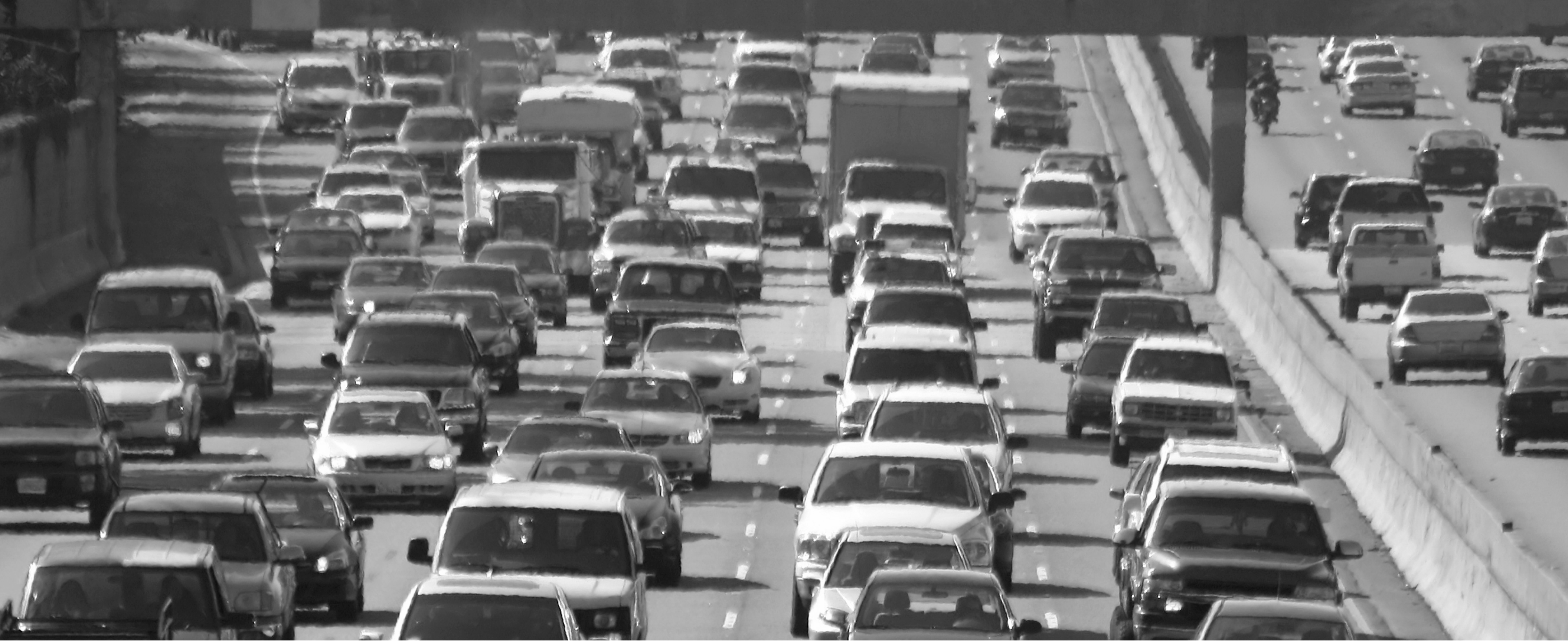

# 2015 Oregon Highway Cost Allocation Study

## An Efficient Fee Demonstration Project White Paper: Appendices

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## CONTACT INFORMATION

Matthew Kitchen and Carl Batten prepared this report. ECONorthwest is solely responsible for its content.

ECONorthwest specializes in economics, planning, and finance. Established in 1974, ECONorthwest has over three decades of experience helping clients make sound decisions based on rigorous economic, planning and financial analysis.

For more information about ECONorthwest, visit our website at www.econw.com.

For more information about this report, please contact:

ECONorthwest

222 SW Columbia Street

Portland, OR 97201

503-222-6060

kitchen@econw.com, batten@econw.com

## DISCLAIMER

ECONorthwest completed this project under contract to the state of Oregon. The State's purpose in commissioning this study was to outline how an efficient fee for road usage could be demonstrated, and why such a demonstration might be undertaken.

