not increase with increased system use. Signals about the cost of transportation *at the time it is consumed* given by the prices charged at the time of consumption are misleading. They do not give a message that decreases driving when roadway capacity is most compromised, and revenues to increase capacity are not forthcoming. As a result, vehicles exceed the capacity of many miles of roadways for several hours each day; in other words, the result is that use exceeds free-flow capacity, that demand exceeds supply, and that roads are congested.

The current transportation system is financed through a combination of use-related taxes and fees, and broad taxing instruments that have little relationship with transportation system use. Most existing use-fees are scaled to recover some set of costs by applying an average charge to all similar users. The fuel tax is an example where the cost to the consumer of fuel is an average cost tax on fuel by volume.

But in reality, the costs imposed by users vary considerably over time and space. Most important, the costs each new vehicle entering a crowded road during rush hour imposes on the existing stream of vehicles may be very high. The costs that same vehicle imposes on the operation of the system and the other users on that same road at 11 o’clock at night may be very low. The premise of congestion-based tolling (also called peak-period or variable pricing or tolling) is that this incorrect pricing leads to an over-consumption of certain types of transportation services (i.e., congestion) and an under-consumption of other transportation services. Correct pricing can reduce this problem.

Conventional road finance exacerbates rather than ameliorates the problem. A low charge on all mileage allows excessive congestion during peak periods. While the congestion prompts road authorities to build new capacity, the low charges cannot cover the costs.

1.2 A REMEDY: VARIABLE ROAD TOLLING

The major surface transportation problem in urban areas is highway congestion. Congestion means too many vehicles in the same place at the same time (i.e., at peak periods). In economic terms, the demand for travel in some places at some times of day exceeds the capacity of the highway system to accommodate, at free-flow speeds, all the vehicles being used for that travel.

There are several ways to deal with situations where demand exceeds supply. One is a random-draw lottery: there are more hunters than elk tags, and more rafters than popular rivers can handle, so the government makes random selections from applications. More common is to ration by standing in line (paying with time): one observes that scheme for all types of popular entertainment events. Travel on urban roadways is rationed by paying with time: if you can tolerate the congestion delay, you can drive.

The most common method of rationing most goods and services, however, is price (paying with money). If there are only a few of the things that a lot of people want, the price will be high. That is the fundamental idea of road pricing: if too many people want to use the same road at the same time, one can ration the use based on price, and doing so has several advantages over rationing based on time.

The theory is solid, but the implementation has been difficult for both technical and political reasons, which are discussed in the sections that follow.

The Theory of Road Pricing

First, it is helpful to define some terms. Since road congestion is what happens during peak periods,[2] economist tend to use the terms "congestion pricing", "congestion-based tolling" and "peak-period pricing" synonymously. Since the charge is for the use of the road, both are a form of "road tolling," "road pricing," or "road-use fees." If the prices are going to be targeted to different times of day that have different levels of congestion, then a flat fee that applies 24 hours a day (e.g., the typical toll bridge) will not work. "Congestion pricing" must be "variable pricing" or "variable tolling". Thus, the rest of this report uses these terms as if they were synonymous: congestion-based tolling, peak-period pricing, and variable road tolling are all the same thing.

Variable pricing, based on peak periods of use, is a common form of pricing in other industries. It is used when capacity is fixed in the short-run, and demand fluctuates significantly between the peak and off-peak periods. Before cell phones, phone companies used peak-period pricing to encourage consumers to shift their use of the fixed capacity of the phone system to off-peak hours (e.g., by charging lower rates evenings and weekends). Some energy utilities use peak pricing. So do theaters. Economists recommend congestion pricing of roads for the same reason private firms use peak-period pricing: to use available resources more efficiently.

How would such pricing work for roads? Imagine that the vehicle you drive could tell a computer what road it is on, and at what time. Location and time correlate to the amount of congestion and delay you are experiencing. Higher (variable) prices during peak periods would encourage you, or travelers with less pressing needs, to shift to other routes or times.

That system has many advantages. By charging selectively at certain locations and times, one can influence the amount of congestion during peak periods. Variable tolling could reduce the immediate need for building new highway capacity. By knowing where people are willing to pay tolls, planners would have a direct measure of where to build more capacity: namely, where drivers are willing to pay high tolls because the travel is so important to them. When those signals suggested that new capacity would be beneficial, the accumulated toll revenues would provide money to pay for those

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[2] Yes, the peak periods are getting longer, but it is still the case that insufferable congestion (Level of Service E or F) does not occur 24 hours a day.

improvements. Fairness could also be improved, as revenue is collected from those who burden capacity directly.

Ideally, variable tolling would apply to all roads in a region, and efficient tolling would be based on costs that vary by volumes on the roadways, vehicle type, facility, and distance. Less comprehensively, it could be applied selectively to certain facilities or vehicle types (e.g., heavy vehicles). Either would be more efficient than current approaches to finance, which are a combination of semi-efficient pricing (fuel taxes, parking charges, mileage fees) and indirect charges (registration fee, general taxes, ramp metering).

Why would such a practice be more efficient? Within regions with relatively mature transportation systems, peak-period demand also drives the need for new investments in roadway infrastructure. Urban transportation systems are sized and built primarily in response to peak-period use. If consumers (travelers) do not perceive the full costs their travel imposes on the system (reasons to be provided shortly), they will consume too many trips. Peak trips are incorrectly (non-optimally) priced, and the price distortions lead to increased cost to the region in the form of congestion delay and wasted resources.

In **Figure 1.1**[3] the "own costs" curve is the relationship between the density of vehicles and the average time it takes a vehicle to traverse a mile of roadway. As vehicle densities increase congestion occurs and this average variable cost (the travel time experienced directly by each vehicle entering the roadway segment) increases. The demand curve in Figure 1.3 shows how pricing (which increases the cost experienced by the user of the facility) can influence facility performance. At a higher cost to use the facility, fewer vehicles will wish to access this segment of road. Without pricing, there is an equilibrium where the demand curve intersects the own costs curve (point F). At this equilibrium there are high social costs (point E).

The "social costs" curve (marginal social cost) depicts the travel time experienced directly by the additional vehicle entering the roadway segment plus the increment of delay that this vehicle imposes on other vehicles in the traffic stream as a result of its contribution to deteriorating facility performance. Where traffic conditions are unstable (high vehicle densities) the delay imposed on subsequent vehicles from added vehicles can be quite high and can continue to be experienced long after the vehicle in question has exited the congested segment of roadway.

If individual drivers were to be made responsible for the actual costs that their travel decision imposes on society (social costs curve) some drivers might not make the same travel decision as when they experience only the average variable costs of travel (their own travel time). Optimal conditions are achieved when the demand curve intersects with the social costs curve (point B), which can be achieved with a congestion toll equal to B-C (represented by the thick red line). The essence of congestion pricing of roads is that drivers should pay for the aggregate delay they impose on other drivers. If they are not asked to pay these costs, they will each make travel decisions that collectively result in a lot of lost time for all travelers.

The benefits of road pricing are the reduction in social costs (area BEF) in the form of higher speeds/less travel time. The toll revenues (area ABCD) are a transfer from road users to the system operator. It is easy to see that the toll revenues are larger than the user benefits, implying that road users (as a general class) will be made worse off under road pricing unless the revenues are used wisely and in a manner that benefits those who pay the tolls.

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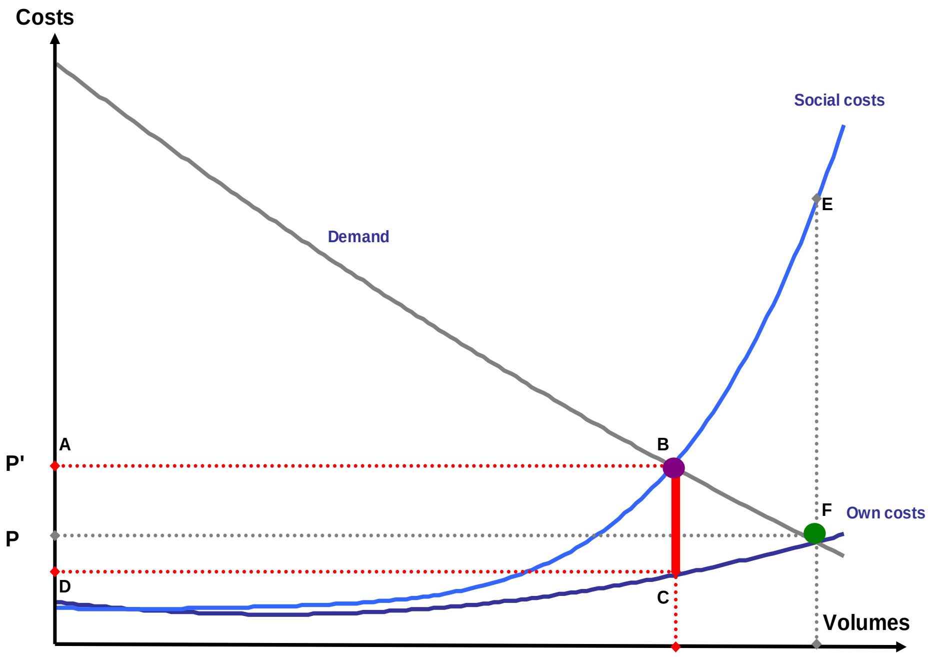
[3] Walters, A.A. (1961): "The Theory and Measurement of Private and Social Cost of Highway Congestion," Econometrica, 29, 676-699.

Figure 1.1 Road Pricing Standard Model



To understand why peak-period tolling can yield savings, it is necessary to understand the role of pricing in rationing capacity costs. Consider the case, for example, of a movie theater operator deciding how much seating capacity to build in his theaters. The market for theater tickets exhibits wide swings in demand (not unlike a freeway); if the theater owner builds to fully accommodate the peak demand, he runs the risk that he will have a glut of capacity most of the time: capacity he often cannot sell to recover costs. Conversely, if he builds only to accommodate the off-peak demand, then he will have problems of too little capacity in the peak, leading to queuing by customers ("congestion") and lost revenues. In either case, the company's resources or the customers' resources (or both) are wasted.

The solution is to allocate the costs of the capacity to those customers who require it (and are willing to pay for it) by charging more during peak periods than off-peak periods. This strategy rations the expensive, peak capacity, making sure it is not overwhelmed by users who are unwilling to pay, while generating the extra revenue needed to defray the costs of the extra capacity that the company has built to accommodate these customers. In addition, charging peak prices makes it easier for the company to determine how much capacity to build over time based on whatever the peak-period customers are willing to pay.

The roadway system today, throughout the United States, does not employ peak-period tolling. Rather, users pay for most of their highway services through a charge per gallon that is collected at the fuel pump. In rough terms, the charge is the same, per mile, regardless of which segments of the roadway are being used, and regardless of whether the travel occurs in the peak or the off-peak period for that particular roadway.

This system of flat fees necessarily has the effect of *under*pricing peak use, and *over*pricing off-peak use, at least in relative terms. The result is that:

- roads are overused and experience queuing (congestion) during the peak periods
- users lose valuable time sitting in congestion

- use of the roads by High Occupancy Vehicles (HOVs) such as carpools and buses is less than it would otherwise be

These problems, in turn, affect the investment incentives and fiscal balance of the road system:

- Congestion provides a misleading signal to road authorities as to which facilities or routes need more capacity, which, in turn, may cause road authorities to build some roadway capacity or routes that the users themselves would not be willing to pay for
- Revenue generated by non-peak users, users on other routes and users from other regions must be used to pay for capacity that is not self-financing

Such a system of finance can remain solvent only if aggregate gasoline tax revenues are sufficient to permit cross-financing of road segments. Otherwise, the cost of revenue-deficit segments of roadway may grow to overwhelm the revenue surplus implicitly generated on other segments. When such a system is applied across a state or the entire nation, cross-financing raises large-scale fairness questions that are not easily handled through political processes.

One solution to this fiscal dilemma is to raise gasoline tax or other broad revenue sources, which can exacerbate underlying issues of fairness. Another is to use congestion tolling to explicitly recognize the true, differential cost of different road segments. The latter solution differs from the former in that it leads to correct rationing of current use and new investment at the same time it helps resolve the transportation fiscal problem.

The theory of congestion tolling is well established, and probably enjoys more agreement among economists than most economic policies. The potential of congestion tolling has been demonstrated theoretically many times, but real-world confirmation has been limited to the few sites where it has been implemented. By extension from other, related real-world examples, however, congestion tolling is potentially an important way to reduce congestion, spare society significant transportation costs, and yield positive economic welfare benefits (if properly applied).

Implementing an ideal variable tolling system has substantial technical and political challenges. Until recently, the policy and political challenges have not been explored in detail because the technical limitations have kept such an approach from serious consideration. But the technical issues are getting easier and cheaper to resolve (as this study demonstrates), and variable road tolling is now getting some serious attention.

The Technology: Charging and Collecting Tolls

Until very recently, the common image of road tolling was handing over bills or coins at a toll booth. While manual toll collection at toll booths is still common, no new toll systems are implemented without at least an electronic/automatic alternative for toll transactions that can support high-speed, non-stop traffic flow. San Francisco's bridges, the new northern bypass in Denver, and east-coast toll roads all have ways to prepay an account that gets debited as a vehicle equipped with a toll transponder (short-range communication device) passes, without stopping, an electronic reader. Managing traffic flow through price is not only feasible; it is the practice on many select road facilities in U.S. metropolitan areas and other countries.

The technology for tolling at a limited number of charge points on a specific highway is well developed, cost effective, and reliable. But applying electronic charges to entire road networks (as a tax replacement or supplemental charge) has been out of reach because of the high costs and design implications of the required roadside infrastructure (overhead gantries supporting electronic toll collection and enforcement equipment).

This situation is changing. Vehicle positioning, with the aid of digital maps and radio transmissions from global positioning system (GPS) satellites, is a large and mature industry. The technology is theoretically able to charge road users on all roads (a requirement of a fuel tax replacement) without large-scale deployment of roadside equipment, and its costs are dropping.

The technical systems are still developing, and the costs to implement them should continue to decline. But these approaches introduce other considerations into the policy debate about how to pay for transportation, such as safeguarding information about where people travel. Technology is no longer an absolute barrier to variable tolling, and the policy and political challenges become more important.

The Structure of a Variable Road-Tolling System

Overview

From a strictly economic or cost perspective, road prices (per mile of travel) should vary with:

- Level of congestion on the roadway. That congestion is a function of many factors, but fundamentally it is caused by perceived value of the travel on that route (travel demand) and the time of travel. Congestion is too many vehicles trying to be on the same road at the same time. The size (number of lanes, etc.) of a roadway is mainly determined by peak-period usage levels. Theory says peak period users should therefore bear the burden of paying for the portion of capacity that is necessitated by their use.
- Type (costliness) of the roadway. Road segments such as bridges, segments built on expensive land, elevated or other complex segments, are more costly to build, and should be paid for by those who benefit from them.
- Type of vehicle. Vehicles that are very slow, wide, long or heavy effectively require greater roadway capacity or sturdier facilities, and accordingly should be charged more for their use.

Thus, a complete congestion tolling system involves incorporating peak-period tolling in a structure that recognizes the type of roadway and type of vehicle. Implementing this kind of pricing completely requires a sophisticated technology to collect the requisite fees or tolls. There are a variety of ways congestion prices can be levied, but not all of them have the flexibility necessary to implement congestion tolling accurately.

Generally, the effectiveness of congestion tolling is the greatest with broad geographic coverage. Broader coverage, especially if it includes all competitive alternative routes, can reduce the problem of *diverted traffic*: traffic that is “tolled-off” the priced facility and now is using and congesting other roadways. A particularly bad form of this problem is *cut-through* traffic on local streets. Though barriers and policing can reduce the problem, the more efficient and fair way to deal with it is to price the alternative routes. Offsetting these advantages is the cost of implementation; which (when relying on roadside tolling equipment) rises sharply with geographic coverage, and as roadways with light use are priced.

Setting congestion prices correctly is important if the policy is to be fair and is to produce economic benefits. It follows from the theory of congestion tolling that congestion prices should be viewed as tools not for manipulating people's driving habits, but for giving signals to people about the costs of their use of the system, which gives them the opportunity to make sensible decisions based on those costs.

The precise calculation of the correct level of congestion prices requires information on the performance of individual roadways, the value of users' time, and other technical factors. An economic principle for the efficient use of resources is that the users of those resources should pay their incremental or marginal cost. Applied to transportation, road users should always bear the costs that their travel (use of the road resource) imposes on the roadway system. These costs are of three broad types:

- Congestion costs are the incremental costs that users' vehicles impose on the performance of traffic stream in which they operate. An individual user bears his own portion of this, of course, by being delayed himself in the traffic stream. But his presence in the stream imposes costs in the form of additional delay on all of the other users in the stream. This cost arises as a consequence of the inherently congestible nature of highways, but will only be significant under certain conditions. Specifically, when the user adds his vehicle to a light traffic stream, these effects are very small; when one more vehicle is added to an already-busy traffic stream, on the other hand, significant delays can be imposed on other users when they are added up.
- Roadway operational costs are any usage-related costs that are imposed on highway authorities or others operating the facilities. This includes such elements as routine maintenance, wear-and-tear imposed on pavements, operating costs of wayside facilities, etc.
- Social or external costs are costs borne by those other than the users or the highway authorities and operators. They would include the social costs imposed through the emission of pollution, creation of noise, accidental death and injury, etc. Many economists would extend the list to include the costs of judiciary, emergency and other public services that are occasioned by use, but borne by other authorities and not by users.

Making users pay, directly and immediately, for costs their use engenders encourages them to economize on costly activity. Patterns of use that demand a lot of the system's capacity at critical times and places adjust to those costs through congestion tolling; usage that imposes a lot of wear and tear on the system is given an incentive to economize through operating charges; and usage that imposes external, social burdens (e.g., air pollution, climate change) is discouraged through charges that are set to try to approximate these social costs.

Implementing congestion tolling does not affect just price levels. The setting of congestion prices has to be coordinated with the highway investment process. Properly applied congestion tolling requires that the revenues be utilized in the most economically-efficient manner. The appropriate congestion prices on the existing road system differ from the prices that should be charged after new additions (or deletions) to the roadway system are made. If congestion prices are levied, traffic volumes during the period being priced might change: setting prices needs to account for the effect of the tolling itself on traffic volumes in order to derive the appropriate price.

Tolling on Existing Roads

In most metropolitan areas, most of the roadways and bridges that will exist 20 years from now are already in place; some have already been "paid for" in the sense that bond debt or other borrowing used to finance their construction has been retired, perhaps long ago. Does that mean that the appropriate price is zero (or only some small amount for maintenance)?

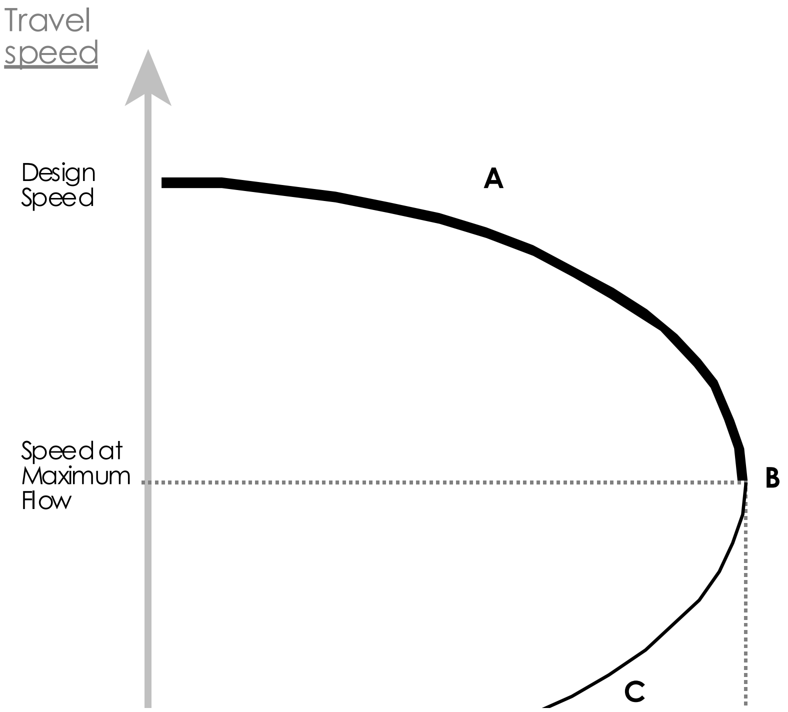
No. The physical costs of concrete, land, and so on may long since have been paid for. But another important cost of peak-period roadway travel is a recurring one: the time that users spend on the roadway and the delays they cause to one another. On existing roads, time costs are the most important resource to manage, and congestion prices must be set to properly allocate time costs among users. Efficient use of this key resource—time—is central to the case for congestion tolling, and is the most difficult to communicate to people unfamiliar with congestion tolling. The essence of congestion tolling is that drivers should pay for the aggregate time delay they impose on other drivers. If they do, the entire system can operate more efficiently.

During peak travel periods, demand for the use of limited roadway space is greater than the capacity for many roads to accommodate these vehicles. As vehicle volumes increase, vehicle flows and speeds decline leading to the travel delays that are so common in major metropolitan areas.

The characteristics of roads determine the specific capacity of that facility to handle traffic. Human drivers, responding to changing conditions, will normally reduce their travel speed in the face of increasing vehicle volumes. Higher vehicle volumes generally mean tighter spacing of vehicles on a given stretch of road, which in turn defines a “safe” travel speed.

Figure 1.2 illustrates the relationship. The region of the curve labeled “A” is characterized by low vehicle volumes and travel speeds near, or at, the free-flow design speed (55 mph or above for limited access roadways). As more vehicles enter the given stretch of road, speeds decrease but total vehicle flow through the portion of roadway increases. As vehicle densities approach the design capacity of the facility (region “B” of the curve), vehicle flow is at its highest, but traffic conditions become increasingly unstable.

Figure 1.2 Highway Speed-Flow Curve



Though decreased vehicle speeds mean closer following distances are possible, at some point the speeds are so slow that despite the density of the vehicles, fewer vehicles pass by a fixed point in a given amount of time: flow has decreased. Vehicle densities continue to increase but both flow and speed diminish (region “C” of the curve) until, at some point, the traffic on the facility comes to a standstill.

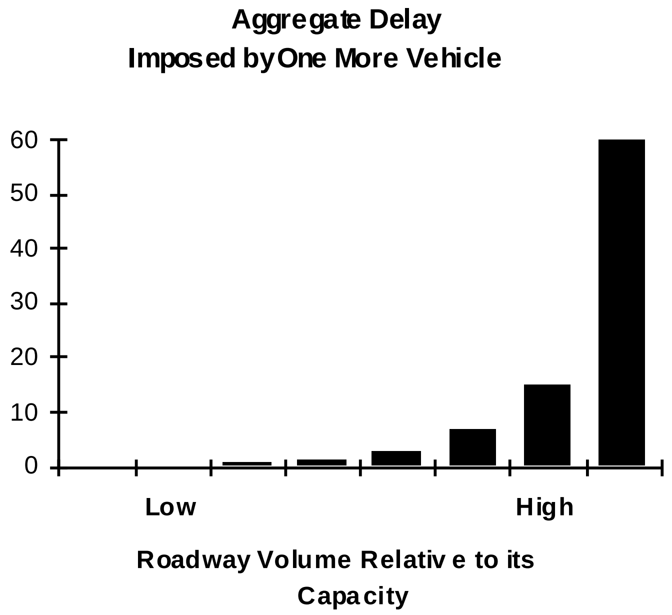
As roads are used more intensely, they require increasing amounts of variable inputs (travel time) per unit of output (flow or distance). In other words, as roads are used more intensely all users experience greater inconvenience or cost in the form of travel delays. Individual drivers on a road, unless possessing unusual empathetic tendencies, do not factor into their decision-making the inconvenience their actions cause for other users of the roadway. Each additional vehicle added to an already congested facility imposes an increment of delay on all the other vehicles already on that facility.

Each vehicle entering a roadway segment is, in effect, the consequence of an individual travel decision. Travelers make such decisions through some intuitive cost-benefit calculation that considers the intended result of the trip (benefit) and their own variable cost factors associated with making the particular trip (vehicle operational costs, travel time). Some costs are not experienced directly by the individual making the travel decision: for example, the costs of air, water, and noise pollution. In the case of a congested roadway, the most significant unconsidered costs are the costs of delay that the additional vehicle contributes to all other vehicles following it onto the congested facility.

A proper consideration and allocation of time costs requires congestion-based tolling because of the way vehicles physically interact on a busy road. When drivers add their vehicles to the traffic stream on a busy road, they slow down traffic and delay other travelers; this is the very nature of congestion. Although the additional drivers may be content with their own portion of the congestion burden, they can ignore the costs they are imposing on others, and have no incentive to consider these so-called spillover effects. In economic terms, each driver's *private* cost is much less than the *social* cost, so they perceive each trip as cheaper than it is (from a social perspective) and they make more trips than are socially efficient.

The spillover effects are not trivial. Speeds drop quickly as roads become congested. For a typical older freeway that is operating at very near its practical capacity, for example, an aggregate delay of up to an hour is experienced by other traffic for each new vehicle that tries to use the roadway. Fi**gure 1.3** illustrates this effect for a typical, urban freeway. Even at lower traffic level, an additional vehicle imposes aggregate time delay of 2 to 15 minutes on other users of a busy roadway.

Figure 1.3 Delays Rise Sharply with Increased Traffic Volumes[4]



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[4] Keeler and Small, 1977

Where traffic conditions are unstable (high vehicle densities) the delay imposed on subsequent vehicles from added vehicles can be quite high and can continue to be experienced long after the vehicle in question has exited the congested segment of roadway. If individual drivers were to be made responsible for the actual costs that their travel decision imposes on society some drivers might not make the same travel decision as when they experience only the average variable costs of travel (their own travel time). The result would be lower vehicle densities on the facility and higher vehicle speeds and flows. In this way economic theory suggests that improved facility performance, and greater societal benefits, can be achieved through the levying of a price equivalent to the difference between individual variable costs (or, in other words, the private marginal costs) and the variable costs to society.

The essence of congestion-based tolling is that drivers should pay for the aggregate delay they impose on other drivers. If they are not asked to pay these costs, they will each make travel decisions that collectively result in a lot of lost time for all travelers. The appropriate congestion price is likely to vary for different roadways. Roadways with very different traffic volumes, alignments, grades, or other factors exhibit traffic flow behavior (and, hence, spillover costs) that is different.

The correct congestion price depends on traffic volumes. The price will be high on roads operating near capacity (very congested) because the spillover effects are the greatest there. Conversely, when traffic is very light the vehicles interact very little, and spillover costs are negligible. The appropriate congestion price is correspondingly small or even zero. (Drivers would still need to pay for wear-and-tear and other roadway operating costs.)

The correct prices depend upon the level of congestion, the value of time, and people's responsiveness to prices. The calculations are not difficult, but they must be tailored to the conditions of a region. The steps for determining the proper congestion prices on existing roads are:

- The roadway segment to be priced is identified, and traffic volume data obtained for the time period and direction of travel on the roadway that is to be priced.
- Engineering information on the behavior of travel speeds under various traffic volume conditions is obtained. From this data and the traffic volume, the effect of an additional vehicle on total traffic delays can be estimated.
- Value of time information is obtained. This is usually from special statistical, travel demand studies, but also can be approximated by knowing the income level of the typical traveler on the roadway.
- The appropriate congestion charge is calculated. It is simply the value of the delay imposed by the vehicle times the value of time that other travelers place on that delay.

Congestion-based Tolling and Building New Roads

As described so far, congestion tolls seem to be calculated only from estimates of congestion burden (the cost of time delay), with no obvious connection to the cost of building roads. But if the process of building new roads is properly integrated with congestion tolling, congestion charges ultimately do bear a relationship to construction costs.

Congestion tolling and construction of new capacity are alternative ways to serve additional vehicles. In some circumstances, it may be less costly for society to build new capacity than to force additional vehicles to use the existing, busy roads at high congestion tolls. Therefore, roadways should be improved as long as the cost of serving additional vehicles with the improved road is less than the cost involved in serving them on the existing roads (indicated by the congestion price).

Congestion tolls and road building costs are related when tolling is properly integrated with decisions to build new roads. Tolling existing roads with appropriate congestion tolls makes it easier to identify the road segments that are candidates for improvement: those on which the congestion prices are high, relative to the cost of defraying roadway improvements in that corridor. Congestion tolling dovetails with a benefit-cost based approach to highway investment decision-making.

Tolling and Transit

Congestion tolling is viewed by some policy makers primarily as a potential source of revenue to finance transit systems. Their view is that transit should be considered as an alternative to new roadway capacity. Whether that makes sense depends upon the particular conditions in the affected corridors. Economic theory says that surplus revenues should be used to the benefit of those affected by the pricing policy (both the ones that pay the new tolls, and the ones that tolls compel to take alternative modes, routes, or times). In the extreme, if the revenues are instead used on projects that provide no economic benefit to affected parties, congestion tolling will reduce the economic welfare of the affected community.

Importance of the Use of Revenues

Clearly, efficient use of the revenues (whether on transit, additional roadways, or otherwise) is central to the efficient functioning of a congestion pricing system. It is sometimes said or implied by advocates of congestion tolling that all travelers will be better off. That is a theoretical possibility that can only become a reality if the toll revenues are spent efficiently to improve travel conditions for those paying the tolls, or somehow returned to the toll payers (e.g., as reductions in their gas taxes). If the revenues were just burned, most travelers would be worse off: they either had to change their travel behavior, or had to pay more to continue it.[5]

Improper use of the revenues also raises public-perception problems. If the revenues are used on a beneficial project, but one that does not benefit those affected by congestion tolling, the congestion tolling policy will be perceived as an unfair tax.

If no transportation improvement passes muster, then most economists would recommend that the revenue be returned to the affected highway customers. This could be done through reductions in other taxes, or through some other lump-sum payment that benefits those affected by congestion toling, without negating the desired congestion tolling effect. Commuter allowances and tax credits are two mechanisms that are frequently discussed in this regard.

In summary, if the existing roadway system is under-built, the cost of roadway improvements will fully use congestion tolling revenues. But if the roadway system is overbuilt, surplus revenues are available, and financing efficient transit services or returning revenues to users may be justifiable.

Variable Tolling Compared to the Current System of Road Finance

The current system of highway finance relies heavily on a flat fee: the motor-vehicle fuel tax (and licensing and registration fees). A comprehensive congestion-based tolling system, in contrast, would institute a differentiated structure of fees, varying by time of day, type of road, and type of vehicle.

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[5] For some travelers, with a high value of time, congestion pricing may increase the speed of their trip enough that the value of the time savings exceeds the toll.

As a practical matter, however, the nature of traffic on some roads (rural roads, for example) may be such that a flat fuel tax or VMT fee is all that is appropriate and would be the most practical and efficient method to use. In such settings the current fuel tax system may be a reasonable proxy for the correct pricing structure. But for busy and expensive facilities, congestion tolling would establish a quite different pattern of prices.

Congestion tolling also has different implications for the types of users on the highways. For example, under the current system, rising levels of congestion do not induce bus or carpool use as a way to economize on the fixed capacity of the roadway, as would be desirable. From an individual commuter's perspective the congestion delay is not avoided simply by riding in someone else's vehicle. In contrast, a congestion price can be reduced by sharing it with other riders, providing a strong incentive for bus or carpool use.

On the investment side, the main difference is in the signals that are used to identify roadways or corridors needing improvement. Without congestion tolling, it is very difficult not to focus investment on the most congested corridors, even if those investments cost more than they provide in benefits. In contrast, congestion prices help moderate congestion, and reduce the "false" signals sent by unpriced, congested roads.

With congestion tolling, there also is a more direct relationship between the revenues and costs for individual road segments or projects, which facilitates doing feasibility analysis on a segment-by-segment basis. That makes it easier to rely on financial criteria to evaluate roadway projects, and may make the debate over allocations of road finance resources less politically-charged, since it will be clearer who pays and who benefits.

Congestion tolling, however, has the major disadvantage of not being a standard procedure. It is different, and raises new issues that can be criticized. Will it really work? Can the technology work reliably and at what cost? What about privacy: should government be trusted with information about where citizens (or at least their vehicles) are at a certain time? Does congestion tolling create opportunities that the rich can afford but the poor cannot, and, if it does, is that fair? The answers to these and other questions are starting to come in, but the next section explains why more research is needed.

Need for a Comprehensive Test

These very real issues of policy (safeguarding user information, fairness of variable charges, revenue and traffic implications) can only be truly investigated with the aid of much more comprehensive information about user choice behavior. And to be useful, information about revealed choices in the face of variable road charges must involve an application of tolls within some real-world setting. This is a major challenge, but one that can be overcome through the careful design of large-scale road tolling experiments.

Such experiments, like this Traffic Choices Study, show policy and design tradeoffs that otherwise remain obscured by a more narrow application of road tolling at the margins of a road network. The Traffic Choices Study was undertaken not because there are clear answers about the right direction for the future, but because the cost of inaction is so high.

Significant current attention has been paid to the issue of traffic congestion in the state of Washington, and in the Seattle metropolitan area. Area businesses are particularly concerned that transportation problems may begin to considerably and negatively influence their ability to be effective participants in an increasingly broad and competitive marketplace. For the central Puget Sound region, this study is a first step at understanding one possible alternative to such a state of affairs.

1.3 THE TRAFFIC CHOICES STUDY: TESTING VARIABLE ROAD TOLLING

Background Leading to the Traffic Choices Study

According to one commonly cited study[6] the Seattle metropolitan area has some of the worst congestion problems in the U.S: residents of the Seattle area can expect to spend approximately 40 percent more time traveling by automobile during peak periods than they would spend if congestion were not present.

Estimates of the cost of congestion to residents and businesses in the central Puget Sound region range from between $1.5 billion to $2 billion annually. These costs are primarily in the form of lost time that cannot ever be recovered. Losses due to congestion are currently between 1% and 2% of total regional personal income. Forecasted future conditions suggest that the value of resources lost through congestion may increase at over three times the rate of growth in personal income through 2030. By 2030, resources lost to delay will be in excess of 3.5% of personal income, representing a sizable drag on the regional economy.

The discussion of transportation pricing and finance reform in the central Puget Sound region emerged as part of the development of a regional transportation plan. The Puget Sound Regional Council (PSRC) created a Transportation Pricing Task Force in 1995 to carry out the plan's policy directives. The Task Force comprised local elected officials, transportation professionals, area business representatives, and environmental and public interest group representatives.

The Task Force's mission was to educate and inform, and provide public and elected officials with a framework for discussion and problem solving. The Task Force's work examined problems with the current transportation financing systems, paving the way for the general consideration of market-oriented approaches to finance. The research also analyzed options for the introduction of more market-oriented finance tools to better ensure that public revenues are adequate to maintain, preserve, and improve the region's transportation system, and to better balance transportation supply with demand. The Task Force also recommended the implementation of tolling demonstration projects to advance local understanding of the opportunities and implications of road tolling.

In May of 2001, The Puget Sound Regional Council's General Assembly of members adopted a new regional transportation plan, *Destination 2030*. Destination 2030 includes $145 billion in planned transportation investments to be made over the next 25 years. Current funding sources are way short of that total investment. Locally and nationally, there is a growing awareness that if improvements to the transportation system are to be made, new capacity investments will need to involve innovative financing strategies.

The Puget Sound region has added little new highway capacity within the last two decades, but is poised to substantially add to the highway system over the next decade. Significant corridor projects are in various stages of planning and together amount to a qualitative change in the entire network of limited access facilities within the core of our region. Yet, there is no reasonable set of assumptions about funding and finance that can pay for all these investments without some use of direct use charges.

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[6] The Texas Transportation Institute's Urban Mobility Report (2005)

Overview of the Traffic Choices Study

To help address this set of problems the Puget Sound region resolved to develop and execute a transportation tolling demonstration project to test the effectiveness of variable road tolling as a tool for managing highway infrastructure and producing revenues for reinvestment in transportation facilities and services. The Puget Sound Regional Council (PSRC)—the agency charged with regional transportation, economic, and growth planning for the central Puget Sound region of Washington State—took the lead.[7] Though the PSRC had undertaken a large amount of work examining various value pricing mechanisms and their impacts, it believed that the introduction of new transportation pricing mechanisms could only be taken forward by implementing a pilot program. This belief was confirmed in the *Destination 2030* plan, which recommended that the region implement a pricing demonstration before 2006.

In 2002, the PSRC developed a concept for a regional tolling experiment using volunteer participants and tolling technology with Global Positioning System vehicle location at its core. The project proposal was developed and submitted to the Federal Highway Administration's Value Pricing Pilot Program (VPPP) and awarded grant funds.

The demonstration was of system-wide (not single-facility) tolling, which was unlike any project previously funded through the VPPP. It offered benefits that no other project, existing or proposed, offered. The demonstration project became known as the *Traffic Choices Study.*

The study was designed to monitor and explain the travel choices of drivers as they faced tolls (which varied by time and location) charged for the use of the roadway network. The primary aims of the study were to (1) accurately describe the behavioral response to the congestion tolling of roadways, (2) better understand issues of policy related to the implementation of road tolling, and (3) test an integrated system of technical solutions to the problem of tolling a large network of roads without deploying substantial physical hardware on the roadside. Related objectives were to:

- *Familiarize the public and policy makers with variable road tolling.* The demonstration project provided a limited number of households with a direct experience with road tolling. Those motorists involved in the project should better understand how price relates to the benefits of their travel choices. Travel decisions in relation to price were made explicit. The technology involved in road tolling is unfamiliar to most people; experience with the technology will make it seem less strange.
- *Generate price response data for use in other analytical efforts.* A properly developed sample stratified by income allows the sample data to be used to develop elasticity estimates for broader analysis of transportation tolling. User response data and elasticity estimates can be incorporated into regional travel demand models as well as various revenue models used to forecast transportation revenues. Appropriately derived elasticity measures can aid in corridor transportation studies where tolling may be considered as a financing or management tool.
- *Develop an understanding of technological applications and standards.* Specific vehicle positioning, communications, and billing applications were developed for the administration of the project, and others will be defined as they would be needed for the broader actual application of a system wide facility tolling program.
- *More finely define a set of policy issues to be addressed in actual program design.* The application of tolling in the demonstration project will allow a more defined set of policy issues to emerge, to be addressed in the design of an actual network tolling program for potential future

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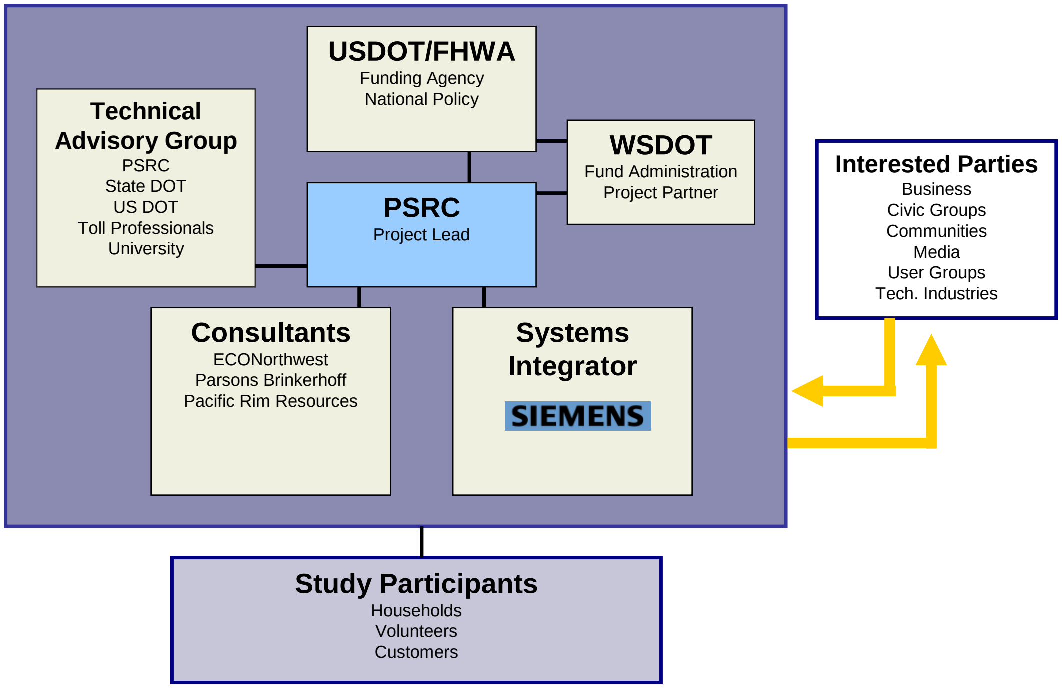
[7] The Regional Council serves as a forum for cities, counties, ports, transit agencies, tribes, and the state to coordinate on important regional issues.

implementation. Generally, these policy issues encompass user privacy, payment security, enforcement, use of revenues, and other elements of program design and marketing.

The PSRC conducted the study in coordination with the Washington State Department of Transportation and the Federal Highway Administration. The PSRC received assistance from of a team of experts in the fields of economic analysis, transportation analysis and engineering, and public involvement (**Figure 1.4**). As “Systems Integrator,” Siemens was responsible for developing the software, providing the in-vehicle on board units and integrating all the systems and components.

The Traffic Choices Study monitored travel behavior before and after tolling for a statistically significant sample of motorists (the participants in the experiment). The participants were charged for access to selected roadway facilities at particular times of day. The demonstration held participants financially harmless by providing them with individualized travel budgets with which to pay the tolls, and gave them the incentive to change travel behavior by allowing them to retain as a cash reward any money left in their budgets at the end of the experiment. The project tested the application of Global Positioning System (GPS) technology to locate participating vehicles in time and space. Chapter 2 and its accompanying appendices provide much more detail.

Figure 1.4 Traffic Choices Study Project Management



Key Features of the Study

The key features of the Traffic Choices Study were (1) in-vehicle, GPS-based billing, (2) a hold-harmless billing design, (3) system-wide tolling, and (4) an experimental vs. control research design.

In-Vehicle GPS-Based Billing

In this pilot, electronic devices [referred to as "in-vehicle meters" or "on-board units"] were placed in participants' vehicles that impose different prices per mile to travel depending upon the location and time of travel. Drivers will be made aware of the tolls both though maps and other printed material, and a real-time read-out on the in-vehicle meter. The location and time of travel of the vehicle will be determined by an integrated GPS antenna/receiver, which will also be used to calculate highway user charges. For study purposes, the hold-harmless billing approach (see below) offers a natural penalty system.

Hold-Harmless Billing

This pilot has special features designed to expose drivers to variable road user charges while still encouraging voluntary participation. Specifically, at the start of the pilot, participants will receive a billing account with a positive, cash balance. Any cumulative in-vehicle meter charges will be debited against this balance. Any funds remaining in the account at the end of the pilot may be kept by the participants. This "hold-harmless" study design gives participants the opportunity to participate without committing their own funds, yet gives them the incentive to adjust their driving behavior so as to enjoy the surplus remaining in the account at the end of the experiment. The effect on behavior should be the same as the effect of paying out of their own pocket, but without the adverse participation effects.

System-Wide Tolling

The GPS approach has been selected because it offers a cost-effective method of tolling ubiquitously. By relying on "In-Vehicle Meters", the need for expensive wayside antennae is eliminated, and even arterial roads can be priced cost-effectively. This is important in a region such as the Puget Sound where the extensiveness of the highway network makes selective tolling pilots difficult to implement without significant diversion. In addition, as changes in vehicle propulsion technologies evolve, there likely will be a need for a replacement for the existing ubiquitous pricing system of fuel taxes.

Experimental vs. Control Research Design

In this proposed demonstration project, the effects of the tolling policy are measured by comparing the travel behavior of participants before and after the policy. Unlike other demonstration project designs that require the participation of everyone on one affected corridor or facility, this study design permits measurement of behavior in multiple places in the network at low cost. This will provide much broader information about the prospects and potential for road tolling in various trip settings, and expose users in a broader geographic area to the principle.

The demonstration project provided a number of households with a direct experience with road tolling. Those motorists involved in the project will better understand how price relates to the benefits of their travel choices. The technology involved in road tolling is unfamiliar to most people; experience with the technology will make it seem less strange. Building public familiarity with a new way of paying for transportation is a crucial element in ultimately securing the necessary public acceptance.

Many states, such as Oregon, California, Georgia, Florida, New Jersey and Texas are currently testing the real world application of a number of use-based market (value pricing) financing approaches. The Traffic Choices Study can significantly contribute to this growing body of knowledge and would also lay the groundwork for a future finance option for major investments in the central Puget Sound region's roadway network.

CHAPTER 2

THE EXPERIMENT

CHAPTER OVERVIEW

The most important purpose of the Traffic Choices Study was to see how drivers changed travel behavior when faced with paying tolls that reflected the amount of congestion a road was experiencing. To learn how drivers respond to tolls, the Traffic Choices Study studied a statistically significant sample of volunteer drivers (the "participants" in the experiment). It established their baseline, "before-tolling" driving routine, and then began charging them for access to selected roadway facilities at particular times. In order to accomplish this task, researchers concluded that the experiment should equip and monitor the movements of no fewer than 450 vehicles (approximately 275 households) for an average minimum of approximately 12 months per vehicle.

Participants did not lose money. They were given an account (their travel budget, or endowment account) from which tolls were deducted. The amount in the account varied by household, and was calibrated based on their "before-tolling" travel behavior. If their driving patterns did not change over the course of the experiment, they would "spend" their account balance by the time the experiment concluded. If they changed their driving patterns to reduce the amount of driving on toll roads, they could keep the difference. This method held participants financially harmless, yet offered them the incentive of keeping their leftover budget if they changed their driving patterns.

Recent interest in less infrastructure-intensive toll systems, and rapid advances in mobile computing and satellite-based positioning technologies, have created an emerging industry for charging systems based on vehicle positioning capabilities. The experiment integrated functions that are already commonly found in automobiles into a single on-board device (referred to more often as the OBU—on-board unit). The meter used Global Positioning System (GPS) technology to provide a highly detailed (second by second) record of travel behavior for each vehicle.

The meter's display showed toll rates and a road description. The meter stored location (spatial coordinates, in latitude and longitude) and toll information, and periodically communicated them to a central computer using cellular wireless communications. Through this approach, the Traffic Choices Study covered an entire road network (including arterial roads) with a toll system without incurring extensive roadside infrastructure costs.

The rest of this chapter describes the steps the project team took to: design the experiment, develop the toll system, recruit and enroll participants, collect baseline data and data during tolling operations, manage participants, administer the system, and close the experiment

2.1 EXPERIMENTAL DESIGN

In the summer of 2005, the drivers in nearly 300 households started paying tolls every time they drove on highways and major arterial streets within the central Puget Sound region of Washington State. The tolls varied depending on time of day: drivers paid the highest tolls during the peak driving hours in the afternoon. Tolls also varied depending on the type of road and time of the week. Meters in over 450 vehicles showed drivers the road they were using and the toll they were being charged, and sent that information wirelessly to a central office. For 10 months, drivers paid real money and felt real consequences for driving during on congested roads at congested times of the day and week, and volunteered for the opportunity.

The Mechanics of the Experiment

In the spring of 2003, the project team began designing an experiment that would require a highly technical simulation of a toll system. The project had a limited budget to create the technical system, yet it needed to support the highly detailed behavioral experiment. The technical system needed to meet a variety of requirements, including:

- Represent a high degree of roadway network detail
- Provide a highly flexible toll schedule
- Assign road users to roads used accurately
- Handle all transactions in a verifiable manner
- Provide direct feedback to the road user about facility use and tolls
- Support behavioral analysis with flexible system for storing participant data
- Provide toll system billing functions
- Equip all participating vehicles with meters, and uniquely identify all those vehicles
- Function without permanently altering participant vehicles
- Support operations with little or no testing
- Meet the project budget

The project team selected the GPS tolling approach because it offered a ubiquitous and cost-effective method of tolling on all roads. By relying on “in-vehicle meters,” the team avoided the need for expensive wayside antennae. GPS allowed for cost-effective tolling of arterial roads, important in the Puget Sound region where the extensive highway network makes selective tolling pilots difficult to implement. GPS technology also has valuable future implications: as vehicle technology changes, it could become a replacement for the existing tolling of roads using fuel taxes.

The toll system needed to handle complex trip characteristics and tolling strategies. In short, it had to be very accurate about where and when vehicles traveled (high precision waypoint locational capability and high frequency waypoint capture capability). In addition, the OBUs needed to be able to communicate user fees to participants as they were incurred, including total trip costs as well as toll rates per mile. They needed to include the capacity to communicate eight to ten different price levels (for different time periods or facility characteristics) and reliably price the over 7,000 road links in the regional network.

The measurement of trips, vehicle miles traveled (VMT), trip purpose, route, origin and destination locations, and so on would be determined, in part, by analyzing the data once the trips were completed. Because daily travel behavior naturally has a large variance, the quality of the data had to be high so as to not introduce spurious variation with missing or imputed data. Because behavior changes measured in this study would be subtle or marginal, losing or misinterpreting data had high costs, so reliability was a critical requirement for the selection of the system for the data retrieval and processing.

While the project team was defining the technical requirements of the system and acquiring a vendor to provide such a system, it was also refining all other aspects of the experiment. The team created requirements for the sample to ensure the findings could be generalized to a broader population of road users, and determined toll rates to closely approximate the short-run marginal costs associated with the use of various elements of the road network. It developed a participant recruitment and management plan, and established a basic methodology for creating household travel budgets (endowment accounts). In summary, the study went through the following steps before implementation:

5/1/2003	Developed approach to toll system vendor procurement
9/1/2003	Issued request for qualifications from System Integrators (toll technology)
10/20/2003	Received System Integrator submittals
11/15/2003	Selected of Siemens as System Integrator
2/5/2004	Held initial design workshop with Siemens
4/1/2004	Signed Siemens contract
4/1/2004	Finished sample design and participant recruitment planning
5/1/2004	Started tolling road network development (geography and road classes)
7/1/2004	Started road digital map file (geo-data) development process
7/1/2004	Started project communications material development
9/21/2004	Started participant recruitment
9/30/2004	Completed back office functionality
10/20/2004	Completed initial participant recruitment
10/20/2004	Completed tolling network geo-data
10/28/2004	Achieved passage of the system Acceptance Test (Siemens)
11/8/2004	Began installation of On-Board Unit (OBU)
11/30/2004	Began second participant recruitment phase
1/1/2005	Finished tariff model - toll rates
2/10/2005	Completed second phase participant recruitment
2/20/2005	Completed OBU installation
3/1/2005	Began baseline data collection

Sample Requirements

Sample size was a key issue: in this experiment, the sample was the study participants, grouped by household. Many households have multiple vehicles. A large sample is always preferred (everything else being equal) to a smaller sample. As a practical matter, however, the advantages of sample size must be balanced against the disadvantages of measurement error if sample size is gained by using a primitive measurement technology that introduces measurement error:

- Statistical precision (generally) only goes up with the square root of the sample size; hence, doubling the sample improves test precision by only 40%.
- Higher variance in measurement, in contrast, degrades precision in direct proportion to the standard error of the measurement distribution; hence, doubling measurement error halves statistical precision.

Holding the methods and precision of data collection constant, a larger sample means larger costs due to the requirements of equipping all household vehicles with the tolling meters and funding their travel budgets. Given the fixed budget, a larger sample size would have reduced the study’s ability to create a realistic travel budget—and therefore, realistic incentive—for the drivers. Too small of a budget would make behavior more difficult to measure and would introduce bias. Premature exhaustion of an Endowment Account balance would not only introduce behavioral bias, but also make more difficult to measure accurately the effect of tolling, and to separate out the wealth effect of Endowment Accounts from the price effect.

For all of these reasons, the project team determined it was better to have high-quality data from a smaller sample than lower-quality data from a larger sample. The team anticipated that the ideal tolling system (given the budget constraints) would equip and monitor the movements of no fewer than 450 vehicles (approximately 275 households) for an average minimum of approximately 12 months per vehicle. A longer data collection period was desirable (all else being equal) to allow more robust analysis once the experiment concluded.

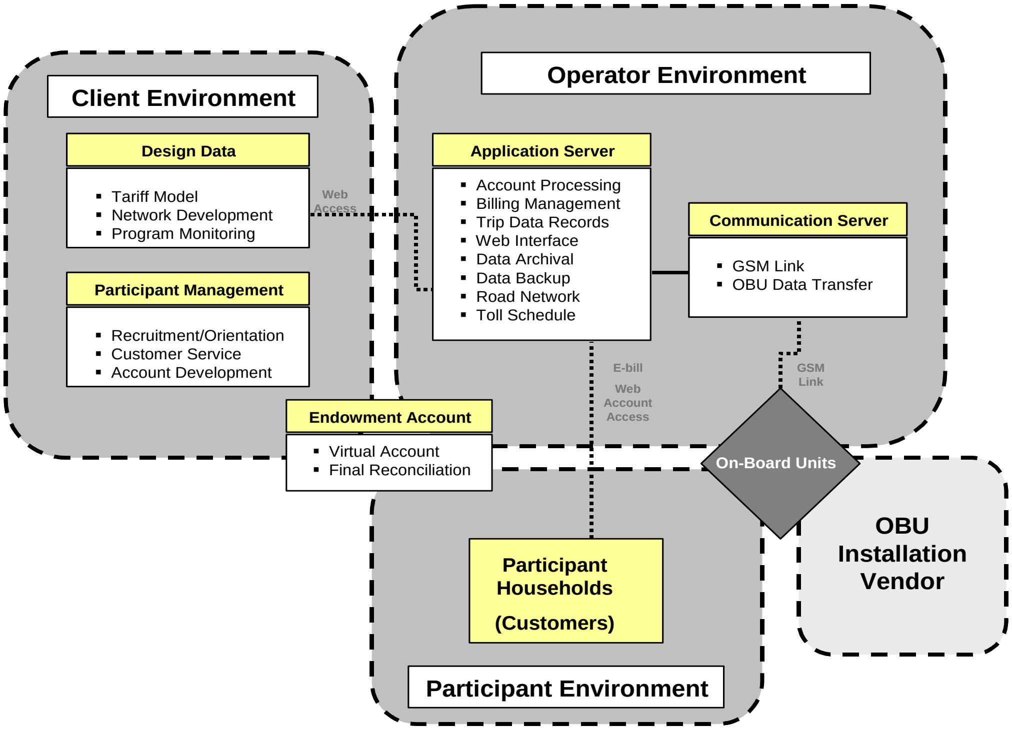
2.2 TOLL-SYSTEM DEVELOPMENT

A controlled experiment to better understand people's behavior during congestion tolling required implementing a network-wide road tolling system. Conventional road tolling technologies would not support this experiment at any reasonable cost. Typical tolling technologies require extensive overhead, or side-mounted, short-range communication equipment to support toll transactions and enforcement. Fortunately, recent interest in less infrastructure-intensive toll systems, and rapid advances in mobile computing and satellite-based positioning technologies, created an emerging industry for charging systems based on vehicle positioning capabilities. The experiment integrated functions that are already commonly found in automobiles into a single on-board device, or meter (referred to elsewhere in this report as the on-board unit, or OBU).

A global positioning system receiver uses radio signals sent from satellites to determine a vehicle's position in space and time. These spatial coordinates match a map of the toll-road network embedded in the meter, and the meter's display shows toll rates and a road description. The meter stores spatial coordinates and toll information, and periodically communicates them to a central computer using cellular wireless communications.

Through this approach, the Traffic Choices Study covered an entire road network, including arterial roads, with a toll system without incurring extensive roadside infrastructure costs. This was essential given the experimental nature of the project. Several European countries employ a similar approach to road network tolling to support heavy-vehicle charging, and this approach is being considered for more extensive application where deploying roadside infrastructure is difficult or prohibitively expensive. **Figure 2.1** shows the organizational framework for this toll system.

Figure 2.1 Toll System Organizational Concept



Toll System Requirements

The project team determined system requirements based on the study's primary objective: to collect information about drivers' use of the road system that would permit detailed assessment of how they made different choices when faced with tolls. The requirements for this experiment differed in important ways from the requirements that would support the implementation of a toll system as a revenue operation: they did not include payment processing and enforcement elements. In most other respects, the core elements of the "experimental" toll system mirrored those necessary for full revenue operations. This connection to practice was reinforced by the fact that the experimental toll system was developed by firms directly involved in toll system design.

On-Board Unit (OBU)

This device within a participant's vehicle showed the driver the current charging rate (toll) for the facility (road) she was driving on, and recorded the vehicle location using GPS technology. The specifications for the ideal OBU for the experiment:

- Capable of storing road map files, road price tables, and collected waypoint data sufficient to permit a toll calculation within the OBU itself. The project team recognized that we might have to settle for an alternate (less desirable) solution with route identification and toll calculation occurring at central data server.
- Capable of wireless communication with the Central Management System (CMS) that occurs at an interval necessary to transmit toll calculations and update account information.
- Permit successful map matching all location points necessary to correctly managing billing processes, and should be designed such that it works reliably under all environmental conditions.

- Readily mountable within the vehicle, be able to be removed without leaving any permanent damage and should incorporate a display of the current charge rate that can be safely read by the driver while driving.
- Tamper resistant and protected from being detached from the vehicle without authorization.

Toll Calculation System (TCS)

The Toll Calculation System (TCS) needed to match the position of the vehicle (from the location data collected by the OBU) with road information and assign a toll value that would be displayed in the vehicle and billed to the account. An ideal TCS would be embedded in the OBU and would allow toll calculations to occur without a transfer of data outside of the vehicle, and would include a map with enough precision to accurately assign prices. The TCS would include a function that allows common routes to be named and priced by name. If the TCS could not provide accurate toll information from within the vehicle, an alternate approach would be to transfer vehicle geo-coordinates to the Central Management System for map matching and toll calculation.

Central Management System (CMS)

The Central Management System needed to collect, store, and organize account data. If the OBU system would not identify routes and calculate tolls internally, these data would need to be transmitted to the CMS and back to the OBU using a local, commercially provided wireless network. The CMS would need to be secure, have redundancy and be capable of backing up data/reports, and be able to log all data received and transmitted.

Endowment Account Management System (EAMS)

Participants were to receive an electronic endowment account based on their travel patterns before tolling was implemented. The Endowment Account Management System (EAMS) would manage those accounts. As participants drove on priced roadways the tolls would be debited from the account balance. The EAMS would communicate with the CMS account data and handle all the billing functions. The EAMS would provide regular (monthly) customer billing statements to experimental participants via mail or internet. The EAMS would also need the capability to reconcile accounts upon identification of errors and the ability to confirm account resolution to the PSRC and the experiment participant. The EAMS would provides web-based customer access to endowment accounts with system updates made on at least a daily basis.

Road Network and Data Resolution

The toll system would need to guarantee functionality of all systems and assure data integrity. The system would have to accommodate the complexity of participant trip characteristics, faithfully simulate efficient system-wide tolling to the participant, and measure pricing response. The system would incorporate a variety of links that are priced at different levels. For the experiment to accurately simulate ubiquitous, efficient pricing, the OBU would, at a minimum, charge tolls and report (to the driver and to the data center) when the driver travels through one of these links.

Table 2.1 displays the number of roadway links in the PSRC travel demand model that carry volume to capacity ratios of various magnitudes. Variable roadway tolling might be expected to apply to links carrying higher ratios of volume to capacity.

Table 2.1 Candidate Links for Tolling

	AM Peak		PM Peak	
V/C Ratio	Links	Link Share	Links	Link Share
0.6	633	3.8%	858	5.2%
0.7	441	2.7%	795	4.8%
0.8	360	2.2%	699	4.2%
0.9	253	1.5%	523	3.2%
1	159	1.0%	276	1.7%
1.1	110	0.7%	228	1.4%
1.2	59	0.4%	169	1.0%
1.3	27	0.2%	114	0.7%
1.4	34	0.2%	44	0.3%
1.5	20	0.1%	49	0.3%
Links V/C > 0.6	2,096	12.7%	3,755	22.8%
All Links	16,500	100.0%	16,500	100.0%

The project team looked to see what would happen if it set the volume-to-capacity threshold at 0.6. It resulted in selecting approximately 2,100 roadway links in the AM peak and 3,800 links in the PM peak as likely candidates for tolling. Budgetary constraints were again important. Establishing tolling on fewer links would make the experiment less like a real, efficient pricing structure. The team decided that the system should price at least 4,500 (i.e. 1,500 + 3,000) and up to 5,900 (i.e., 2,100 + 3,800) links.

For experimental purposes it was also important to measure how drivers use non-priced links. Ideally, the time of day, distance, speed, and path of trips on non-priced links would be captured by the OBU at a similar level of detail as priced links, but simplification of these data has less impact on the overall experiment design. Collected trip data for all links would include trip-level and vehicle-miles-traveled data sorted by vehicle and time period, departure times, trip lengths and paths (where paths are different roads, but not different lanes of the same road), and origins and destinations.

Toll System Procurement

With general technical requirements in mind, in the Fall of 2003 the project team began the process of finding a vendor who would produce the technology for the tolling system. Because the project required such complex technology, the PSRC issued a “notice of intent to solicit proposals” to give potential bidders sufficient time to prepare a proposal. The notice of intent outlined general details of the systems integration services being solicited so that potential bidders could, if necessary, explore institutional relationships, develop general systems integration architecture, or conduct any other preparatory work they deemed necessary. In the notice of intent, the PSRC asked that any interested organization submit a Statement of Interest if they wished to be considered further.

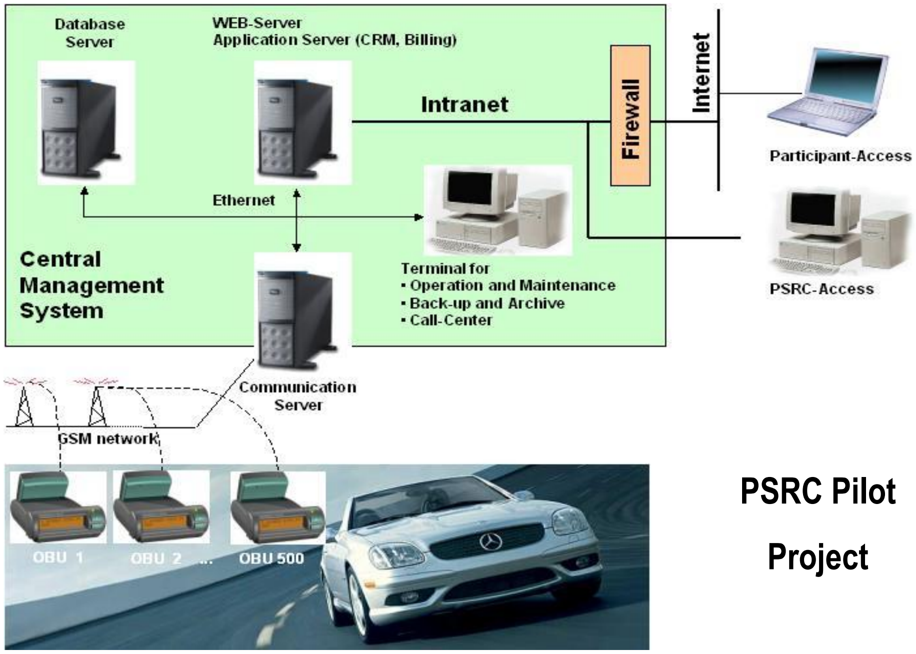
After receiving and reviewing the *Statements of Interest*, the Traffic Choices Study team evaluation committee provided the most appropriate candidates with the full Request for Proposals. This request provided more details about the purposes of the project and the specifications of the desired system for data collection and billing (as discussed above), so that potential systems integrators could provide a more detailed explanation of their specific qualifications.

The most important function of the technology was data collection, not technology development or demonstration. The technology had to be a complete, reliable system for collecting data, within the constraints of budget and schedule. The ideal system would be one that had been specifically designed for road tolling applications. The systems integrator needed to demonstrate that system components worked for road tolling purposes, at least for the duration of the experiment. The request for qualifications required vendors to produce an integrated system including hardware, software, and various data systems ready to work when the project began.

This practical approach to procurement was particularly important to the early success of the Traffic Choices Study. Often, complex technology projects will draft highly detailed specifications against which vendors are evaluated and then contracted. The Traffic Choices Study budget and schedule did not permit extensive design iteration, and instead relied on securing a technology partner with a strategic interest in the success of the project who would develop the design specifications independently.

Over a dozen firms from half a dozen countries expressed interest in participating as system integrators, and the PSRC asked five to submit a full statement of qualifications. In 2004, the PSRC chose Siemens to supply, implement, and support the various parts of the project. Siemens was responsible for providing the overall system software and integration, including the OBU application; and was responsible for local project management and coordination.

Figure 2.2 Siemens Toll System Overview



PSRC Pilot Project

The Siemens system proposed OBUs that would collect real-time position data and visually notify the motorist when they entered a tolled facility. Using Global System for Mobile communication (GSM) technology, the OBU would communicate with the "back office system" (Central Management System) which would handle user accounts, store positional data, and generate monthly road use statements. The Siemens GPS-based tolling system was the first system of this type in North America.

The PSRC project team and Siemens participated in a pre-contract design workshop and agreed on general terms as well as a set of technical system final specifications, (see Appendix XX*)*. The technical specifications addressed all of the components of the system including the on-board equipment, back office functions, tariff model components, and billing functionality.

Toll Road Network Development

Efficient road tolling recognizes that motorists should pay for those costs that they impose on the system, including the congestion costs they impose on other users of the system. Congestion varies across time and space within the road network, and ways that drivers respond to congestion-based charges include taking different roads in the network. Thus, any experiment attempting to understand the behavioral implications of efficient road tolling needs to be able to levy tolls on most major components of a region's road network: major surface roads and highways. Tolls must adjust depending on the facility, facility class, and time of day. Identifying the specific road network to which tolls, or charges, may be applied is a critical preliminary step in creating a successful tolling system.

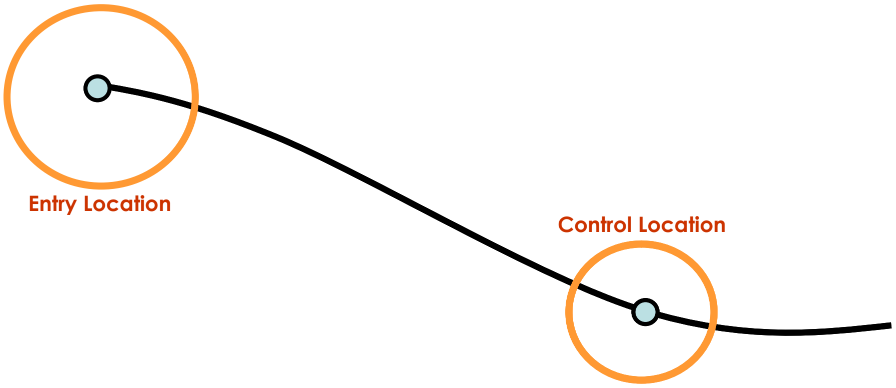
Base Map

A road tolling system that uses the Global Positioning System to match vehicles with the roads they use must also make use of a highly accurate digital map of the underlying road network. A vehicle's position in space and time can be determined with the use of GPS radio receiver technology to some reasonable degree of accuracy. But this position must be superimposed on a road map, or a set of spatial coordinates and attributes that represent actual road network characteristics. This digital road map is connected to the rules for setting toll levels, which are formulated within a toll (tariff) model database. These connections between maps and tariff models are the information used by either the back office or the OBU to correctly charge drivers for their road use.

Many digital map files of the U.S. road networks are commercially available for use in such a road tolling system, although they vary in accuracy and network detail. Digital map accuracy is a function of how closely information in the digital map database approximates the actual road geometry. The Traffic Choices Study required a detailed digital base map that was sufficiently accurate to match drivers and roads with effectively no match errors. Accuracy is a function of several things, including the ability of the GPS device to correctly resolve its location, the accuracy of the base map of the road network, and the map matching approach employed by the positioning/tolling device, as well as sources of unknown error.

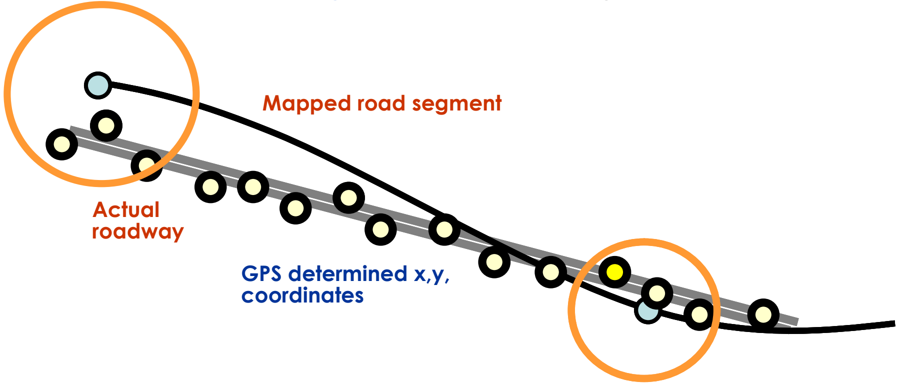
Base map requirements also depended on the methods for linking data about a vehicle's location with that map base. The Siemens tolling OBU matches GPS derived coordinates with the digital road map in the following manner. Any given road segment (say a portion of a road between any points of access and egress) is characterized by sets of spatial coordinates (latitude and longitude). One set of coordinates identifies the entry point of the road segment, while another set of coordinates identifies some other point on the road segment, downstream of the entry location in the direction of traffic flow (Figure 2.3). Each set of coordinates also has an associated radius measure that defines a circle around that point location. This circle is a zone within which GPS returns (the vehicle location at a given point in time determined by the GPS signal receiving device) are "captured" and associated with that defined point in the road segment. The radius is sized to accommodate the extent of road geometry (multiple lanes), digital map error, and GPS signal error.

Figure 2.3 **Example Road Segment**



The OBU records drivers' use of toll roads by logging the GPS return every second that a vehicle equipped with an OBU traversed a road segment included in the toll network. This resulted in a trail of vehicle location points. The system matched the vehicle location with the toll charge by correctly associating the GPS return with that segment's entry and control location coordinates, as shown in Figure **2.4** below. Other logic checks were supported by the system, such as consistency of direction of travel.

Figure 2.4 **Map Matching Concept**



The PSRC possessed a digital road file of sufficient scale and accuracy to be used as part of the tolling system, although it required some modifications as described in detail below.

Extent of the Road Network

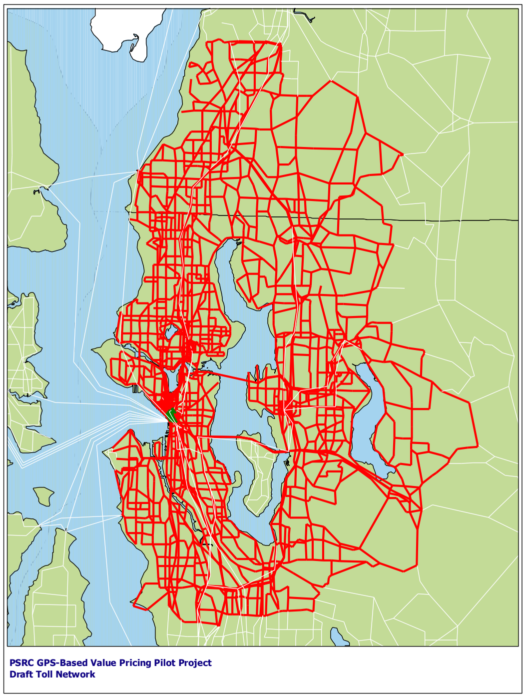
The OBU provided by Siemens was limited, by design, as to the number of road segments that could be stored as a network of tolled roads. This limitation could be changed in future designs. The practical implication of the limitation was that it reduced the geographic extent of the tolled network. Under the assumption that every link or roadway segment within a defined geographic area (e.g. the 16,000 one-way links within the PSRC's model network) would potentially be tolled, the 8,000 link memory constraint of the OBU meant that the experiment would have to limit tolls to geographic subsets of that network.

Selection of the final network geography interacted with other aspects of experimental design. Project participants needed to live and work in the same, or similar, geography to ensure that they drove on roads in the tolled network. This required equipping participant vehicles in ways that were convenient to participants' homes and workplaces.

The result was a road network extent that focused on South Snohomish County and North-Central King County. This network was loosely bounded by Puget Sound to the west, north Everett to the north, the east boundary of the Sammamish Plateau to the east, and Renton/SeaTac to the south, as shown in Figure **2.5**.

The network represented downtown Seattle by a single zone (other than I-5 and SR99) rather than the individual network links, because of concerns about poor GPS signal reception amidst taller buildings and reflective surfaces. Travel downtown could either be priced with a flat toll charge or a uniform toll per VMT.

Figure 2.5 Proposed Toll Network



Digital Road Network File

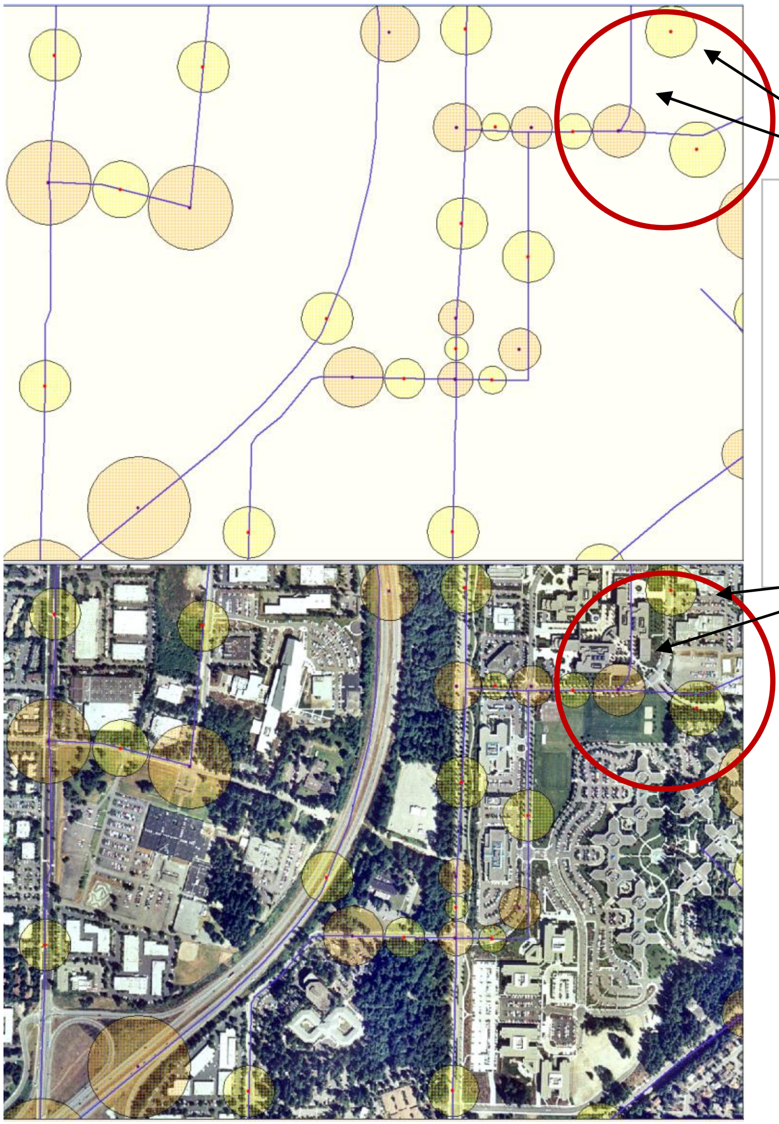
Siemens provided a document outlining the requirements for a base map and for converting the digital map file into a road network data file. This document is included as *Appendix XX*. The implications for the road base map included:

- The size and differentiation of links within the road map determined the degree to which polygons or waypoints in the OBU meaningfully capture information about toll use
- Since the network represented road segments by link end and intermediary points, link details were constructed to recognize road curvature, proximity to parallel facilities, and road network density
- For tolled roads link end points reflected intersections and other access/egress points
- For tolled roads link end points coincided with expectations about different toll prices, and links approximated travel demand model road network files

The project team elected to use an existing road file that was built from the U.S. Census Tiger files. The original map files had been updated and improved in many parts of the region. The original files had a horizontal positional accuracy reported as no worse than 1:100,000 scale (+/- 167 feet). In many areas the accuracy was no worse than +/- 20 feet (Seattle, Pierce County). The map file is used to display travel demand model data as the links correspond to model link segments.

The PSRC and Siemens staff worked collaboratively to refine the geo-data file produced from the digital map. The geo-data file automatically generated road segment entry points and control points, and Siemens and the PSRC assigned entry points at the termini of road segments and control points at road segment midpoints. To refine the geo-data file, Siemens and the PSRC team removed unnecessary road segments, or links, in the network. These links were primarily artificial aspects of the travel demand modeling network. For example, the model contained separate road links for high occupancy vehicle lanes and for parallel general purpose lanes. Because the Traffic Choices project did not differentiate between parallel lanes on a single road, these links were removed. Also removed were links of very small length, such as 10-meter ramps, as it would be difficult to support the necessary density of link detail without confounding the map-matching logic.

Figure 2.6 Network detail and detail with aerial imagery



This figure demonstrates a number of aspects of the network refinement effort. A highway in close proximity to an arterial street requires correct placement of entry and control points, as well as correct sizing of the radius measures. The region within the circle includes digital road line work that does not match the aerial photo, and requires adjustment of the control point location.

Once this step was complete, the team visually inspected the entire road network with GIS software. It overlaid the geo-data upon the road network line work, and compared it against aerial photo images. This inspection caused the team to refine the data in two more ways, repositioning entry and control points and resizing each radius to (1) avoid any conflict or intersection between the resulting zones, and (2) correct for any observed errors in the original digital base map. The team compared the data to a third-party commercial digital map file. Figure **2.6** shows an example of the corrections we made.

Finally, the team focused on parts of the road network where there was complex geometry, or dense network detail. We field tested these regions to ensure correct matches between OBU equipped test vehicles and the geo-data, and refined any areas where we found map matching ambiguity. By the end of the process, the team had field tested approximately half of the road network.

Tolling of dense road networks with facilities that have only minimal access controls requires special attention to the quality of the toll system base map, issues of GPS accuracy, and the overall approach to facility use determination.

Tariff Model

The social marginal cost of travel exceeds the private marginal cost recognized by the vehicle user; that is, our travel costs others more than it costs us. A driver will usually consider only his own time and “out-of-pocket” monetary costs of travel (private costs), and not the costs that his travel imposes on everyone else traveling in the system (external costs). The costs to society (social costs) are the sum of the private and the external costs. Since external costs are being ignored, drivers perceive driving to be cheaper than it really is. If every driver faced a toll equal to the external cost she imposed on other users, roadway capacity would be more efficiently allocated, and drivers would be less likely to over-consume roadways (or become part of congestion problems). The project team based the toll structure in this study on this principle.

The team used the PSRC’s model to estimate VMT-weighted average toll rates that would approximate the full, social costs of travel on different roads at different times of day. Drivers do not use some sections of road enough for a toll to be charged at all times of the day and/or directions of travel, but to simplify the tariff structure the toll schedule was tied to average toll rates (based on the weighted, average external costs imposed per vehicle). By using weighted average external cost toll rates some roads will be overpriced, and others underpriced; that disadvantage is at least partially offset by the fact that the research needed some variability of this type for the statistical analysis and the assessment of the confidence intervals around resulting elasticity estimates. The team used analysis of toll network patterns and link- and trip-based toll costs to derive a series of summary trip statistics, as shown in Table **2.2**. It generated these trip statistics, by time period, from the PSRC regional model for trips both originating from and destined to points within the defined study area/toll network.

Table 2.2 Selected PSRC Model Trip Statistics

Trip Statistic	*AM Peak*	*PM Peak*	*Off Peak**
Average Trip Length (all modes)	**6.9 mi**	**6.0 mi**	**5.7 mi**
Median Trip Length (all modes)	**4.4 mi**	**3.5 mi**	**3.1 mi**
95th Percentile Trip Length (all modes)	**18 mi**	**17 mi**	**16 mi**
Weighted Average Toll Rate — Freeways	**$0.30 / mi**	**$0.44 / mi**	**$0.07 / mi**
Weighted Average Toll Rate — Arterials	**$0.14 / mi**	**$0.23 / mi**	**$0.04 / mi**
Maximum Trip Cost for 95th Percentile Trip**	**$5.16**	**$7.21**	**$1.03**

* Off Peak refers to the remaining 18 hours of the day

** At average toll rates

Toll prices were based on an assumption that the average value of drivers' time is $12.00 per hour. This is approximately 50% of the average wage rate (based on literature exploring travelers' revealed values of time) in King County for 2003. The PSRC regional model incorporated toll prices as increases in the volume-delay functions, expressed in minutes per mile.

Table **2.2** shows that the average arterial road toll rate per mile was one-half of the average freeway toll rates during both the three-hour AM and PM peak periods. Combined, the two peak periods are 25% of the day, but account for 43% of daily VMT. For the model's off-peak period—the remaining 18 hours of the day with highly variable traffic conditions ranging from peak shoulder hours to the middle of the night—the average arterial toll rate was 57% of the same freeway toll rate. Because these average rates for arterial roads were consistently about one half the cost of rates for freeway roads, the team simplified the study by assuming that the arterial toll rate per mile would always be one-half of the corresponding freeway rates at any given time of day.

The project team based the range of tariff structures and toll schedule options on the composite measures shown in Table **2.2**. Each tariff structure considered types of variation, including travel direction, proximity to the urban core areas, and differentiation by time of day. The team considered the pros and cons of these options, weighing the statistical analysis advantages of complexity against the need for participants to have a simple, understandable toll structure.

Table **2.3** shows the final toll structure. The system is not so complex or overwhelming that it encourages participant attrition or passive detachment.

Table 2.3 Final Tariff Structure

Time Period		*Description of Time Period*	*Toll Rates*	
			Freeways (Class 2)	*Non-Freeways (Class 1)*
A	PM Peak Period	4-7 PM (Mon-Fri)	$0.50 / mi	$0.25 / mi
B	AM Peak Period	6-9 AM (Mon-Fri)	$0.40 / mi	$0.20 / mi
C	Midday	9 AM-4 PM (Mon-Fri)	$0.15 / mi	$0.075 / mi
D	Weekend Peak	10 AM-7 PM (Sat-Sun)	$0.20 / mi	$0.10 / mi
E	Off Peak & Weekend Off Peak	7-10 PM (Mon-Sun) 7-10 AM (Sat-Sun)	$0.10 / mi	$0.05 / mi
F	Late Night	10 PM-6 AM (Mon-Sun)	N/C	N/C

Back Office (Data Management)

Traffic Choices Study used a pre-existing, integrated set of toll system applications developed by Siemens in Austria. Siemens designed the system for full-scale deployment and adapted it for this project. Siemens, though a local contractor, installed nearly 500 OBUs in participant vehicles. The OBUs recorded and stored the vehicle's position on links (with longitude and latitude values with GPS timestamp). The OBUs transmitted this data at least once per day to a Central Management System, which processed and stored this data in a database (which was also accessible through a web interface). *Appendix XX* details the design of this back office. Overall, the system provided the following functions:

Data management and setup
- Web Account administration
- Participant administration
- Vehicle administration
- OBU administration
- Tariff administration
- Association of OBUs with vehicles and participant accounts

Operation
- Toll link recognition and tariff selection
- OBU toll preview
- Location stamp recording
- Invoice generation
- Trouble ticket handling

System Maintenance
- Tariff updates
- Geo-data updates
- Parameter updates
- Software updates
- Status and error logging

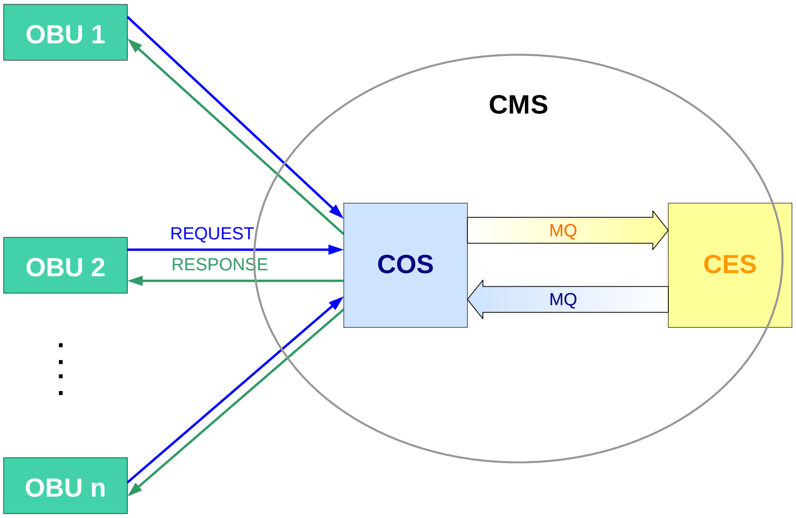
In summary, the main components of the back-office system were:

- *On-Board Units (OBUs):* collected GPS position data and recognized toll road links. When a previously defined amount of data had been collected, or a time limit was reached, the OBU connected via a GPRS Internet connection to the Communication Server and sent the recorded data.
- *Communication Server (COS)*: permanently connected to the Internet, it resolved incoming OBU messages, converted them and forwarded the data to the Central System. Any data exchange with the OBU was executed via the COS.
- *Central Management System (CMS)*: consisted of two parts: an Application/Web server and a Database Server. The Application/Web Server received the data from the COS and stored it in the Database Server. The Web Server provided restricted access to the stored data via the Internet, allowing participants as well as administrators or service personnel to view or modify it. COS, CES and other IT components together formed the Central Management System.

Data Communication

The study contracted for local wireless telephone and data communication services to allow communication between the OBU and the CMS. The wireless service provider issued SIM chipsets for each OBU used in the project. Figure 2.7 illustrates the system.

Figure 2.7 Communications between System Components



The OBUs were not permanently connected to the COS, but transmitted their collected data at least once a day. OBU and COS communicated with each other using a request/response principle. The OBU sent a request to the COS. The COS evaluated the request and sent a response, including any information about tolls or other factors. Normally, the COS did not initiate the communication. All devices communicated using HTTP to make sure software component usage (web server) was standard throughout the experiment and for scalability. The devices communicated more detailed information using a higher level protocol as a payload of the HTTP protocol.

The COS had a permanent connection to the CMS and created a gateway for incoming data, handling up to 500 connections at any given time. Persistent Message Queues (MQ) allowed for communication between COS and CES, and each side could initiate communication. The communication was asynchronous; therefore there was no real-time confirmation of receipt of messages.

Wireless communication allowed OBU components to be updated, including: tariff data, parameters, firmware code, and geo-data. For each of these components the OBU maintained a current (active) version and stored a future (awaiting activation) version. Updates could only occur to the future version. For administration and distribution purposes, the time between initiation of an update and activation time needed to be at least 5 days. Each version contains an activation timestamp. When the OBU reached the activation timestamp of the future version, it activated this future version. If the update process in the OBU fails, the OBU is able to switch back to the previous version.

The OBU software was capable of full and delta updates. Tariff and parameter data were done as full updates; firmware and geo-data were normally done as delta updates. After generating the update, an external update generator tool (patch for delta updates and compression) created a component update package that the web interface transfered to the CES and to the OBUs via the COS.

The update process had the following steps:

1. External tools (geo-data, firmware, parameters) or the CES generated the update files
2. The external update generator tool produced the component update package
3. The CES uploaded the component update package files
4. The web interface allowed for initiation and activation of updates
5. The CES transmitted the component update package file(s) to the COS upon initiation

6. The COS stored the version information and the component update package file
7. As soon as an OBU connected to the COS, the OBU sent its current component versions
8. The COS compared the versions and - if necessary – notified the OBU about an existing newer version
9. The OBU requested the new component version
10. The COS sent the requested component update package file
11. On each following reboot, the OBU checked if any update needed to be activated

Data Storage and Management

Siemens purchased the back office hardware and software and delivered it to the hosting location. The requirements for their software and hardware included:

Software Requirements / Licenses

- 1x Oracle 9i, Standard Edition for 2 CPUs
- 3x Red Hat Linux ES 2.1, Standard Support
- 1x Web Server Certificate

Hardware Requirements

Description	**Quantity**
DB-Server	
Fujitsu Siemens Primergy TX300r rack edition, 2xXeon 2.66GHz, 2GByte RAM, 3x36GB U320 10k, U320 RAID 5 Controller, DAT-Streamer 36GB, floppy, DVD	
PY TX300r X/2.66/512, FSC	1
Rack-Mouting 19" (4U) incl. 1 power supply module hot plug, 4 hot plug fans (2x redundant); Dual system board with Xeon Processor, 2 GB DDR-RAM PC2100 ECC; floppy disc 3,5"; DVD-drive; PCI graphics, 2x Gbit Ethernet LAN , Fast-IDE Controller (for 2x1 device) and 2-channel U320 SCSI Controller (Host-RAID incl.) on-board; temp control for CPU module and FSC PDA-function; Software: ServerView, ServerStart on CD.	
Processor XEON DP 2.66GHz/512kB/533MHz	1
DAT-Streamer DDS Gen5 36GB 3.5" hot plug	1
HDD U320 10k 36GB hot plug 1"	3
RAID Ctrl U320 2-ch 2i/2e 128MB lsi	1
EBS 2 CR telescope adapters	1
RemoteView Software 3.10	1
RemoteView Service Board	1
RV Cables RX100/300, TX150/200/300	1
Server COS	
Fujitsu Siemens Primergy RX200, 1xXeon 2.66GHz, 1GByte RAM, 2x18GB U320 10k, floppy, DVD	
PY RX200 X/2.66/512 1G RAID-LSI lp	1
Rack-mounting 19" (1U) incl. Power supply with cable and universal rack mounting kit, fan unit with 5 fans, Dual system board mit 1x Xeon DP Processor; 1GB DDR RAM PC2100 ECC, 1-Kanal RAID Controller card PCI, floppy disc 3,5"; PCI graphics, 2x1Gbit Intel LAN on-board , Fast-IDE Controller (for 2x2 devices) on-board; temperature control for CPU module and FSC PDA-function; Software: ServerStart package incl. ServerBooks CD, ServerSupport CD and ServerView CD.	
HDD U320 10k 18GB hot plug 1"	2
Remote View Software 3.1	1
Remote View Service Board	1
RV Cables RX 200	1
DVD-ROM ATAPI 0.5"	1

Server CES	
Fujitsu Siemens Primergy RX200, 2xXeon 2.66GHz, 2GByte RAM, 2x18GB U320 10k, floppy, DVD	
PY RX200 X/2.66/512 2G RAID-LSI lp	1
Rack-mounting 19" (1U) incl. Power supply with cable and universal rack mounting kit, fan unit with 5 fans, Dual system board mit Xeon DP Processor; 2GB DDR RAM PC2100 ECC, 1-Kanal RAID Controller card PCI, floppy disc 3,5"; PCI graphics, 2x1Gbit Intel LAN on-board , Fast-IDE Controller (for 2x2 devices) on-board; temperature control for CPU module and FSC PDA-function; Software: ServerStart package incl. ServerBooks CD, ServerSupport CD and ServerView CD.	
Processor XEON DP 2.66GHz/512kB/533MHz	1
HDD U320 10k 18GB hot plug 1"	2
Remote View Software 3.1	1
Remote View Service Board	1
RV Cables RX 200	1
DVD-ROM ATAPI 0.5"	1
OTHER EQUIPMENT*	
PRIMECENTER Rack 12 U, FSC	1
Rack console RC22 1U,TFT, KB DE/INT, D/P/3rd P Racks, FSC	1
Console switch 4x (ES4+) 1U, FSC	1
UPS 3000 VA, 2U, APC	1
Rack Covers	
FIREWALL / SWITCH*	
PIX 515E Firewall, Cisco, Restricted Edition	1
8 Port Switch	1

Siemens first tested the back office in Vienna, Austria, using OBUs located in Seattle. The test involved geo-data provided by the PSRC and wireless communication services. After the successful test phase, Siemens began the system integration services necessary for working in the USA, including installation of third-party software and Siemens' tolling system applications on the hardware, configuration of software, and tests of software and back office operations.