Throughout the report we have identified our sources of information and assumptions used in the analysis. Within the limitations imposed by uncertainty and the project budget, ECONorthwest has made every effort to check the reasonableness of the data and assumptions and to test the sensitivity of the results of our analysis to changes in key assumptions. The fact that we evaluate assumptions as reasonable does not guarantee that those assumptions will prevail.

The contents of this document do not necessarily reflect views or policies of the State of Oregon.

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# APPENDIX A: TRAFFIC CHOICES STUDY ANALYSIS OF BEHAVIOR

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

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*.[1] 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."[2] 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.[3] 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.

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

[2] 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.

[3] 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.

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. 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:

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

where:

$b$ = the estimated value of $\beta$

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:

$$Y_i = \alpha + (\beta_0 + \beta_1 H_i) G_i + \beta_2 H_i + \varepsilon$$
$$= \alpha + \beta_0 G_i + \beta_1 H_i G_i + \beta_2 H_i + \varepsilon \Rightarrow$$
$$\Delta Y_i = (\beta_0 + \beta_1 H_i) \Delta G_i + \varepsilon$$

where

$H_i$ = a vector of household characteristics

$G_i$ = generalized cost of travel

= vehicle operating and travel time costs + tolls

$= O_i + P_i$

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:

$$e_Y^G = b G_c / Y_c$$
$$e_Y^P = \left[\left(\frac{\Delta Y}{Y_c}\right) \Big/ \left(\frac{\Delta P}{P_c}\right)\right] \approx b(\Delta P / G_c)(G_c / Y_c)$$

where

$b$ = the estimated value of $(\beta_0 + \beta_1 H_i)$

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:

**Exhibit A.1. 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 |

- 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).

## 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.[4] 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 (Exhibit A.2).

**Exhibit A.2. 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. 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

[4]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.

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 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.[5] 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.[6]

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.[7] 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 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. Exhibit A.3 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.

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

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

[7] 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).

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 experimen¬tal 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.

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 exhibits (A.4 through A.6) and are displayed in the figures below.

Analysis of the data revealed important changes in household driving patterns that could significantly reduce congestion if variable tolling were imple¬mented within a regional road network. Many house¬holds 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 link¬ing 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 per¬sisted 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.