Siemens monitored the servers, network and data storage elements of the system for availability and operating status. If any part of the operating environment experienced service problems or failure, Siemens would be responsible for determining and correcting the problem. Siemens coordinated the management services, including fault resolution, configuration, account, network configuration, and backup.

Siemens and the project team shared the responsibility of managing the participant, or customer, accounts. The PSRC established the account balance for each participant. Each month, the Siemens tolling system identified the amount in tolls generated by each participant, and deducted the monthly toll charges from the appropriate account. Siemens identified the balance of the account on each month's billing statement, which it e-mailed to each participant.

Siemens hosted the data collected about the participants, which PSRC could access at all times online. With this online access, the PSRC could view data for each OBU, identify tolled links used by each OBU, and identify tolls generated by each OBU. The detailed types of data available included:

1. Mobile Originated Data
    - Message Identifier
        - Message type
        - Additional information
    - Date and Time

        - Date
        - Time
    - License Plate
        - Number
    - Segment Data
        - Segment number
        - Price
        - Additional information
    - Position Data
        - GPS-x
        - GPS-y
        - GPS-info (i.e., satellites)
    - OBU Status
        - GSM Status
        - GPS status
        - Fraud Detection
        - HW Status

2. On Board Unit / User-Related Data
    - Vehicle Data
        - License plate
        - Initial date and time
        - Additional information
    - OBU information
        - OBU identification number
        - Identifier (i.e., serial number) for the GSM-SIM card
        - Additional information
        - SW Version
        - Geo-Data version
        - Price table version
        - Data telephone number
        - IP Address
    - User Data
        - Identifier
        - Name
        - Address
        - Email
        - User Name for web
        - Password for web
        - User account in the ‘before’ condition (without tolling)
        - User account in the ‘after’ condition (with tolling)
        - Billing data
        - Additional demographic data

In addition the project team requested reports of vehicle-miles of travel (VMT) data, which Siemens generated in a post-processing manner using the GPS location data. PSRC received various types of VMT data, including VMT on priced facilities (recognized links) with a toll charge, VMT on priced facilities (recognized links) with zero toll charge, and total VMT.

The toll system also included a web-based interface that the participant could access, described later in this report and in Appendix XX.

System Testing and Approval

By the fall of 2004, all the technical elements of the toll system worked, including hardware, software and associated services, GSM service, internet service, geo-data, and tariff model. The project team began a series of final tests. Acceptance test protocol is explained in *Appendix XX*. The team determined that the final tests needed to demonstrate the ability to (1) create additional datasets of participants, OBUs, and cars; (2) mount the OBU in the cars; (3) assign the OBU to a specific license plate number and participant; (4) communicate between OBU and CES using GSM and Internet; (5) recognize toll links; (6) show how participants could access their information (trips, GPS tracking information, current account balance, general user information, tariff model, billing) online; and (7) administer and maintain the system online.

The project team selected two cars and two drivers for the test. Siemens created the data for the driver (participant) and mounted the OBUs in the cars. Siemens activated the OBUs using a binding process on the web interface. After the binding the OBUs were fully functional and were ready for tolling. The project team selected test trips, and the drivers drove the selected routes. Their OBUs recorded and stored data from the routes and transmitted them through the GSM network and the COS Server to the CES. Siemens also tested web access, by reviewing the data from the test routes online. The details of information available for the participants depended on the phase of operation of the pilot project. Siemens demonstrated administration and maintenance procedures by updating the geo-data and/or the price tables of the toll system and by changing the participant's data.

Siemens evaluated the quality of received information, such as recognition rate of tolled links, by reviewing each recorded tolled link for every OBU in the back office. To completely demonstrate functionality Siemens needed to show that the system was ready for operational phase 1 (without displaying any toll information) and subsequent phases where a tariff table would be loaded and charges would be shown to the tester.

Siemens administered all tests successfully on October 28 and 29, 2004, with project representatives in witness during all test elements. The project team concluded that administrative and back office functions were operational, on-board unit installation met all requirements, and the on-board unit successfully recognized 98.37% of tested toll segments of the road network.

Siemens had conducted additional tests during a ten-day period prior to the formal test application. They drove approximately 50% of the entire road network, and documented that they achieved a road segment identification rate in excess of 98%.

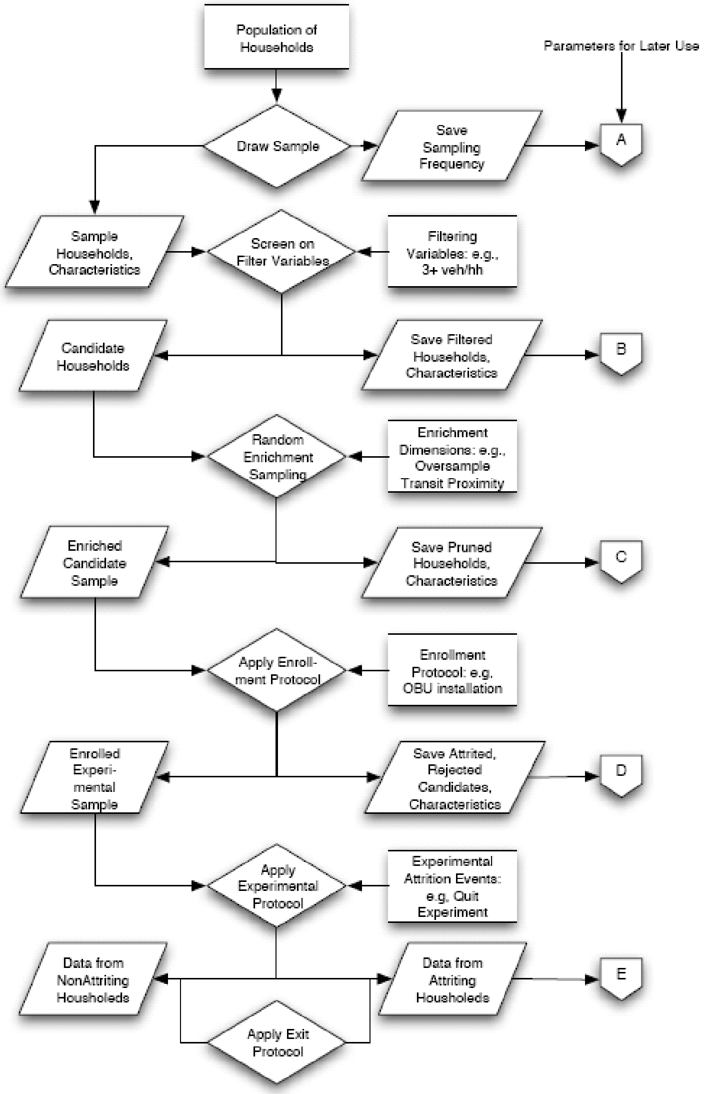
The tolling system performed as expected, and met basic system operating requirements. Further work on system refinement and design of enforcement and billing systems would be required prior to any full system deployment.

2.3 PARTICIPANT RECRUITMENT AND ENROLLMENT

For the Traffic Choices Study to succeed, the team needed to recruit a suitable sample of volunteer households. Participating households needed to meet a specific set of sample requirements while also being an otherwise random sample of households within the central Puget Sound region. The research team established the household as the unit of behavioral analysis because in many households vehicles are shared among household members. The costs of equipping households owning a large number of vehicles, especially where vehicles outnumbered drivers, limited the sample to households with three or fewer operating vehicles. The geographic extent of the tolled network also limited the population of households to a similar geography. It was important that the household members typically drove on roads to which tolls would be applied. The desire to better understand choice behavior when alternatives to paying the toll were present led to an over-sampling (enrichment) of households the project team determined had "quality" transit alternatives available near their home location. Figure **2.8** displays the project sampling flowchart.

The recruitment approach took steps to make sure that the results could be translated back to the full population of regional households from which the participants were a sample. The study uses statistical techniques appropriate for ensuring the ability to eventually generalize from the sample (participants) to the larger population (households in the PSRC area), and for handling issues of self-selection and attrition during the analysis of the project data.

Figure 2.8 Sampling Flowchart



Sample Design

The basic goal of the Traffic Choices Study was to measure the response of traveler behavior to road pricing as if such tolling were in place throughout the road network in the Puget Sound region. The project hypothesized that people would respond to tolling by changing their trip frequency, trip time, and vehicle miles traveled (VMT). The goal of the sample design was to configure the experiment within its budgetary and practical constraints to provide an opportunity to measure demand response consistent with conventional statistical criteria of robustness. This section summarizes sample design issues and solutions; details are provided in *Appendix 7*.

Statistical Control in Impact Measurement

The structure of the experiment approximated true experimental protocol, which would expose certain participants (experimentals) to the pricing protocol (the treatment), and not expose others (controls). In a conventional experimental/control design, randomly recruiting experimentals and controls means that the experiment can ignore unobservable, idiosyncratic behavioral parameters because they are assumed to be statistically identical in the two participant groups.

Unfortunately, the implementation of a true experimental/control design was not feasible because of the small sample sizes and the high variance in travel behavior across households. The study could not assume that the presence of unobservable characteristics in controls and experimentals would cancel each other out. To establish a control group, the team instead adopted a “self-control” approach wherein experimental households served as their own controls: that was done by studying behavior before (in a “Baseline” period) and after the implementation of tolling. This design controls for unobservable differences between tastes, preferences, etc. of the experimental and control households. While this offered better control for idiosyncratic behavior of individual households, it introduced the need to control for changes in behavior over time.

Control for Self-Selection Bias

The experimental design needed to anticipate and control for self-selection and attrition bias. For example, if households with certain characteristics were more likely to enroll or drop out of the experiment (e.g., those whose routes and schedules required them to always take the same road at the same time, independent of the tolls), the results would be biased. The project could not compel participation nor control attrition, and participants could bias the experiment both by joining it and choosing to leave it unless the team took steps to control for these behavioral tendencies.

The main demand that the need for self-selection bias control imposes is the need to gather information on those who chose not to participate, and those who chose to drop out of the program. The latter is relatively easy once the experiment is underway. The former requires that the recruitment process capture information from both those who decline to participate and those who agree to participate.

Sample Enrichment

Although the project sought to observe drivers’ responses to the tolling protocol, in reality many households would not have feasible opportunities to form carpools, take transit, or change the time or frequency of their travel. It is difficult to predict which households have the greatest prospect of change in reaction to tolling.

Carpool formation, however, is known to depend on the number of workers in the household (increases the probability of carpool formation), and household income (reduces the probability of carpool formation). Therefore, enriching the sample with a disproportionate (relative to the population) share of households that have multiple workers and lower incomes would improve the prospects of observing carpooling as a reaction to tolling. Similarly, transit use increases with proximity to transit services and decreases with higher household incomes and number of private vehicles in the household. Hence, the opportunity to observe a transit response to tolling would be increased if the sample were enriched with lower-income households, with greater transit accessibility, and fewer vehicles in the household.

Because of the small number of vehicles that could be outfitted with electronic equipment in the experiment, enrichment for both carpooling and transit use would occur relatively naturally by enriching the experiment with single- and dual-vehicle households. These households would tend to be of lower income, and (for those with multiple workers) more likely to form carpools. Similarly, households with relatively fewer vehicles would also be more likely to use transit, if accessible. Hence, the primary dimension of enrichment not already influenced by the equipment restrictions on the experiment was transit accessibility. Since transit use in the Puget Sound region (as a share of all work trips) is relatively low, significant enrichment toward those with strong accessibility to transit would be required to test the effect of tolling on transit mode choice.

Sample enrichment, of course, makes the statistical sample of household used in the impact regressions non-random, violating a condition for estimation of efficient and unbiased coefficients. Special statistical techniques, related to weighted regression, would be necessary to estimate the regression coefficients in an appropriate manner. The weights used in the weighted regression were calculated by comparing the proportion of households with enriched characteristics to households in the population as a whole with those characteristics. In summary, the various desired features of the sample frame interacted with the fiscal and physical limitations of the experiment. Table 2.4 shows the basic recruitment goals and constraints.

Table 2.4 Draft Recruitment Goals

	Recruitment Parameter or Constraint	Measure
	SELF-SELECTION CONTROL VARIABLES	
0	Population proportion with information on household income	100%
1	Population proportion with information on age of head of household	100%
2	Population proportion with information on household location	100%
3	Population proportion with information on persons per household	100%
4	Population proportion with information on drivers per household	100%
5	Population proportion with information on persons driving in congested conditions	100%
6	Population proportion with information on number of vehicles	100%
	CANDIDATE RECRUIT VARIABLES	
7	Number of households with 3 vehicles (target, constrained by OBU max)	5%
8	Number of households with 2 vehicles (target, constrained by OBU max)	40%
9	Number of households with 1 vehicle (target, constrained by OBU max)	55%
10	Proportion of households already carpooling	0%
11	Proportion of households with transit accessibility	50%
12	Proportion of households with at least one worker commuting in peak period and direction on congested facilities within study area	100%
13	Proportion of households with second worker commuting in off-peak period and direction or outside of study area	Max 20%
14	Proportion of households with installation-compliant vehicles	100%
15	Proportion of households with plans to purchase additional vehicles in study period	0%
16	Proportion of households with plans to move in study period	0%
17	Proportion of households with likelihood to change employment status in study period	0%
18	Number of OBUs	Max 500

Recruitment and Enrollment

During the fall of 2004 the Traffic Choices Study team began recruiting households for participation in the project. The team encountered many logistical challenges as part of the recruitment process, including the need to (1) obtain commitments from households for the duration of the experiment (up to 18 months); (2) get signed liability waivers and participation agreements from each household; (3) provide sufficient information about the intent of the project without revealing exact details about the experimental treatment (tolling policies); (4) install in-vehicle equipment for all vehicles in each participating household; and (5), do all of these things without significantly inconveniencing the volunteer households and causing pre-experiment attrition.

The recruitment process started with a suitably large list of households to which the study team would randomly place calls. The list had extensive information about households, including estimates of household income, household members, and address and housing characteristics. As indicated in the previous section on sample design, the research design required this type of household information for households that chose not to participate as well as for those that did participate in the project. The selection made sure to include households that had good access to transit by associating each household location with a small geographic region (Transportation Analysis Zone from the regional travel demand model) where a measure of transit travel times (weighted average transit travel time from origin geography to all other zones) was already determined. By making sure the list included more households with good transit accessibility, the random-call process provided the desired enrichment for transit accessibility. Table **2.5** shows the basic steps leading up to and including household recruitment.

Table 2.5 Recruitment Plan

1.	Finalize recruitment screener	Aug. 10
2.	Finalize Recruitment Plan	Aug. 10
3.	Recruit participants	Aug. 16-Sept. 3
4.	Finalize installation schedule	Sept. 3
5.	Dev. & mail introductory/confirmation letter	Sept. 10
6.	Develop Participant Manual	Aug. 9-Sept. 3
7.	Mail 350 manuals to participants	Sept. 17
8.	Installation reminder calls	Sept. 24
9.	Participate in first install; ID issues for future	Oct. 1
10.	Installation Period	October 1- finish
11.	Missed appointment follow ups	One day after
12.	Rescheduling of installation	Within one week
13.	Participant database development	Two weeks after recruitment
14.	E-mail and snail mail system development	Two weeks after recruitment
15.	Identification of media appropriate participants	Within two months of install
16.	Project update e-mails/mail	Bi-Monthly
17.	One-on-One Participant Management	Ongoing
18.	E-mail Q & A for all participants	As needed
19.	On-line survey development	Two weeks before pilot completion
20.	Request participants to complete on-line survey	Two weeks before pilot completion
21.	On-line survey analysis	Two weeks after pilot completion
22.	Focus group plan	September
23.	Focus group recruitment	Two weeks before pilot completion
24.	Focus group facilitation	Two weeks after pilot completion
25.	Focus group analysis	Four weeks after pilot completion

The recruitment proceeded over a number of weeks and in multiple waves. First, the recruiters obtained a verbal commitment from households and then called these households back to schedule appointments for equipping the vehicles. Early experience indicated that too many households were agreeing to participate with no true commitment to following through with the most onerous aspect of their participation: equipping their vehicles. The process was revised so households scheduled appointments for installation at the end of the initial recruitment call. This minimized the number “no shows” for installation appointments with the project’s third-party installation vendor (CarToys Inc.), which was under contract with Siemens ITS.

Once recruited, households received orientation materials, a commitment form, and installation forms for each household vehicle. Households were to (1) complete and return the commitment forms, and (2) bring the vehicle installation forms to the participating CarToys retail location where they had scheduled appointments. Upon completion of the equipment installation the households were eligible for compensation equal to $50 per household vehicle.

On-Board Units

Installation of the OBUs was usually completed in under 30 minutes, assuming an available installation bay and technician. The OBUs were wired into the vehicle wiring harness for power, and mounted on the vehicle dashboard by securing a mounting bracket with automotive adhesive tape. The dual-purpose GPS/GSM antennae were adhered to the interior of the windscreen in a location with clear view of open sky. All wiring was channeled between the dash and the windscreen, as allowable. The physical installation process is documented in *Appendix 8*.

During the installation process, each vehicle received a user account stored in the system administrative database. Prior to any scheduled installation, a user account was established for each participating household, which contained information about each household vehicle. At the time that an OBU was installed in a participant vehicle, the installation technician initiated a database “binding” process through which the specific vehicle was associated with a specific OBU serial number. Once successfully completing the binding process the technician tested the wireless communication between the OBU and the system back office. This binding process assured that the team associated the trip records and toll transactions recorded by the OBU with the correct vehicle and user account. The team began installing the OBUs in participating vehicles in November 2004 and finished in January 2005.

2.4 BASELINE DATA COLLECTION

The Traffic Choices Study was a behavioral experiment designed to better understand driver response to tolls that are applied to an entire network of regional roads. It measured behavioral response at the level of individual households, and participating households served as their own experimental controls. It was critical for the project to be able to collect sufficient baseline travel information about each household to ensure that it could measure behavioral responses in a statistically accuracy manner. Baseline travel information also allowed the project team to design a travel budget for each household. The travel budget would be entered as an account balance in the toll system, and would need to be sized to cover toll costs for that household over the full duration of the tolling experiment, assuming the household travel behavior remained unaffected by the tolling treatment.

Baseline Household Travel Information

As each participating household completed the equipment installation, the toll system logged all vehicle trip activity in the trip-record database. By February of 2005, the team was recording baseline travel data for most of the final participating households. Given the social experimentation objectives of the study, the ideal participant management strategy involved some degree of benign neglect. The research team wanted to manage the participants as little as was practical in order to limit the possibility that conducting the experiment could distort behavior in some manner. Yet volunteer households naturally had some curiosity about the nature of the project. Thus, the baseline data collection period involved providing participants general information about the aims of the project, and how the study would proceed, without supplying information that would either give participants insight into how to “game” the experiment for financial gain, or suggest to participants that there might be a “right” way for them to behave.

During this phase of baseline data collection the OBUs displayed the name of the road being driven on, thus giving participants a sense of how the unit operated, but they did not display toll rates or trip-toll totals. The participants did not know the specifics of the toll structure, or how their baseline period driving behavior might influence their compensation for participating in the project. From the participant perspective this baseline period was a technical trial, or test period, with no material consequence to other aspects of the project.

In March 2005, however, the project faced a serious technical challenge. The toll system OBUs communicated to the tolling back office through a commercial cellular service, and the cellular network code was embedded in the application software. For wireless devices that do not embed the network code in their application software, a code change would result in the device cycling through a set of available codes until it successfully connected with the network. The OBUs used in the Traffic Choices Study had embedded codes to prevent the toll system from incurring costly roaming charges on OBUs that move beyond the reach of their home network provider, as would be a major concern in the European market. All software updates to the OBUs, as described in a previous section of this report, also were transferred over this wireless network.

As a result of consolidation in the cellular market, the project’s commercial carrier changed network configurations such that the communication network code embedded in the OBU application software was no longer operable. Without cellular service, the OBUs could not call back to the central communication server, and could not acquire updates to software that, in principle, could modify the cellular network code in the application software. The only practical solution to this problem was to physically connect a laptop computer to each OBU, and transfer a software update through the OBU serial port. Technicians could perform the software update process in about five minutes: the bigger challenge was getting participants to get to the technicians so that they could make a physical connection with each OBU in each participating vehicle. Most households were able to return to the installation locations for the quick software updates, and for this trouble the team issued them a $25 gift certificate. In those cases where returning to the installation sites represented a sizable burden, the project team sent technicians to places of work or residences to perform the update.

Within a couple of weeks nearly all OBUs were once again functional, but the temporary technical problem did introduce a brief hiatus in the baseline data collection period, and did result in a few early household attrition cases. In response to these issues, the project team decided to extend the baseline data collection period through the end of June 2006. The final result was a minimum of three months of baseline data for each participating household, but in many cases six months or more of baseline data were associated with each household.

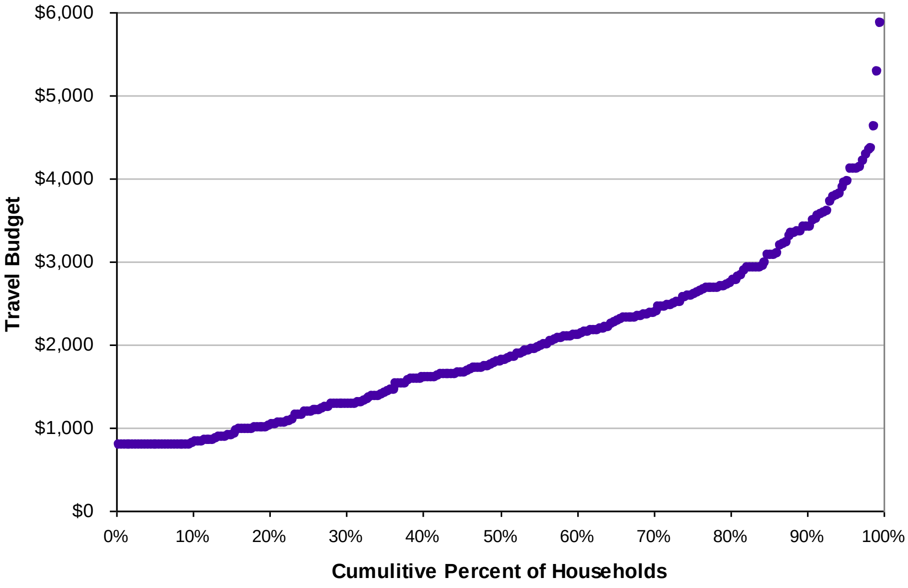
Endowment Account (Travel Budget) for Participants

Toward the end of the baseline data collection period the project team began estimating the travel budget needed by each household to cover all expected toll costs over the course of the toll treatment period. During the baseline data collection period the team used the toll system to log toll-road use by each participant just as it would do during toll operations. In this way, the team knew how each household vehicle would be exposed to tolls over a suitable period of time (3-6 months depending on the household). From this data it was possible to develop reasonable estimates of potential toll exposure over the next 10-month period.

The concept was to provide for each household a budget as a balance in their toll system account that would be approximately exhausted if they did not modify their behavior in any manner in response to their exposure to the tolls. In practice, it was not essential to get the travel budget estimation exactly “correct,” but it was important to make sure budgets were not too low. During the tolling treatment, participants would have tolls deducted from their travel budget, and if the money ran out, any data collected near or after a zero account balance would be useless to the experiment. This meant that an overestimation bias in the development of the travel budgets was preferable to an underestimation bias, within the limits of the overall project budget.

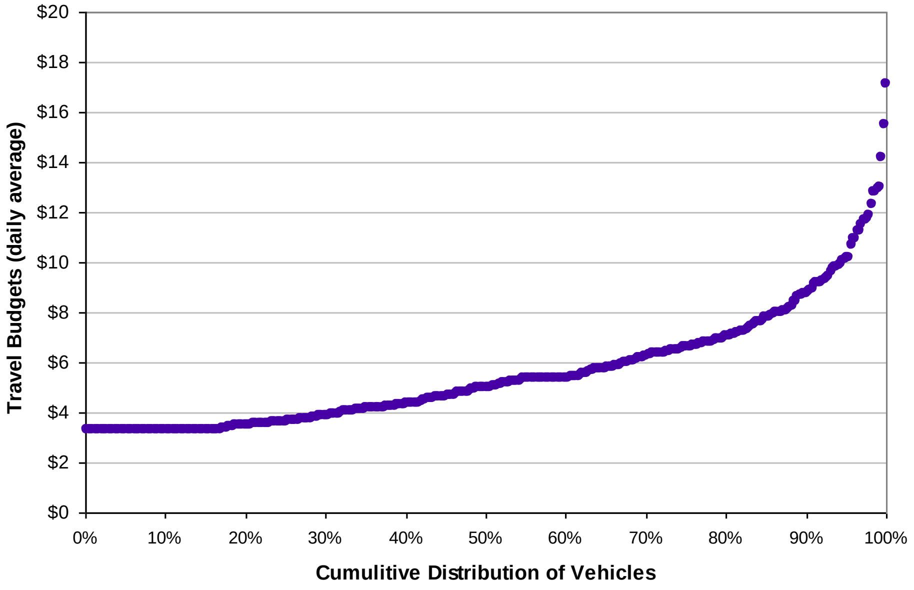
Figure **2.9** displays the distribution of household travel budgets across all participating households at the start of the tolling treatment period (July 1, 2005) of the project. The concept and the reality was that the money in the travel budgets had become the property of the participating households, and the research team was relatively confident that the budgets would cover toll costs over the ten-month period of toll operation.

Figure 2.9 Distribution of Travel Budgets by Household (all vehicles)



Ninety percent of participating households had travel budgets between $800 and $4,000 for the 10-month duration of toll operations. Developing travel budgets for households with lower auto use inherently involved a greater degree of estimation uncertainty, so the team set these budgets at a minimum threshold of approximately $800 to safeguard against early attrition. Figure **2.10** displays the same travel budget information, but on a daily per vehicle basis.

Figure 2.10 **Distribution of Travel Budgets (Daily Equivalent) by Vehicles**



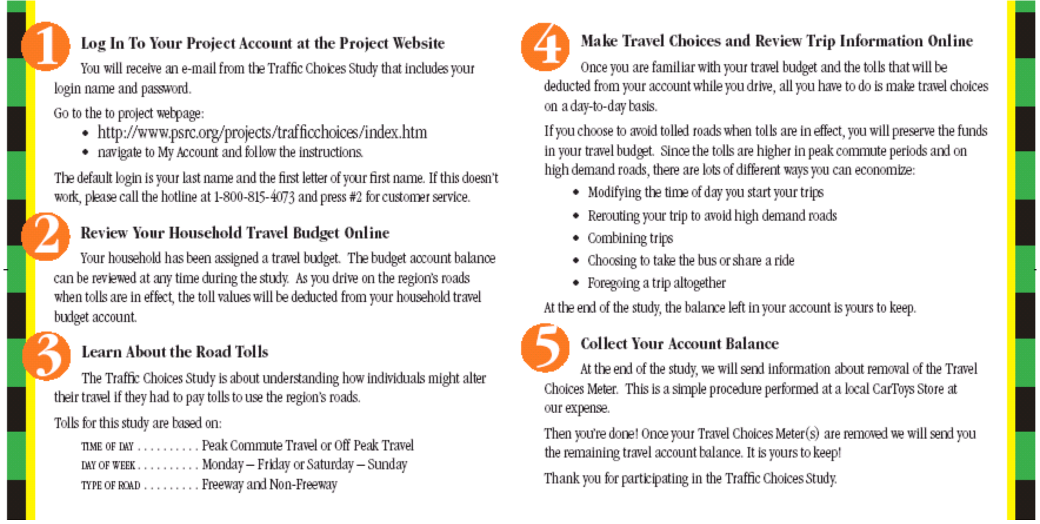
Participant Orientation and Communication

During June 2005, the team mailed participants orientation materials and offered them the opportunity to attend one of four scheduled orientation sessions. This orientation was the first time that we provided participants with full information about how the experiment would be operated.

Materials providing all necessary information about participation in the study were sent through the mail and electronic media. Appendix 10 is a copy of the orientation cover letter. The materials included instructions for how to log into online participant accounts (activated when tolling began), how to view their account balance, how to monitor data about their travel activity, and how to manage account details (passwords and communication with the project team). It was critical that participants understood that their household account balance was their money, and also critical that they understand that as they used toll roads the toll value would be deducted from their balance. Orientation sessions were informal, optional, and focused on answering any questions that participants had about project details.

The most critical orientation material was a foldable, plasticized toll map that could be stored easily in a vehicle. This map included a graphic representation of the toll road network and the toll rates (Figure **2.12**). On the back of the toll map were various instructions such as how to contact the project team, basic information about the on-board tolling device, and some simple steps to guide the households in their participation (Figure **2.11** below).

Figure 2.11 **Getting Started with the Traffic Choices Study**



1 Log In To Your Project Account at the Project Website

You will receive an e-mail from the Traffic Choices Study that includes your login name and password.

Go to the to project webpage:

- http://www.psrc.org/projects/trafficchoices/index.htm
- navigate to My Account and follow the instructions.

The default login is your last name and the first letter of your first name. If this doesn't work, please call the hotline at 1-800-815-4073 and press #2 for customer service.

2 Review Your Household Travel Budget Online

Your household has been assigned a travel budget. The budget account balance can be reviewed at any time during the study. As you drive on the region's roads when tolls are in effect, the toll values will be deducted from your household travel budget account.

3 Learn About the Road Tolls

The Traffic Choices Study is about understanding how individuals might alter their travel if they had to pay tolls to use the region's roads.

Tolls for this study are based on:

TIME OF DAY . . . . Peak Commute Travel or Off Peak Travel
DAY OF WEEK . . . . Monday – Friday or Saturday – Sunday
TYPE OF ROAD . . . . Freeway and Non-Freeway

4 Make Travel Choices and Review Trip Information Online

Once you are familiar with your travel budget and the tolls that will be deducted from your account while you drive, all you have to do is make travel choices on a day-to-day basis.

If you choose to avoid tolled roads when tolls are in effect, you will preserve the funds in your travel budget. Since the tolls are higher in peak commute periods and on high demand roads, there are lots of different ways you can economize:

- Modifying the time of day you start your trips
- Rerouting your trip to avoid high demand roads
- Combining trips
- Choosing to take the bus or share a ride
- Foregoing a trip altogether

At the end of the study, the balance left in your account is yours to keep.

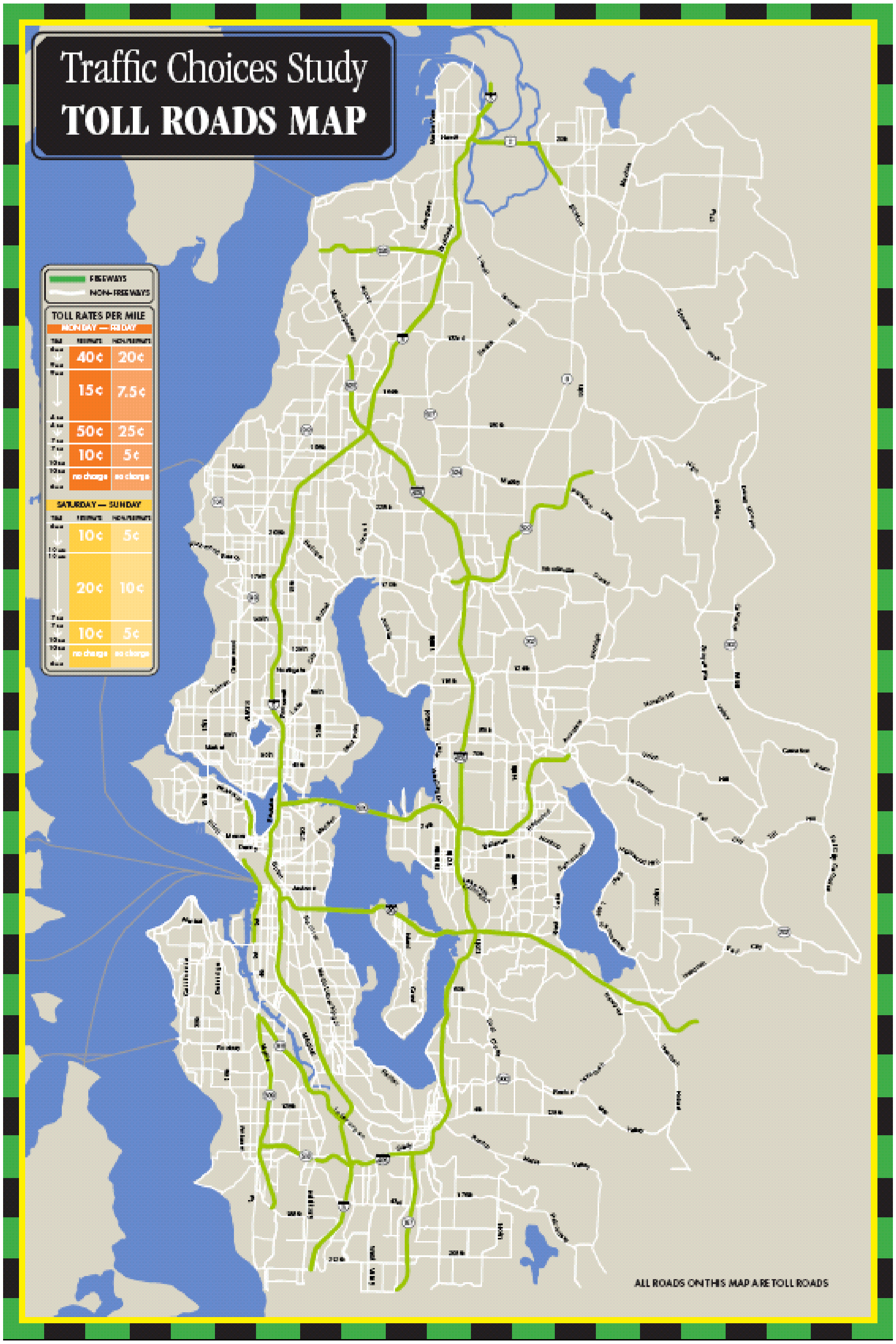
5 Collect Your Account Balance

At the end of the study, we will send information about removal of the Travel Choices Meter. This is a simple procedure performed at a local CarToys Store at our expense.

Then you're done! Once your Travel Choices Meter(s) are removed we will send you the remaining travel account balance. It is yours to keep!

Thank you for participating in the Traffic Choices Study.

Figure 2.12 Traffic Choices Study Toll Roads Map



2.5 TOLLING OPERATIONS (DATA COLLECTION)

On July 1, 2005, the Traffic Choices Study tolling system became operational. Study participants were provided passwords allowing them to log into their on-line accounts to review their travel budgets. As they drove their vehicles on tolled roads the appropriate charges were deducted from their account balance. The OBUs, which had previously been displaying only the name of roads driven, now displayed the name of the road and the toll rate per mile. The OBUs also displayed the cumulative toll incurred during the current trip, allowing the participants to gain a better understanding of the cost of their travel decisions.

Figure **2.13** shows the OBU display. The top view shows a toll road link that has just been detected. The first line displays the sum of all detected links while the second line displays the name of the road link, as well as the costs per mile. The bottom view shows the detection of a second road link, with the first line summing the total tolls incurred for the particular trip.

Figure 2.13 On Board Unit Display

During the first week of tolling participants were gaining familiarity with the toll structure and its implications for their own particular travel demands, and so the research team did not use data from this period in the analysis of user behavior.

2.6 PARTICIPANT MANAGEMENT

Participants had a single point of contact. A team of customer management professionals served as the coordination clearinghouse for all aspects of project management that directly touched the participants, or "customers", including:

- Installation services
- In-field technical services
- Non-technical customer care
- Participant account management

- Routine communication with the participants
- Monitoring of participant compliance
- Billing questions
- Equipment removal
- Participant compensation

Approach to Customer Services

The general approach to customer services was to provide the participants with a number of accessible and easy ways to communicate with the project team directly in the event of a problem or question, but otherwise to try to not interfere with the participants' natural involvement in the experiment. The team maintained a participant-oriented web page throughout the project containing basic information for participants, and also provided a project customer care phone number and e-mail address.

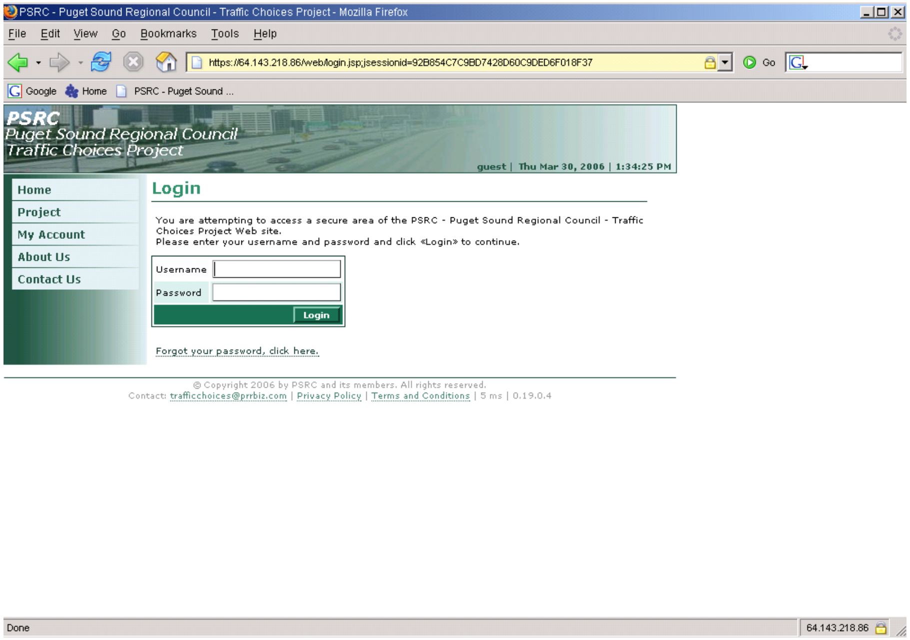
In the event of a customer problem, the participant could phone or e-mail the project directly, and expect a response within 24 hours. Questions went to technical people on the project team best able to handle them and to provide a remedy to any problems. If the problem was technical in nature (the OBU display was not working properly) a Siemens representative was notified to find a solution or schedule a participant visit.

Most calls and e-mails received through the customer service channels were non-technical in nature. For example, over the course of the 10 months of tolling and the total of over 18 months of total operation, some households reported types of lifestyle or vehicle status changes, including: a change in residential location, a sale of a vehicle, a stolen vehicle, or a change in employment location or status. In addition, participating households were asked to inform the project team of vacation periods in excess of a few days. Because these changes were important to the behavioral analysis, we recorded them. In specific cases, changes resulted in forced attrition from the project.

Participant Accounts and Billing

On-line accounts were a primary tool for the participants to monitor their own travel experiences, reflect on trip choices, and gauge the overall consequences on their account balances. Within approximately 24 hours of making any given trip, a participant could log on to his account and view trip record details. By default the most recent week of trip activity was viewable by the participants, but all trip records could be reviewed by using a simple calendar search function. Figure **2.14** displays the participant login interface.

Figure 2.14 Participant Login



Login

You are attempting to access a secure area of the PSRC - Puget Sound Regional Council - Traffic Choices Project Web site.
Please enter your username and password and click «Login» to continue.

Username
Password
Login

Forgot your password, click here.

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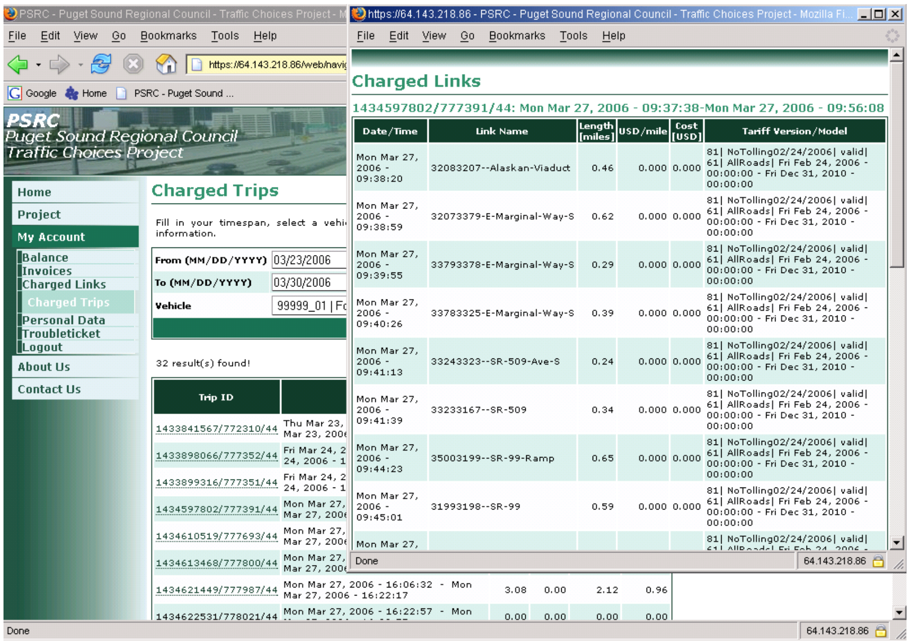
Contact: trafficchoices@prrbiz.com | Privacy Policy | Terms and Conditions | 5 ms | 0.19.0.4

The study provided participants with detailed information about their vehicle trip activity and their use of tolled facilities. The system stored each vehicle trip (determined by changes in vehicle ignition state), along with details about the links (segments of tolled roadway) traversed during the trip. Figure 2.15 displays a series of trip records as well as an inset window of tolled links for one specific trip. With this level of available detail, participants readily see the financial consequences of various types of travel behavior. Alternately, participants could simply wait until they received their invoice of all trip records issued each month. Once participants logged in to their account, they could immediately review their account balance. Figure 2.16 shows an account balance report.

Figure 2.15 Charged Trips Detail



Charged Trips

From (MM/DD/YYYY) 03/23/2006
To (MM/DD/YYYY) 03/30/2006
Vehicle 99999_01

32 result(s) found!