**Exhibit A.3. Household and Vehicle Sensitivity to Toll Costs: All Tours**

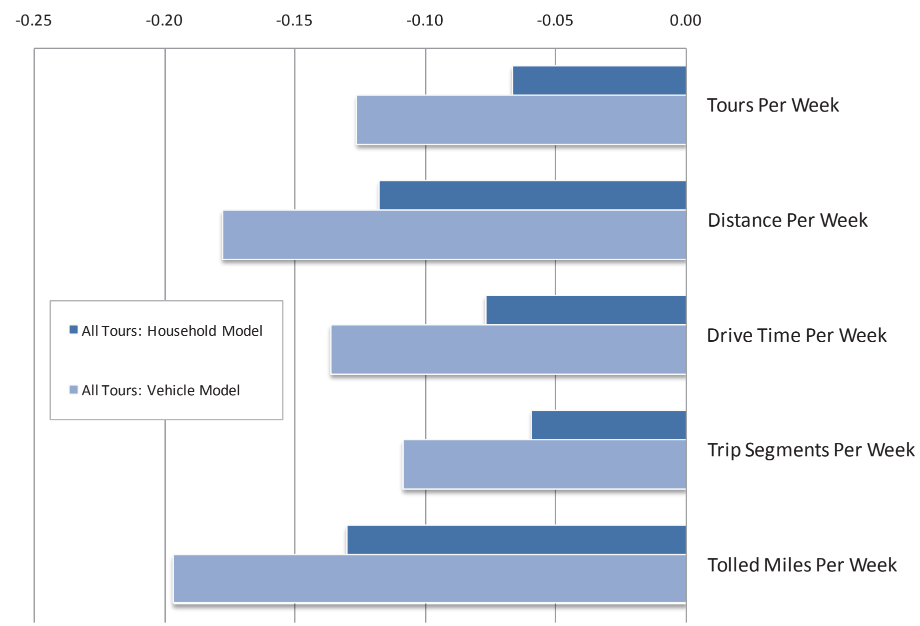
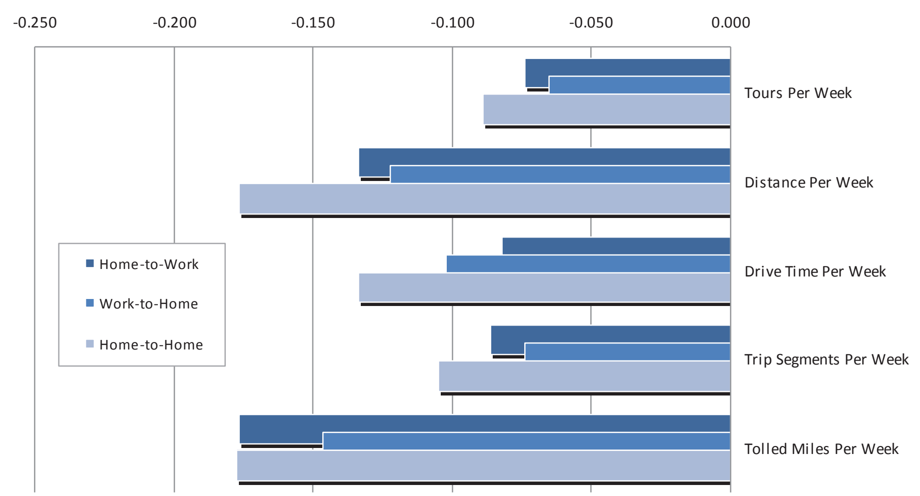
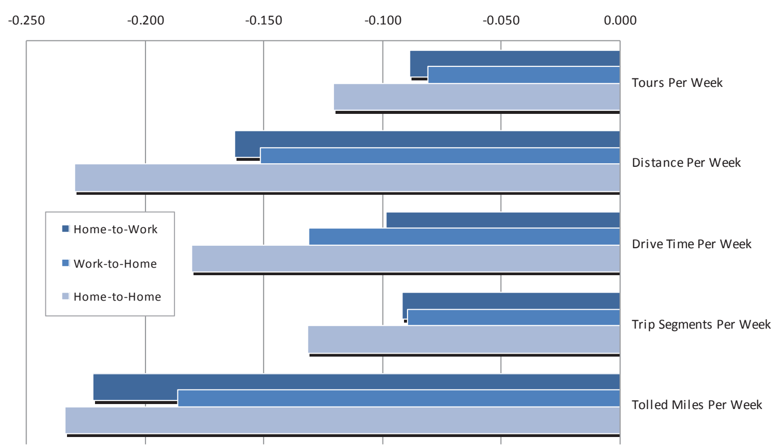