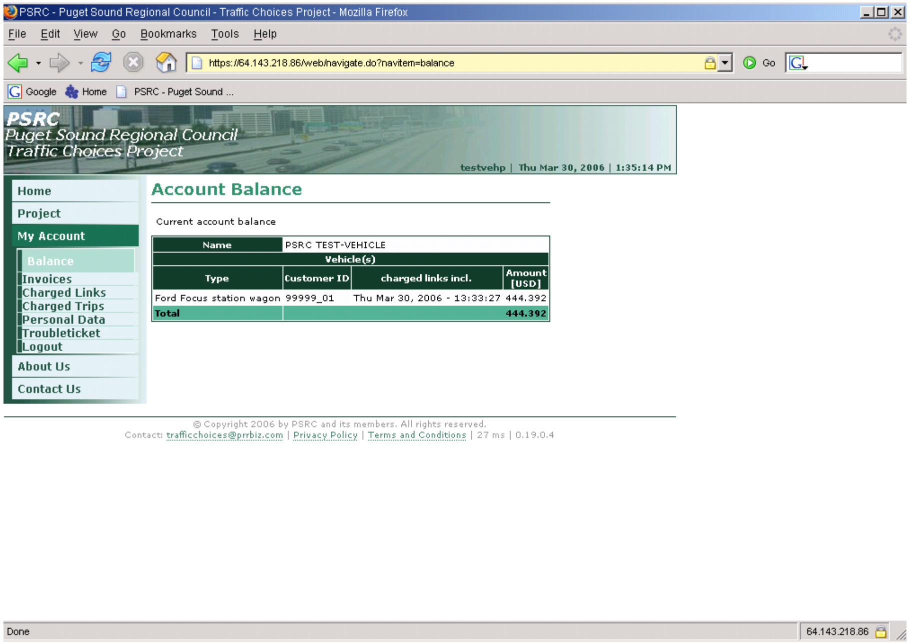
Trip ID
1433841567/772310/44
1433898066/777352/44
1433899316/777351/44
1434597802/777391/44
1434610519/777693/44
1434613468/777800/44
1434621449/777987/44
1434622531/778021/44

Charged Links

1434597802/777391/44: Mon Mar 27, 2006 - 09:37:38-Mon Mar 27, 2006 - 09:56:08

Date/Time	Link Name	Length [miles]	USD/mile	Cost [USD]	Tariff Version/Model
Mon Mar 27, 2006 - 09:38:20	32083207--Alaskan-Viaduct	0.46	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:38:59	32073379-E-Marginal-Way-S	0.62	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:39:55	33793378-E-Marginal-Way-S	0.29	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:40:26	33783325-E-Marginal-Way-S	0.39	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:41:13	33243323--SR-509-Ave-S	0.24	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:41:39	33233167--SR-509	0.34	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:44:23	35003199--SR-99-Ramp	0.65	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27, 2006 - 09:45:01	31993198--SR-99	0.59	0.000	0.000	81| NoTolling02/24/2006| valid| 61| AllRoads| Fri Feb 24, 2006 - 00:00:00 - Fri Dec 31, 2010 - 00:00:00
Mon Mar 27,					81| NoTolling02/24/2006| valid|

Figure 2.16 Participant Account Balance



Account Balance

Current account balance

Name	PSRC TEST-VEHICLE		
Vehicle(s)			
Type	Customer ID	charged links incl.	Amount [USD]
Ford Focus station wagon	99999_01	Thu Mar 30, 2006 - 13:33:27	444.392
Total			**444.392**

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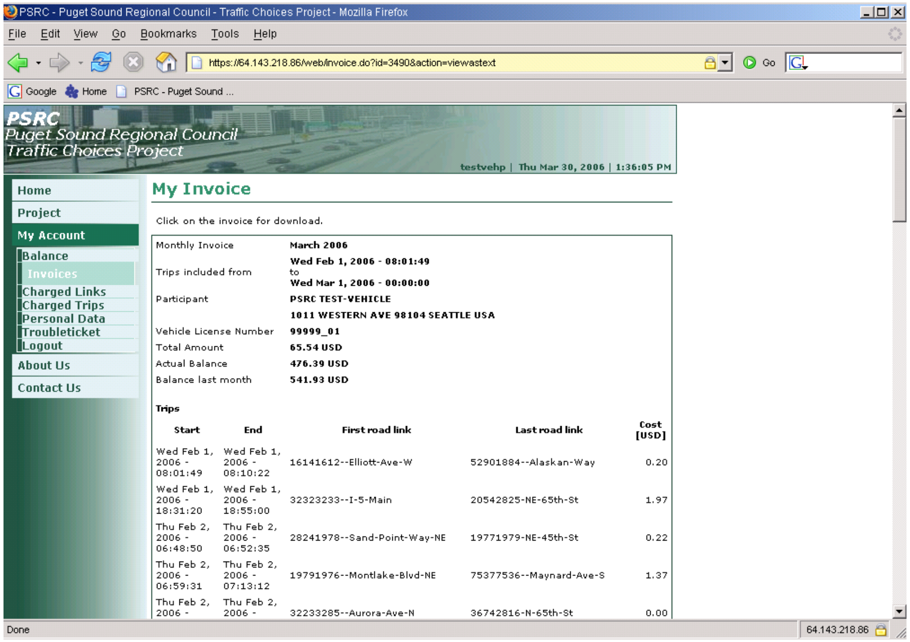
Contact: trafficchoices@prrbiz.com | Privacy Policy | Terms and Conditions | 27 ms | 0.19.0.4

The study maintained individual account balances for each household vehicle, but also summed them to provide a single household balance. Since vehicles might be shared across household members, the single household balance was the dollar value that was still available to the household as its potential payoff at the end of the project. In this way, one household vehicle could have a negative balance while another had a positive balance, and in sum the household could still have a positive value in their account. Each month an invoice summarized trip records and was e-mail to participants and was available on-line through their account interface. Figure 2.17 shows a monthly invoice.

Figure 2.17 Monthly Invoices



My Invoice

Click on the invoice for download.

Monthly Invoice	**March 2006**
Trips included from	**Wed Feb 1, 2006 - 08:01:49** to **Wed Mar 1, 2006 - 00:00:00**
Participant	**PSRC TEST-VEHICLE**
	1011 WESTERN AVE 98104 SEATTLE USA
Vehicle License Number	**99999_01**
Total Amount	**65.54 USD**
Actual Balance	**476.39 USD**
Balance last month	**541.93 USD**

Trips

Start	End	First road link	Last road link	Cost [USD]
Wed Feb 1, 2006 - 08:01:49	Wed Feb 1, 2006 - 08:10:22	16141612--Elliott-Ave-W	52901884--Alaskan-Way	0.20
Wed Feb 1, 2006 - 18:31:20	Wed Feb 1, 2006 - 18:55:00	32323233--I-5-Main	20542825-NE-65th-St	1.97
Thu Feb 2, 2006 - 06:48:50	Thu Feb 2, 2006 - 06:52:35	28241978--Sand-Point-Way-NE	19771979-NE-45th-St	0.22
Thu Feb 2, 2006 - 06:59:31	Thu Feb 2, 2006 - 07:13:12	19791976--Montlake-Blvd-NE	75377536--Maynard-Ave-S	1.37
Thu Feb 2, 2006 -	Thu Feb 2, 2006 -	32233285--Aurora-Ave-N	36742816-N-65th-St	0.00

Start-up Participant Surveys

At the beginning of toll operations participants completed a household survey. Its main purpose was to verify household and driver characteristics, and to learn typical travel activity and a few key attitudes important to the project. Households had to verify the number of household members and vehicles, and link household members with their primary vehicle. Household members provided information about their primary commuting mode of travel, home location, housing ownership, presence of children, employment status, age of head of household and income. While most of this information was already available for each household it was analytically important to verify key household attributes in this manner. Surveys were administered through a password-enabled, web-based survey instrument.

Attrition

During the administration of any program some participants will elect to withdraw, or will be forced to withdraw because of changes in life circumstances. In cases of social experimentation, attrition can result in bias unless proper steps are taken to statistically “remove” attrition bias. The experimental design controlled for attrition bias through proper recruitment and household data management.

Attrition also introduced challenges for managing participants. The simplest form of attrition occurred when an entire household unit could no longer participate in the experiment. In cases where a household relocated outside of the study area, attrition was the inevitable consequence. In other cases individual household vehicles were rendered inoperable (needing repair, totaled, or stolen) while a second vehicle remained functioning. In these cases an attempt was made to accommodate changes in vehicle fleet (e.g., selling one vehicle and purchasing another) if it could be arranged in a timely manner. But in a few cases circumstances resulted in forced attrition.

Attrition could also result from the exhaustion of a household travel budget. This occurred in only a couple of cases. But once a household account balance was reduced to zero (actually even as the account approached zero) there was no longer an effective economic incentive (i.e., there was no experimental treatment). Without the positive account balance, behavioral data was of no real use to the project. In this way, a small amount of natural attrition did occur toward the end of the experimental period. This point highlights how important it was to closely monitor household account activity and travel behavior over the course of the study.

2.7 SYSTEM ADMINISTRATION

The study handled administration of various aspects of toll system management through an administrative account with a web-based user interface. The administrative account was similar to that provided to participants, but with more account privileges and functional options. Through this administrator function the project team could do all the following:

- Create, review and modify participant accounts
- Create or modify system user accounts
- Bind and unbind OBUs to participating vehicles
- Create or modify vehicles in the database
- Create or modify tariff models (toll rates, road segments, calendar details)
- Change system parameters
- Upload files to OBUs
- Request OBUs to call into the central system

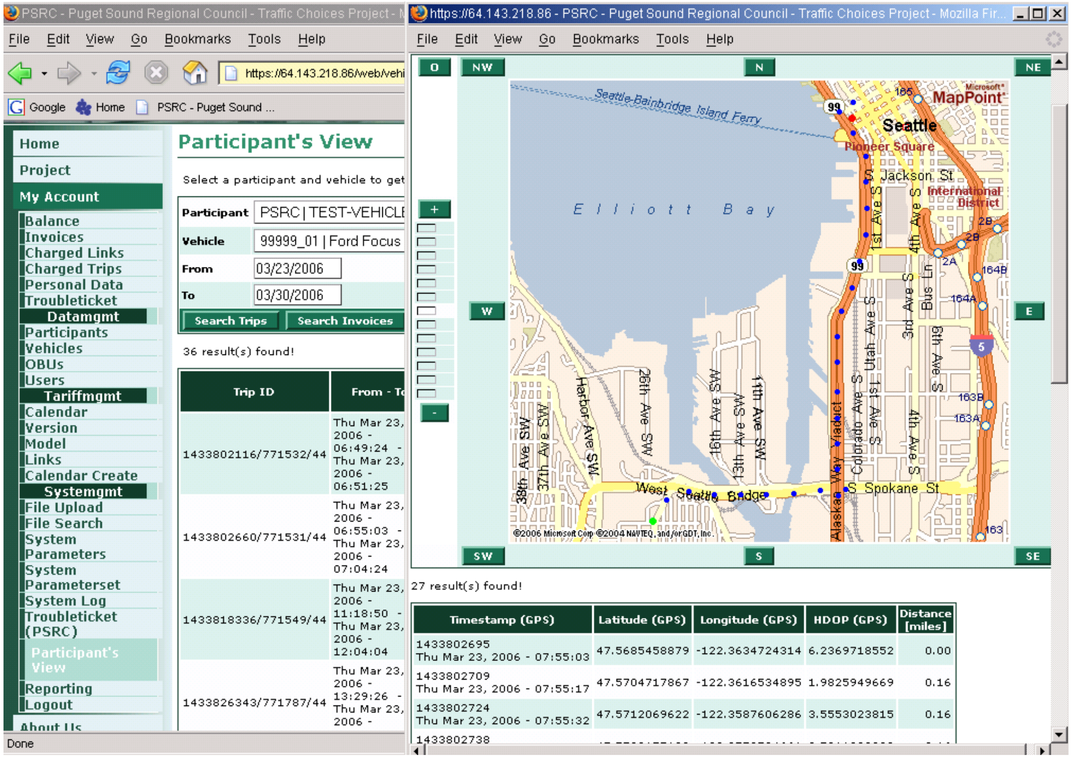
- Download standard summary reports
- Review each participant's log of trip records

Many other administrator functions—including handling of the raw data transferred from each OBU and monitoring OBU communication status—were managed behind the scenes through communication directly with the application and communication servers.

The system was able to support standard tasks required to keep participant/customer accounts up to date, and to respond to customer inquiries. During the course of the experiment the research team had to make a number of changes to participant accounts, including modifying address, contact, and vehicle information. The team did not change toll structures, or tariff models, and managed file uploads to the OBUs directly through the communication server. The primary system administration tasks involved simple account maintenance, the retrieval of summary files for analysis, and system and behavioral monitoring.

During the course of the experiment the researchers could review individual trip records to assess proper functioning of in-vehicle equipment, establish internal integrity of household information (e.g., match of home address and place of residence physical location), and establish user compliance. Below are two graphical displays of sample trip records. Trip records consist of a trip identifier, sets of matched road network segments or links, and the GPS-determined location stamps. Figure **2.18** shows a short length/duration trip with start and end point visible, and Figure **2.19** displays a longer length/duration trip records for the same PSRC agency vehicle.

Figure 2.18 Trip Record (Short)



Participant's View

Select a participant and vehicle to get

Participant	PSRC | TEST-VEHICLE
Vehicle	99999_01 | Ford Focus
From	03/23/2006
To	03/30/2006

Search Trips Search Invoices

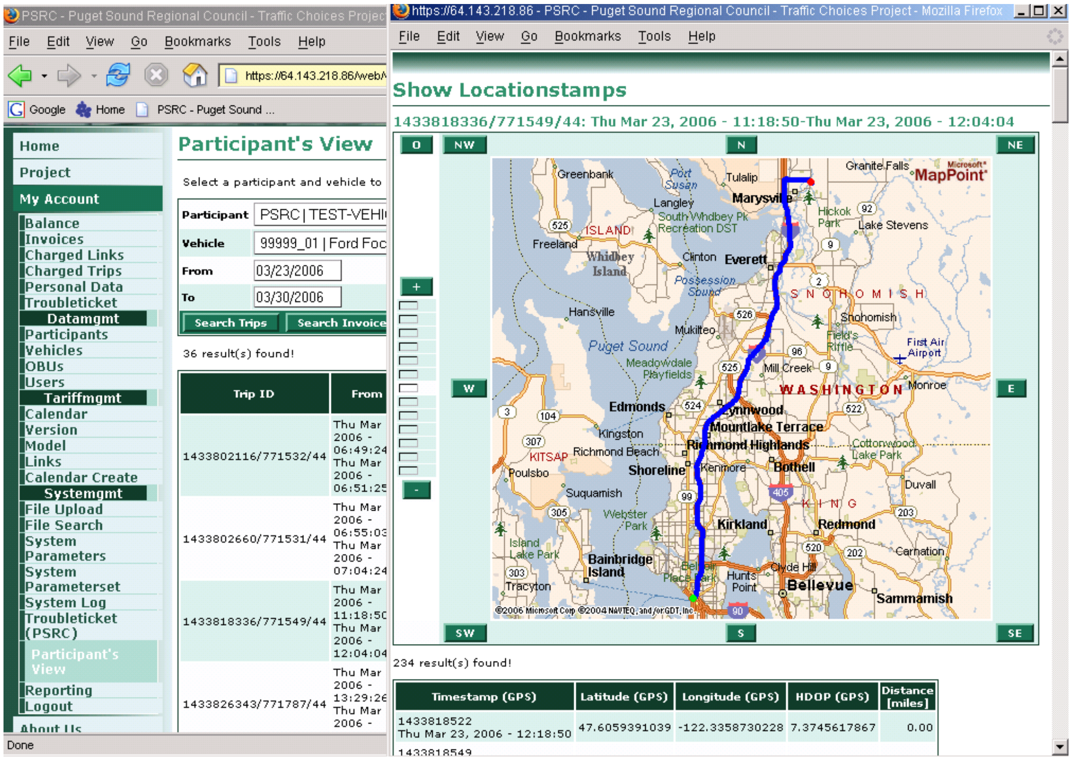
36 result(s) found!

Trip ID	From - To
1433802116/771532/44	Thu Mar 23, 2006 - 06:49:24 - Thu Mar 23, 2006 - 06:51:25
1433802660/771531/44	Thu Mar 23, 2006 - 06:55:03 - Thu Mar 23, 2006 - 07:04:24
1433818336/771549/44	Thu Mar 23, 2006 - 11:18:50 - Thu Mar 23, 2006 - 12:04:04
1433826343/771787/44	Thu Mar 23, 2006 - 13:29:26 - Thu Mar 23, 2006 -

27 result(s) found!

Timestamp (GPS)	Latitude (GPS)	Longitude (GPS)	HDOP (GPS)	Distance [miles]
1433802695 Thu Mar 23, 2006 - 07:55:03	47.5685458879	-122.3634724314	6.2369718552	0.00
1433802709 Thu Mar 23, 2006 - 07:55:17	47.5704717867	-122.3616534895	1.9825949669	0.16
1433802724 Thu Mar 23, 2006 - 07:55:32	47.5712069622	-122.3587606286	3.5553023815	0.16
1433802738				

Figure 2.19 Trip Record (Long)



Participant's View

Select a participant and vehicle to

Participant	PSRC | TEST-VEHI
Vehicle	99999_01 | Ford Foc
From	03/23/2006
To	03/30/2006

36 result(s) found!

Trip ID	From
1433802116/771532/44	Thu Mar 2006 - 06:49:24 Thu Mar 2006 - 06:51:25
1433802660/771531/44	Thu Mar 2006 - 06:55:03 Thu Mar 2006 - 07:04:24
1433818336/771549/44	Thu Mar 2006 - 11:18:50 Thu Mar 2006 - 12:04:04
1433826343/771787/44	Thu Mar 2006 - 13:29:26 Thu Mar 2006 -

Show Locationstamps

1433818336/771549/44: Thu Mar 23, 2006 - 11:18:50-Thu Mar 23, 2006 - 12:04:04

234 result(s) found!

Timestamp (GPS)	Latitude (GPS)	Longitude (GPS)	HDOP (GPS)	Distance [miles]
1433818522 Thu Mar 23, 2006 - 12:18:50	47.6059391039	-122.3358730228	7.3745617867	0.00
1433818549				

Monitoring the Tolling and Data-Collection System

We stored all project relevant data in a relational database, and grouped data in five categories:

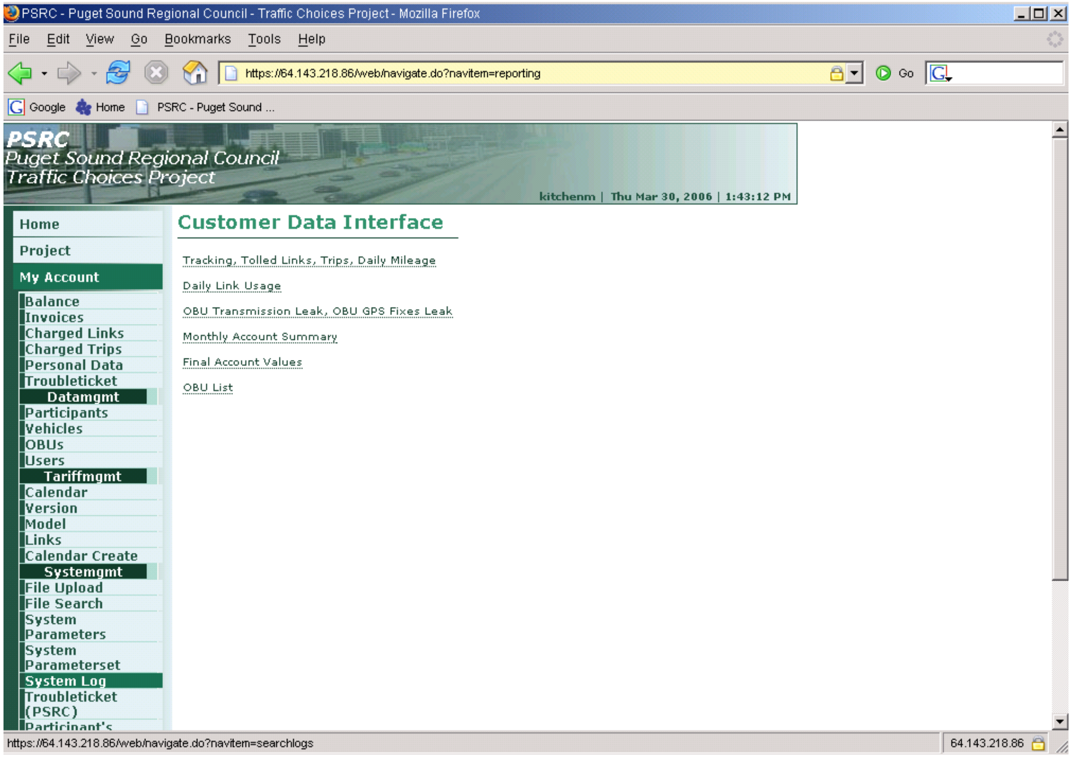
- *Main data.* Each participant was registered in the database and linked to one household. Each vehicle was mapped to exactly one household. A unique serial number identified OBUs. Only one active OBU could be mapped to one vehicle at a time. The team handled replacement of OBUs via a mapping table. The system maintained the history of bindings to ensure the integrity of sampled data related to one vehicle, and respectively one participant.
- *Geographical data tables (road data).* Several hierarchical organized tables identify all tolled roads stored in the database. Road links were the smallest units of a road. Researchers used several attributes like name, length, and so on to provide a basis for tolling fee calculation and statistical analysis. They described a road as a list of links and identified it by its name.
- *Tariff data.* The tariff database contained all the attributes of the tariff system, including name, activation time, and up to several tariff models. A tariff model stored the information of the tolling fee levied for one road link. An entry in the model consisted of day category (e.g. working day, weekend) and the time range within a day for which it was valid. For each calendar day the system assigned and stored one day category (i.e.., weekday or holiday).
- *Tracking/booking data.* The system stored GPS coordinates and GPS timestamps recorded by the OBU, and saved tolled road links identified by the matching algorithm in the OBU as data packets. The system extracted links were from these packets and stored them in the link table. It also linked erroneous packets to an error table to simplify error analysis. The system managed accounting of charged links in the account table. The system stored invoices sent to the participant in the invoice table.

- *System tables.* System tables managed users of the web interface and their privileges. These tables included system parameters for the central system (e.g., price per tolling unit, web interface language), and also parameters used for controlling the OBUs. They also contained logging and tracing information (workflow information, error messages). System messages handled all text messages occurring in the central system (web interface, log, trace, etc.)

Monitoring aspects of system operation in a system with potential for handling a large number of active accounts requires that summary information be easily available for review and analysis. This study met that requirement through the pre-experiment design of standard reports of project data.

The customer (toll-system client) data interface (CDI) also served as an export interface for (1) delivering data of recorded vehicle movements; (2) reporting; and (3) providing final account values (Figure **2.20**). The export filter was accessible via the web interface, and data could be exported as text files in '.csv' format or as read-only 'sql' views directly communicated to the systems database (which required direct access to the system).

Figure 2.20 **Customer Data Interface**



There were different export types for predefined reports and selectable export filters. The sorting of the output was fixed. The export types were:

- Vehicle related data: tracking data, tolled links, trips
- Daily base reports: Daily link usage, daily mileage
- Vehicle monitoring: OBU transmission leak, OBU- GPS fixes leak
- Account data: Monthly account summaries, final account values

Table **2.6** shows the design for a single report table. Appendix 5 provides information about the back office design and functions.

Table 2.6 Tolled Links File

data fields	*filter*	*sorting*
Participant *Lastname, firstname, birth date, street, ZIP, town*		
Vehicle *License plate number, vehicle type*	All vehicles or a specific vehicle	1.
OBU *OBU serial number*		
Date/Time *Date, local time*	From date/time – to date/time	2.
GPS data *Latitude, longitude, hdop*		
Trip ID *Unique trip identification number*		
Tolled Link *Unique Link ID, Link short description, Link long description, Tariff Amount*		

Monitoring the Data on Travel Behavior

Participating households were to inform the research team about changes in their participation status, and any atypical circumstances. The researchers wanted to know, for example, whether a household was on vacation or avoiding vehicle use as a response to the tolling treatment.

In practice, relying on the participant to volunteer this information proved unpredictable. The researchers devised other monitoring efforts to make sure that they identified anomalous conditions and treated them appropriately in the analytical phase of the study. They downloaded and processed household account details daily to keep a continuous record of changes in participant accounts, including date of last transaction and value of changes in account balances. They generated weekly reports listing vehicles/OBUs that had not communicated with the central system during the prior week. They provided this list of households to members of the study team responsible for participant management so that they could contact the households directly to determine the cause of the change in vehicle activity.

Through these methods the team was able to identify the rare cases of OBU malfunction, identify households that might be candidates for premature attrition due to account balances, and also create a log of household vacation activity.

2.8 CLOSING THE EXPERIMENT

Toll operations for the Traffic Choices Study continued through February 24, 2006. System operations represented a small-scale version of a full revenue operation, including toll system customer service functions and user invoicing for toll charges. By the end of the study the toll system had performed in the following manner:

- Fielded hundreds of customer service calls
- Issued over 4,000 customer billing invoices
- Supported over 100,000 OBU-to-central system communication transactions
- Recorded over 700,000 individual vehicle trip records
- Logged over 4.5 million vehicle miles traveled in trip-records database

Participant Exit Surveys

At the end of the tolling operations the team asked participant households to have the tolling equipment professionally removed from their vehicles and to complete an exit survey. Each household received information about the state of their account balance and notice of their final compensation amount. An exit survey captured self-reported information about household behavior over the course of the experiment, recorded any major events at the household level that might have had a major influence on behavior, and asked a few attitudinal questions about tolling technology and policy. Appendix 11 contains the survey instrument.

In particular, the survey verified changes to household composition, employment status, periods on vehicle non-use, and other events that would be likely to result in atypical vehicle use activity, or constitute "non-compliance" on the part of the participant households. The survey was only somewhat useful for identifying sources of non-compliant or atypical household travel behavior, but it did provide some interesting information about study participation which is summarized in the next section.

Removing the On-Board Unit

Participating households had to return, with their vehicles, to the locations where the tolling equipment was installed. Technicians removed all on-board equipment and restored vehicles to their pre-study condition. In a very few cases participants reported minor vehicle damage associated with the removal of the equipment. In all but one of these cases the damage was glue residue left behind from the adhesive tape that technicians used to mount the equipment on the vehicle dash. Technicians easily and fully removed the glue residue once the project team learned about the problem. In the one remaining case the vehicle dash was permanently damaged during the de-installation process, and the project fully compensated the vehicle owner for the damage.

Participant Compensation

After an initial period of household baseline travel data collection, and just prior to exposing these households to toll as they used the region's road network, the team provided each household with a toll-system account with a positive cash balance. As described earlier in this report, the account balances were estimated such that each household would face an appropriate financial incentive to economize on their road use behavior. In other words, each account balance was sized to reflect each household's baseline use of the road network, such that if it did not modify its behavior over the course of the 10 months of the toll experiment they would exhaust the cash reserves in their account. In practice, we added some additional value to the household accounts as compensation for participating in the experiment, and to minimize the losses associated with early attrition from the project.

Specifying the account balances was an exercise defined by competing risks. If the account balances were systematically too small many households would be forced out of the project prior to the end of the experiment, thus compromising the quantity and quality of behavioral data available to support the primary project analysis. As accounts approached a zero balance participants would lose their economic incentive to participate and the opportunities for using household data for behavioral analysis would diminish. Sizing the account balances too large would clearly be a financial risk for the project and would commit limited resources unnecessarily to household compensation without adding additional value to the analysis of behavior. Managing these risks meant that the project team had to develop, prior to observing the effects of the experiment, fairly reliable expectations about the kind of response to tolls the participants would exhibit.

In the end, the team managed to balance the risks and assign account balances that succeeded in providing the right financial incentives while not unnecessarily exhausting project resources. Total account balances at the start of the project summed to just under $540,000. The project budgeted $250,000 to cover final payouts to participants at the end of the project, while actual payouts to 273 households came in just under $200,000 (where $40,000 represented a guaranteed base level of compensation to each household just for participating over the 18 month project period). Figure 2.21 shows the cumulative compensation for all households; Figure 2.22 shows the average household compensation for household deciles.

Figure 2.21 **Total Participant Compensation**

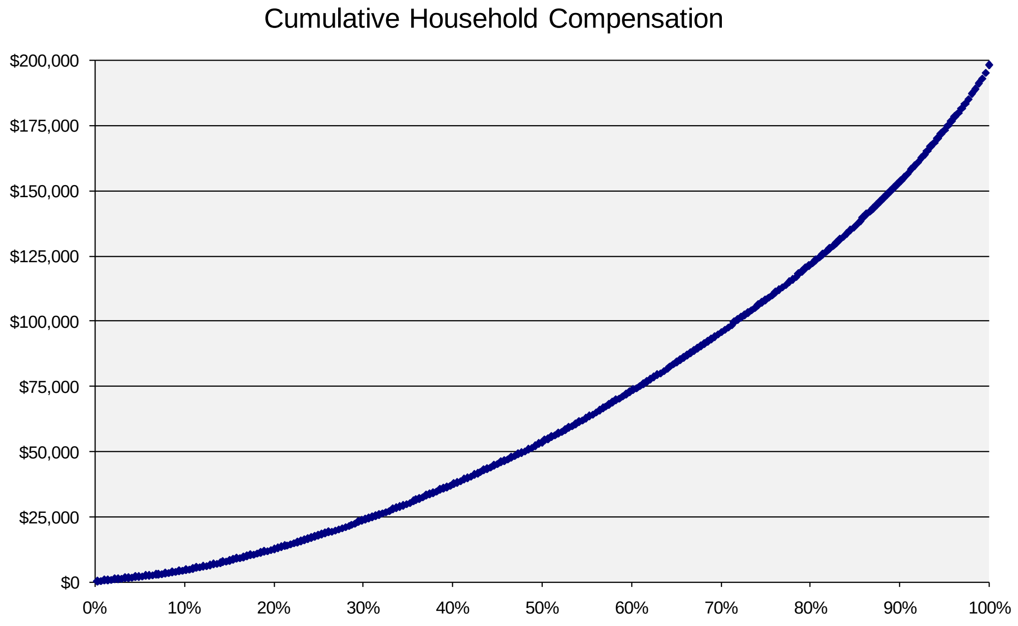
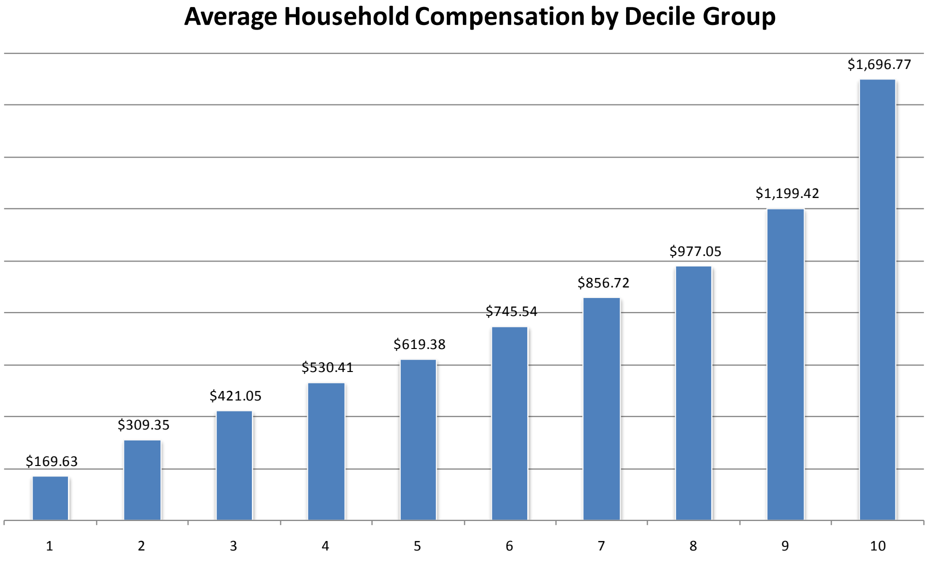
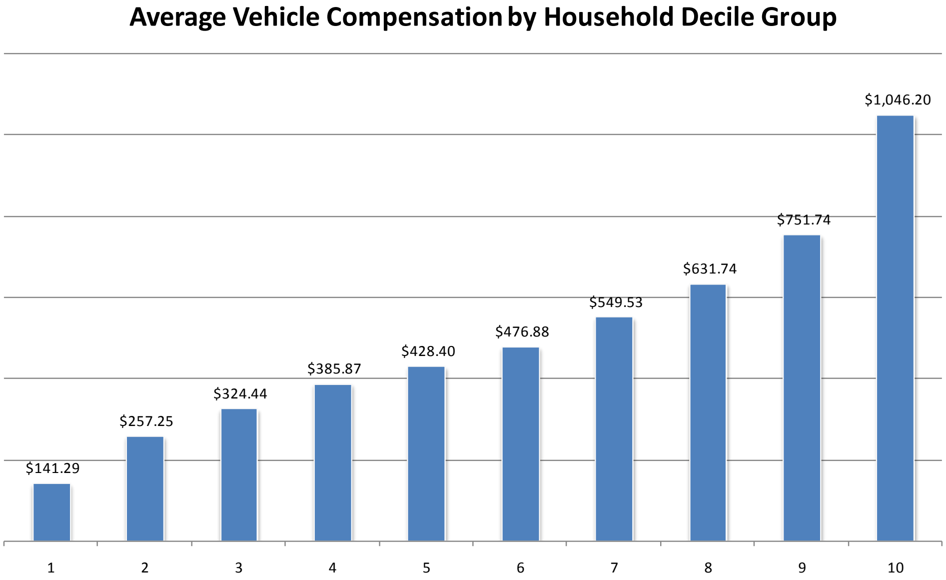


Figure 2.22 **Average Compensation Per Household**



Since households had one, two, or three vehicles associated with a single household-level tolling account, measuring compensation on a per vehicle basis is helpful in understanding the compensation distributions. Figure 2.23 displays the average compensation per vehicle for each of the household deciles (low- to high- household compensation values).

Figure 2.23 Average Compensation Per Vehicle



Providing households with their appropriate compensation was the last step in the operation of the tolling experiment. The core of the project—recruiting participants, equipping vehicles with OBUs, collecting baseline travel information, exposing households to a tolling treatment, removing in-vehicle equipment, and compensating households—took 18 months. The next step was to begin data preparation and analysis.

CHAPTER 3

BEHAVIORAL ANALYSIS

CHAPTER OVERVIEW

The Traffic Choices Study was not intended to comprehensively inventory all factors that contribute to differential travel behavior. Rather, impact studies, such as this, introduce big shocks in the variable of primary interest (toll costs) and the influence of unaddressed variables is minimized because of the delta structure of the impact model. The basic analytical approach to understanding behavioral response to tolls involved estimating linear impact regressions with observed dimensions of travel demand (across households, vehicles, and workers) as dependent variables, and with measures of the generalized costs of travel (tolls, out-of-pocket costs and time costs), household demographics (income and number of drivers), seasonal factors, and a measure of transit viability as explanatory, or independent variables.

All vehicle trip data, collected by the in-vehicle tolling device installed in all participant vehicles, were matched to participant home and work locations. All trips were then linked together into tours. The end result of the tour formation process was that all 700,000+ trip records in the trip database were organized into 200,000+ individual tours categorized by purpose. These tours would become the organizing framework for all analysis of travel behavior. An important aspect of the Traffic Choices study, beyond understanding behavioral responses to tolling the road network, was the opportunity to observe travel behavior across a sample of households for an extended period of time. Travel surveys are often performed to support the development of travel models or other aspects of transportation planning. Large-scale surveys, however, are expensive to administer, and are often limited to collecting travel diary information about a few days of consecutive travel.

Primary findings from the Traffic Choices Study document the magnitude of the short-run response to tolls, across a broad range of behavioral dimensions. Short-run elasticities of demand were estimated for models explaining household, vehicle, and worker behavior independently. Also, the elasticities do not need to factored together to interpret findings, they can be thought of as total derivatives. The models were developed in such a way as to ease the process of making sense of the direct results of the analysis.

There is no single answer to the question of how participants changed their travel in order to save money by paying fewer tolls. Each household is unique; with specific flexibilities and constraints. The experiment, and road tolling in general, makes the most of people's individual opportunities and preferences to realize broader social benefits.

Analysis of the data has revealed important changes in household driving patterns that could significantly reduce congestion if such a tolling policy were implemented within a transportation *network. Many households made notable changes in their travel practices. Households that modified their travel did so in many different ways; taking fewer and shorter vehicle trips, choosing alternate routes and times of travel, or linking trips together to reduce vehicle use in aggregate. Some households altered their routine travel practices (such as how they moved between home and work), other households made changes when they could, in more irregular ways over the course of daily events. Some claim that these changes have persisted even beyond the end of the study. Other households appear to have had very limited opportunities, in the short-run, to avoid using high demand roads during peak travel times. All these results are consistent with the study team's expectations.*

The Traffic Choices Study also provided an opportunity to observe values of time directly as a function of actual route choices made over the course of the experiment. Participants faced a financial incentive to avoid routes with high toll values. In many cases participants chose longer, more time consuming routes that resulted in lower toll costs. The principle finding is that the value of commute (home-to-work tours) travel time appears to be close to 75% of the wage rate (higher than is often assumed in the absence of revealed preference data) for the greater Seattle metropolitan area.

3.1 DATA PREPARATION

The tolling system (on-board devices and back office functions) provided by Siemens produced vehicle use data records appropriate for all aspects of toll system operation and user account management. These data records, organized around vehicle trip details (where changes in vehicle ignition state signaled the beginning and end of a specific trip record) were the basis for the creation of an analytical dataset that would support the project's core behavioral analysis. The requirements of behavioral analysis, however, necessitated some additional data preparation.

Consolidation of Data Sources

There were numerous steps required to convert the raw, GPS system data and other information to an analytical dataset. The various steps involved in creating the Database Management System (DBMS) are memorialized in programming code, but the data flow comprised three basic steps:

1. Data was assembled in native form from the Siemens back office DBMS, from surveys of participants, from recruitment databases, PSRC internal GIS sources, PSRC travel model data, and from private sources as the Oil Price Information service (OPIS).

2. The native data formats were converted to SQL tables and linked through key fields in a consolidated SQL database. Through this mechanism, virtually any data element can be joined to other data elements to associate households, vehicles, trips, demographic characteristics, network features, trip end locations, local fuel costs, survey results and other data.

3. The SQL database was queried to produce data views that can, in turn, be imported and managed by statistical analysis packages. In general, detailed and complex computations are made at this level since SQL is not suited well to certain types of arithmetic manipulation.

The primary empirical findings are the result of either SQL query exercises or statistical analysis.

GPS Data Elements

The data from the Siemens back office processes were the most complex and time-consuming aspects of the DBMS efforts. The vehicle tracking and accounting information in the Siemens data center is very high-resolution data, and was provided as views rather than a full, normalized database or database tables. Views are, by their nature, a snapshot of calculations and tabulations made from the underlying SQL database. Although the views represented a comprehensive snapshot of travel activity over the course of the experiment, the data they contain is not necessarily organized in the same way that the underlying relational database tables. To re-integrate the data into a manipulable SQL database requires importing each table into a new database and reestablishing or creating desired relational connections among data tables.

The Siemens views data was reconstructed into a SQL database in Postgres®, a widely used SQL engine. ECONorthwest programming staff performed this database reconstruction step by importing and linking data views one at a time. The result is a so-called normalized database in containing all of the necessary relational linkages to permit assembly of the desired analytic datasets.

Other Data Sources

Other data sources were merged into the normalized database of Siemens tracking and accounting data. In some cases, geocoding or other preparatory efforts were required to create the key fields necessary to support links to other data tables in the SQL file. For example, grid-cell demographic information was obtained from PSRC staff to support linking of regional, spatial demographic indicators to trip origins and destinations. That data had to be processed to permit capturing this information in a useful, spatial grain. Similarly, survey results, in the form of exports from on-line survey tabulations or spreadsheet data needed household ID and other information transformed to be compatible with the primary data structure. An analogous effort was required to match data from phone survey listings with the experimental participant data.

Building Analytic and Descriptive Data Extracts

Once a normalized database exists, it can be queried to extract data. Two types of query exercises were conducted. The most important extracts are those developed to analyze participant behavior in reaction to the toll experiment. In addition, however, the travel data contains a wealth of information on the patterns of travel and vehicle utilization over the course of the experiment. Thus, the study team staff produced both analytic and descriptive data extracts.

The nature of the analytic data extracts was guided by the experimental design. The experiment was designed as a "self-control" or before-after design. That is, statistical control was obtained by a base or control period of data collection during which tolling was not in place. The impact of tolling is measured by comparing that control period behavior with experimental period behavior. In fact, a crossover design was implemented wherein a back-end control period was created by ceasing the toll experiment and measuring travel behavior during this post-experimental period.

The implications of this experimental design for the analytic dataset development are that the extract is a panel data structure—i.e., a time series of cross-sectional data. Three different panels were extracted using different participant units of measurement: household, vehicles, and workers. The unit of observation of travel behavior was defined to be tours; that is, aggregations of trips that were closely linked, serially, in time. Individual trips (measured by ignition state changes) thus became tour segments. The number and characteristics of tours were available by day of the week, hour of the day and by day (measured as the number of days from the beginning of the experiment).

Tour purpose was not available from diary or other such sources, and had to be inferred from the nature of the tour. During the data extract process, extensive queries were run to determine the regularity and location of trip ends to infer a workplace-oriented trip. (School trips, thus, are treated equivalently with regular work trips.) Tours that started at home and ended at such a location were considered home to work tours. Conversely, tours that started at the workplace and ended at home were considered work to home tours. Tours starting and ending at work were considered work-to-work tours, and similarly, tours staring and ending at home were considered home-to-home tours. The process of inferring and assigning a tour purpose was performed as part of the data extraction process.

Since information on the start time, end time, number of segments, distance traveled, tolls paid, drive time and total tour time are available, indicators of all of these dimensions of tours can be constructed separately for each household, vehicle or worker. It was determined that the primary aggregation unit would be weekly. Thus, the analytic datasets were panel data, with a weekly time-serial frequency. Other and higher frequency analyses were performed, but consolidation to weekly rates provided the greatest consistency and preserved the maximum amount of useful participant data.

Because the experimental design included measurement of what the tolls would have been (given participants control period behavior) both a control toll and an equilibrium toll is measured for every tour. This is a crucial feature of the analytic design, since the control toll is statistically exogenous and thus can be used as the experimental toll treatment measures.

In addition to analytical data extracts, descriptive data extracts also were produced. Various measures of behavior were extracted by querying the database. Because of the high dimensionality of the central, SQL database, descriptive abstracts of great variety could be created. It is estimated that full cross-tabulation, across all variables, time periods, units of observations, etc., would yield several thousand-report tables. Few of these are reported herein, but the SQL framework for the DBMS permits extensive queries.

The general nature of the descriptive abstracts performed is as follows:

- The statistical characteristics of selected database measures were measured. The mean, standard deviation, and relative variance, for example, were calculated for such variables as the number of tours, distance, drive time, speed, total time, departure time, arrival time, and freeway miles observed in the DBMS.
- Variables also were cross-tabulated by various “units of observation”, e.g., household, household & vehicle, and household & workplace. Further cross-tabulation was done to provide more specific analysis by number of vehicles, number of workers, income categories and weekend/weekday day.
- These descriptive abstracts also could have been differentiated by control vs. experimental status. In general, however, since such tabulations provide insights inferior to those obtained through statistical analysis, little such tabulation is reported herein.
- The output of the descriptive data abstracts was structured so as to permit easy preparation of density functions (or histogram representations) and cumulative distributions of characteristics.

Some of the resulting descriptive abstracts are presented elsewhere in this report. The following discussion elaborates on some of the more important variables present in the DBMS.

Household Income

Household income estimates for each household, as well as other demographic information, were originally contained in the participant recruitment call list. The results of phone recruitment occasionally found a non-listed household through calling a phone number on the list. In these cases, all household demographic information from the call list was no longer applicable for that recruited household. A participant household survey, administered early on in project administration and described above, sought to verify key demographic details for each household, including household income. Not all households provided income information as part of the survey returns. At the end of the operational part of the study the project team imputed income estimates where necessary to complete the household dataset. Income imputation is described in greater detail in Appendix 15.

Associating Trip Ends with Home and Work Locations

The in-vehicle tolling device installed in all participant vehicles generated detailed trip records, but did not directly permit the recording of the purpose of the trip. Since the analysis of demand response to tolls was expected to be influenced by trip purpose, it was necessary to devise a method through which trip purpose could be inferred from the underlying toll system data records. Home locations were initially pulled from the original recruiting call list and were then updated and maintained as part of the project participant contact database. Home locations were also verified throughout the project through the monitoring of trip record files (start and end points for vehicle trips). Work locations were determined after the completion of the data collection period by processing patterns of trip records in association with land use and employment spatial data maintained by the Puget Sound Regional Council. A number of heuristics were employed in automating the identification of household employment locations where each household could be associated with multiple employment locations in necessary. The workplace location identification methods made use of information about trip timing, frequencies or patterns, dwell times, and the employment and land uses at trip ends. These methods are described in more detail in Appendix 16. It should be noted that this process assigned a workplace location to any location a given household treated like a workplace location, regardless of whether work occurred in this location or not. In other words, if a household member repeatedly visited a location and dwelled at that location for a sufficient time often enough, (and where land use data would not support further distinctions between say school and work activities) this location was considered a work location. Regular volunteer activities, school activities, etc. were treated as a work location. For purposes of studying travel behavior this limitation is not particularly important as the regularity and relative inflexibility of these activities make them similar, in regard to travel behavior, to work activities.