**Exhibit A.4. Household Sensitivity to Toll Costs by Tour Purpose**



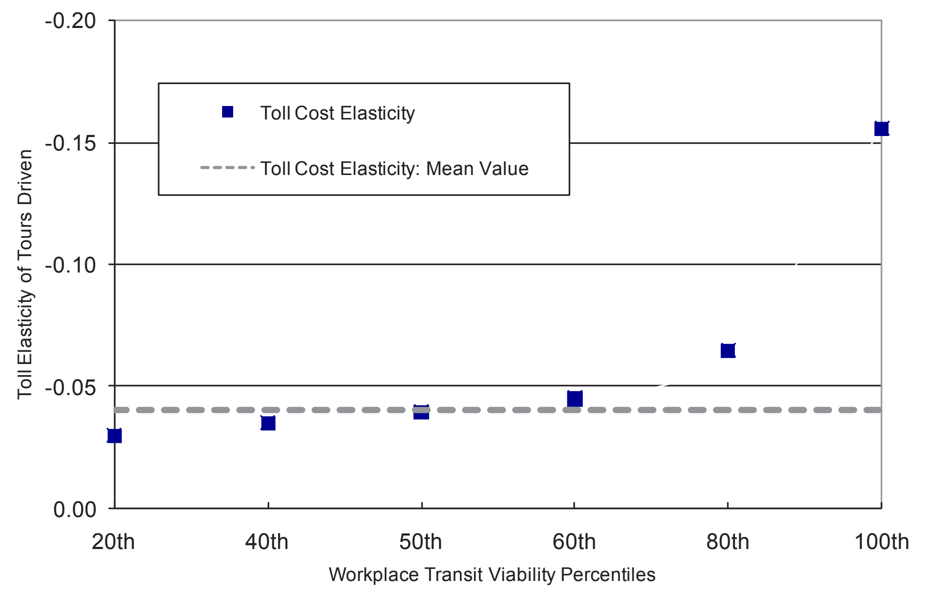
On average, demand response measured by households is less pronounced than when measured by individual vehicles. As expected, households have the ability to integrate travel planning across vehicles or individual household members. Demand response is less pronounced as income increases, as demonstrated through an examination of the sign of the coefficients for income. And the workplace models that contain a measure of transit viability[8] 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. Exhibit A.7 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.

### Exhibit A.5. Vehicle Sensitivity to Toll Costs by Tour Purpose




### Exhibit A.6. Workplace Sensitivity to Toll Costs by Tour Purpose


### Exhibit A.7. Influence of Transit Quality on Toll Elasticity of Home-to-Work Tours




[8]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.

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 Exhibit A.8 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 proj¬ect, the trip was made during the lower toll-cost time of day. This probability dropped to 20 percent when the trip typically occurred within 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 dif¬ferent 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.

## 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 Exhibit A.8.

**Exhibit A.8. Home-to-Work Probability of Shifting to Lower Toll Period**

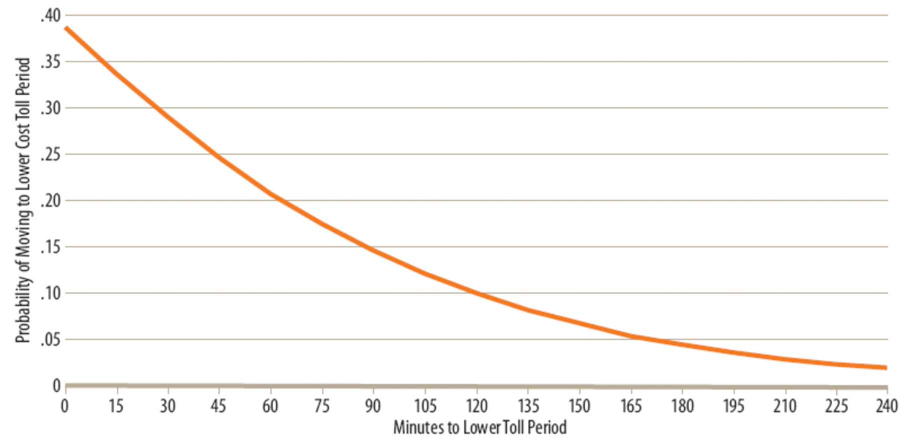
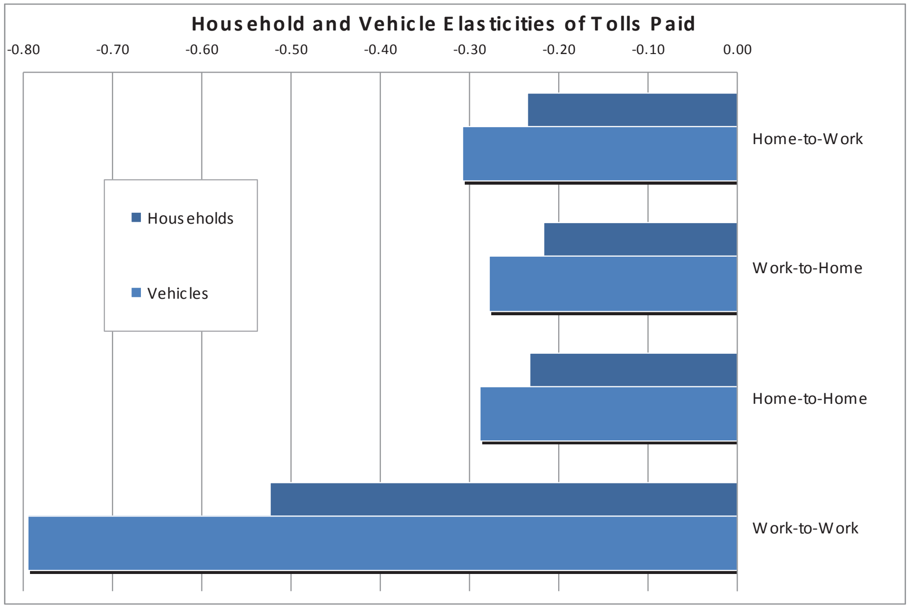