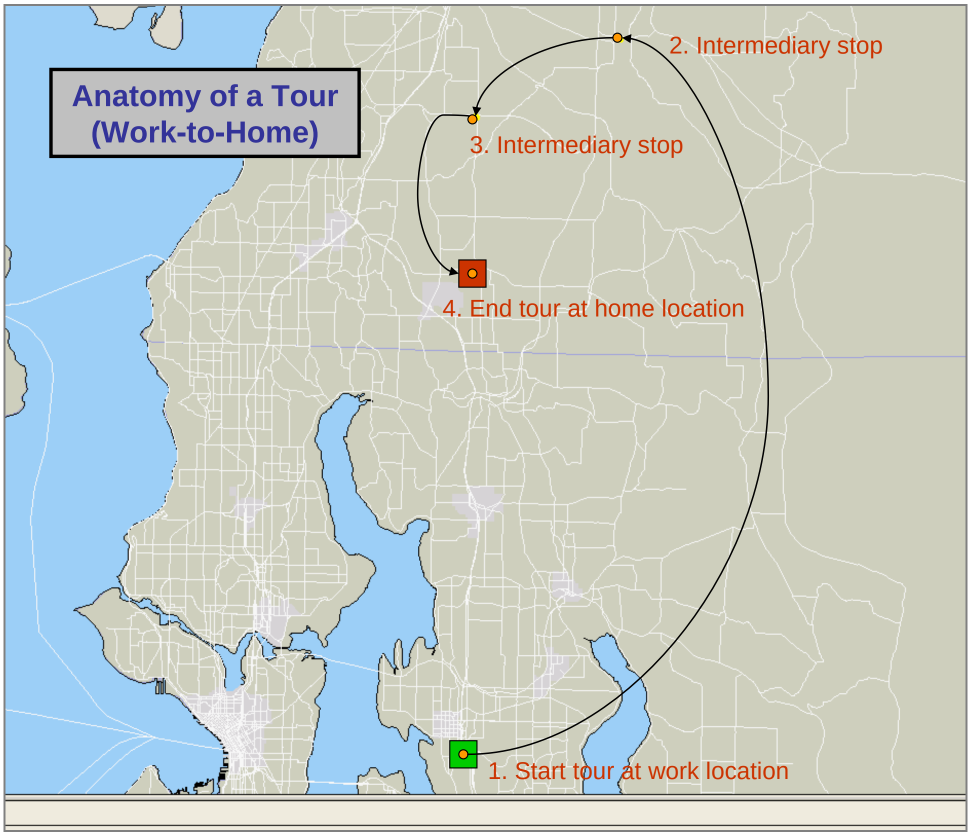
Converting Trips to Tours

With all appropriate trips associated with home and work locations, all trips were then linked together into tours, where tours would become the organizing framework for all analysis of travel behavior. The definition of a tour was determined by available, and unambiguous, information about each participants home and work locations. This resulted in the following primary categories of tour purposes:

- *Home-to-Work:* Tours that have their origin at the home location and their destination at the work location, including all stops in between home and work.
- *Work-to-Home:* Tours that have their origin at the work location and their destination at the home location, including all stops in between work and home.
- *Home-to-Home:* Tours that have both their origin and their destination at the home location, including all stops in between home and home.

- *Work-to-Work:* Tours that have both their origin and their destination at the work location, including all stops in between work and work.

Figure 3.1 Anatomy of a Tour



The above tour framework differs from many approaches to tour orientation but is directly supported by household level information about home and work locations. **Figure 3.1** displays the basic anatomy of a sample Work-to-Home tour from the project trips database. In this example, the vehicle started this tour at the work location, made two intermediary stops prior to ending the tour at the home location.

The end result of the tour formation process was that all 700,000+ trip records in the trip database were organized into 200,000+ individual tours categorized into one of the above four tour categories.

Final Participant Households

Travel data was collected for all households with vehicles equipped with tolling devices, but a few households were excluded from the final analytical database due to some known problem with the continuity or usability of the experimental data. These problems included situations where:

- Not all vehicles in a household were equipped for a sufficient period during the experiment
- The household was deemed to be a candidate for very early attrition (not enough experimental data) or was a late starter (not enough control data)

- An equipped household vehicle was stolen, sold or replaced where a sizable period elapsed during which replacement vehicles were present in the household but not equipped with a tolling device
- Any other known cause for considering the household to be non-compliant

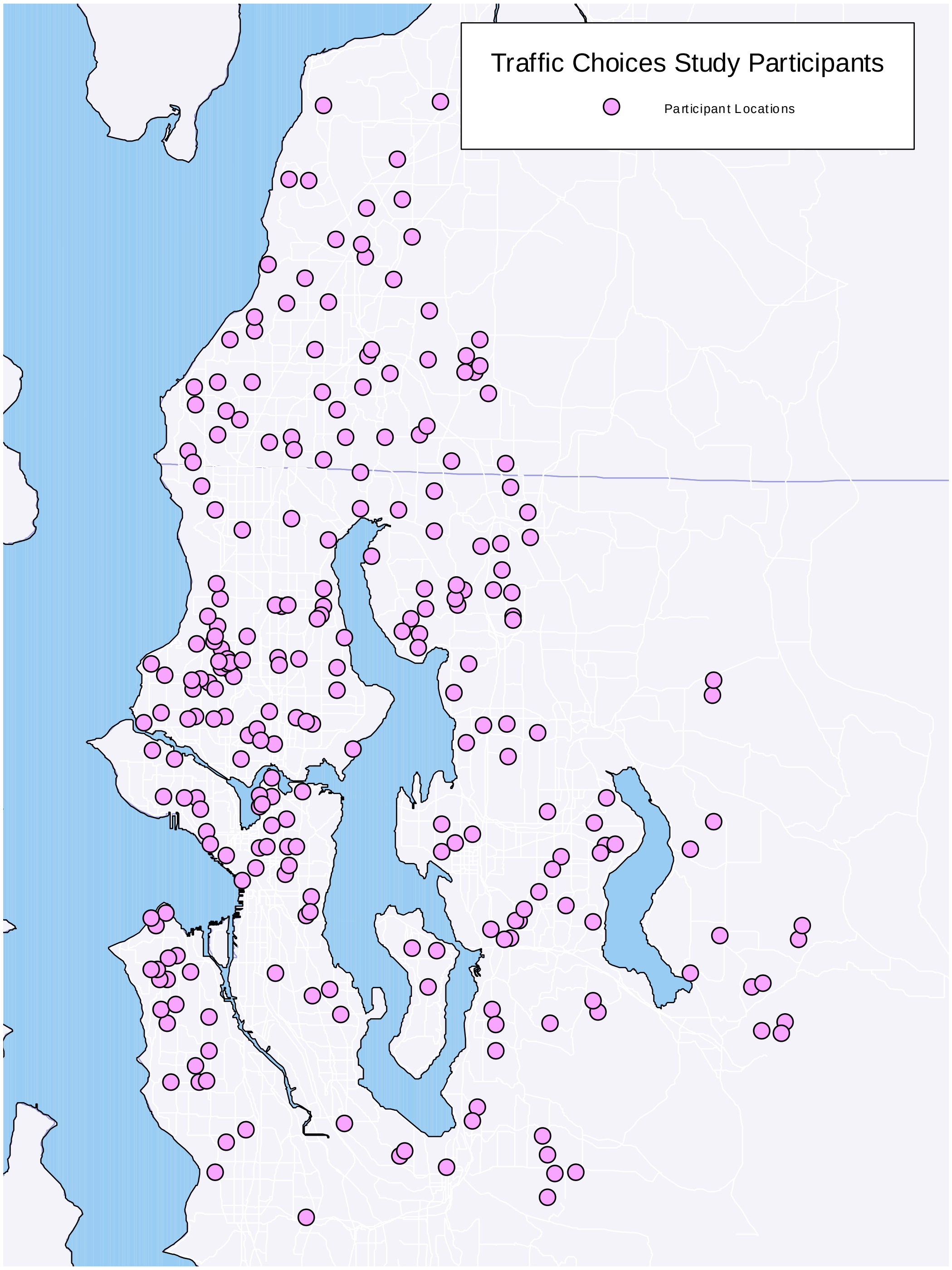
4.2 INFORMATION ABOUT THE HOUSEHOLD SAMPLE

As described earlier in this report, the recruitment of households for participation in the Traffic Choices Study employed the use of a commercially available household call list. The recruitment needed to screen households that could not be compliant with project requirements (e.g. too many or no vehicles; never driving on congested roadways; etc.) and also enrich the sample with households with some opportunity to make use of non-auto travel opportunities (availability of transit services) in response to tolls.

Enrichment for viable transit services was accomplished by associating each household in the call list with a geographic analysis zone with known transit service "quality" and then randomly removing from the list households from zones that did not meet a service "quality" threshold. The remaining portion of the sample was thus enriched for higher transit service availability. A call list that began with over 250,000 households was "enriched down" to a list with just over 190,000 households. This enriched list was partially utilized during the recruitment process, which resulted in 776 households that passed the recruitment screen and did not refuse to participate.

Initially, the recruiters informed candidate households that they would be contacted within a couple of days to schedule an appointment for in-vehicle equipment installation. This practice led to a large percentage of people changing their minds about participation prior to having the equipment installed. After the first few days of recruitment the recruiters began to schedule installation appointments at the time households agreed to participate. This improved the retention rate between the recruitment call and installation. At the end of the recruitment process, there were 307 households with installed tolling equipment in all their households' vehicles. The home location of final households is displayed in **Figure 3.2**.

Figure 3.2 **Study Participant Locations**



As was described in an earlier point in this report, in March of 2005 the project faced a serious technical challenge. The toll devices communicated to the tolling back office through a commercial cellular service. The project's commercial carrier changed network configurations such that the communication network code embedded in the OBU application software was no longer operable. Without cellular service, the OBUs could not call back to the central communication server, and could not acquire updates to software that, in principle, could modify the cellular network code in the application software. The only practical solution to this problem was to physically connect a laptop computer to each OBU, and transfer a software update through the OBU serial port. Returning to the installation sites was a burden for participating households and resulted in the loss of a number of participant households even before the project was underway. The project got underway with 276 enrolled households. **Table 3.1** displays this information in tabular form along with rates of attrition over various stages of the project operation.

Table 3.1 Participation and Attrition

Participation and attrition rates

Category	Number of Households	Participation Rate	Attrition at Each Stage	Cumulative Attrition
Total enriched call list	196,451			
Phone numbers called	126,796			
Working, non-business phone numbers	99,267			
Household member reached	53,229			
Household not ineligible	43,465			
Household did not refuse	776			
Household installed all toll meters	307	0.7%		
Household fully enrolled at start of operations	276		10.1%	10.1%
Household awarded non-zero compensation after the study	239		13.4%	22.1%

A Representative Sample

In order to participate, a household had to meet specific criteria about vehicle ownership and use; and the study attempted to over-enlist households with the opportunity to make use of available transit services. While randomness was maintained in the application of the screens and enrichment process, these sample requirements departed from a pure random sampling of households. The recruitment screener was described in an earlier section of this report. Other information about the participating households, not included in the recruiting call list was collected as part of two surveys administered at the beginning and at the end of the study's operation. The surveys collected household demographics, associated household members with enrolled vehicles, and asked a few attitudinal questions of the households. Survey response data was used by the project team to gain insight into the representative nature of the households by making comparisons with the 2000 Census 5% PUMS microdata sample from a similar geography from which the study recruited households. The study sample was compared with the full census sample and with a census subsample, filtered in a manner consistent with the household recruitment screens that were applied in the study.

This gives some indication of whether the screening process imposed notable bias, and whether bias was introduced in some manner independent of the screens that were applied. The filters applied to the census sample are displayed in **Table 3.2** and a comparison of means between the study sample with the census sample are contained in **Table 3.3** below.

Table 3.2 Filters for Census 5% Microdata Sample

Description	Share of HHs	Share of persons
At least one HH member commutes to work by car, truck, or van	67.4%	71.9%
At least one HH member leaves for work between 6-10AM or 3-7PM	65.8%	69.8%
Household owns between 1 and 3 vehicles (inclusive)	85.9%	85.4%
All three above criteria are met	53.3%	57.2%

Table 3.3 Household Sample Characteristics

Sample/Population Characteristic	Project Sample		Filtered Census			
	Mean	St. Dev.	Mean	St. Dev.	Ho*: $\mu 1 - \mu 2 = 0$	Test Stat.
Average "household size"	2.3	1.37	2.6	1.35	reject	2.62
Average number of childer under 16 per HH	0.63	1.00	0.60	0.96	non-reject	0.32
Average age of head of household	47	12.90	42	12.13	reject	4.38
Average household income	$ 66,713	$ 40,123	$ 84,467	$ 76,765	non-reject	2.35
Average number of vehicles per HH	1.6	0.67	1.9	0.70	reject	3.23
Share of HHs owning own home	79%	0.41	63%	0.48	reject	3.52
Share of HHs renting their home	17%	0.38	37%	0.48	reject	4.13
Share of HHs with other living arrangement	3%	0.18	1%	0.07	reject	3.86
Share of HH drivers that are male	40%	0.49	50%	0.50	reject	2.62
Average age among HH drivers	45	13.06	39	13.63	reject	5.33
Share of HH drivers completing less than HS (< 12)	7%	0.26	10%	0.30	non-reject	1.05
Share of HH drivers completing HS or more (12+ yrs)	93%	0.26	90%	0.30	non-reject	1.05
Share of HH drivers completing 4-yr degree or more (16+ yrs)	62%	0.49	43%	0.50	reject	4.03
Share of HH drivers completing more than a 4-yr degree (17+ yrs)	34%	0.48	14%	0.35	reject	5.99
Share of drivers employed part-time	9%	0.29	17%	0.38	reject	2.67
Share of drivers employed full-time	66%	0.47	71%	0.45	non-reject	1.23
Share of drivers not employed (retired, students, homemaker, etc.)	24%	0.43	12%	0.33	reject	4.81
Sample/Population Characteristic	**Project Sample**		**Unfiltered Census**			
	Mean	**St. Dev.**	**Mean**	**St. Dev.**	**Ho*: $\mu 1 - \mu 2 = 0$**	**Test Stat.**
Average "household size"	2.3	1.37	2.3	1.38	non-reject	0.87
Average number of childer under 16 per HH	0.63	1.00	0.47	0.90	non-reject	2.41
Average age of head of household	47	12.90	47	16.62	non-reject	0.35
Average household income	$ 66,713	$ 40,123	$ 70,560	$ 71,633	non-reject	0.73
Average number of vehicles per HH	1.6	0.67	1.7	1.02	non-reject	0.59
Share of HHs owning own home	79%	0.41	59%	0.49	reject	5.74
Share of HHs renting their home	17%	0.38	41%	0.49	reject	6.47
Share of HHs with other living arrangement	3%	0.18	1%	0.09	reject	4.03
Share of HH drivers that are male	40%	0.49	49%	0.50	reject	3.32
Average age among HH drivers	45	13.06	43	17.54	non-reject	1.79
Share of HH drivers completing less than HS (< 12)	7%	0.26	13%	0.34	non-reject	2.40
Share of HH drivers completing HS or more (12+ yrs)	93%	0.26	87%	0.34	non-reject	2.40
Share of HH drivers completing 4-yr degree or more (16+ yrs)	62%	0.49	37%	0.48	reject	7.44
Share of HH drivers completing more than a 4-yr degree (17+ yrs)	34%	0.48	12%	0.32	reject	9.74
Share of drivers employed part-time	9%	0.29	16%	0.37	reject	3.21
Share of drivers employed full-time	66%	0.47	59%	0.49	non-reject	2.45
Share of drivers not employed (retired, students, homemaker, etc.)	24%	0.43	24%	0.43	non-reject	0.03

*At the 99% confidence level

The 1999 equivalent of the study sample's mean household income is somewhat smaller than the mean value of census sample for the same geography, although the null hypothesis (no difference in means) is not rejected at the 99% confidence interval. A number of possible reasons could explain this difference.

1) The census sample was not able to be weighted in a manner that replicates the study sample enrichment for transit availability. This weighting process would have required spatial detail not available for the census 5% sample. Had weighting for transit availability been possible it might have emphasized census micro geographies with average income lower than the average for the entire study geography.
2) The installation and servicing of in-vehicle equipment, as well as the general burden of participation might have selected out households with higher than average household income.
3) The reporting of income as part of the study survey might have resulted in underreporting of income as compared to the census. The study survey did not ask for a decomposition of the elements of income; which requires deliberative responses leading to the reporting of a more complete estimate of household income for the census sample.

Sample characteristics for which the null hypothesis is rejected (when compared to the filtered census sample) include household size, age of head of household, number of vehicles, home ownership rates, and college-level educational attainment. When compared with the unfiltered census sample the null hypothesis is rejected for home ownership rates and college-level educational attainment, but not household size, age of head of household and number of vehicles. It is possible that the original recruitment call list underrepresented renter households due to a higher degree of household location "churn" for renters.

The differences in these less gross characteristics could be important if the characteristics are material to travel behavior and its key determinants, such as values of time. If they are material, then the econometrics employed for analysis of the data would suffer, implicitly, from a missing variable problem which imparts bias. However, this appears to be a minor concern for the following reasons:

- First, once income is controlled for, there is no clear expectation that these dimensions (e.g. home ownership) are especially material to travel behavior.
- Second, some of these characteristics (e.g. education level) where tested in models and found to be immaterial.
- Third, with a small sample and limited degrees of freedom, we do not have high expectations of isolating putative effects or achieving superior control with such secondary characteristics.
- Finally, there are certain household characteristics that are difficult theoretically, in fact, to link unambiguously to a household's behavior. The education level of the head of household, or the average of all adults in the household, may or may not be a dimension that clearly parses behavior of one household versus another. Unlike income and number of drivers, it is not clear what functional form would capture the effect of greater household education levels, even if there is one.

The randomness of our sample also becomes less important since we use econometric impact tools to quantify behavioral relationships. It is true that a poorly drawn sample should be recognized by using weighted regression techniques which, can under the right circumstances, have material effect. However, in a linear model, with reasonably random weighting, the effects are not material. Indeed, our intentional enrichment of transit accessible households actually assists in measurement of a rare characteristic. We do not want to "correct" for this overweighting with an inverse regression weight or this effect would lapse again into unmeasurability. However, the underlying justification of enrichment implicit in that argument is that the enriched characteristic is not bringing in other biases. That is, we cannot make the assertion of the innocuousness of enrichment if it also over-enriched the sample in the incidence of some other unmeasured variable.

The study was not intended to comprehensively inventory all factors that contribute to differential travel behavior. Rather, impact studies, such as this, introduce big shocks in the variable of primary interest and the influence of unaddressed variables is minimized because of the delta structure of the impact model.

Descriptive Statistics on Household Travel

An important aspect of the Traffic Choices study, beyond understanding behavioral responses to tolling the road network, was the opportunity to observe travel behavior across a sample of households for an extended period of time. Travel surveys are often performed to support the development of travel models or other aspects of transportation planning. Large-scale surveys, however, are expensive to administer, and are often limited to collecting travel diary information about a few days of consecutive travel. While only being able to observe vehicle travel directly, the Traffic Choices study measured dimensions of vehicular travel unambiguously (without reporting error) and over an extended duration. This offered a unique opportunity to better understand the complexity and variability of vehicle travel both across and within the households of our region.

Travel characteristics averaged over all participating households are of interest, as are the distributions of the characteristics of travel across households. The rich dimensionality of this data is challenging to represent in charts and tables. For example, an average participating household departed for work at 8:45 a.m., drove 12.3 miles at an average of 28.6 miles per hour for 25.3 minutes and arrived at work at just before 9:15 a.m. This kind of summary is interesting but hides the significant variation across and within households. **Table 3.4** below displays average tour characteristics (along with standard deviations and relative variances) for multiple tour purposes and different classifications of households by household characteristics.

And as another example of the kind of information gathered about household travel, the figures below (**3.3 – 3.10**) display the distributions of measured dimensions of travel activity for home-to-work and work-to-home tours for all participating study households.

And yet such statistics fail to convey the complex interactions between elements of trip-making. For example, it is possible to examine the relationships between departure time and other aspects of home-to-work tours. One-quarter of participating households had an average home-to-work departure time prior to 7:30 a.m., with the remaining three-quarters of households departing after 7:30 a.m. When examining household quartiles departing after 7:30 a.m. there was no statistical difference in average speeds, drive times, or miles driven. When compared to the quartile that departed before 7:30 a.m. with those departing after 7:30 a.m. (**Table 3.5**) there are significant differences in both miles driven and speeds, but not for drive time. This appears to be evidence consistent with departure time sorting where households making longer commute trips are, on average, departing earlier, possibly to avoid the most congested conditions. The result is that both groups spend about the same amount of time driving but over different distances and at different speeds. Interestingly, departing after standard commute hours (latest quartile departed after 9:30 a.m.) does not appear to result in higher average tour speed conditions for those households.

Table 3.4 Tour Travel Characteristics across Households

Home-to-Work Tours (weighted averages)

		Tour Freeway Miles			Tour Distance (Miles)			Tour Drive Time (min)			Tour Speed (mph)			Tour Total Time (min)			Tour Departure Time			Tour Arrival Time		
Households	Tours	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.
All Households	183.17	5.46	3.56	2.22	12.26	7.70	0.67	25.35	13.95	0.57	28.63	7.19	0.24	68.40	230.87	2.92	8.75	2.18	0.24	9.23	2.09	0.22
0-24,999*	103.50	1.88	2.24	6.69	10.12	19.15	1.69	18.86	18.38	1.13	25.92	20.46	0.41	143.06	350.45	3.69	9.23	2.17	0.24	9.41	2.04	0.22
25,000-49,999	165.18	4.37	2.51	3.15	10.28	5.38	0.52	23.38	12.41	0.51	26.52	5.81	0.22	73.68	232.25	2.81	8.90	1.92	0.21	9.23	1.74	0.18
50,000-74,999	174.17	5.65	3.29	1.76	12.83	8.63	0.69	25.46	13.75	0.55	30.37	9.15	0.28	60.75	213.60	2.89	8.60	2.06	0.24	9.12	1.94	0.20
75,000-99,999	213.04	5.15	4.09	1.71	11.57	8.59	0.77	22.70	14.83	0.65	29.40	6.60	0.23	59.08	231.17	2.93	8.90	2.50	0.27	9.33	2.50	0.26
100,000 & Over	197.75	6.71	4.35	1.48	14.11	7.39	0.58	29.55	14.42	0.50	28.70	6.29	0.23	77.48	240.44	2.84	8.54	2.06	0.24	9.15	2.00	0.22
One Vehicle	151.77	5.20	2.78	2.04	11.13	7.11	0.66	22.63	12.44	0.57	29.11	7.91	0.25	62.14	206.36	2.69	8.89	2.00	0.22	9.29	1.90	0.20
Two Vehicles	202.17	5.78	3.98	2.04	13.29	7.99	0.66	27.37	14.46	0.55	28.67	6.64	0.24	73.25	245.83	2.99	8.58	2.24	0.26	9.12	2.17	0.23
Three Vehicles*	375.14	4.23	4.83	5.17	10.24	8.89	0.80	24.69	19.23	0.74	24.98	7.53	0.32	65.27	255.84	3.86	9.32	2.81	0.28	9.87	2.69	0.25
0 Workers*	45.44	6.43	2.40	1.03	16.22	20.49	0.93	28.61	15.00	0.61	31.95	27.98	0.44	203.79	435.83	2.06	10.16	2.21	0.22	10.51	1.96	0.18
1 Worker	164.83	5.50	2.89	2.04	11.71	6.37	0.58	23.95	11.88	0.51	29.06	7.11	0.24	62.55	203.23	2.79	8.55	1.94	0.22	8.98	1.82	0.20
2 Workers	244.31	5.49	4.15	2.01	12.82	8.64	0.71	26.86	15.35	0.59	28.44	6.95	0.25	70.99	250.55	3.03	8.72	2.26	0.26	9.26	2.23	0.23
3 Workers*	382.00	6.79	17.28	2.54	15.38	31.80	2.07	32.83	63.34	1.93	25.96	8.83	0.34	134.48	380.36	2.83	13.79	7.14	0.52	14.84	7.37	0.50

Work-to-Home Tours (weighted averages)

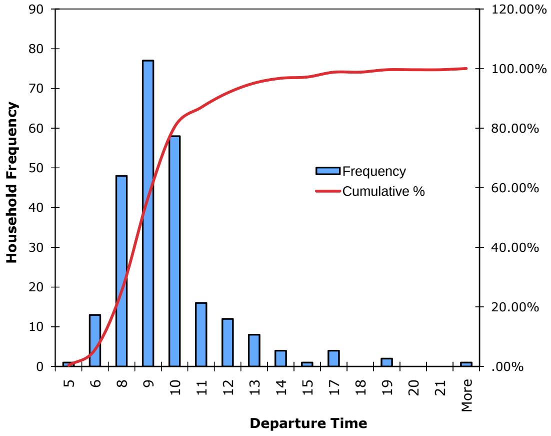
		Tour Freeway Miles			Tour Distance (Miles)			Tour Drive Time (min)			Tour Speed (mph)			Tour Total Time (min)			Tour Departure Time			Tour Arrival Time		
Households	Tours	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.
All Households	183.27	5.79	4.95	2.17	14.18	12.68	0.94	32.00	22.97	0.74	26.38	8.48	0.31	93.23	257.07	2.42	16.33	2.35	0.15	17.30	2.58	0.16
0-24,999*	103.50	2.26	3.29	4.60	11.09	18.06	3.03	24.11	18.60	1.08	27.72	73.88	2.20	172.70	681.96	4.93	15.37	1.75	0.12	16.20	1.83	0.12
25,000-49,999	165.29	4.68	4.55	2.50	12.48	12.37	1.04	30.22	22.22	0.76	24.94	9.57	0.36	104.35	308.47	2.81	16.38	2.09	0.13	17.35	2.50	0.15
50,000-74,999	174.17	5.84	4.30	2.24	13.97	9.50	0.68	31.43	20.23	0.64	27.05	6.31	0.23	80.04	203.80	2.13	16.42	2.39	0.15	17.34	2.62	0.16
75,000-99,999	213.17	5.33	5.58	2.06	13.68	12.79	0.94	30.39	23.56	0.81	26.60	7.97	0.30	81.88	200.87	2.15	15.93	2.63	0.17	16.85	2.84	0.18
100,000 & Over	197.91	7.49	5.71	1.41	16.50	13.75	0.88	36.33	23.31	0.67	27.36	7.34	0.27	107.40	283.25	2.41	16.67	2.27	0.14	17.76	2.41	0.14
One Vehicle	151.83	5.35	4.49	2.41	13.32	14.44	1.09	30.46	24.13	0.81	26.19	10.90	0.39	96.32	262.86	2.37	16.39	2.30	0.15	17.34	2.62	0.16
Two Vehicles	202.31	6.27	5.24	1.93	15.09	11.84	0.85	33.52	22.64	0.71	26.79	7.02	0.26	91.24	255.55	2.44	16.39	2.39	0.15	17.35	2.57	0.15
Three Vehicles*	375.29	4.29	5.26	2.79	11.44	8.70	0.77	28.21	18.33	0.67	23.90	5.86	0.25	90.96	232.35	2.49	15.37	2.36	0.17	16.52	2.45	0.16
0 Workers*	45.33	6.46	3.20	1.73	16.62	12.39	0.72	36.79	21.45	0.61	26.45	11.69	0.34	248.24	485.85	1.87	16.61	2.04	0.12	17.74	2.31	0.13
1 Worker	164.90	5.84	4.50	2.19	13.84	11.64	0.92	31.24	21.42	0.72	26.86	10.00	0.36	93.52	247.66	2.41	16.52	2.22	0.14	17.50	2.47	0.15
2 Workers	244.46	5.86	5.32	1.84	14.50	12.28	0.88	32.92	21.96	0.70	26.17	6.83	0.26	87.51	233.19	2.35	16.23	2.48	0.16	17.18	2.67	0.16
3 Workers*	383.00	6.71	13.53	2.02	15.35	23.96	1.56	33.10	43.87	1.33	25.50	7.79	0.31	184.99	337.25	1.82	10.60	3.99	0.38	12.80	4.46	0.35

Home-to-Home Tours (weighted averages)

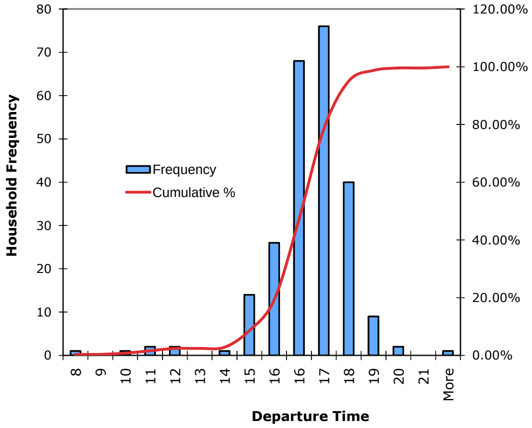
		Tour Freeway Miles			Tour Distance (Miles)			Tour Drive Time (min)			Tour Speed (mph)			Tour Total Time (min)			Tour Departure Time			Tour Arrival Time		
Households	Tours	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.	Average	Stddev	Rel. Var.
All Households	440.91	4.65	9.49	2.52	15.97	35.58	2.23	35.06	51.60	1.48	20.11	20.78	0.78	227.82	751.19	3.14	13.83	4.17	0.30	15.77	4.30	0.27
0-24,999*	417.88	5.36	9.55	2.42	17.49	46.62	2.35	35.09	58.28	1.56	18.88	19.84	1.02	268.64	849.05	3.21	13.97	3.88	0.28	15.72	4.20	0.27
25,000-49,999	295.42	4.81	9.77	2.55	16.13	32.06	1.94	37.62	50.74	1.34	18.87	15.95	0.80	245.86	840.26	2.96	14.28	4.20	0.30	16.17	4.45	0.28
50,000-74,999	423.34	4.69	9.38	2.45	14.94	31.21	2.08	32.73	44.84	1.39	20.94	39.63	1.07	214.28	637.62	2.86	13.85	4.16	0.30	15.66	4.34	0.28
75,000-99,999	499.90	4.13	9.04	2.70	15.17	34.48	2.36	32.94	48.82	1.52	20.06	14.46	0.65	209.45	780.70	3.65	13.73	4.19	0.31	15.62	4.29	0.28
100,000 & Over	563.92	4.82	9.74	2.45	17.22	41.14	2.42	37.19	59.60	1.62	20.36	12.58	0.63	244.98	816.76	3.21	13.65	4.14	0.30	15.79	4.18	0.27
One Vehicle	256.63	5.00	9.54	2.44	16.15	31.56	1.93	35.65	46.62	1.33	19.33	14.33	0.68	247.10	761.73	2.73	14.16	4.20	0.30	16.03	4.53	0.29
Two Vehicles	620.02	4.57	9.51	2.52	16.08	37.98	2.37	35.10	54.42	1.56	20.49	24.12	0.84	219.67	737.14	3.25	13.68	4.16	0.31	15.66	4.20	0.27
Three Vehicles*	616.71	3.29	8.61	3.15	12.44	22.49	1.84	29.60	38.15	1.31	19.01	9.16	0.48	227.56	931.65	4.20	13.97	4.09	0.30	15.72	4.52	0.29
0 Workers‡	426.52	4.30	9.09	2.66	15.42	33.24	2.14	37.30	51.96	1.41	17.78	10.86	0.64	289.86	893.56	3.06	13.58	3.75	0.28	15.68	4.05	0.26
1 Worker	387.41	4.59	9.17	2.50	15.50	32.94	2.12	34.07	47.49	1.42	20.64	30.09	0.93	218.82	747.03	3.21	13.88	4.08	0.30	15.76	4.29	0.27
2 Workers	566.93	4.78	9.90	2.48	16.65	40.34	2.44	35.60	57.37	1.61	20.18	13.71	0.68	227.21	729.96	3.08	13.78	4.34	0.32	15.79	4.31	0.27
3 Workers*	791.50	1.63	6.76	4.15	8.19	15.70	1.97	23.38	31.24	1.37	16.72	7.27	0.44	169.43	868.22	5.09	13.84	3.96	0.29	15.39	4.18	0.27

Figures 3.3 through 3.10 Selected Household Travel Characteristics

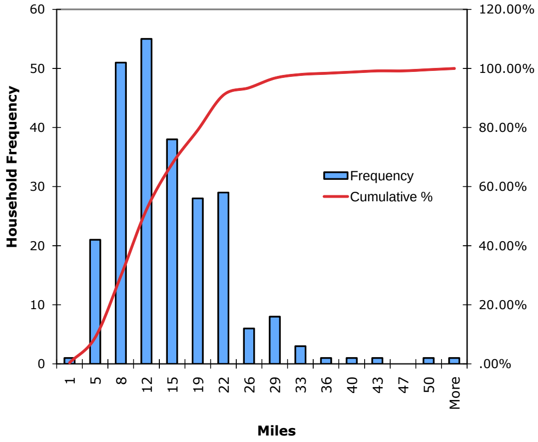
Average Home to Work Departure Time



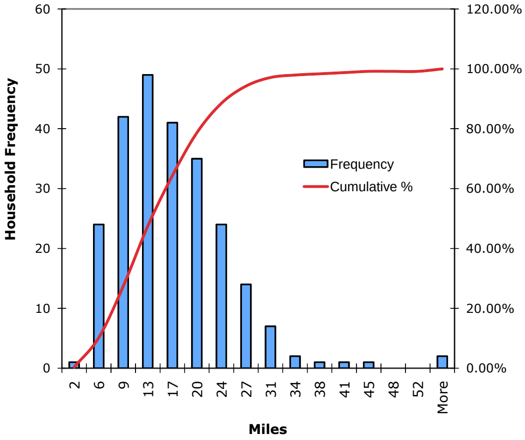
Average Work to Home Tour Departure Time



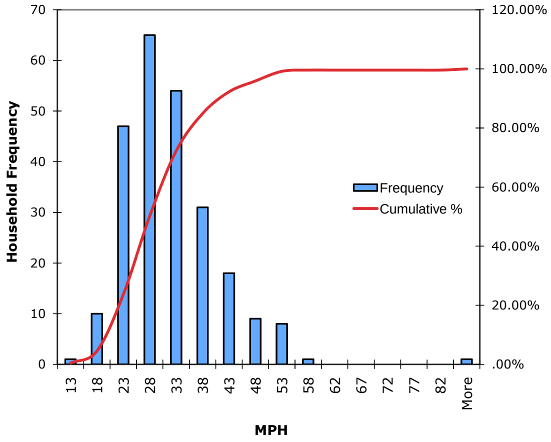
Average Home to Work Distance (miles)



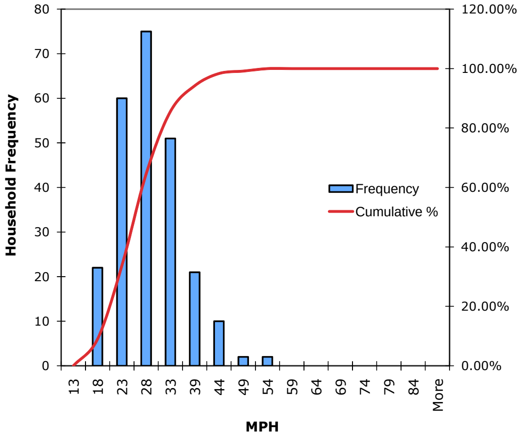
Average Work to Home Distance (miles)

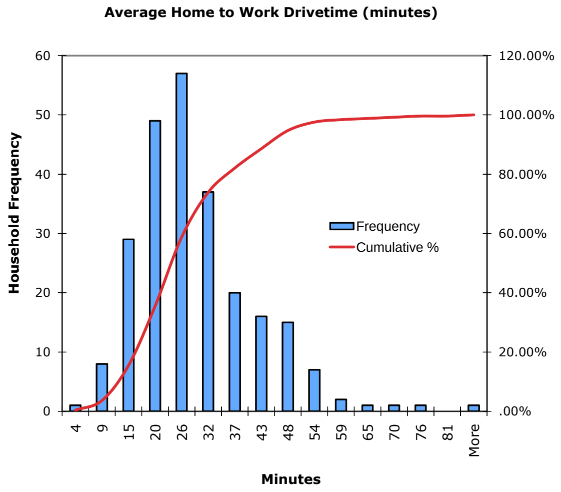


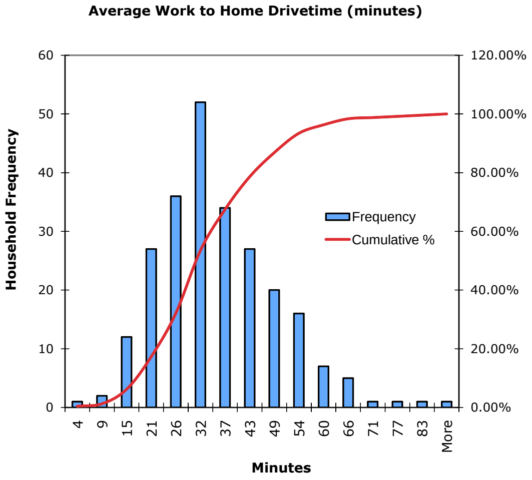
Average Home to Work Speed (mph)

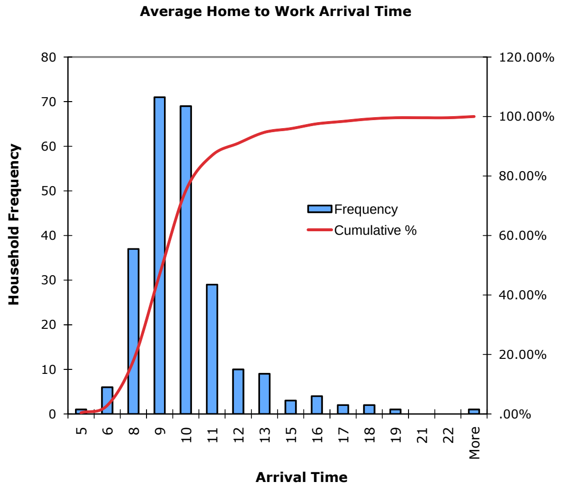


Average Work to Home Speed (mph)









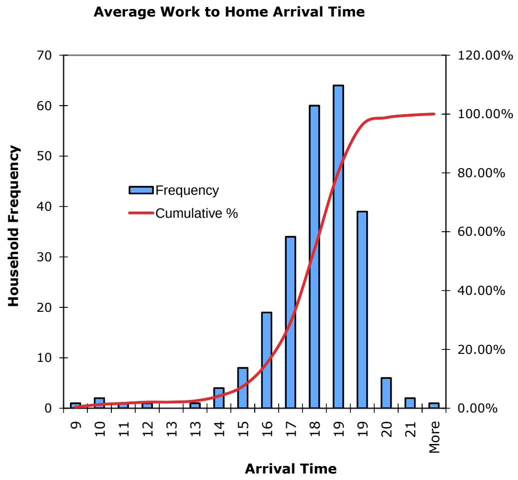


Table 3.5

Tour Characteristic	Departure Time	N	Mean	Std. Dev.	Std. Error	Mean Diff.	Lower CI	Upper CI
Tour Speed (mph)	Departing before 7:30 a.m.	60	33.8	8.4	1.1	6.3	4.1	8.6
	Departing after 7:30 a.m.	180	27.4	7.5	0.6			
Tour Distance (Miles)	Departing before 7:30 a.m.	60	14.8	8.8	1.1	2.8	0.7	5.0
	Departing after 7:30 a.m.	180	11.9	6.7	0.5			
Tour Drive Time (min)	Departing before 7:30 a.m.	60	26.4	11.7	1.5	1.0	-2.4	4.4
	Departing after 7:30 a.m.	180	25.4	11.4	0.8			

Exit Survey

Two household surveys were administered during the course of the study. The first was used to verify household characteristics, and the second was designed to verify changes to household composition, employment status, periods on vehicle non-use, and other events that would be likely to result in atypical vehicle use activity, or constitute “non-compliance” on the part of the participant households. The second survey, administered at the end of the study, also asked a few attitudinal questions and tried to better understand how participants responded to aspects of the study design and tolling technology. Key results are below.

Households	260
Equipped Vehicles	401
Reported behavior in response to tolls	
• Used transit more often	11.5%
• Traveled less often	34.5%
• Combined trips more often	51.7%
• Traveled by a different route more often	44.6%
• Carpooled with household members more often	23.4%
• Carpooled with non-household members more often	14.8%
Someone in household changed behavior	60.4%
Reviewed account information on the web	Average of 0.7 times per month
Reviewed the monthly invoices	Average of 1 time per month
Utilized the toll information displayed on the OBU	75%
Of those above:	
• Each trip	28%
• Once a day	11%
• At least once a week, but not every day	20%
• Less than once a week	42%
Household that reported a change in economic circumstances	8%
Of those above, for the positive	75%
Comments about the on-board equipment	
■ Appreciated the information it provided	19%
■ Found the appearance of the meter unattractive	13%

Focus Groups

At the end of the study in April 2006, two focus groups were conducted with a number of the participants to develop a better understanding of their experience over the past 18 months. The main goals of these focus groups were to investigate the following:

- Explore how the implementation of the GPS-based tolling system changed travel behavior (a supplement to the primary behavioral analysis data gather in the vehicles' tolling device)
- Explore the underlying motivations behind any behavioral changes
- Explore opinions and preferences on this type of pay per use tolling when compared to existing transportation taxes
- Explore perceptions of the fairness of the tolling structure
- Understand concerns about personal privacy that might arise from recording facility use behavior
- Identify system design refinements likely to be needed prior any further analysis of wider-scale implementation potential

Focus groups are a preferred methodology to uncover these types of authentic core values and beliefs. They can provide access to the underlying reasoning behind people's thoughts, feelings, and behaviors. Focus groups can also help define themes and hot buttons, but their findings cannot be extrapolated to larger populations (such as can be done with random sample surveys).

Each group lasted approximately 1¾ hours with eight participants each. A moderator guide structured the discussions. The dynamic nature of the focus group process leads to the same topic areas being covered across groups, albeit in similar but not identical ways. Audio and video recordings were made of the groups, and were observed from behind a one-way mirror by representatives of the PSRC and the consultant team.

All participants from both focus groups had completed the online exit survey and expressed interest in participating in further study. The groups included a mix of men and women, age groups, and views on transportation funding and concerns about privacy. Specifically, we used the level of privacy concern expressed in the exit survey to bring together groups in which one group was more concerned than the other. Key findings included the following:

- Overall, participants reported they changed their travel behavior over the course of the study.
- Changes in behavior were largely driven by financial reasons to start with, but once changes were made, some perceived additional benefits such as:
    - Savings in time
    - More comfortable or interesting drive
    - Time to read on the bus
- The availability of real-time tolling cost information displayed on the traffic meter heightened some participants' awareness of the cost of travel.
- The monthly invoices were a useful supplement to the traffic meter as they presented road use information over time and in aggregate.
- Varying opinions on the fairness and effectiveness of tolling indicates that there are many interrelated factors to address when considering broader implementation.
- Participants think that revenue generated from a system such as this should go to maintaining and improving our transportation system.
- Privacy of data is a concern, but not to the extent that it would derail the use of this technology.
- Distrust about how government uses revenues complicates the evaluation of the relative merits of different taxing schemes.

A full focus group summary report is included as Appendix 18.

4.3 EXPLAINING THE DEMAND RESPONSE TO TOLLS

Analytical Approach

The Traffic Choices Study experiment, like all social experiments, was conducted in a potentially messy, or noisy, environment. Social experimentation must be carefully designed to minimize, or control for, the "corrupting" effects of non-random occurrences that have nothing to do with the experimental treatment. In this case, these potential non-random occurrences were both of the kind that could be predicted (seasonality), and therefore designed around, but also those for which no reasonable prediction could be made in advance (household disruptions). Lucky for social science research, advanced statistical techniques have developed to a point where much can be learned from experiments in complex settings when data is appropriately collected. The Traffic Choices Study produced a high volume of household-level vehicle trip data records, collected over an 18 month period. This resulted in numerous repeat observations (records of the same kind of trip activities) over a relatively modest sample of participating households.

Households acted as their own control through the observation of before-tolling and after-tolling behavior. However, the control and experimental periods of the project were not of equal length and did not occur in exactly the same months of the year, thus indicators of traffic seasonality and direct measures of fluctuations in fuel costs were included in order to better control for these elements of the experimental observations.

The basic analytical approach to understanding behavioral response to tolls involved estimating linear impact regressions with observed dimensions of travel demand (across households, vehicles, and workers) as dependent variables, and with measures of the generalized costs of travel (tolls, out-of-pocket costs and time costs), household demographics (income and number of drivers), seasonal factors, and a measure of transit viability as explanatory, or independent variables.

Theoretical Expectations

Theory provides considerable guidance regarding the anticipated effects of the experimental design. The imposition of tolls where none had been levied before will raise the perceived cost of travel, everything else being equal. We will call this initial effect the *impact* of the tolls and the associated generalized costs. It is the initial effect because we expect the traveler to respond to the tolls' effect on generalized cost. Since the demand for travel is a derived demand from the desire to perform other activities (working, shopping, sightseeing, etc.), the higher generalized costs impair the utility of the primary travel purpose. Consequently, theory suggests that the traveler will seek ways to mitigate this impact, so as to preserve as much as possible of the value ("utility") of the primary purpose of the travel.

There are numerous ways that the traveler can respond to the increase in the generalized cost of travel. In the short-run, the traveler can:

- Travel by alternative paths to reduce the increase in generalized cost. Some paths, though involving longer travel times, may offer sufficiently lower tolls that generalized costs are reduced.
- Change the number of times that the affected tours occur. If the traveler has the opportunity to work at home or consolidate multiple tours into a single tour, total generalized costs per period may be reduced below the initial tolled level.
- Select another mode of travel. If transit service is available, or if the traveler can form and use a carpool cost-effectively, the generalized cost of the travel may be able to be reduced below their impact level.

- Travel at a different time. Since the tolls in the experiment varied by time of day (to approximate the variable burden of travel at different times on regional road capacity), there may be opportunity to make tours at alternative times.

In the longer run, travelers can make other choices that can economize on the generalized costs of travel. The experiment was not expected (by participants) to be long-term, so the incentive to make such adjustments was not strong. However, for completeness, it should be said that, with a permanent tolling program, one might expect travelers to:

- Change the locus of employment, residence, or both.
- Make changes in the time or path of travel, as a consequence of re-negotiated workplace and residence choices.
- Change the vehicles used for travel to economize on operating costs or to provide higher amenities to offset the costlier travel.

Thus, we expect the effect of the tolling to be some combination of the following:

- Reduce the number of auto tours, either through tour suppression or through changes in mode.
- Increase the number of trip segments per tour to economize on the total cost of travel across all travel purposes.
- Reduce the amount of tolls paid per tour relative to the impact toll level per tour.
- Alter the time of travel in favor of lower-toll times of travel.
- Alter the path taken, with attendant changes in distance traveled and time spent traveling. Depending upon the opportunities available to change paths, modes and the time of travel, the duration of travel and distance traveled per tour may either increase or decrease.

For any given tour purpose, the response may be different from that postulated above since the household likely considers its costs and opportunities of travel in an integrated fashion. That is, it may be able to offset the toll impact of, say, the home-to-work tour by modifying the work-to-home tour, or work-to-work or home-to-home tours. Similarly, impacts on one household member may be able to be offset by changes in behavior of other household members. The less integrated is the household's thinking (or the greater ore the constraints on integrated planning), the less likely are such accommodations.

Across households of various demographic characteristics, we generally expect:

- The response to tolls to be less responsive ("elastic") for higher income households. The theoretical logic here is that such households have less binding household budget constraints and higher utilities associated with the primary purposes of travel.
- An ambiguous relationship between travel response and the number of drivers in the household. On the one hand, the greater the number of drivers the higher the probability that cost-effective carpooling can be implemented. On the other hand, the coordination or integration of a household level response may be made more complicated by the diverse travel purposes and opportunities across members in the household.
- Households with more viable transit options to display more toll-elastic behavior regarding auto tours, drive time and distance traveled, at least in the home-to-work and work-to-home periods.

The Travel Choices Study, and the high-resolution data it yielded, is a unique data resource. As such, it permits examination of dimensions of response (such as trip chaining) that are impossible to study well even with large, household survey instruments. Unlike such instruments, the Travel Choices data instrumentation persisted for more than a year, permitting observation of even statistically-rare travel events. On the other hand, large cross-sectional household surveys, though reporting data from shorter periods of observation, are better sources of long-run adjustments to changes in generalized costs of travel.

In this regard, it is useful to consider the results reported herein with those summarized in recent state-of-the-practice reports that use the household panel method. One such useful summary of the disaggregate modeling of urban travel demand is offered in Daniel McFadden's, *Disaggregate Behavioral Travel Demand's RUM Side A 30-Year Retrospective*.[8] As that report suggests, there is reasonable consistency in the findings regarding the coarser dimensions of travel behavior (such as revealed values of time), but less reliable insights regarding such things as the time of day of travel and trip chaining behavior.

Measuring Transit Viability

The study's household sampling methods were designed to enrich the sample for households located in proximity to available transit services. Households on the recruiting call list were assigned a dummy variable for transit "viability"[9]. However, since there was no way of knowing common trip destinations for household members, and due to the limits of the household recruitment call list, the enrichment process did not produce a household measure of transit "viability" ideal for inclusion in the econometric analysis. At the conclusion of the experiment it was possible to unambiguously measure the usefulness of available transit services between specific, and frequently paired, origins and destinations. This analysis was limited to household vehicle trips that were associated with the household work locations. In this case, a transit "viability" function was estimated as the ratio of auto and transit generalized costs (time and cash costs) associated with each origin and destination zone in a base year run of the region's travel demand model. A continuous measure of transit "viability", tied directly to actual household-level travel patterns, permitted analysis of the relative importance of work trip transit service availability (worker models only) to the behavioral response of the participants when faced with tolls on the roadways.

Empirically, we estimated the probability of a household utilizing transit for their home-to-work commute through the following two steps:

1. We computed the difference between the estimated generalized cost of commuting by auto and the estimated cost of the same commute by transit. The generalized cost of the auto commute is composed of the individual's value of time plus the operating cost of the vehicle. The generalized cost of the transit commute is composed of the individual's value of time cost for each component of the transit trip (walk time, wait time, boarding time, and in-vehicle time) plus the cost of the transit fare.[10] With only a few exceptions, this difference (auto VOT minus transit VOT) was typically negative. That is, the generalized cost of transit was higher—often much higher—than the generalized cost of commuting by auto.
2. The differences in generalized cost of commuting by auto vs. commuting by transit, which range from as high as $0.61 to as low as -$76.93, are positively correlated to the probability of choosing transit over auto. For those individuals where the VOT of commuting by auto or transit is approximately the same, other studies have found the probability of taking transit to be approximately 30%.
3. For those individuals where the generalized cost of transit is higher than the generalized cost of commuting by auto, the probability of taking transit is much lower. In order to convert the differences in generalized cost, estimated in step 1, into estimates of the probability of taking transit, they are first rescaled so that the differences vary between $0.00 and -$20.00.

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[8] http://elsa.berkeley.edu/wp/mcfadden0300.pdf

[9] Transit "viability" was estimated from the regional travel demand model, where for each transportation analysis zone the weighted average of transit travel times were computed between each zone and all other zones.

[10] It is widely recognized that value of time differs between auto and transit commuting and differs among the components of transit commuting, with in-vehicle transit value of time being significantly lower than the value of walk time, wait time, and boarding time. Value of time of auto driving is approximately mid-way between in-vehicle transit value of time and the value of time of the other components. These differences in value of time are accounted for in the analysis.

The rescaled differences were then hypothesized to be approximate equivalents to utility log-sums and were converted into transit accessibility probabilities using logit transformation arithmetic:

4. $$P(transit) = \frac{1}{\left(1 + e^{-z}\right)}$$

where P(transit) is the probability the commuter will use transit and Z is the hypothesized log likelihood ratio.

The result of this exercise, is an estimate of the viability of transit as an alternative to auto commuting. Consistent with the earlier studies, the estimates of the probability of taking transit during work-related travel are conservatively truncated at 0.40.

Inconsistency within Households

Existing evidence and theory suggest that, all else being equal, when faced with higher tolls to use a network of roads facilities motorists will not choose to drive on those toll roads more than they would when no tolls are present. A select group of study households violated this expectation over the 18 months of the study's operation. There are a number of potential reasons why households would behave in a manner that appears to be internally inconsistent when viewed from the perspective of the experimental observer. First, we need to establish the conditions under which a household is considered to have been behaving in a way that is internally inconsistent. When faced with higher tolls (in this case any tolls) on the road network, these households both incurred higher toll costs than their control driving would have incurred, and they drove more or longer distances. Essentially, these households exhibited upward sloping demand curves and negative values of time. These households were flagged and assigned a dummy variable during the econometric analysis. This dummy term was interacted with other explanatory variables.

Specifically, a household was flagged if:

(a) The average weekly tolled miles it drove during the experimental period was greater than the average weekly miles it drove during the control period, and

(b) The average weekly minutes it drove during the experimental period was greater than the average weekly miles it drove during the control period.

The possible reasons for why a household might behave in such a manner are numerous, and are expected to occur during a lengthy social experiment such as the Traffic Choices Study. Changes in home, or work locations, the presence of an additional driver in the household, any new non-discretionary need to frequently use a household vehicle could cause results that are inconsistent with economic theory and common sense. If these changes are observed they can be accounted for in a manner that brings the observed behavior back in line with theory. The project went to great lengths to minimize the effect of these events on the experimental data. First, households were screened during recruitment, asked about the likelihood of major life changes occurring over the following two years. Household vehicle use patterns were monitored over the course of the project, where households were contacted when anomalous patterns (such as vacation related inactivity) emerged. Households were also surveyed at the conclusion of the study to determine if any number of major household changes did happen during the course of the data collection period. All these measures were, of course, insufficient to ensure that all causes of seemingly anomalous behavior were accounted for.

The Impact Model Methodology

There are numerous methods that might be used to measure behavioral responses to tolls. In this study, behavioral responses were measured using what will be referred to as the impact model approach. Specifically, in keeping with the experimental nature of the data, the behavior of individuals is measured relative to the behavior they exhibited in the control period.

In the impact model approach, the behavioral changes are measured relative to what the presumed behavior would have been "but for" the imposition of the experimental tolls. We wished to facilitate measurement of arc elasticities and to avoid the econometric hazards of endogenous right-hand-side (RHS) or "independent" variables. Thus, the experimental toll treatment is the *toll that would have been paid* (computed using control period behavior), but for their response to the experiment. That is, the toll actually paid (which is a variable that is endogenous to the experiment), is not used as a RHS variable, but, in fact, studied as an impact or dependent variable.

The general econometric formulation of the impact equations follows from specification of a general behavioral relationship, and its transformation into an experimental minus control, impact formulation:

$$Y_i = \alpha + \beta X_i + \varepsilon$$

$$\Rightarrow \Delta Y_i = \beta \Delta X_i + \varepsilon$$

where:

Y_i = a measure of travel behavior, e.g., number of tours per week

X_i = a vector of measures of traveler and travel cost indicators expected to influence behavior

$\Delta Y_i = Y_i^e - Y_i^c$ = experimental minus control behavior

$\Delta X_i = X_i^e - X_i^c$ = experimental minus control conditions

The general behavioral formulation can be through of as the demand for, say, tours as a function of the X-vector of traveler and travel cost indicators. The impact formulation reformulates the econometric model to a difference or delta model. Note that his eliminates the intercept (alpha) term in the general, behavioral model. This eliminates a parameter from the model, which is advantageous from the standpoint of the degrees of freedom available in a limited sample-size setting, but, of course, also means that the underlying behavior model itself cannot be completely characterized.

This general formulation is not a constant-elasticity model. However, the arc elasticities (i.e., the elasticity measured at variable means) can be calculated. Assume, for the sake of this discussion, that there is only one RHS variable comprising the X-vector, say, the generalized cost of travel. Once the difference model is estimated on the data, the elasticity of Y with respect to X can be calculated as follows:

$$e_X^Y = \left[\left(\frac{\Delta Y}{Y_c} \right) \bigg/ \left(\frac{\Delta X}{X_c} \right) \right] = \left[\left(\frac{\Delta Y}{\Delta X} \right) \bigg/ \left(\frac{Y_c}{X_c} \right) \right]$$

$$= bX_c / Y_c$$

where:

b = the estimated value of β

The implied elasticity is dependent upon the estimated coefficient, and the values of X and Y used to solve the elasticity formulation. In the presentation above, it is assumed that the control period values are used; alternatively, the experimental equilibrium values can be used. The implied elasticity will vary slightly with the values employed.

The actual empirical formulation was elaborated to permit traveler characteristics to influence the computed elasticity. This results in the general formulation:

$$\begin{aligned}
Y_i &= \alpha + (\beta_0 + \beta_1 H_i)G_i + \beta_2 H_i + \varepsilon \\
&= \alpha + \beta_0 G_i + \beta_1 H_i G_i + \beta_2 H_i + \varepsilon \Rightarrow \\
\Delta Y_i &= (\beta_0 + \beta_1 H_i)\Delta G_i + \varepsilon \\
&\quad \text{where} \\
H_i &= \text{a vector of household characteristics} \\
G_i &= \text{generalized cost of travel} \\
&= \text{vehicle operating and travel time costs} + \text{tolls} \\
&= O_i + P_i
\end{aligned}$$

This formulation allows the elasticity of Y to be measured with respect to generalized costs, G, and tolls, P, once the delta formulation is estimated using sample data. The computation of these elasticities proceeds as follows:

$$\begin{aligned}
e_Y^G &= b\,G_c / Y_c \\
e_Y^P &= \left[\left(\frac{\Delta Y}{Y_c}\right) \Big/ \left(\frac{\Delta P}{P_c}\right)\right] \approx b(\Delta P / G_c)(G_c / Y_c) \\
&\quad \text{where} \\
b &= \text{ the estimated value of } (\beta_0 + \beta_1 H_i)
\end{aligned}$$

Because there is, technically, a zero control period toll, the toll elasticity measure can be measured only at the equilibrium toll, not in the control period. However, the general implication of these computations is that the elasticity of Y with respect to tolls, P, will be lower (in absolute value) than the elasticity with respect to generalized cost. Specifically, the elasticity will be different by a proportion approximately equal to the ratio of tolls as a share of total, generalized cost in the final equilibrium. Separate econometric exercises were performed that suppressed the non-toll deltas in generalized cost. Since, the only realm for exogenous change in generalized costs (other than tolls) is the inadvertent "experimental" effect introduced by changing (market) fuel costs, toll elasticities also could be measured directly by suppressing these other exogenous effects. In either case, the most meaningful elasticity is the generalized cost-based elasticity because of the theoretical and empirical issues surrounding the measurement of toll elasticities directly. The discussion that follows describes the variables employed in the econometric exercises.

Dependent Variables

All trip records were associated with one vehicle and each participant household was associated with one of more vehicles, and all trips linked to a work location were associated with a working household member. As a result, regression models were developed to explain household, vehicle, and worker demand response to tolls. Trip data for households, vehicles, or workers was assembled into weekly measures of trip making behavior, such as the number of tours (per tour type) made each week of the study. These measures of travel demand were the dependent variables in the linear modeling. A table follows (**Table 3.6**) with mean values of these dimensions of demand at the household-level for the data collected during the project's non-tolled control period. The dependent variables included

- Number of Tours
- Tour Distance
- Tour Drive Time
- Trip Segments
- Tour Tolled Distance
- Tour Start Time, and
- Tolls Paid

The table displays mean values for dependent variables on a per tour basis (which aids intuitive interpretation), while the impact models that follow explain changes in the demand variables on a per week basis (weekly measures produced the most stable models).

Table 3.6 Mean Values for Dependent Variables

Household Mean Values of Dependent Variables (Control Period)

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Tours Per Week	4.46	4.46	9.04	2.26	18.65
Tour Distance	11.99	13.78	11.74	5.15	11.31
Tour Drive Time	23.28	30.10	27.03	13.13	25.26
Trip Segments Per Tour	1.08	1.40	2.19	1.42	1.71
Tour Tolled Miles	9.17	10.56	8.12	3.55	8.28
Tour Tolled Cents Paid	235.73	282.43	122.01	53.71	171.40
Tour Start Time	8.65	16.54	14.37	12.78	13.38

Vehicle Mean Values of Dependent Variables (Control Period)

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Tours Per Week	2.51	2.54	6.07	0.92	11.96
Tour Distance	11.84	13.63	11.33	5.68	11.46
Tour Drive Time	23.54	30.20	25.97	14.81	25.05
Trip Segments Per Tour	1.27	1.68	2.27	1.71	1.72
Tour Tolled Miles	9.02	10.34	7.85	4.10	8.41
Tour Tolled Cents Paid	221.87	265.23	119.93	64.93	185.19
Tour Start Time	9.02	16.30	14.39	12.77	13.34

Workplace Mean Values of Dependent Variables (Control Period)

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Tours Per Week	3.49	3.54	NA	1.32	NA
Tour Distance	12.11	13.86	NA	5.93	NA
Tour Drive Time	24.08	30.63	NA	15.15	NA
Trip Segments Per Tour	1.28	1.60	NA	1.72	NA
Tour Tolled Miles	9.32	10.73	NA	4.27	NA
Tour Tolled Cents Paid	229.37	281.29	NA	71.54	NA
Tour Start Time	8.94	16.49	NA	12.74	NA

Explanatory Variables

The Traffic Choices Study was primarily a study of the behavior of drivers in response to paying tolls for the use of the road network. It follows that the primary explanatory factor in the modeling of travel demand behavior was delta **general costs**, which is a measure of the incremental change in the cost of the tour between the control and experimental period. Delta general costs is composed of the toll cost that would be assessed on the typical tour route taken by each household during the control period (but for it being the control period) plus an estimate of the incremental change in the vehicle operating cost between the control and experimental period.[11] Other important explanatory elements that were included in the modeling were **household income**, the number of drivers **in the household**, dummy variable for **summer weeks**, measures of **transit accessibility** for each household (described in more detail above), and a **dummy variable for households that exhibited highly anomalous behavior** in response to the toll "treatment" (also described more above). Also included were interaction terms where the household dummy was interacted with other primary explanatory variables. Below is a table with mean values for explanatory variables for each of three levels of analysis focused on the household, the vehicles, and workers respectively. In each case mean values are provided for each tour purpose (**Table 3.7**).

Table 3.7 Mean Values for Explanatory Variables

Household Mean Values of Explanatory Variables

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Toll Costs	233	278	121	66	171
Dum HH	0.327	0.327	0.327	0.327	0.292
Dum HH * Delta Toll Costs	73	87	36	22	44
Transit Access * Delta Toll Cost	83	105	46	22	67
HH Income * Delta Toll Costs	19,376,925	23,002,583	9,430,299	5,159,637	13,259,877
HH Drivers * Delta Toll Costs	396	468	199	108	275
Summer Dummy	0.275	0.275	0.275	0.275	0.275

Vehicle Mean Values of Explanatory Variables

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Toll Costs	222	265	120	65	185
Dum HH	0.353	0.247	0.352	0.322	0.296
Dum HH * Delta Toll Costs	83	70	36	10	52
Transit Access * Delta Toll Cost	70	89	40	21	62
HH Income * Delta Toll Costs	20,313,347	24,006,097	10,081,247	5,596,941	16,090,817
HH Drivers * Delta Toll Costs	412	486	217	113	330
Summer Dummy	0.275	0.275	0.275	0.275	0.275

Workplace Mean Values of Explanatory Variables

Variable	Home-to-Work	Work-to-Home	Home-to-Home	Work-to-Work	All Tours
Toll Costs	229	281	NA	72	NA
Dum HH	0.396	0.266	NA	0.396	NA
Dum HH * Delta Toll Costs	90	75	NA	31	NA
Transit Access * Delta Toll Cost	10	12	NA	3	NA
HH Income * Delta Toll Costs	20,345,065	24,686,856	NA	5,931,561	NA
HH Drivers * Delta Toll Costs	412	508	NA	117	NA
Summer Dummy	0.269	0.269	NA	0.269	NA

Short-run Price Elasticities of Demand

Primary findings from the study record the magnitude of the short-run travel behavior response to tolls, across a broad range of behavioral dimensions. Short-run elasticities of demand were estimated for models explaining household, vehicle, and worker behavior independently. Models were estimated explaining behavior in regard to changes in generalized costs of travel and are reported in regard to the changes in toll costs. As stated previously the elasticities with regard to generalized costs are the most meaningful and are contained in Appendix 19. However the elasticities with regard to toll costs (illustrated in tables and figures below) may be more intuitively understood as they can be interpreted as direct estimates of the actual magnitude of changes in behavior. In other words, if the elasticity of tour distance is reported as -.12, this can be thought of as estimating a reduction in tour distances of 12 percent across the sample of households. Also, none of the elasticities need to be factored together to interpret findings, they can be thought of as total

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[11] The incremental change in vehicle operating cost in was calculated as the difference in the average gasoline price per gallon during week *t* of experimental period and the average price per gallon during the control period multiplied by 0.05 (the inverse of 20 miles per gallon) multiplied by the average control period tour length in miles.

derivatives. The models were developed in such a way as to ease the process of making sense of the direct results of the analysis.

Household, Vehicle, and Workplace Models

Analysis of the impact of tolling on driving behaviors was conducted from three separate perspectives: the household, the vehicle and the workplace. The reason for conducting the analysis from the different perspectives was to examine the extent to which behaviors differed under different units of observation. We consider the household to be the baseline perspective of the GPS study as it is generally viewed as the decision making unit by economists and it forms the basis of observation in the GPS study. The Household models are based on the GPS data aggregated to the household level. All vehicle tours—regardless of driver—originating from or concluding at the household are aggregated by purpose (e.g. home-to-work) in the household tours. The debit accounts from which tolls were paid were set-up for households, not for individual drivers, thus decisions affecting the accounts were made at the household level.

Analysis was also conducted from the perspective of the individual vehicle, which may be regarded as an imperfect proxy for the individual driver—imperfect because residents of a household often share the use of one or more vehicles. Nevertheless, the vehicle perspective allows for examination of changes in driving behavior as it affects choices associated with driving the individual vehicle.[12] The distinction between the household and vehicle perspectives is subtle and is largely an issue of aggregation (i.e., household level data represents the aggregation of vehicle level data), but we were interested in testing the a priori assumption that the elasticity of driving behavior would be greater at the vehicle level than at the household level. That is, households would have greater ability to adjust their behavior in response to tolling by adjusting their use of individual vehicles than by adjusting their aggregate commuting behavior.[13]

The third perspective considered in the analysis was the workplace. The data generated in the analysis does not indicate definitively which tours originated or concluded at an actual place of work for the participants of the study. However, by screening the data through a number of filters (e.g. point-to-point vehicle tours that occurred on a routine schedule and remained at the location for a sufficient amount of time), we were able to isolate those tours that likely corresponded with a workplace. Nevertheless, some of the tours that we defined as workplace oriented were likely not.[14] For example, routine commutes by students to school may be defined as workplace tours in our analysis, as would routine tours by individuals to volunteer in a school, church, senior center, or other facility. From a practical perspective, these tours are similar enough to a workplace-oriented tour to be considered as such. Again the distinction between aggregating the GPS data at the household or workplace level may seem academic, but we were interested in testing the a priori assumption that from the elasticity of driving behavior would be smaller at the workplace level than at either the household or vehicle level. That is, households may shift between vehicles and may choose to carpool in order to save on tolls, but they have less discretion regarding the decision to commute and the timing of the commute to their workplace.

Impact model results are presented below for all dependent variables except **Tour Start Time Per Week** and **Tolls Paid Per Week**. Tour start time analysis using logit model estimation is described later in the report as these models produce findings that are easier to interpret than the impact models that focus on the absolute value of the tour start time adjustments. And the explanation of

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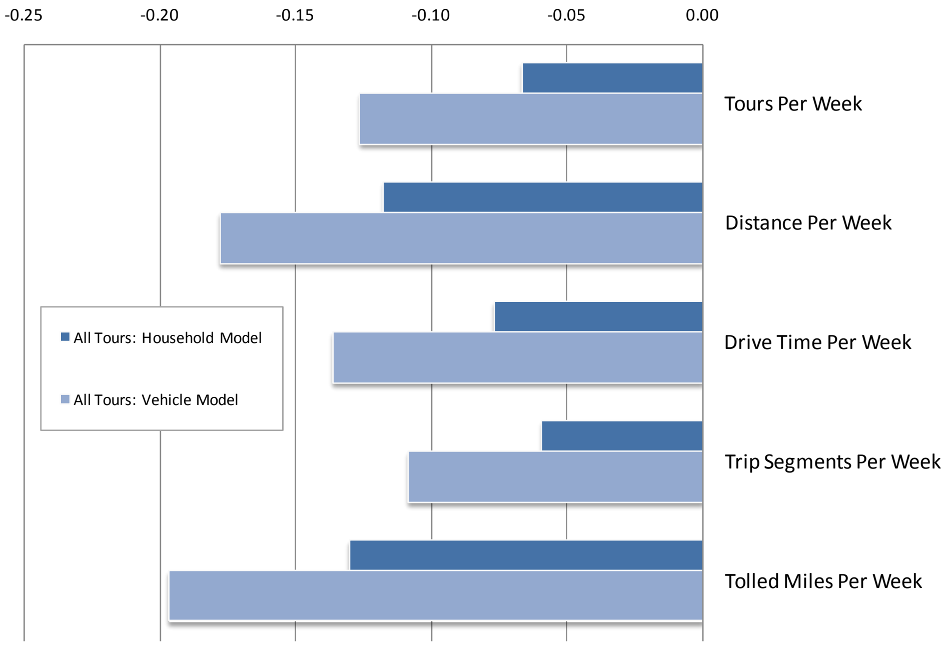
[12] Because the GPS data were collected at the vehicle level, it is the most disaggregate of the three perspectives.

[13] For example, members of a household could carpool, thus reducing the use of one or more vehicles while still engaging in their necessary commutes.

[14] Our screening procedures also likely left out workplace oriented commutes, such as those to workplaces that shift on a frequent basis (e.g. construction workers shifting between job sites or ending one job and beginning another).

tolls paid is likewise discussed independently since these models are distinct from the other measures of demand in that tolls paid is a measure of aggregate demand response to the experimental tolls. **Figure 3.11** below displays household and vehicle level demand elasticities for all tours, followed by figures displaying household, vehicle and workplace elasticities for home-to-work, work-to-home and home-to-home tours.

Figure 3.11 Household and Vehicle Sensitivity to Toll Costs: All Tours



When measured across all types of travel purposes, and all study participant households (or vehicles), the toll policy used in the study resulted in a number of important changes in aggregate travel demand. These included:

- 7% (and 13%) reduction in all vehicle tours (tours per week)
- 12% (and 18% reduction in vehicle miles traveled (miles per week)
- 8% (and 17%) reduction in tour drive time (minutes of driving per week)
- 6% (and 11%) reduction in tour segments (segments of tours per week)
- 13% (and 20%) reduction in miles driven on tolled roads (tolled miles per week)
-

The participating households altered the nature and amount of vehicle use in response to experimental tolls that increased the costs of travel but did not result in improved travel times. To demonstrate the full consequences of the variable toll policy the study needed to estimate a new demand and supply equilibrium. These results are presented in Chapter 4 of this report.

The specific effects on individual tour types (home-to-work, work-to-home, and home-to-home) were both higher and lower than these aggregate figures (**3.12 – 3.14**) and are displayed in the figures below.

Figure 3.12 Household Sensitivity to Toll Costs by Tour Purpose

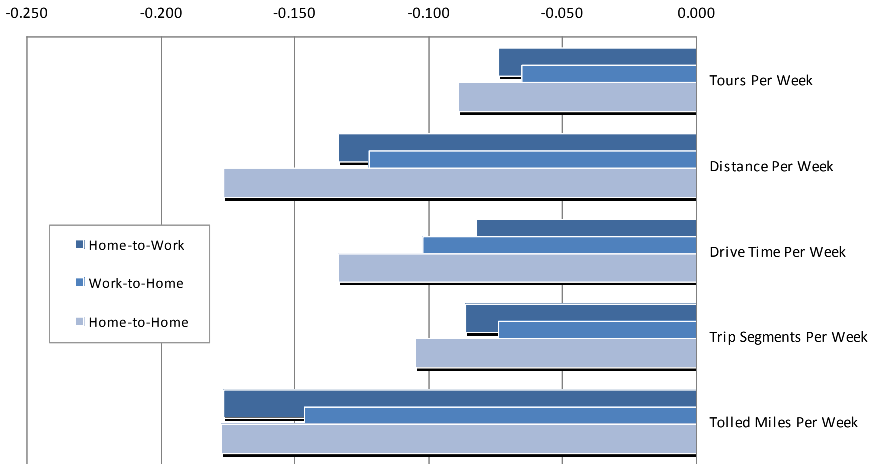


Figure 3.13 Vehicle Sensitivity to Toll Costs by Tour Purpose

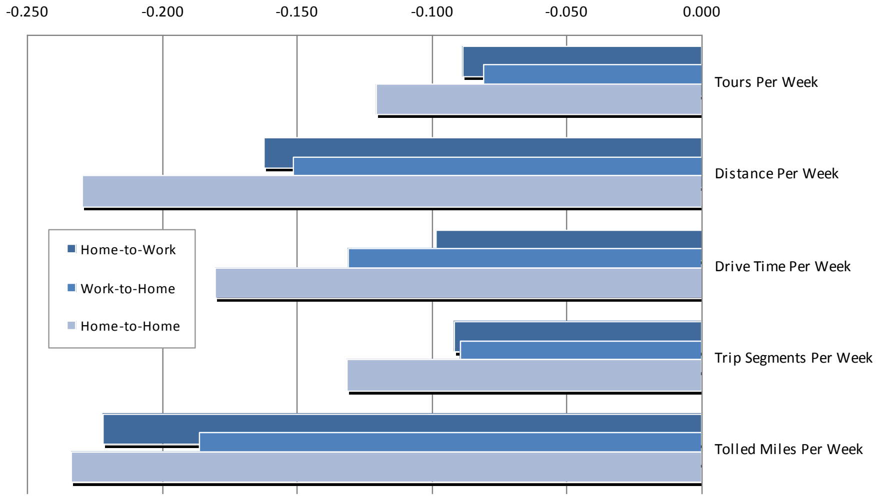
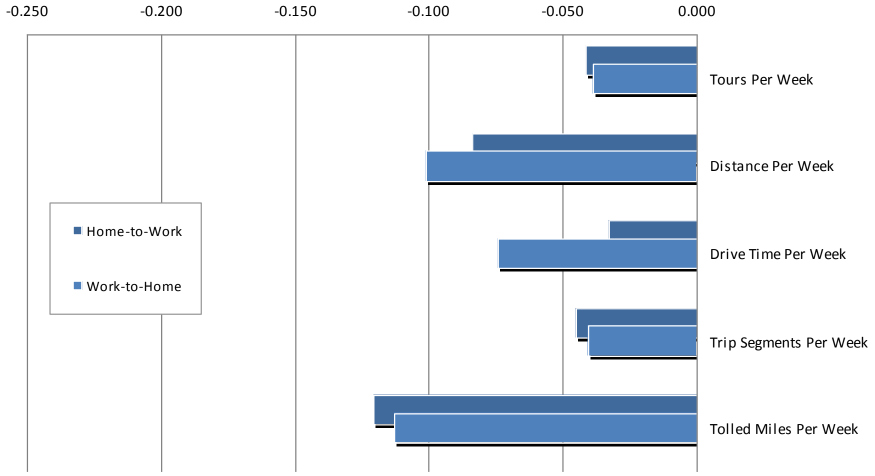


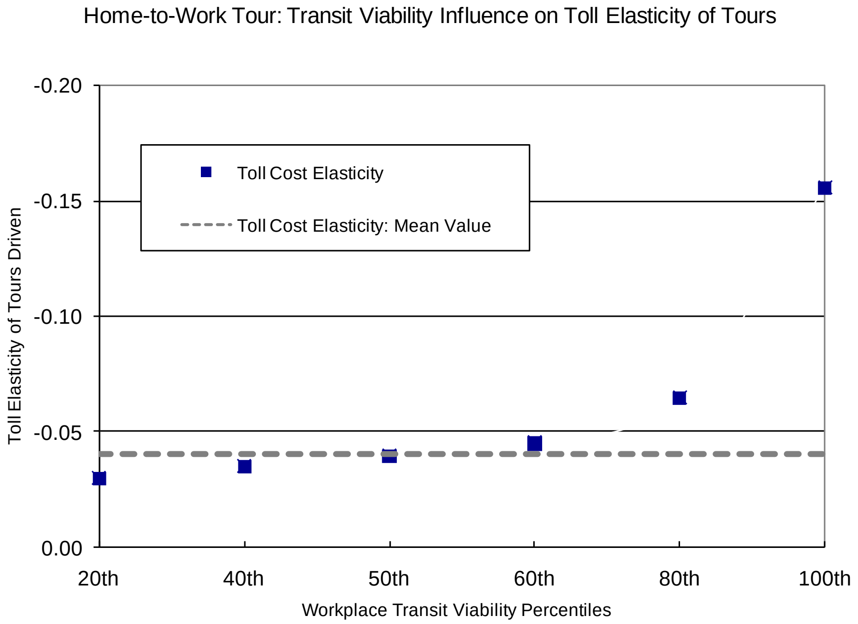
Figure 3.14 Workplace Sensitivity to Toll Costs by Tour Purpose



Analysis of the data revealed important changes in household driving patterns that could significantly reduce congestion if variable tolling were implemented within a regional road network. Many households made notable changes in their travel practices. Households that modified their travel did so in many different ways: taking fewer and shorter vehicle trips, choosing alternate routes and times of travel, or linking trips together to reduce vehicle use altogether. Some households altered their routine travel practices (such as how they moved between home and work); other households made changes when they could, in more irregular ways over the course of daily events. Some participants report that these changes have persisted beyond the end of the study. Other households appear to have had very limited opportunities, in the short-run, to avoid using high demand roads during peak travel times.

On average, demand response measured by households is less pronounced than when measured by individual vehicles. As expected, households have the ability to integrate travel planning across vehicles or individual household members. Demand response is less pronounced as income increases, as demonstrated through an examination of the sign of the coefficients for income (see Appendix 19). And the workplace models that contain a measure of transit viability[15] matched to the specific origin and destination locations for work related tours demonstrates that a higher quality of the transit alternatives to driving is modestly associated with a larger price elasticity of demand for vehicle use. **Figure 3.15** displays the influence that the availability of quality transit options has upon the Home-to-Work tour toll elasticity of tours taken per week. Each study work tour was ranked for the quality of transit services available between home and work locations. The toll elasticity of tours for the Home-to-Work tour measured across all workplace locations was approximately -0.04. This value did not change notably over most of the distribution of measures of worker's transit viability. For the workers with the best transit service options (above the 90th percentile) the tour response (effect on the number of vehicle tours per week) increased to as much as -0.16. Current transit service options appear to provide only a small degree of opportunity to avoid paying tolls in all but the most transit "friendly" of circumstances.

Figure 3.15 Influence of Transit Quality on Toll Elasticity of Home-to-Work Tours



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[15] Transit viability is measured as a ratio of transit generalized costs of travel and auto generalized costs of travel between each individual origin and destination zone pair. This ratio is then transformed into a scale factor between zero and one.

Tour Start Time Response

In addition to the behavioral responses discussed above, study participants could also respond to tolling by moving the start time of their tour into a lower cost toll period. We considered three statistical modeling frameworks to examine the start-time response of study participants.

1. Ordinary Least Squares (OLS) model based on the absolute value difference in start time between the control and experimental period.
2. Ordered probit analysis to examine the probability that participants chose one of the three options between the control and experimental periods
   a. Moved to a higher toll-cost period in experimental period
   b. Remained in the same toll-cost period in the experimental period
   c. Moved to a lower toll-cost period in the experimental period
3. Binomial logit analysis to examine the simpler question: what is the probability that a participant would move to a lower toll-cost period?

In the OLS modeling approach, we analyzed participant behavior in a manner similar to the analysis of the other behavioral responses. We compared the average weekly start time for each tour type in the experimental period to the corresponding average start time in the control period. The absolute value of the difference in the start time—in minutes—was regressed on the same explanatory variables considered in the other behavioral models. Although this was an intuitively appealing approach (i.e., we didn't care if commuters began their commute earlier or later, we only wanted to measure the absolute value of the difference in starting time), this approach had a critical shortcoming: the dependent variable is censored at zero because we measured the absolute value of difference in start time.[16]

The ordered probit modeling approach was considered because it allowed us to directly model the three possible ordered responses of the participants: moving to a higher toll-cost period, staying in the same toll-cost period, or moving to a lower toll-cost period. The results of these models were reasonable with respect to sign and significance of the coefficients, however the results have very limited practical use. For example, though we were able to statistically confirm the a priori assumption that the higher the "but for" toll faced by the participant, the more likely they are to move to a lower toll-cost period, the results of the ordered probit model do not allow for the development of behavioral elasticity estimates to apply outside of the model.

The binomial logit model was considered because of two key strengths. First, it provides a modeling framework to address the simpler and more relevant question "to what extent do drivers respond to tolls by changing the start time of their tour to a lower cost period?" This is the relevant economic question and one easily developed from the GPS data. Second, using the coefficients estimates from the logit regression model, it is a simple matter to estimate the probability that a driver will move to a lower toll-cost period given either the difference in toll cost between the two periods or the time (in minutes) to the nearest lower-cost toll period.

The probability of moving to a lower toll-cost as a function of the proximity to the nearest lower cost toll period (given the specific toll structure employed by the experiment) is displayed in **Figure 3.16** below. If a study participant typically made a work trip (during the baseline/no-tolling part of the project) at a point in the day that is within 15 minutes of a lower toll-cost time period, then there is a 40 percent probability that during the tolling part of the project, the trip was made during the lower toll-cost time of day. This probability dropped to 20 percent when the trip typically occurred within

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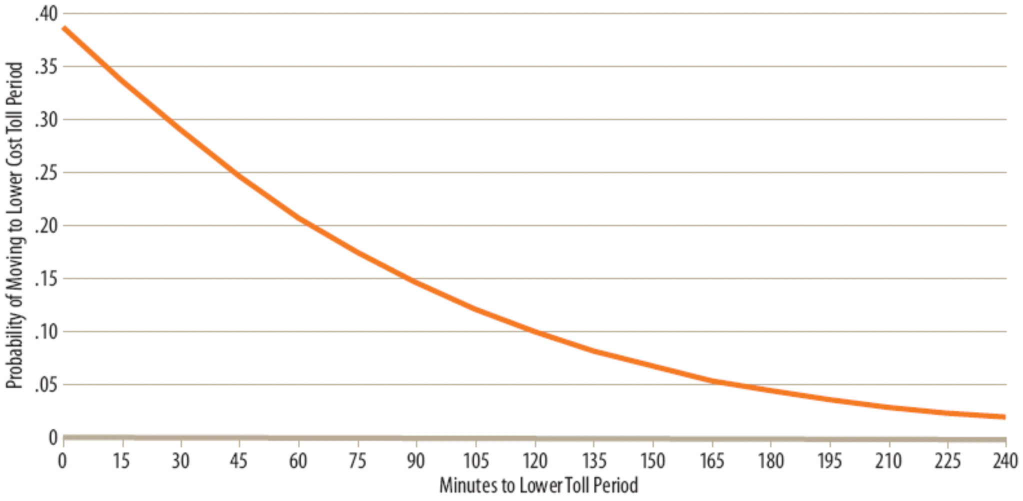
[16] OLS regression fails to account for the (zero) limit in the data. An alternative approach, to Tobit model, was considered. The Tobit regression model (see Green (1993) for more information on Tobit regression) accounts for the censoring problem inherent in some economic data, but was deemed to not be a practical alternative for these data.

60 minutes of the lower toll-cost time period, and was below 5 percent when the trip would have occurred within 180 minutes of a lower toll-cost time period. This is strong evidence of time shifting response to tolls when the departure delays necessary to avoid some increment of toll costs are small. A more finely tiered tolling structure (with shoulder tolls different from the peak and off-peak period) than the one used in the study would afford opportunities to finely tune the performance of major road facilities.

Figure 3.16 **Home-to-Work Probability of Shifting to Lower Toll Period**



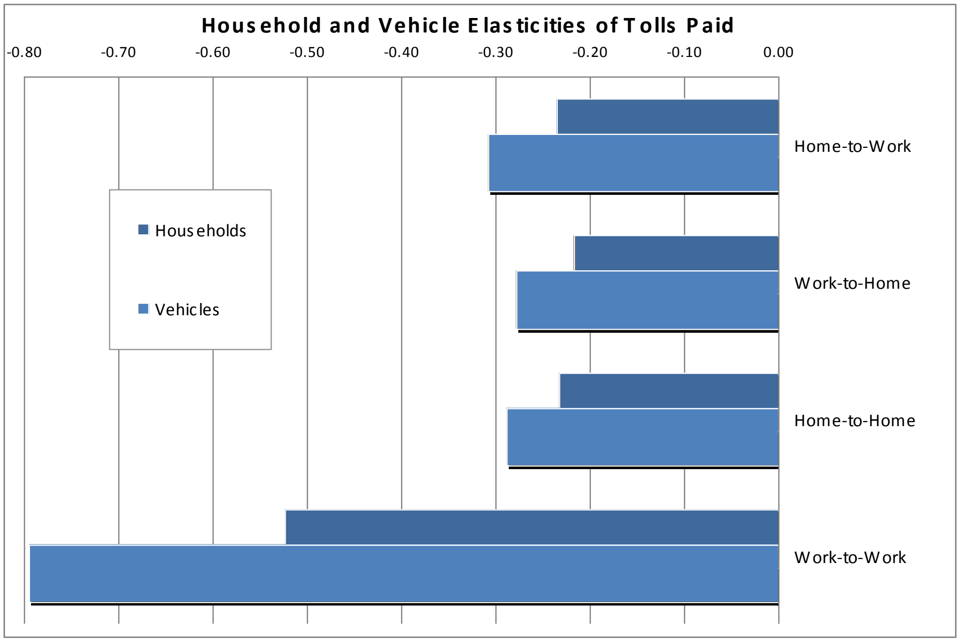
Elasticity of Tolls Paid

In the context of a tolling experiment, the tolls actually paid are a behavioral outcome of the experiment. This behavioral dimension is of interest because it measures the ability of the participants to avoid the nominal, experimental toll treatment. In addition, the observed willingness of participants to travel slower paths to reduce toll exposure reveals that the tolls were at meaningful levels relative to the value of time. Going into the experiment, tolls were set using value of time information from PSRC's regional travel model. Had there been no response of tolls paid with regards to base case experimental toll levels, then the meaningfulness of the experimental toll levels might have been called into question. The finding of a high elasticity of tolls paid with respect to the experimental toll treatment confirms that behavior is plastic with respect to toll levels.

Interpretation of the measured elasticity of tolls paid with respect to the experimental tolls or generalized cost has to be done carefully. The measured elasticity of tolls paid is quite high. There is a natural tendency to interpret this as meaning that tolls as a new increment to generalized costs of travel are easily, and significantly, avoided. However, it must be recalled that the experimental toll that constitutes the right hand side variable of the impact regressions is the toll per tour that would be paid under the touring conditions observed prior to the experiment. The left hand side variable, however, is the weekly total quantity of tolls paid--not the toll paid per tour. The latter can be computed, of course, because the reaction of the number of weekly tours also is measured. However, the reported elasticity is between a per tour price, and a per week quantity. In such a setting, the elasticity correctly renders the response, but by no means are participants able to avoid a high percentage of the toll charged per tour.

From the perspective of a regional implementation of toll policy, the elasticities of toll revenue with respect to statutory toll levels also is of interest. From a static perspective, it is tempting to estimate toll revenues by applying the statutory toll levels to existing trip or VMT quantities. What the high elasticities measured in the experiment reveal is that nominal or static toll revenues are higher than those that actually will be revealed in toll paying behavior. This is an obvious point, of course, since we expect behavior to respond to tolls. However, policy makers can use these elasticities to quickly determine the revenue potential of a particular toll policy. That is, use of these measures permits a short-hand means of rendering the dynamic revenue implications of a toll without having to articulate the full complexity of the path through which tolls paid adjusts to a nominal toll change. Elasticities of tolls paid (by tour purpose) for both households and vehicles are displayed in **Figure 3.17** below.

Figure 3.17 Toll Cost Elasticity of Tolls Paid



Value of Time Observations

In 1992 Kenneth Small observed that there appeared to be sufficient consistency in the evidence to suggest that the value of time spent travelling to work could be approximated by 50% of the gross wage rate. Small observed that this was a reasonable average that would vary considerably (between 20% and 100%) across regions and possibly even more among subgroups of a population. Recently Small and David Brownstone estimated values of time savings and improvements in travel time reliability for two California road pricing projects, the I-15 HOT Lanes in San Diego and the State Route 91 (SR91) facility in Orange County. Their empirical results confirm original estimates and reveal values of time of $20-$40 per hour (50%-90% of area average wage rates) during the morning commute.

Common assumptions about values of time often focus upon the 50% of gross wage rate estimate, even through Small's original conclusion emphasizes the heterogeneity of value of time both across and within a given population. Often this simplifying assumption is a result of the lack of available local data about people's reveled behavior in the face of time-money tradeoff opportunities. As an example, the PSRC regional travel demand model has historically employed value of time assumptions that are approximately 50% of average regional wage rates for each of four household income quartiles. With no tolling projects or demonstrations in operation, the region has had to adopt more global estimates, and has only recently conducted stated preference experiments in an attempt to refine such estimates.

The Traffic Choices Study provides the opportunity to observe value of time directly as a function of actual route choices made over the course of the experiment. Participants faced a financial incentive to avoid routes with high toll values. In many cases participants chose longer, more time consuming routes that resulted in lower toll costs. These explicit decisions allowed the study team to estimate value of time across the study sample, and over an extended period of observation.