**Exhibit A.8. Toll Cost Elasticity of Tolls Paid**



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# APPENDIX B: PRIVACY AND ROAD USE FEES

To better assess the issues of privacy policy and network road fees it is essential to try to answer a few basic questions. First, are there clear established rights to privacy? Second, what specific concerns are privacy advocates likely to have with a GPS-based network charging system? Third, what specific information about users is likely to collected and stored by such a system? Fourth, what standards for privacy protection might be helpful in the design of toll system privacy protections? All these questions are distinct from questions regarding data security. It is assumed that tolling data can be made reasonably secure, but that privacy concerns may still persist.

While certain Constitutional provisions have come to be referred to as rights of privacy, there is no clarity as to what the right to privacy is, as granted under the U.S. Constitution and Bill of Rights. And case law concerning what is private and what is not private is often fraught with ambiguity. The First Amendment protects speech and religious belief and can be construed to be a protection of the privacy of thoughts and beliefs. The Third Amendment protects against the quartering of soldiers during war time and is seen as a protection of the privacy of the home. The Fourth Amendment protects against unreasonable searches and seizures, and may be seen as a protection of the privacy of a person and their possessions.

In general, however, what one does in a public space, such as a public road right-of-way is not necessarily considered to be private. There is no clear expectation of privacy while one uses public rights-of-ways. Data stored and collected about individual's use of roads may, depending upon local laws, be protected in some manner as private information. While establishing privacy as a right in the context of questions of road tolling may be challenging; often there is a general public sentiment that such information is, in fact, private information and should not used without the consent of the individual users.

In 1995 the European Parliament passed Directive 95/46/EC[10], on the protection of individuals with regard to the processing of personal data and on the free movement of such data. This Directive is an example of specific direction on how information collected by governments about private individuals should be managed.

The main provisions of the Directive include Article 6, stating that Member States shall provide that personal data must be:

(a) processed fairly and lawfully;

(b) collected for specified, explicit and legitimate purposes and not further processed in a way incompatible with those purposes;

(c) adequate, relevant and not excessive in relation to the purposes for which they are collected and/or further processed;

(d) accurate and, where necessary, kept up to date;

(e) kept in a form which permits identification of data subjects for no longer than is necessary for the purposes for which the data were collected or for which they are further processed.

Article 7 lays out criteria for making data processing legitimate by indicating that Member States shall provide that personal data may be processed only if:

(a) the data subject has unambiguously given his consent; or

(b) processing is necessary for the performance of a contract to which the data subject is party or in order to take steps at the request of the data subject prior to entering into a contract; or

(c) processing is necessary for compliance with a legal obligation to which the controller is subject; or

(d) processing is necessary in order to protect the vital interests of the data subject; or

(e) processing is necessary for the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller or in a third party to whom the data are disclosed; or

(f) processing is necessary for the purposes of the legitimate interests pursued by the controller or by the third party or parties to whom the data are disclosed, except where such interests are overridden by the interests for fundamental rights and freedoms of the data subject which require protection under Article 1 (1).