The value of time can be computed for each household, vehicle, or worker unit of observation. It is implicit in the observed rate at which participants demonstrated willingness to trade a change to a path with longer drive time against reduction in tolls (relative to the “but-for” control toll.) An example illustrates the basic value of time measurement procedure:

- Say, for simplicity, that the control period path involved 30 minutes of drive time, but possible exposure to a 140 cent toll, and the actual, experimental path involved 40 minutes of drive time, and a 40 cent toll.
- The implication is that the traveler was willing to incur 10 minutes of additional drive time to spare a 100 cent toll cost. In this hypothetical case, the revealed value of drive time is thus 10 cents per minute of drive time, or six dollars per hour of drive time.
- Formally:

$$VoT = \text{value of time in dollars per hour} = \frac{60}{100}\left(-\Delta P/\Delta T\right)$$

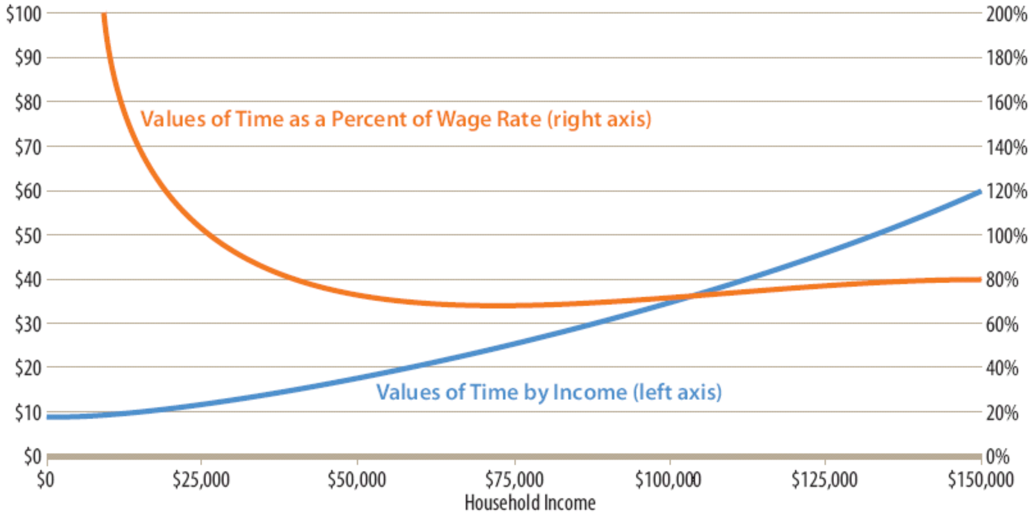
$$\text{where:}$$

$$\Delta P = P_e - P_c = \text{experimental vs. control toll, in cents}$$

$$\Delta T = T_e - T_c = \text{experimental vs. control drive time, in minutes}$$

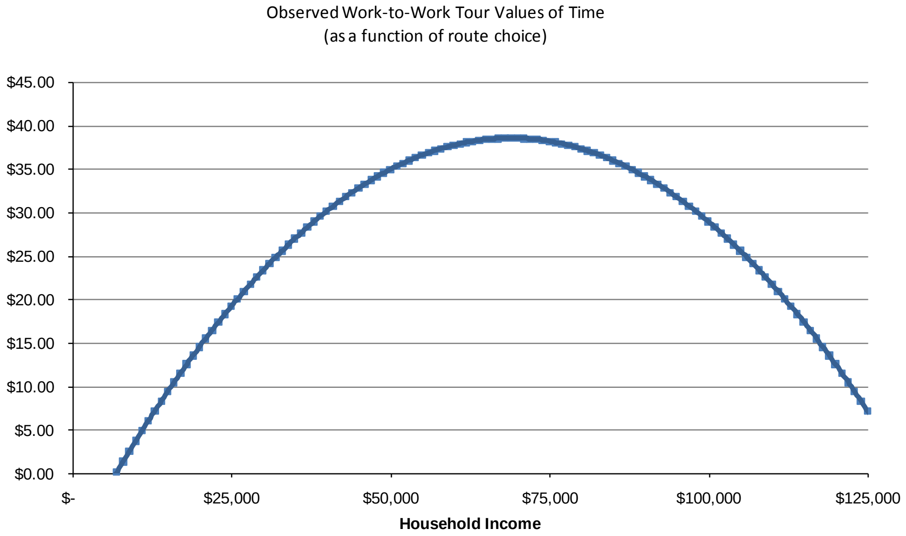
The computation above was performed for individual units of observation (households, vehicles, and work trips). The principle finding is that the value of commute (home-to-work tours) travel time appears to be closer to 75% of the wage rate for the greater Seattle metropolitan area. This is generally consistent with the range of findings of Small and Brownstone mentioned above. **Figure 3.18** plots home-to work values of time against household income and also displays the fraction of wage rates that these values represent. Value of time is displayed as a line fit to the observations across households. Since the line is fit to observations caution should be used when relying upon value of time estimates at the very low and high end of the income distribution as there are fewer experimental observations in these regions. It is notable that value of time as a function of income initially drops steeply as income rises and then appears to gradually rise again for upper incomes.

Figure 3.18 Observed Home-to-Work Values of Time: Function of Route Choices



Values of time were also observed for other tour types. Below in **Figure 3.19** values of time are displayed for the work-to-work tour. Within the project tour dataset there are considerably fewer observations of work-to-work tours, and in truth these tours probably represent a non-homogenous set of activities that both start and end on the work location, with no home stop in between. These tours, however, exhibit an interesting value of time distribution when plotted against household income. Work-to work tour values of time initially rise with income and then fall again. At first, this appears non-intuitive, but is a plausible result of a greater likelihood of higher income work-to-work tours being "on-the-clock" tours, or at least of importance to workplace productivity. It is even conceivable for compensated work related travel to exhibit a negative value of time as a function of route choice.

Figure 3.19 Observed Work-to-Work Values of Time: Function of Route Choices



One of the most striking aspects of the Traffic Choices Study is the high degree of internal consistency in the analytical results. The statistical techniques employed to explain user behavior are complex and often difficult for non-technicians to interpret, so it is reassuring to discover that the basic findings of the impact models are consistent with theoretical expectations, and with each other.

Observed changes in behavior are in the right direction (demand goes down as price goes up) and of appropriate magnitudes, relative to each other and the general empirical body of evidence from other studies.

The idea that the variable tolling of roads can result in substantial improvements in traffic conditions is unfamiliar to most motorists. There is a natural skepticism about how this might work, and how individuals might be affected by such an approach to road financing. If motorists do not believe that the traffic reduction benefits of road tolling will materialize, they will see the policy as a veiled attempt to simply raise revenues for government. The Traffic Choices Study has demonstrated that households and motorists faced with variable tolls do make the small adjustments in their travel that will translate into large-scale reductions in roadway congestion. Many study participants even characterized their travel changes as minor, but the sum total of all their individual decisions can be shown to result in important shifts in the time, amount, and mode of travel so as to minimize the amount of time the region's residents would be stuck in traffic. The implications of these findings are explored in more detail in the rest of this report.

CHAPTER 4

IMPLICATIONS FOR ROAD MANAGEMENT

CHAPTER OVERVIEW

The behavioral results presented in Chapter 3 are not equilibrium results, where decisions reflect all the costs and benefits resulting from road tolling. An important extension of the analytical findings was to emulate the experiment within a full network travel demand model, such as the models maintained by the PSRC. Assigning tolls to the entire modeled road network resulted in a number of key changes in the way the transportation network (a network of existing and funding improvements through the year 2010) performed, as compared to a base no-toll scenario. First, there were 4.8% fewer vehicle trips under network tolls (trip generation response and a modest mode choice response). In addition to changes in mode of travel there were notable changes in the timing of vehicle trip-making. Most notably, vehicle trips were reduced during the AM and PM peak travel periods, and vehicle trips increased during the nighttime (including the early morning). And, of course, vehicle trips rerouted to avoid tolls and take advantage of improved speeds on some facilities.

Changes in transportation network system performance can be used to estimate the benefits to transportation system users associated with a road tolling strategy. Changes in mode choices, route choices and time of day choices do not necessarily result in positive user benefits, even if the result is less traffic during peak travel periods. Changing mode, route or time of travel implies that users are opting for a previously less attractive alternative for meeting their travel needs. The Puget Sound Regional Council employs a dedicated modeling tool to implement the correct accounting of consumer surpluses, or user benefits in a number of areas including; time benefits, reliability benefits, operating cost savings, accident cost savings and vehicle emission cost savings.

The direct benefits to transportation system users that result from a network application of road tolling are sizable, and dominated by the value of travel time benefits. These are an estimate of the social welfare, or "efficiency", benefits associated with the correct pricing of congested roads. While the analysis represents a first order approximation of optimal tolling policy, a number of important observations can be made. The toll revenues that result are considerably larger than the direct user benefits. This is to be expected, but emphasizes the importance of using those revenues to provide further benefits to the road system users. Those who benefit most from network tolling are users with high values of time (higher income users and trucks). Transit users and high occupancy vehicles occupants all realize benefits from tolling as well. All users pay more in tolls than they realize in user benefits, implying that everyone would be worse off under tolling if the revenues were simply disposed of instead of reinvested, or rebated to taxpayers in the form of lower taxes and fees.

4.1 ROAD PRICING: WHY, AND WHY NOT

If most economists think that variable road pricing (or congestion pricing) is such a good idea, why isn't it being implemented anywhere at any large scale? Many non-economists probably feel that this is a question that answers itself. Some of the main arguments for and against road pricing are highlighted below. This set of viewpoints is not an exhaustive exploration of evidence, but rather an outline that sets the stage for more detailed exploration of a few key aspects of policy that follow. The statements below are simplistic and abstract from the complexity of specific applications of road pricing, but as a result offer a clear and largely uncontroversial set of statements about the advantages and disadvantages of just the kind of tolling/road pricing systems that the Traffic Choices study has attempted to better understand.

Road Pricing Addresses Many Interrelated Problems

- Road pricing can reduce reoccurring delay on the roads and improving travel reliability. In the beginning of this report we go into some detail about how roadway congestion pricing can lead to the spreading of peak traffic over space and time in such a way that leads to improved speeds for the vehicles that choose to pay the toll to use the previously congested road facilities. Long part of theoretical arguments, since Singapore implemented it in 1975 road pricing has proven to be a successful approach to managing traffic flows. Careful design of toll policies and systems is required to provide the maximum travel benefits to users of the systems, but there is little debate that road pricing (in its many varieties and forms) can be a powerful tonic for the seeming intractability of traffic jams. As we point out later in the report, the user benefits from a theoretical application (modeled) of network tolling in the Puget Sound region prove to be quite large indeed.

- Road pricing can help to finance transportation projects even when traditional financing approaches have proven insufficient. Of course road tolling raises revenues, most people would argue there would be little to recommend it if it didn't. But the real point is more subtle than one might think at first. What is unique about tolling is that toll revenues represent user's willingness to pay to use the specific road facilities at the time that they are making the choice to use them. In this way, road pricing is very different than other funding sources, even other user fees such a fuel taxes. High "value" facilities can generate sufficient revenues to help pay their financing costs even when public sector revenues dedicated for transportation purposes are otherwise scarce. And, it is the case in most U.S. metropolitan areas that the divide between the costs of improvements and available revenues is growing.

- Road pricing provides a powerful signal for investment that is hard to ignore. If a road authority generates sizable revenues from a toll facility it is a clear indication that users value the services that facility provides. If the revenues are sufficient to pay all operating and financing costs of the facility and also make some useful improvement to the facility, it would be reasonable to expect that such an improvement would be made. From a purely self-interested perspective, the road authority might increase "profits", or revenues as a result of improving the facility. Happily, this is also what would most benefit the users, or customers. Failing to turn sizable revenues around as investments in the transportation systems that generate those revenues is the act of a monopolist who does not care about the well-being of the road users.

- Road pricing lessens, or even eliminates, the current disconnect between who pays and who benefits. As describe in detail earlier, fuel taxes and general taxes lack a direct connection with the costs that users impose on the transportation system. And this is especially true under congested conditions, and when large-scale new investments are being considered for portions of the transportation network. Of course, many people may like the broad nature of tax measures (many people paying low rates) and the targeted nature of new capital investments (fewer people reaping large benefits). But it is reasonable to expect that these are folks that may not pay their “fair” share under the current approach to financing. Road pricing enforces the relationship between costs and benefits at the point of the individual user, and at the point they choose to access the benefits. If I benefit sufficiently from the use of the facility I am willing to pay, otherwise I am probably not.

- Road pricing can overcome the problem that the flow of funds for improvements often doesn’t make its way to the facilities that experience the greatest demand. This is a subtle variant on points above. Current financing methods have resulted in complex processes for the allocation of tax revenues by purpose and jurisdiction. Constraints on the use of funds can mean that the most meritorious projects may not always be eligible for some sources of funding. Road pricing would highlight “inconsistencies” in funding eligibility and the allocation, or distribution, of those funds.

- In the long-term there is likely to be a need to replace fuel taxes as a mainstay of highway financing. A number of efforts are underway to better understand the future of fuel taxes as a source of transportation funding for states and the U.S. Department of Transportation. What is clear, is that there are a range of reasons why fuel taxes will be less useful in the future than they are today. Long-term limits on supplies of crude oil, increasing pressure to improve the fuel efficiency and carbon efficiency of vehicles, and the political challenges of increasing the tax rates on a tax on the volume of fuel sold (rather than its value) all contribute to concern that fuel tax proceeds may be diminishing over time. Many alternate approaches to financing transportation in the long-term (15-20 years out) appear to center around the application of tolls and direct use fees applied to larger networks of roads.

- Road pricing could mean that non-SOV services become increasingly viable. To the extent that current peak period road related revenue sources are less than the actual costs of providing road services, road pricing could make transit services and carpool formation more attractive to users. Higher demand for peak period transit and vanpool services might result in higher fare box recovery for those services. High-occupancy vehicles that make use of the vary roads that get congested (everything that doesn’t have its own dedicated right-of-way) would also realize operational efficiencies (better speeds and reliability) as a result of the congestion mitigation realized through road pricing. These operational efficiencies provide direct benefits to the users of these services, thus making them more attractive and also reduce the costs of providing the same services. Some have dubbed this the virtuous cycle of road pricing and transit supply.

- A limited application of tolling causes diversion, congesting previously uncongested facilities. The point here is that when only a part of the system is tolled, users may find alternative untolled routes. This diversion causes problems on the diversion routes, slowing traffic and imposing other costs (such as higher accident costs). Some diversion may be hardly noticeable, while other situations will be untenable. Attempts to control diversion often limit the usefulness of the original tolling concept (either as a congestion management or financing instrument). Over time, an alternative may be to place tolls on the diversion routes. This kind of pressure (control diversion or toll alternative routes) has already emerged in the case of heavy vehicle tolling in Germany. In its logical extension, eventually, this approach may start to look like a network-wide road pricing system.

There Are a Plenty of Arguments for Not Implementing Road Pricing

- Road pricing is a significant departure from current practice. Even though road pricing was the norm until about a hundred years ago, it is the case that paying directly for road use today is reserved for a subset of the highways in the U.S. Most common on bridges, some state throughways, and facilities owned by toll authorities in a handful of states, road tolling is a facility specific instrument and is not used as a mainstay for road system finance (approximately 5% of highway revenues nationwide). Financing the road network (maintenance, operations, and new investments in supply) through direct fees for use would be a major change from current practice, both for the owners and the users of the system. There are few good models of wholesale reform of public policy, most reform is incremental.

- <u>With road pricing there will be new winners and losers.</u> It is undoubtedly true that making changes to transportation finance will result in a shift in the distribution of costs and benefits throughout members of society. Changes in the distributions of costs and benefits raise questions about fairness. Even when it is accepted that the existing distribution of costs and benefits that result from current transportation financing and investment policy may be socially undesirable, it is difficult to avoid questions of fairness that arise from any proposed reform. Important points on the question of farness of road pricing include:
  - How the revenues get used will largely determine who is made better or worse compared to current conditions.
  - Users are not a homogenous group; even sub-groups of society are not homogenous in their demands and preferences.
  - Households and individuals have varying preferences over time and circumstances.
  - Responses to varying preferences that offer choices (product differentiation) will minimize issues of "fairness".

- <u>Alternatives to driving alone on busy roads are limited.</u> This, of course, is true for many users. People face real constraints that limit the flexibility they have to respond to changes in the costs for using key roads. This is especially true in the short-run. Over time, there is a lot more flexibility in people's lives than is commonly recognized. Each year, on average one out of six households moves their place of residence. Other major life changes provide opportunities for households to adjust to a complex set of influencing factors. Still, the short- run presents challenges, and a poor set of alternatives to commuting alone in urban areas on key roads during peak driving times would make road pricing burdensome for many people. Ideally, road pricing would be implemented in conjunction with improvements to services that support alternative choices, such as bus transit, roadway operations, and flexible scheduling at work sites. In truth, many of these support services have languished absent the positive reinforcement road pricing could provide.

- <u>Everyone would be worse off if the toll revenues are not used wisely; which highlights current feelings of distrust about government priorities.</u> It is unavoidable that the revenues of road pricing must be used to "good" purpose for the policy to be broadly beneficial. Happily, road pricing would provide indisputable information about where and when investments in transportation supply should be made. And it also provides the revenues. It is even possible, that at a network scale, road pricing would generate more revenues than can be effectively used for investment. In that case, it is possible that the charges are too high in some locations (and should be adjusted), or that other transportation taxes and fees have not yet been reduced (and should be). Still, people will want to understand explicitly what commitments have been made for the use of road pricing revenues.

- <u>Unless toll revenues in part offset existing taxes and fees there is an increased fiscal burden on consumers of transportation services.</u> Layering road pricing upon existing taxes and fees would result in household transportation-related expenses that are higher than can be supported by efficiency arguments. It is not yet clear that the application of road pricing on an entire road network should result in a larger fiscal burden on society as a whole. It is possible that society is investing at the right level, but is still facing road demands that are greater than the supply, as currently managed. Road pricing would change the distribution of the fiscal burdens to rely more on those who place the demands upon the system, and modify user behavior in a manner that more efficiently uses that system. If revenues are larger than the cost of efficient investments, then failing to reduce other taxes and fees in the face of road pricing revenues would likely be damaging to consumers of transportation services.

- <u>The technology that makes road pricing possible may compromise user privacy.</u> Any road charging approach where the charge varies by geographic location (facility, zone or jurisdiction) and time period (day of week or time of day) presents the possibility that sensitive information would be generated, stored, and potentially misused. This is the case because personal information about individuals is associated with time and location of travel.

- <u>Implementation of road pricing would be complex, intrusive and costly.</u> Without question the administration of any road pricing system would be more complex and costly than the collection of fuel taxes or vehicle registration fees. Costs and complexity are real issues, and have largely been the reason why direct access fees have not been more broadly implemented to date. These concerns still remain, but are diminishing through advances in technology and business practices. The costs of implementing a road pricing system are coming down at the same time as the effectiveness of existing financing approaches is being eroded. Costs must be weighed against the benefits, of course, but it is still reasonable (and wise) to question whether current administrative and management practices are up to the challenges presented by network road pricing.

What follows is a further exploration of a few of the critical issues in the implementation of network-wide road pricing. The first to be addressed is the broad question about the technical and administrative feasibility of road pricing. Since, if such a system is impossible to implement, there is little point in further contemplation of its policy implications. This report argues that a system for charging for the use of an entire network of roads is indeed feasible, and even cost-effective given the sizable opportunities to realize broad benefits to society. Of course, these benefits depend upon sensible policy about how road pricing revenues would be used, which is a topic that is addressed in some detail in what follows. The application of road tolls and the use of those revenues will have consequences for how costs and benefits get distributed throughout society. Policy-makers and the public will want to understand these consequences in order to make some determination about how such an approach can be designed to ensure fairness. And finally, the technology that makes network road pricing possible creates circumstances where road users personal and road use information are collected and stored by the toll operations. This situation could lead to compromised user privacy if careful consideration of how data is managed and protected is not explicitly taken into account.

4.2 A FEASIBLE NETWORK TOLLING SYSTEM

Standard practice in electronic toll collection involves the use of relatively simple in-vehicle radio tags, or transponders. The toll tags contain a unique electronic signature, which is communicated to roadside equipment as the equipped vehicle drives on a toll facility. Current systems use various short-range communication technologies and protocols, and are typically procured from vendors that supply proprietary hardware and software elements. Roadside equipment includes the toll tag readers and any equipment necessary for vehicle classification and enforcement, and equipment to transfer all necessary transaction information to a central toll operations center. This electronic toll collection approach has proven to be an extremely successful model since the mid 1980s.

Similar technology has been used in the Singapore area pricing program since 1998. The London Congestion Charging Zone also relies upon roadside equipment for vehicle identification and account processing, although of a different nature. Automatic number plate reader video cameras capture the license plates of each vehicle entering or driving within the charging zone, where cameras are positioned at all points of access to the zone and also at key intermediary locations within the zone.

All of these approaches require that dedicated roadside tolling equipment be deployed in a manner that covers the full extent of the tolling network, and as a consequence also require new civil infrastructure any time that a pricing network is expanded or altered. The approach to network pricing that was investigated as part of the Traffic Choices Study does not rely on roadside equipment for vehicle charging, although enforcement does depend upon strategically located vehicle identification equipment. The in-vehicle tolling devices locate the vehicle on the road network and communicate directly with the central tolling operations system. This should result in significantly less civil infrastructure, and enable flexible extensions or alterations of the road tolling network, say in the case of including likely traffic diversion routes.

Still, there are few true network tolling programs in operation. Heavy vehicles are tolled on major roads in a few European countries, and the Netherlands is making real progress toward a national kilometer charging program to be implemented for heavy vehicles in 2011 and all other vehicles by 2016. With few operational systems, and none that rely exclusively on GPS tolling technology, there have been lingering questions about the complexity and cost of such an approach.

Yet, an extremely important emerging realization (to which the Traffic Choices Study has contributed) is that the implementation of full network tolling is no longer fundamentally constrained by technological limitations. The toll system elements implemented for the Traffic Choices Study met the base requirements for toll system operations. Indeed, it is technically possible to implement the same pricing policy principles within the highway realm that have, for so long, been in common use in virtually all other markets in the economy. This is not to say that there are no issues that need to be addressed in an actual implementation. But the Traffic Choices Study is a strong “proof of principle” from a technological standpoint.

There were important aspects of toll systems operations that were never implemented during the behavioral research; enforcement, for example. A number of these topics are addressed in a review of existing practice, and state of the research for GPS-based tolling that is contained in Appendix 20. As a consequence, the study team had Siemens (the study’s technology consultant) assist in outlining the basic structure for full road network implementation (Appendix 21). Implementing such a system would involve managing a range of technical, institutional, enforcement, legal and cost issues. While not a proposal, the architecture provides some insight into questions about the level of effort and cost that would be required.

System Scale and Extent

The variable pricing implementation scenario encompasses the four counties within the central Puget Sound region (King, Kitsap, Pierce, Snohomish Counties). **Table 4.1** summarizes the centerline miles of roadway in the region by functional class.

Table 4.1 **Centerline Miles of Roadways within the Central Puget Sound Region**

Functional Class	Centerline Miles
Rural Interstate	99
Rural Principal Arterial	147
Rural Minor Arterial	526
Rural Major Collector	748
Rural Minor Collector	396
Urban Interstate	255
Other Freeways	218
Urban Principal Arterial	723
Urban Minor Arterial	1182
Urban Collector	1165
Grand Total	**5472**

The network pricing system is a satellite-based solution that is able to differentiate location, time and vehicle properties for those vehicles equipped with a GNSS[17] – based On-Board Unit (OBU). The system concepts and overall architecture are based on the following key drivers:

- Nearly all vehicles[18] which enter and/or travel within the area would be charged; the amount being dependent on several factors, including:
  - Distance traveled (i.e., segments)
  - Time of day / day of week
  - Roadway type (expressway , arterial)
  - Vehicle type (cars, trucks)
- Those vehicles not equipped with an OBU are still charged, using a daily “flat rate” fee structure
- High levels of service and availability (24/7) would be provided, coupled with the ability for rapid recovery from any failures.
- The system would meet significant requirements for business continuity (no loss of data and continuous service in case of disaster), including replicating the central components in two separated locations, and providing rapid and transparent switching between the locations. All data would be replicated over both locations so that even in the case of a disaster no data is lost. The data centers themselves are connected over communication lines with additional redundancy.
- Appropriate levels of information security would be provided, including:
  - Confidentiality – to protect against unauthorized access of data
  - Integrity – to assure the completeness and correctness of information and the processing functions (to prevent malicious or accidental alteration of data)
  - Availability – to assure unrestricted access to data by authorized personnel

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[17] GNSS stands for **Global Navigation Satellite System**, the standard generic term for satellite navigation systems that provide autonomous geo-spatial positioning with global coverage. A GNSS allows small electronic receivers to determine their location (longitude, latitude, and altitude) to within a few feet using time signals transmitted along a line of sight by radio from satellites

[18] Some vehicles would likely be exempted from the charges, such as transit buses and police, fire, and other emergency vehicles

Business Architecture

The business architecture describes the structure of the business in relation to customers (i.e., drivers and users), markets, and channels. The business architecture envisioned for the network tolling scenario consists of two basic programs:

- **Main Program** – The main program is intended for most of the vehicles belonging to residents and companies resident within the four-county region. This main program consists of an On Board Unit (OBU) that is permanently mounted to a vehicle during its entire lifetime. Determination of location and time (and subsequently the number of miles driven by road type and time of day) is based on an OBU which uses GNSS for location detection. Residents and companies resident outside the congestion pricing area (but that frequently enter and travel within the pricing zone) are also included in this main program.
- **Occasional Program** – The occasional program is intended for residents with "non- regular" vehicles (e.g., motorcycles, classic cars), or who choose not to have an OBU installed in their vehicle due to limited usage of the vehicle (e.g., campers). The occasional program is also used for non-residents that drive into and travel within the priced network on an in-frequent basis. The occasional program offers a flat rate charge for the usage of the road network for a specified time period. The exact road usage is not measured or recorded. The flat rate is calculated in a way such that it is more expensive than the congestion charge based on the OBU-based Main Program.

The business processes of the network tolling system are shown in **Figure 4.1** and summarized below.

Figure 4.1 Congestion Pricing Business Processes

Registration of Users

Under the Main Program, the installation of an OBU to a vehicle must be done by an authorized technician. Owners of registered vehicles might have this performed as part of the annual emissions test; or perhaps they can arrange a date for OBU installation with a technician authorized by PSRC. After OBU installation, the vehicle owner/user registers for participation in the main program. It is envisioned that the tolling system operator will have access to all available data on registered vehicles and their owners via a vehicle licensing database. The user must also specify the desired payment method and provide the associated data (e.g. bank account number), the channel for invoices and the associated data (post address, e-mail address, etc.) and contact details.

For the Occasional Program, the user must register over a variety of possible channels (internet, phone), and must specify the license plate number (and State), address, and the usage period (daily, weekly, monthly, annual). The vehicle category may also be specified; or this information can be acquired (or verified) from the vehicle licensing database.

Measurement / Recording of Road Usage / Movement

As previously noted, under the main program, road usage (distance, road types, time of day) is recorded by the OBU. These OBU data are transferred to the Electronic Tolling Back-Office (ETBO) using a mobile communication network for further processing. Road usage is not measured or recorded under the occasional program, other than a determination of whether or not a vehicle traveled within the tolled road network on a particular day (using Automated License Plate Readers (ALPR)) as part of the enforcement process.

Determination of Charge

Costs for road usage under the main program are determined based on the measured and recorded data about road usage (i.e., miles driven by type of road and time of day), coupled with vehicle classification information. The occasional program offers only a flat rate for the usage of the road network for a period of time. The flat rate is based on the vehicle category and the registration period (i.e., day, week, month, and year).

Billing and Payment

Invoices for road usage under the main program are generated (monthly) and can be distributed over several channels (e-mail, internet, postal service) depending on the choice of the user. Payment is possible by several methods (e.g., direct debit, credit cards, debit cards, and checks).
The occasional program requires prepayment via any of the same payment methods used for the Main Program.

Customer Care

Customer care addresses all functions related to road user services and support, including:

- Responding to user questions, including common information and questions (FAQ) about the tolling system and programs (e.g. how to participate, tariffs, billing, etc.), and also questions about an individual participant (e.g. actual status of account)
- Administration of user attributes (e.g. contact details, billing details)
- Handling various types of user complaints
- Exchange of defective OBU's
- Channel management

With respect to the last bullet, channel management provides friendly, flexible and efficient interaction with customers. It is envisioned that a network tolling system would support both inbound and outbound customer contact, with the following contact channels:

- Internet (including mobile devices)
- Telephone (including interactive voice response)
- E-mail
- Fax
- Correspondence by posted letter
- Face to face at customer service centers (also called contact points)

To minimize costs, customer self-services – such as internet services should be made widely available and strongly encouraged for all processes requiring client interaction. Nevertheless, an agent should be available whenever the client requires help.

Enforcement

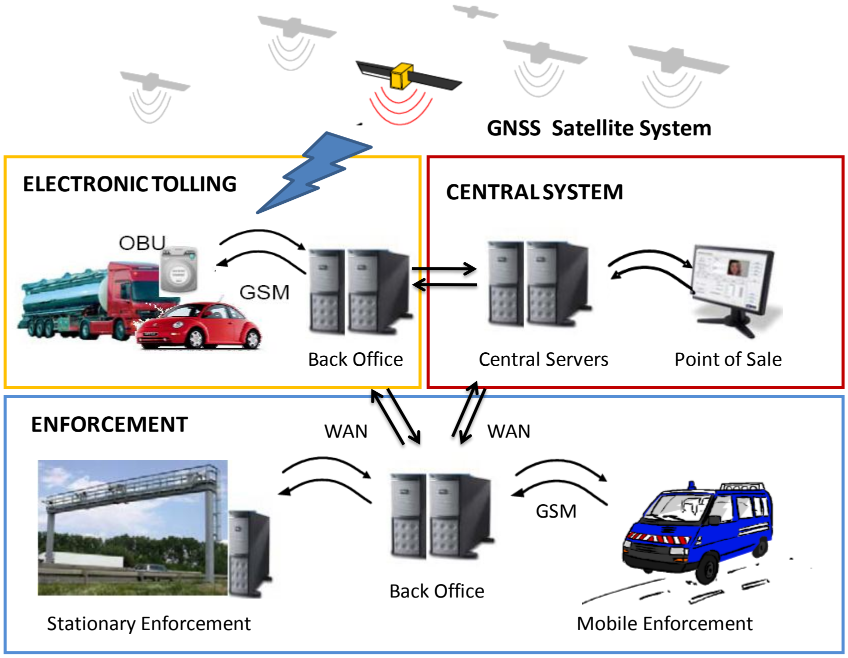
Good enforcement coverage is vital to the success of the system. Appropriate control mechanisms must be implemented to ensure road user compliance. Road users should realize that their compliance is checked, and that non-compliant behavior (e.g., an occasional user who does not register and pay the flat fee) will likely be discovered and penalized.

Automatic enforcement equipment is used to check the compliance of road users when they enter and are driving within the tolled network, all without immediate human intervention. Stationary and transportable / mobile enforcement setups are utilized. Photographs are taken of each checked vehicle, and automatic license plate recognition (ALPR) equipment determines the vehicle identification. The license plate number is sent to the enforcement back office (EFBO), along with location and timestamp, which checks all available information (enforcement and usage records, occasional program registration status) for consistency and compliance. In the event of a possible violation (e.g., there is no record that the vehicle owner / driver paid the congestion charge, they paid for the wrong category of vehicle, condition of the license plate prevents an automated read with the required degree of certainty), the EFBO sends a notification to the ETBO for subsequent action. Some or all of the following steps may be necessary in order to process and send an administrative bill to a non-compliant user and receive payment:

- Manual check of the number plate of the violator using the evidential record, which may consist of a color picture, infrared picture, plate number and state, timestamp of the enforcement case, and place / location of the enforcement case.
- Inquiry concerning the number plate of the violator
- Preparation of the evidential record together with the administrative bill for the violation registered person.
- Sending out the administrative bill and possible follow up.

A block diagram of the tolling system is provided in **Figure 4.2.** The major elements and building blocks of the system are described in greater detail (including assumptions on which the cost model is based) below.

Figure 4.2 High Level Architecture for Road Network Tolling System



Electronic Tolling System

The electronic tolling subsystem is the operational core of the toll solution. Its main task is to collect vehicle road usage information from the OBU's. From the collected road usage information, the charges are calculated and applied, using a flexible tariff model that is capable of handling different tariffs dependent on date and time, location and type of road, and vehicle categories. The accumulated charge information is provided to the Central System.

On Board Units (OBU)

The road usage information for the Main Scheme is collected by use of GNSS (GPS) location information and geographical data (geo data), using an OBU installed in each vehicle. It is assumed that the cost of purchasing and installing the OBU (and any repairs / replacement of defective OBU's) will be borne by the system; not by the users. By not requiring the road users to pay for the OBU themselves – coupled with a tariff structure that significantly favors the Main Scheme as compared to the Occasional Scheme in terms of user costs – it is envisioned that this will result in a large percentage of the road users opting for the Main Scheme. In general, there are two approaches for the processing and distribution of data between the OBUs and the System Back-Office:

- **Thick Client** – This approach consists of an intelligent On Board Unit that contains the latest version of all necessary tolling information (road user charging tariffs), geographical data (road categories, boundaries), and processing power to calculate the charge for each trip. Only the amount of the trip charge is transmitted to the Back-Office, which takes care of the processes associated with debiting the account and management.
- **Thin Client** – With this approach, the OBU does not contain any geographical (map) information, and only performs a minimum of processing. It acts like a simple sensor providing position information, which is transmitted (in an encrypted format) to the Back-Office. There, the information about tariffs, road categories etc. is stored and applied to calculate the trip charges.

Table 4.2 summarizes the main advantages and disadvantages of both approaches.

Table 4.2 Advantages of Thin and Thick Client Approaches for OBU's

	Thin Client	**Thick Client**
Operational Cost	Relative low, since OBUs are "dumb" devices, resulting in lower unit costs and lower failure rates. Little difference in communication costs.	Relatively high, since OBU's are intelligent, resulting in higher unit costs and higher failure rates. Little difference in communication costs.
Updates / Flexibility of Tariffs, Roads, Schemes, etc	High Flexibility. Not necessary to update data in OBU since all pricing and geo data are kept centrally.	All OBUs need to be updated (downloaded via wireless communications) for every change in scenario of tariff pricing.
Privacy	Requires encryption of trip data for transfer to Back Office; and trusted Third Party to ensure user privacy	Only road charge data (i.e., no trip location information) are transferred to Back-Office
Value added services	OBU may be used as a "probe". Traffic flow information can be easily deducted and generated at central.	Generation of traffic flow data is more cumbersome
Evolution of charging algorithms	Charging and map matching are in the Back Office, easily accessible and therefore can be more easily evaluated and improved	Map matching algorithms are in the OBU, hence more difficult to access, evaluate and improve.
User Displays (vehicle position / charges)	Generally not feasible	Feasible

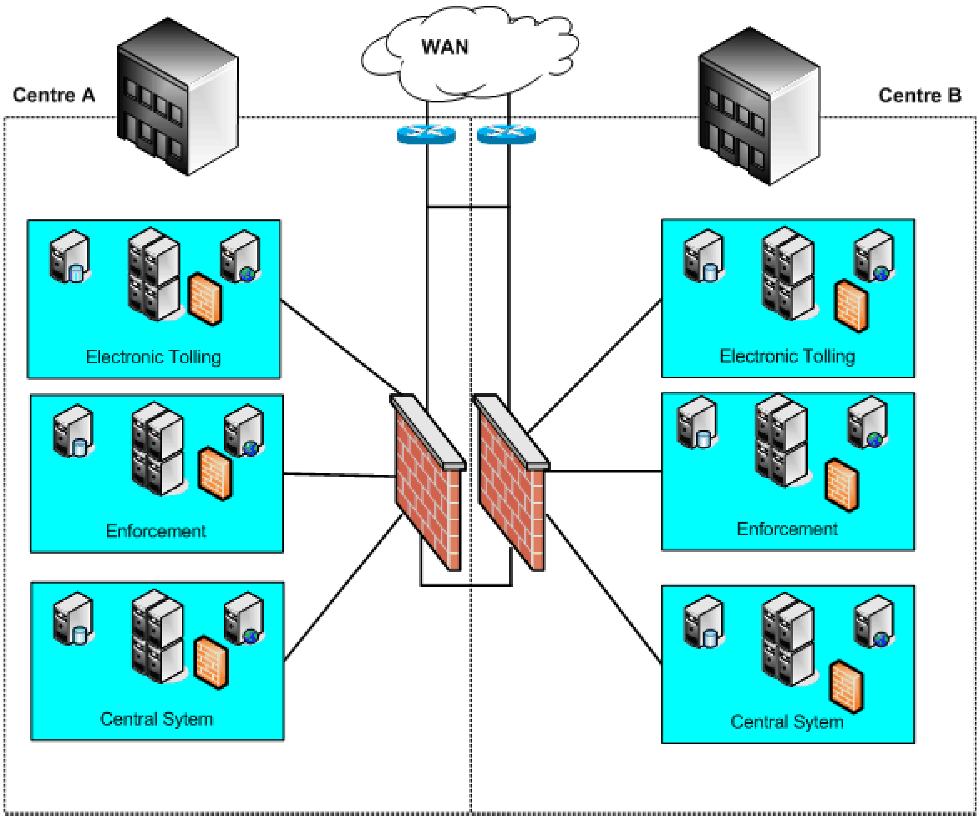
Both a thin and thick client approach can work in the same system. For the purpose of the cost model, it is assumed that a thin client approach will be used, resulting in lower unit costs for OBUs). That said, some users may be willing to pay the additional cost of a "thick client" OBU and the increased privacy and enhanced user displays. Accordingly, the final design for a road network tolling system should accommodate both approaches. Other costs associated with OBUs include the following:

- OBU Installation – As previously noted, it is envisioned that users will have their OBUs installed as part of the annual emissions test; or they can arrange a date for OBU installation with a technician authorized by PSRC. Owners of large fleets could optionally become authorized for storing and installing their own OBUs.
- Training of authorized technicians for the installation of OBUs
- Replacement of defective OBU's (the cost model assumes that 5% will need to be replaced annually)
- Storage and distribution of spare OBUs

Central System / Back Office

The subsystems Electronic Tolling, Central System, and Enforcement share a common central infrastructure which is distributed over 2 separated highly secure data centers. All external physical interfaces have redundancy built into each data center. The data centers themselves are connected over redundant lines (**Figure 4.3**). The infrastructure of the individual sites is designed in a way so that it can handle the whole load in the case of one site failing completely.

Figure 4.3 **Central System Architecture**



As previously noted, the electronic tolling subsystem is the operational core of the system. Its main task is to collect vehicle road usage information based on the OBUs. From the collected road usage information, the charges are calculated and applied, using a flexible tariff model which is capable of handling different tariffs dependent on location / roadway type, date and time, and vehicle categories. The **Electronic Tolling Back Office (ETBO)** is structured into several applications to divide the system into easy manageable parts with clear interfaces. This modular design ensures good maintainability.

The **Enforcement Back Office (EFBO)** receives charging violations in the form of enforcement records transferred from the roadside units. The EFBO performs violation process as discussed in the previous section on Enforcement. The EFBO also monitors the enforcement field equipment, providing information about faults and alarms of equipment and devices, system performance, and statistic data. Detailed historical logs are maintained for all components.

The **Central System (CS)** handles back office processing. Whereas usage data and enforcement data flows into the system, the CS produces invoices and fines, and provides means for customer interaction to the system. A Management Information System provides the necessary data to account for its performance.

Vehicle data can be verified through an interface to the vehicle registration database. The customer registration includes the type road usage charging (i.e., Main Program use of OBU, or Occasional Program). Occasional Program users that have properly registered are included in a “white list” of vehicles that do not use OBU and therefore do not store any usage data in the system. The white list is an important exception category in the enforcement of the road usage charging.

The financial data includes the payment channel that the customer wants to utilize to pay the invoices. CS provides the billing engine that aggregates usage data into periodic invoices. The billing engine interfaces to the accounting system, which relates sent invoices to received payments. The billing engine also sends out fines for violators of the road usage charging.

Usage data are fed into CS from the electronic tolling back office (ETBO) which aggregates the usage data into “Charge Coded Data”, thereby shielding the privacy sensitive road usage data from CS, which only exists to facilitate the administrative processes. The enforcement back office (EFBO) feeds violation data into CS.

Customer Relationship Management (CRM)

The CRM sub-system provides an interface to the users for obtaining information about the tolling system, such as viewing invoices from the web interface. The CRM also supports complaint handling and exemption approval. The CRM system supports several customer contact channels including telephone, fax, mail, internet, and call centers. The CRM system is the core of the solution responsible for managing:

- Billing and payment, for both pre-paid and post-paid accounts.
- Asset management, including OBUs and enforcement hardware.
- Customer Care Portal, providing online access for users to retrieve information (e.g., charging scheme structure and tariffs, how to comply with the scheme, OBU distribution network, contact information, news, FAQ´s, online registration, information about account status)
- Claim Management, including incorrect payment and enforcement claims. (Note – It is envisioned that claim management will primarily involve manual processing, but this needs to be supported by a system that provides evidential records or payment details/history to the personnel resolving these kinds of conflicts.

Call Center

The Call Center operates 24 hours per day, 7 days per week. Call Center operations are critical to the successful delivery of good customer service. Staff training and development is important, as well as the deployment of leading edge Call Center technology, including a call-back service.

Services are available in the most common languages and are supported by a highly automated process of call handling. Interactive Voice Response (IVR) and operator support are used to ensure efficient use of time for both caller and the call centre. The following services are provided through the call center:

- Provide general information about tariffs, procedures, location of OBU installation points, etc
- Provide Account and Transaction information only after user account identification.
- Provide enforcement information after violator verification
- Account modification for OBU accounts upon user request after user verification
- Registration and payment for the Occasional Scheme, using credit card payment methods
- Answer queries, including call back services when questions cannot be answered directly
- Register complaints, follow up is either by mail or by e-mail.

Systems Management and Related Processes

Systems management performs functions allow for adequate, continuous and safe operation of the system. This includes IT support for the central hardware and software, and for the interfaces to other subsystems and external systems (e.g., ETBO, EFBO, Vehicle Licensing Agencies, Banks, DOTs). Other systems management functions include:

- Accounting - The Central System provides an interface to a Nominal Ledger accounting package used for internal accounting. This allows standard profit & loss and balance sheet reports to be generated, and reconciliation of the information stored in the Central System.
- Supervision - Supervision is made on activities to verify that measures still adhere to applicable legislation and rules for accounting and personal data protection. Auditing Reports containing management and financial information are generated.
- Determine tariffs (measure effects and adjust tariff parameters) - Anonymous road usage data and appropriate statistics regarding road usage in relationship with tariffs can be developed, thereby permitting additional analyses and findings regarding implication of tariffs. Further it should be possible to compute what-if scenarios regarding the implication of tariffs based provided and derived data.
- Security - Security mechanisms for access control, history logging, encryption, intrusion detection and prevention systems, authentication, authorization, external and internal firewalls, auditing and single sign-on must be provided.

Security and Privacy

With respect to the last bullet, every system that collects personalized or even non-personal data is likely to become subject to discussions related to privacy issues. Though privacy will be ensured by policy, the system solution has to be able to address any and all privacy requirements derived from policy. **Table 4.3** summarizes some of the principles and measures to protect privacy.

Table 4.3 Principles and Measures to Protect Privacy:

Principles	Measures/Remarks
Capture only data necessary for the defined purpose	Define which data are captured for what purpose, and let the public know what data are collected and why
Don't keep data longer than necessary	Ensure that obsolete data will be permanently deleted.
Distribute data only when necessary	Field components capable of processing data should perform the data reduction autonomously.
Maintain anonymity as far as possible	If the system is used for other purposes than road pricing (e.g. traffic data monitoring) de-personalization is possible and should be done.
Make sure data can not be accessed by unauthorized individuals	Encryption of data-flow at insecure communication channels. Hierarchical access rights for individuals only to data of relevance within a secured area. Payment via a web based application will be done over https: protocol, already common in other payment processes.
Mitigate impact of intrusion	System redundancy and encapsulation of critical processes are not only measures to maintain system availability but will also minimize the impact of intrusion. The external system interfaces are reduced to the absolutely needed and secured by state of the art hardware and software system components.
Transparency	Consultation with the local people about the capturing zone of the cameras so that they do not intrude into private rooms, restaurants, businesses etc

The thin client solution requires trip data processing in a centralized system to determine charging data. The privacy aspect requires special attention and additional organizational and technical measures for this solution. This can include:

- The ETBO is a dedicated entity, and collects all trip data from road users and transforms this into the charging data (Charge Coded Data). The ETBO is rather isolated from the other subsystems and its operation is controlled by a Trusted Third Party, which provides regulation and assessment of all data handling.
- OBU owners are provided access to the data stored about them. This can be combined with a service to give the OBU owners access to their trip data and check their invoices (whereby sufficient security measures are deployed).
- The OBU trip data – without OBU ID and therefore anonymous – will be used as a basis for statistical section trip time calculation. Such data may be provided as statistical data to support DOT traffic management and traveler information services.

For enforcement, similar security principles are applied as for OBU charging. All vehicles passing are photographed and these digital images are stored in the roadside equipment. The License Plate Number with date, time, and position data is sent to the EFBO. As soon as the EFBO determines that user is compliant to the scheme, the corresponding image is deleted. In case of violation, the image is collected to the EFBO for further processing.

Back office systems are separated by internal firewalls. Back office communication is also validated by intrusion detection system. None of the back office servers are accessible directly from internet. Traffic from the internet portal is sent (via security systems) to load balancers and then to application servers. Application servers communicate with database servers via internal security systems. This protects all internal servers from invalid access.

Enforcement

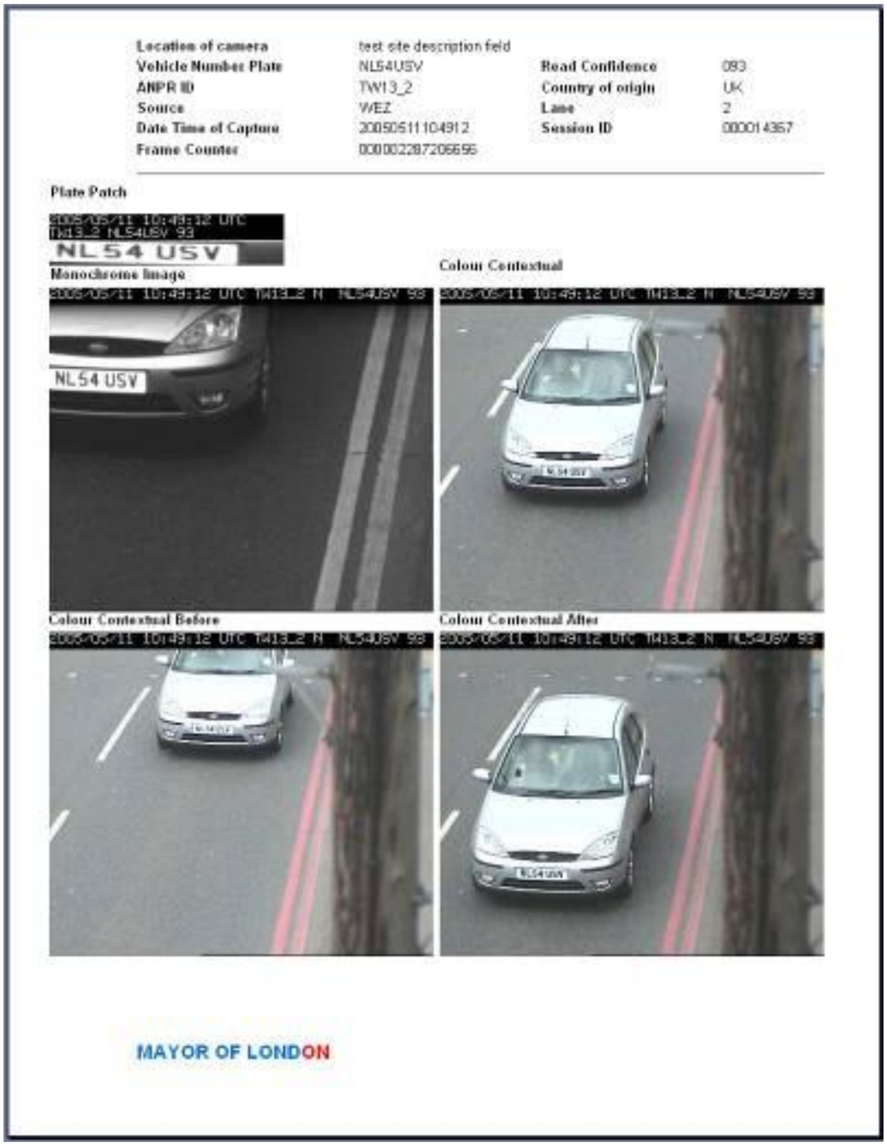
Enforcement is essential to the success of a road tolling system, and especially the Occasional Scheme. There are several attributes that must be considered in developing the enforcement subsystem:

- The enforcement process must be automated to the greatest extent possible, and have high throughput. Manual processing steps result in slow processing (threat of cumulative backlog), threat of high error rate (false positives, user acceptance!) and in high operational costs.
- It is nearly impossible (i.e. very expensive) to achieve 100% enforcement coverage for the entire charging area. Given the large number of roadways, intersections and interchanges, and alternative paths within the charging area, the installation of enforcement equipment to cover each and every road and possible trip would be cost prohibitive. Enforcement activities and equipment should focus on the major roadways that carry the greatest amount of traffic.
- It is nearly impossible (i.e. very expensive) to achieve 100% enforcement coverage for a given road cross section. For very busy roads such as freeways and major arterials, the frequency of vehicles passing is too high to check them all with a high degree of reliability. The equipment can only sample road user behavior.
- Effective enforcement is not achievable with fixed enforcement locations only. A large part of the road network within the four – county region consists of minor arterials and side streets where (as noted in a previous bullet) it is not cost-effective to install fixed enforcement equipment. Accordingly, it may be easy to avoid fixed enforcement equipment locations by users who are so inclined (i.e., those individuals without an OBU or who have not registered for the Occasional Scheme). Transportable and mobile enforcement equipment should be used to cover these other roads as appropriate.

The cost model for the road network tolling system is based on an enforcement scheme that operates with automatic license plate recognition (ALPR) as the primary input from the roadside, with evidential photographs taken simultaneously. ALPR technology for congestion pricing enforcement is being successfully used in London. The ALPR sites are typically installed just inside the entrances to the London congestion charging zone. The ALPR functions are provided by a fully integrated solution that is a combination of a color overview camera plus a monochrome IR camera with an integral LED illuminator to acquire high quality IR images of license plates. The internal ALPR Processor employs dedicated hardware for image pre-processing and plate finding coupled with an embedded processor. It also has local storage capacity for thousands of vehicle records.

The outcome of the ALPR process is a Summary Record which contains the time-stamped vehicle plate number, and an Evidential Record which contains the Summary Record plus the image set (**Figure 4.4**). Each record is marked with a value between 0 and 99 indicating the confidence level of the ALPR process. Evidential Records are authenticated and encrypted via a secure key handling enforcement session protocol and transmitted to an enforcement back office (EFBO) back location they are automatically compared to one or more databases to determine if pre-payment has already been made or if the vehicle is “exempt”, in which case no further action is required and the records are deleted from the camera. Otherwise, a fine is assessed and a bill is prepared and mailed.

Figure 4.4 **London Summary Record from ALPR**



Location of camera	test site description field		
Vehicle Number Plate	NL54USV	**Read Confidence**	093
ANPR ID	TW13_2	**Country of origin**	UK
Source	WEZ	**Lane**	2
Date Time of Capture	20050511104912	**Session ID**	000014367
Frame Counter	000002287206656		

Stationary Enforcement

The cost model assumes that fixed enforcement assemblies will be installed along the freeways (e.g., I-90, I-5, I-405, Routes 520 and 99) and major arterials (e.g., Routes 202, 203, 900, 509, 9, 527) where high traffic density results in need for high throughput, and where it is difficult or inconvenient for a driver to avoid passing the check point. The permanent installation enables optimization of equipment and communication facilities, ensuring good coverage on high traffic frequency locations. The stationary assemblies will be installed at the entrances to the road pricing area and in the vicinity of major interchanges and intersections (e.g., SR 520 / I-405, I-90 / I -405, SR 520 / I-5, I-90 / I-5) within the zone.

Figure 4.5 is a schematic of the roadside equipment for stationary enforcement along the freeway. This assembly typically consists of several components such as sensors for determination of the vehicle category (length, width, number of axles, trailers …), ALPR equipment for reading the license plate electronically, and a cabinet containing a gantry server for handling communications, storing evidential records until evaluated and controlling the other devices on the gantry. Along the arterial streets, ALPR cameras will be mounted on poles similar to what is used in London (**Figure 4.6**). Classification detection is not included for the arterial assemblies.

Figure 4.5 Schematic of Stationary Enforcement Assembly

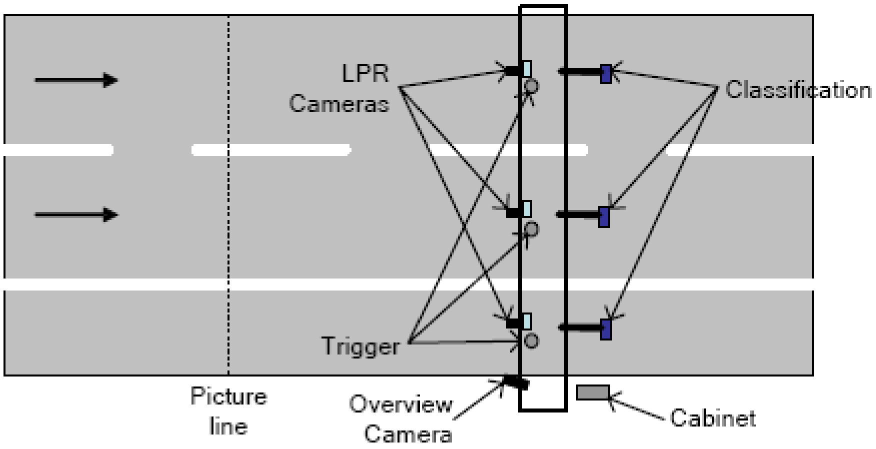


Figure 4.6 Pole-Based ALPR / Enforcement Installation in London

Transportable Enforcement

This type of enforcement is selected to get a high visibility of enforcement while checking the most significant parameters in order to determine compliant behavior. Transportable enforcement is purely based on ALPR. The transportable enforcement equipment consists of a compact setup that can be placed at the roadside. A pole carries cameras for taking evidential photographs and for ALPR. The base of the pole contains the gantry server and infrastructure components (e.g. power supply). The equipment is designed and dimensioned to operate autonomously for several days, after which the data must be transferred to the EFBO for further processing and the power supply must be recharged. Transportable enforcement offers several advantages, including:

- No long term "learning effect" by drivers as to how they bypass and avoid enforcement

- The ability and option to place the stationary portable enforcement at each and every place of interest.
- No additional gantries have to be erected.

Mobile Enforcement

Mobile enforcement equipment consists of ALPR equipment mounted on top of an enforcement vehicle, and a terminal inside the vehicle for accessing road user data in the central system (**Figure 4.7**). Dedicated staffs operate the mobile enforcement units. Mobile enforcement has the same advantages as transportable enforcement, but with even greater flexibility – the moment of surprise is high, it is impossible to predict for offenders where and when they are checked; and parked vehicles can be checked.

Figure 4.7 Mobile Enforcement Vehicle in London

Enforcement Back Office (EFBO)

The EFBO consists of the central components responsible for supporting the enforcement field components. It handles all data transfer, retrieving needed information from the central system, compiling and delivering enforcement records to the central system. It distributes black lists to the field components and collects messages about blacklisted vehicles.

Due to the high number of vehicles in the system, it is important to avoid manual processing to the greatest extent possible. The system first determines whether a vehicle with its recognized license plate is in violation. The matching of the ALPR-information with the payment information is done on basis of raw ALPR-data, irrespective the reliability level. This could even be with one character of the license plate not read or misread[19]. In a second step, the violation is checked with the reliability of the ALPR result taken into account. Violator license numbers that are read and classified with a high

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[19] It is noted that the ALPR subsystem for the London congestion charging achieves a 93 % capture rate with an 85% overall accurate read.

reliability will be processed fully automatically. Violator license plate numbers that are read with low reliability or that cannot be classified automatically will be processed manually.

Manual post-processing is inevitable for a certain percentage of the enforcement records collected. For this task, workplaces must be set up within the EFBO and equipped with the necessary data access and support features. This equipment is basically a terminal for accessing and editing enforcement records and retrieving related information. Training and supervision processes ensure reliable and fair demeanor of the enforcement personnel. Other EFBO activities and services are summarized below:

- Delivering Enforcement Records - All information (photos, license plate numbers etc.) of a suspected violation are compiled and delivered to the central system automatically. No manual checks are performed.
- Checking of Enforcement Records - In the case of disputes or for other reasons, it is sometimes necessary to perform further checks on selected enforcement records. The enforcement subsystem offers support for these tasks including delivery to manual enforcement back office terminals, where manual checks help to validate the correctness of suspected violations. The original record plus a summary of the checking conclusions are delivered as the result.
- Prosecution of Blacklisted Vehicles - Additionally to collecting enforcement records, the equipment also serves for tracking down offenders. This is facilitated by distributing lists of vehicles to the field enforcement components (stationary and mobile units). These (and the personnel involved) are therefore able to look out for suspects. Alarms are triggered and transmitted as the result of this service as soon as blacklisted vehicles or OBUs pass enforcement stations.

Enforcement for OBU-Based Vehicles

The operation of the ALPR – based enforcement subsystem described above is focused on potential violations of the Occasional Scheme. Enforcement activities are also directed towards the OBU – equipped vehicles, including:

- Data Mining - Information collected in the central system can yield suspicious patterns. Sudden reductions in road usage, gaps in tracking data and other types of behavior can be an indication that charging violations are committed.
- Checking of OBE History - The OBU can hold a history of status and usage records. Tracking information (with higher granularity) held in the OBU might be checked during enforcement, on cancellation or re-installation in a new vehicle, or in the course of the regular vehicle inspection. This information can lead to indications of non-compliant behavior.
- Comparison of Odometer Reading with Toll Records - In the course of the regular vehicle inspection, or during manual enforcement, an odometer reading can be taken and compared with the mileage registered in the tolling system.

Data Communication

The communications infrastructure is a key element of any road pricing system. If the network cannot properly support the exchange of information between system elements (e.g., OBUs, enforcement / ALPR field devices, and central systems / back offices, it can inject a serious constraint on the overall operation, resulting in lost revenue and reduced system credibility on the part of the road users. The bandwidth (i.e., how much information can be transmitted) and the latency (i.e., are the transmissions received in a timely manner) are major, and interrelated, considerations when designing and operating a communications subsystem. The following communications infrastructure and services are necessary:

- Wireless network services for communication between the OBUs and the Electronic Tolling Back office (ETBO). It is envisioned that **General Packet Radio Service (GPRS)** – a Mobile Data Service available to users of Global System for Mobile Communications (GSM) – will be used. GPRS has become ubiquitous wireless data service, available now with almost every GSM network. GPRS is a connectivity solution based on Internet Protocols that supports a wide range of enterprise and consumer applications. GPRS currently provides data rates from 56 up to 114 Kbps.

- Communications network between enforcement stations and the Enforcement Back Office (EFBO). ALPR information sent back to the back office for each captured plate includes a color and infrared picture, a detected and digitized number plate, time stamp of the picture, and the address / location where the picture was location. Based on the London experience, the size of this data file, including photographs, is 140 kb for each plate capture. It may not be necessary to transmit the pictures for each capture; but to only transmit the pictures upon request from the EFBO – such as in the case of a possible violation, where there is the need to include a picture as part of the evidential record. Without the pictures the data file is 50 kb. As a fair amount of latency can be tolerated, the wireless GPRS network can also be used for this network (especially for the mobile enforcement). It is envisioned that some of the stationary stations may be located in such a manner that existing communications networks (e.g., Washington DOT fiber along the interstates) can be used for communications, provided appropriate security measures can be implemented.
- Communications between ETBO, EFBO, central system, and redundant locations. As these are fixed (i.e., non-mobile locations) requiring large bandwidth, it is envisioned that some sort of leased (and secure) circuits will be used for this network.

Estimate of Costs

The architecture for an implementable road pricing program is not an attempt to satisfactorily address all aspects of system design or refine a system based on detailed local conditions or public attitudes about such a system. It is meant to be a fairly generic approach to outlining a basic business model and estimating the costs of implementation on a general scale.

In 2006, the Dutch government initiated a process of industry consultation in order to better reflect the range of costs likely to be encountered if the government selected to implement a national program for kilometer charging. Kilometer charging is being considered as a replacement for existing vehicle taxes and fees. The Dutch Cost Monitor[20] invited 12 separate parties from industry to provide written guidance on an approach to kilometer charging and help to refine estimates of implementation costs. Siemens was one of a few parties invited to produce a report on the total system costs. The estimate of implementation costs that follows is based, in part, on insights gained from the Dutch Cost Monitor applied to the above system architecture and local conditions in the central Puget Sound region. The total body of evidence produced through the Dutch Cost Monitor was reviewed and taken into account as the estimates of cost that follow were produced. Such an approach to estimating costs contains many uncertainties and does not reflect a myriad of forces that influence actual implementation costs, such as market competition, industry involving highly dynamic technical innovation, and assignment of risks.

The largest category of initialization costs for road pricing are the in-vehicle equipment and installation. Largest costs associated with annual operations involve the wireless communication functions. The cost model developed for assessing the implementation of a road pricing system assumed that 90% of the vehicles located within the tolling network region would opt for the Main charging program and have tolling equipment installed in the vehicle. The remainder would opt for the Occasional User program. Moreover, it is assumed that 10% of the vehicles in select counties adjoining the tolling area would also have OBU's installed. **Table 4.4** identifies the number of vehicles by class within the tolling region and **Table 4.5** displays the full results of the cost model.

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[20] http://www.verkeerenwaterstaat.nl/english/topics/mobility_and_accessibility/roadpricing/index.aspx

Table 4.4 Vehicles Affected by Road Pricing and Using Main Scheme

Vehicle Class	Status	In PSRC Region	90% Requires OBU PSRC Region	Adjoining counties	10% Requires OBU Adjoining counties	Total
Passenger	All within the region; 10% of adjoining counties	2,351,693	**2,116,524**	436,972	**43,697**	**2,160,221**
Motorcycle	Annual fee (no OBU)	104,837		25,315	-	-
Light Truck	All within the region; 10% of adjoining counties	588,817	**529,935**	152,577	**15,258**	**545,193**
Commercial	All part of a heavy vehicle program	108,070	**97,263**	27,994	**2,799**	**100,062**
For Hire	Annual fee (no OBU)	2,702		153	-	-
Government	All in region (except emergency vehicles)	3,316	**1,658**	696	-	**1,658**
Total	Total	3,159,435	**2,745,380**	643,707	**61,754**	**2,807,134**

> ***A transition to road network tolling would be costly and complex. It must be seen to be worth the sizable up-front effort.***

Table 4.5 Estimated Implementation Costs for a Road Pricing Program

System Elements	Capital (2008 Dollars)	Annual (2008 Dollars)
OBU and installation	$665,000,000	–
OBU / Installation – New Vehicles	–	$31,500,000
OBU – Repair / Replacement	–	$25,200,000
Training / Certification – Installers	$500,000	$50,000
Spare OBUs	$1,750,000	$20,000
OBU Subtotal	$667,250,000	$56,770,000
Stationary Stations	$20,000,000	$1,060,000
Transportable Stations	$1,875,000	$187,500
Mobile Stations / Vehicles	$1,200,000	$1,400,000
Enforcement Back Office	$5,000,000	$2,750,000
Enforcement Subtotal	$28,075,000	$5,397,500
Central System	$25,000,000	$20,000,000
Staff / Operations Training	$500,000	$100,000
Space for Central System / Back Office / Call Center	–	$200,000
Central System Subtotal	$25,500,000	$20,300,000
Data Communications Subtotal	–	$201,758,800
Other Subtotal	$27,715,000	$3,500,000
Grand Total	$748,540,000	$287,726,300

> ***The costs for GPS-based tolling systems are dominated by the initial investment in in-vehicle tolling equipment, and the communication of data during operations. Over the last few years costs have declined dramatically and are expected to continue to come down***

4.3 GENERALIZATION OF THE RESULTS

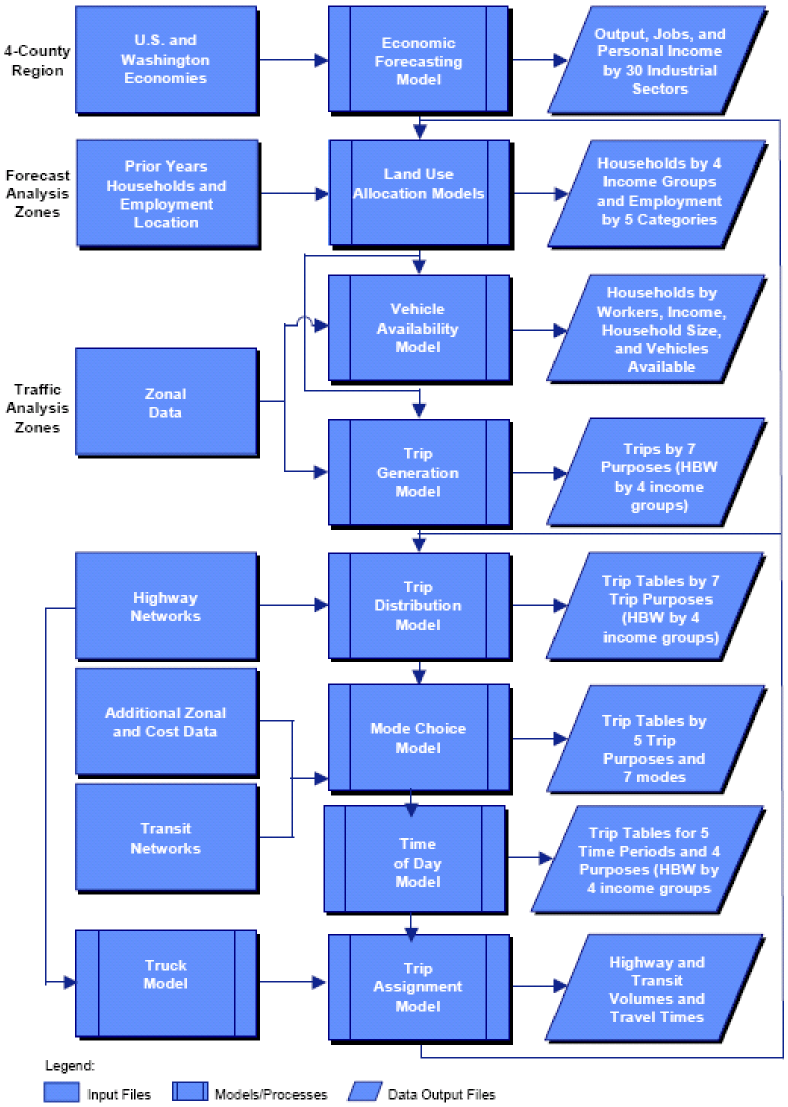
The analytical findings described in Section 3 can be thought of as the pure results of the tolling experiment. To the study team's knowledge, these results are the most comprehensive measures of demand response to network tolling in existence. Yet, as important as these findings are, they will seem abstract for many readers and policy analysts. The pure results are also limited by the primary constraint of the experiment; it's small scale relative to the magnitude of the population of road users. Participants in the experiment made explicit choices about the value of various dimensions of trip-making behavior, but did not enjoy the network efficiencies (speed improvements on the roads) that would result for an actual implementation of road pricing to all users. The results are not equilibrium results, where decisions reflect all the costs and benefits resulting from road pricing. An important extension of the analytical findings is to emulate the experiment within a full network travel demand model. Such a model is maintained by the PSRC as part of our regional transportation planning responsibilities.

Representing the results of the experiment in a travel demand model requires some thought about the appropriate interaction between the experimental setting and the nature and structure of the network demand model. Most important is the observation that the Traffic Choices Study was a short-run experiment where participants did not make long-run choices (e.g. residential location choices) based on the experimental tolling treatment. The travel demand model, on the other hand has features that represent long-run response, such as trip distribution. The modeling approach is described in some detail below. Also, the representativeness of the experimental sample must be considered. At the beginning of this chapter the sample is compared to a much larger census 5% microdata sample, and was found to be representative of the census sample for all the major household attributes (household size, number of drivers, and household income) important to travel demand model estimation. The goal of this exercise was to better articulate the likely consequences of implementing network tolling in terms that are understandable to a broad audience. The travel demand model results were then used to estimate user benefits, toll revenues, and general performance of the road network.

Network Modeling Approach

The basic approach to the modeling exercise was to introduce results from the Traffic Choices Study into appropriate steps in the travel demand modeling and to organize the model steps in a manner consistent with the short-run nature of the experiment. A 2010 model year and network were chosen as the platform for emulating the experimental results. The PSRC model is an advanced "4-step" model with *time-of-day* and *vehicle availability* as added elements in the operation. **Figure 4.8** displays the various steps in the PSRC travel demand modeling process. Modeling of the Traffic Choices Study results involved three specific departures from standard model practice: 1) introduced a trip generation response to tolling, 2) employed values of time consistent with the findings from the experiment, and 3) limited the trip distribution response to tolls. Each issue is discussed in more detail below.

Figure 4.8 Land Use and Travel Demand Forecasting Process



Trip Distribution

Trip generation within the PSRC model does not directly respond to changes in the generalized cost of travel. If tolling were to be implemented on the entire road network, however, the total amount of travel demand would likely be lower than for non-tolled conditions. The Traffic Choices Study directly measured this demand response for trip-making with a set of impact models (described earlier in this report) for the number of total tours. The tours examined in these impact models were auto tours, but where transit viability (between origin and destination zones) was a significant explanatory variable. By estimating the tour elasticity with respect to generalized costs of travel, with the transit measure reduced to zero (implying no available transit alternative), the models allowed the team to establish expectations about the magnitude of total trip generation response to network tolling.

A base case of the travel demand model (without tolls) and a traffic assignment with the toll structure in place were used to produce weighted average deltas in the generalized costs (time and model costs) of travel from each traffic analysis zone to all other zones. These zonal measures of change in generalized costs were used, along with the tour elasticities from the study's impact regressions, to modify the number of trips generated from each traffic analysis zone prior to completing the rest of the travel demand model steps.

Values of Time

As was reported earlier, the Traffic Choices Study measured time and money trade-offs as a function of route choices made by the study participants. The general finding was that values of time are approximately 75% of wage rates estimated from household income. These findings were incorporated into the travel demand modeling as part of traffic assignment and mode choice, and represent about a 50% increase in values of time over the previously employed parameters.

Trip Distribution

By making use of the estimated elasticity of demand for tours with regard to changes in generalized costs, the travel demand modeling of network tolling started with a modified set of trip tables for use in the downstream steps of the modeling process. The Traffic Choices Study was a short-run experiment, where short-run responses were limited by previous household level choices, such as home locations. In the long-term, if road pricing were implemented, these constraints are relaxed and the magnitude of the measures of demand response to tolling should be larger. It is likely that the relationship between short-run and long-run response is complex. For example, without the flexibility to change home locations many households might find that they take fewer trips altogether in the short run in order to avoid tolls on every mile of travel. Over time, as home locations rearrange, trip distances may drop allowing households to increase the numbers of trips in exchange for the smaller distances (and less toll exposure). This is speculation, of course, but points out that dimensions of travel choice interact strongly over time.

One dimension of long-run response that clearly did not occur during the experiment was the changing of the location of residences and workplaces in response to the tolls. The travel demand modeling of the experiment also needed to limit this response. To this end, the trip distribution process of the modeling was implemented without tolls as an influencing factor. Once trips were distributed, origins associated with destinations, the mode choice and assignment elements of the model were implemented with the study's toll structure embedded in the traffic assignment and feedback through mode choice.

Modeling Results

Assigning tolls to the entire modeled road network resulted in a number of key changes in the way the transportation system (a network of existing facilities and funded improvements through the year 2010) performed, as compared to a base no-tolls scenario. First, as a result of the implementation of the elasticity of trip/tour generation and the tolls influencing mode choices, there were 4.8% fewer vehicle trips as a consequence of network tolling. Mode choice results from the Base and Toll scenario are displayed below (**Table 4.6**). In addition to changes in mode of travel there were changes in the timing of vehicle trip-making. Most notably, vehicle trips were reduced during the AM and PM peak travel periods, and to a lesser degree in the Midday, and vehicle trips increased during the nighttime (including the early morning). These results are displayed in **Table 4.7** below.

Table 4.6 Modeled Mode Choice Results (Base Case and Network Tolling)

Home Based Work	Base	Toll
SOV	79.3%	78.1%
Carpool	7.2%	7.9%
Transit	9.2%	9.5%
Transit–walk	7.2%	7.9%
Transit–auto	2.0%	1.6%
Bike	1.4%	1.7%
Walk	2.8%	2.9%

Non Work Trips	Base	Toll
SOV	46.0%	45.0%
Carpool	45.5%	46.4%
Transit	2.2%	2.3%
Bike	0.9%	0.9%
Walk	5.5%	5.5%

Table 4.7 Modeled Time-of-Day Results (Base Case and Network Tolling)

Percent of Person Trips	Base	Toll
AM	15.7%	13.3%
Midday	37.8%	36.3%
PM	21.1%	18.4%
Evening	17.4%	18.5%
Night	8.0%	13.5%
Total	100.0%	100.0%

Percent of Vehicle Trips	Base	Toll
AM	13.1%	12.1%
Midday	42.1%	40.5%
PM	20.6%	18.9%
Evening	18.5%	19.0%
Night	5.7%	9.6%
Total	100.0%	100.0%

And, of course, vehicle trips rerouted to avoid tolls and to take advantage of improved speeds on some facilities. Total vehicle miles travel in the tolling scenario were notably lower (-7%) than for the base no-toll case. The total hours of vehicle travel within the region were also lower (-5%) in the tolling scenario.

Time-of-day variable tolling is designed to result in travel time savings on the road network. The travel modeling results can be used to estimate travel times between selected locations within the modeled region. **Table 4.8** depicts drive alone work trip travel times (in minutes) between select downtown locations in the central Puget Sound region during the afternoon peak period for the *Base Case* and the *Network Tolling Case*. Variable tolls result in sizable travel time improvements, especially in the primary flow of traffic where conditions in the *Base Case* are poorest. These same results are displayed in graphic form in **Figure 4.9**.

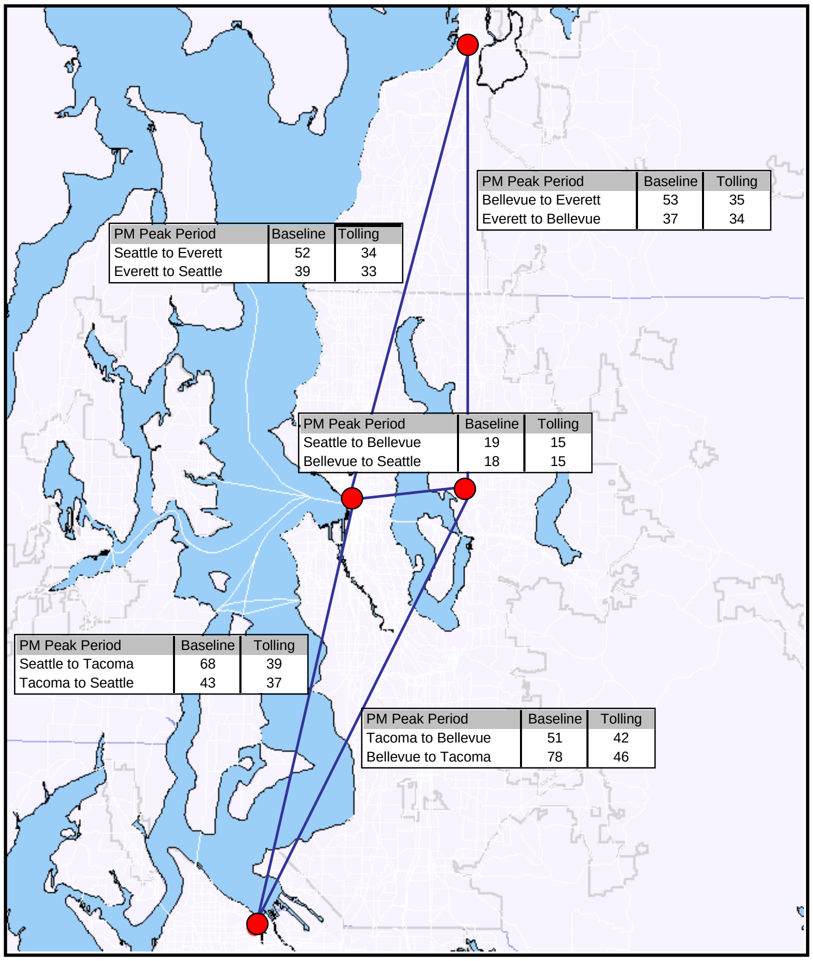
Table 4.8 Afternoon Peak Period Travel Time in Minutes (Drive Alone Work Trips)

Origin to Destination	Baseline (No Tolls)	Variable Network Tolling
Seattle to Bellevue	19	15
Bellevue to Seattle	18	15
Seattle to Everett	52	34
Everett to Seattle	39	33
Seattle to Tacoma	68	39
Tacoma to Seattle	43	37
Tacoma to Bellevue	51	42
Bellevue to Tacoma	78	46
Bellevue to Everett	53	35
Everett to Bellevue	37	34

Traffic Chocies Study variable tolls on the entire 2010 model network

Times are an average for all trips between locations independent of routing

Figure 4.9 Afternoon Peak Period Travel Time in Minutes (Drive Alone Work Trips)



The Benefits and Costs

The costs of implementing a road pricing system on a network of road facilities is not small, as demonstrated in the above description of one approach to implementation. The annual costs of operating such a system are significantly larger than the current approaches to transportation finance. For example, administrative costs for a tax on the volume of fuel sold are in the range of less than 1% of the fuel tax proceeds. A rough order approximation of the fuel taxes paid by residents of the four counties in the central Puget Sound region is $500 million per year; administrative costs apportioned to this region might be in the range of $5 million per year.

As has been emphasized throughout this report, a road pricing system generates revenues for investment but also limits the wasted time resources associated with overconsumption of scarce peak period roadway capacity. So a full accounting of the costs and benefits of road pricing compares the implementation and operating costs of the program with the full benefits to society of more efficiently allocating road space resources. The tolling revenues themselves are treated as an economic transfer since the revenues represent a cost to road users and a benefit to the toll system operator. In the case of public sector management of a tolling system the revenues can be expected to be reinvested in the transportation system or used to offset other taxes and fees that support public investments.

Changes in transportation network system performance (summarized above) can be used to estimate the benefits to transportation system users associated with a road tolling strategy. Changes in mode choices, route choices and time of day choices do not necessarily result in positive user benefits, even if the result is less traffic during peak travel periods. Changing mode, route or time of travel implies that users are opting for a previously less attractive alternative for meeting their travel needs. Either the newly chosen mode, route or time of travel has become more attractive as a result of the policy change, or the previous choice has become less attractive. There is a loss of utility associated with new choices that result from a deterioration in service quality or increases in costs to the user, all else being equal. There will also be increases in utility to those users who can take advantage of improvements in travel speeds that follow from lower traffic volumes on previously congested roadways. The main point is that correct accounting for user benefits requires detailed calculations using highly disaggregate data that is produced by the network transportation models. The Puget Sound Regional Council employs a dedicated analysis tool to implement the correct accounting of consumer surpluses, or user benefits including; time benefits, reliability benefits, operating cost savings, accident cost savings and vehicle emission cost savings.

User benefits are accounted for by comparing a policy, or investment scenario, with a baseline scenario. The PSRC benefit-cost analysis tool estimates benefits in the following areas:

- *Time Benefits.* These are the value of time savings (positive or negative) that result from the policy or investment. These values are not derived from simple calculations of the differences in total time dedicated to travel, but rather from correct consumer surplus accounting. See A Manual of User Benefits for Highways, 2003[21] for more details. The value of time savings is estimated using the values of time that are used in the travel demand modeling.

- *Reliability Benefits.* These are the value of the benefits of improved reliability associated with the policy or investment. Reliability is the degree to which facility performance (speeds) vary from the mean or typical condition. A high degree of variation implies that there is a higher risk of experiencing particularly onerous conditions; low variation implies lower risks. The risk is translated into a “certainty equivalent”, or willingness-to-pay for the reduction in risk.

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[21] ASSHTO; A Manual of User Benefit Analysis for Highways, 2nd Edition

- *Vehicle Operating Cost Savings.* These are the reductions or increases in the costs of operating (fuel, oil, etc.) the personal vehicles used in meeting mobility needs.

- *Tolls or User fees.* The benefit-cost tool also accounts for changes in the incidence of user fees from the base case to the policy or investment scenario. These fees are considered both a cost and a benefit, or a transfer from those who pay the fee to the entity that collects the fee. While users will immediately perceive these fees as losses, the resources are not actually lost, but rather are available for reinvestment in programs and projects that should provide benefits to users.

The direct benefits to transportation system users that result from a network application of road pricing are sizable, and dominated by the value of travel time benefits. These are an estimate of the social welfare, or “efficiency”, benefits associated with the correct pricing of congested roads. **Table 4.9** contains the summary of daily and annual direct user benefits and the value of the toll revenue transfer from road users to toll system operator. All values are in year 2008 dollars.

Table 4.9

User Benefits	Daily	Annual
Time Benefits	$ 3,992,190	$ 1,037,969,460
Reliability Benefits	$ -	$ -
Operating Cost Savings	$ -	$ -
Accident Cost Savings	$ -	$ -
Emission Cost Savings	$ -	$ -
Total User Benefits	$ 3,992,190	$ 1,037,969,460
User Fees (Toll Transfer)	$ 9,660,750	$ 2,511,795,114

An accounting of the benefits that accrue to users of the transportation system is an important first step in understanding the very large potential merits of network scale road pricing. However, many policy-makers and members of the public will also want to know how those benefits (and the toll burden) get distributed throughout society. The regional travel demand model does include, as separate vehicle classes, an accounting of travel for four individual income classes, as well as other classes of users (trucks, transit, other high-occupancy vehicles, walk and bike). Accounting of income classes is reserved for only home-based work single occupant vehicle trips. So, if trips switch modes from auto to transit or vanpool between the base and the policy or investment scenarios, tracing the user benefit implications becomes slightly less precise. However, retaining this user class disaggregation in the calculation of user benefits provides a reasonable approximation of the distribution of benefits across these classes of users. **Table 4.10** contains data about the portion of travel time user benefits that accrue to each class of users. The table also displays the portion of the toll burden borne by each user class.

Table 4.10 Daily User Benefits Without Accounting of Revenue Dispensation

User Category	Time	Operating Costs	Reliability	Tolls	Total User Benefits
Drive alone home-based work					
Low-income	-$4,237.55	$2,879.95	$77.89	-$111,459.39	-$112,739.10
Low middle-income	$48,664.48	$12,015.81	-$4,020.51	-$391,627.16	-$334,967.38
High middle-income	$299,562.32	$29,797.01	$15,747.74	-$1,054,050.81	-$708,943.73
High-income	$865,158.48	$46,848.85	$68,841.43	-$1,745,207.90	-$764,359.14
Drive alone non-work	$548,909.37	$121,593.05	$68,872.94	-$4,203,786.37	-$3,464,411.01
Carpool and Vanpool	$339,375.37	$65,697.11	$41,550.26	-$1,978,324.12	-$1,531,701.38
Transit	$156,137.49	$0.00	$0.00	$0.00	$156,137.49
Light truck	$1,524,141.85	$131,363.10	$260,178.98	-$2,147,544.47	-$231,860.55
Medium truck	$557,553.38	$65,040.04	$70,483.24	-$707,268.03	-$14,191.37
Heavy truck	$648,423.62	$50,158.92	$71,483.56	-$861,077.58	-$91,011.49
All Users	**$4,983,688.80**	**$525,393.83**	**$593,215.52**	**-$13,200,345.82**	**-$7,098,047.67**

Low income drive-alone users experience a loss in travel time benefits, and low-middle income users experience only modest gains. Trucks benefit significantly under this tolling scenario. It should be noted that the toll policy did not attempt to optimize the truck toll rates based on the costs (congestion, accident risks, emissions, and road damage) that trucks impose as a consequence of their size and weight. Transit users and high-occupancy vehicle occupants all realize benefits from tolling. All users pay more in tolls than they realize in user benefits, implying that all classes of users would be worse off under tolling if the revenues were simply disposed of instead of reinvested or rebated to taxpayers in the form of reductions in other taxes and fees.

The benefits of road pricing were estimated for a single year of operation. These benefits were based on a test of full network implementation within the regional travel demand model. These annual benefits (starting with a 2010 modeled year) were extended to a 30 year implementation scenario (2015-2044) making some basic assumptions[22] about the effects from forecasts of traffic growth on the annual estimate of benefits.

Done right, network tolling could provide broad social benefit, including lower vehicle emissions, fewer accidents, travel time savings, improved roadway performance reliability, and lower operating costs.

Table 4.11 displays the benefit and cost findings as well as the value of the toll transfer. The present value of the time savings benefits is well over $36 billion, with total implementation and operating costs of approximately $5.5 billion. The net present value (benefits less costs) of the benefits to society from implementation of this network wide scenario of road pricing is estimated in the range of $28 billion. Over the implementation period for this scenario the present value of toll revenues is estimated at $87 billion.

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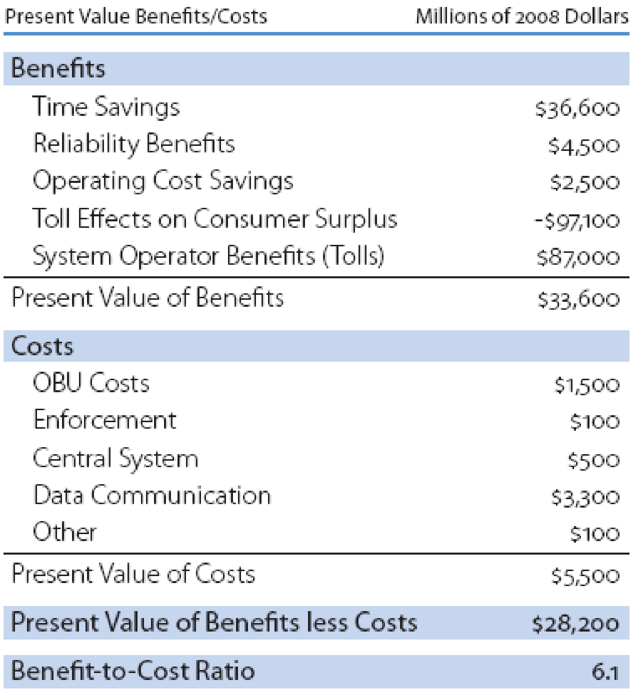
[22] Overall regional traffic volumes will grow by 2%, real income growth is expected to be approximately 1%.

Table 4.11 Benefits and Costs of Network Road Pricing



Present Value Benefits/Costs	Millions of 2008 Dollars
Benefits	
Time Savings	$36,600
Reliability Benefits	$4,500
Operating Cost Savings	$2,500
Toll Effects on Consumer Surplus	-$97,100
System Operator Benefits (Tolls)	$87,000
Present Value of Benefits	$33,600
Costs	
OBU Costs	$1,500
Enforcement	$100
Central System	$500
Data Communication	$3,300
Other	$100
Present Value of Costs	$5,500
Present Value of Benefits less Costs	$28,200
Benefit-to-Cost Ratio	6.1

> ***A conservative analysis of the benefits of network tolling in the Puget Sound region indicates that the present value of net benefits could exceed $28 billion over a 30-year period.***

The direct benefits to transportation system users are sizable, and dominated by the value of travel time benefits. These are an estimate of the welfare, or “efficiency”, benefits associated with the correct pricing of congested roads. While the experiment was an approximation of optimal pricing policy, a number of important observations can still be made.

First, those who benefit most from network tolling are users with high values of time (higher income motorists and trucks). Transit users and occupants of high occupancy vehicles all realize benefits from tolling as well. Second, the toll revenues that result are considerably larger than the direct user benefits. This is to be expected, but emphasizes the importance of using those revenues to provide further benefits to the road system users. The third point follows from the second: this analysis makes no assumptions about the use of those revenues; which might be used to make improvements to the transportation system (leading to further user benefits) or to offset other taxes and fees (a transfer directly back to the users that also eliminates welfare losses associated with the taxes and fees).

The revenues from network road tolling, in our modeling analysis, are in excess of $13 million (year 2008 dollars) per average weekday. Once again, these may not be optimal toll rates, where the rates that result in the greatest net benefits to society may generate either higher or lower revenues than those analyzed here. Based on 260 weekdays of tolling; the scenario results in more than $3.4 billion in gross annual revenues. As a comparison, all the transportation agencies in the central Puget Sound region collected approximately $3.1 billion in transportation related revenues (revenues used for transportation expenditures) in 2005.

Absent the rationing of supply based on willingness-to-pay (tolling), it is very difficult to gauge the ideal level of investment in transportation supply. But it appears that network tolling revenues are sufficient to replace all non-use fee forms of transportation revenues currently used to invest in the road system, and would still leave considerable revenues left over for road improvements, and the support of transit or other service operations on the road network.

The user benefits are large, but the toll revenues that result are considerably larger. This is to be expected, but emphasizes the importance of using those revenues to provide further benefits to the road system users through reinvestment, or rebating other taxes and fees.

Congestion-based tolling generates revenues for investment but also limits the wasted time resources associated with overconsumption of scarce peak period roadway capacity. So, a full accounting of the costs and benefits of road tolling compares the implementation and operating costs of the program with the full benefits of more efficiently allocating road space resources. The tolling revenues themselves are treated as an economic transfer since the revenues represent a cost to road users and a benefit to the toll system operator. In the case of public sector management of a tolling system, the revenues could be expected to be reinvested in the transportation system or used to offset other taxes and fees that support public investments.

Under the implementation scenario outlined above, the tolls paid by users and collected by the operator exceed the value of the user benefits. This is expected under all but the most congested pre-tolling road network conditions. If toll revenues are somehow squandered, the effects on society from road tolling will be negative. This finding reinforces the general conclusion that it is not productive to discuss road tolling without simultaneously addressing the issue of how toll revenues will be used.