[10] http://ec.europa.eu/justice_home/fsj/privacy/index_en.htm

The Directive also covers the subject's rights of access to the data, rights of notification about data processing and rights to formally object to data processing, how data can get transferred to other parties, judicial remedies, liabilities and sanctions. Member States are required to "bring into force the laws, regulations and administrative provisions necessary to comply with this Directive".

Such an approach renders less ambiguous questions about whether any given governmental program complies with basic privacy protections. In the case of a road tolling system, it is feasible to design systems, practices and safeguards that will meet international standards, thus moving any debate about privacy from the abstract to the particular.

If one was to take the European case one step further, this Directive is implemented in the specific case of the Netherlands by means of the Personal Data Protection Act.[11] This is a useful example because the Dutch government is planning on implementing a nation-wide road tolling system based on GPS technology. As a result the Dutch government will have to explicitly consider how such a tolling system will comply with national law protecting personal information.

## PRIVACY CONCERNS THAT MIGHT BE RAISED BY A NETWORK TOLLING SYSTEM

### Illegal or unauthorized use of personal data

Even as more commerce and personal transactions take place through digital means, the illegal possession and use of personal data is rare. But when a breach in corporate or institutional security does occur it can have sizable consequences for innocent parties. Most often, such cases, which may receive much publicity, involve the illegal compromise of an institutions computer systems containing account holder information, possibly including records allowing access to financial accounts. However, data security and encryption technology has become so advanced that an actual breach of a computer system is extremely rare. And situations where account holder files have been access mostly involve situations where an unsecured storage medium has been stolen (such as data temporarily stored on an employees laptop), or are the result of users directly and unknowingly providing access to account information (account information and passwords stored on individuals unsecured home computer systems or account holders responding to requests to provide account information to someone posing as a legitimate account manager). Still, technical all systems have vulnerabilities, and a road tolling system with a large database of account holder information could never be 100% immune to breaches in security.

One suggested way to address data security for road pricing applications is to limit the detail of information a road tolling system would contain in its central office. This is the so-called Thick-Client model discussed elsewhere. Since information about specific road use is never sent to the central office two important points of data vulnerability become less critical; data transmission and central data storage. However, it is important to realize that detailed data will still be stored (at least temporarily) within the vehicle itself. The user end of the data chain is possibly the point of greatest security risk, as examples of breaches in the security of financial accounts suggests.

### Official use of data for other than intended purposes

Another concern regarding the storage of detailed information about people's physical movements within their vehicles involves the availability of that information to "official" entities to support purposes other than those originally intended by the road tolling program. Law enforcement, for example, might be keen to make use of information about the movements of "parties of interest". Lawyers involved in litigation might find use for similar information in particular cases. In the clearest cases, most people would have no quarrel with the selective and responsible use of this kind of data when employed to catch a dangerous criminal. It is the many hypothetical and more ambiguous circumstances that engender a healthy skepticism on the part of the average person. Road pricing would not be the first situation where such complex questions about privacy protections are raised. Legal and institutional structures can be put into place to minimize the opportunities for unintended use of personal data. The Directive of the European Parliament discussed above is an example of such a legal framework. Still, the process of sorting all this out can often be a messy business involving courts and legislative refinements taking place over a number of years. The approach that focuses on legal and institutional protections is one that must, by necessity in the short-run, say: trust us; we will be responsible in keeping your

[11] http://english.justitie.nl/themes/personal%2Ddata/

personal information secure. The point here is that the notion of trust is essential, and that institutional protections often involve what has become referred to as a “trusted third-party” (an institution that has controls over the processes but has not direct interest in the control of the data itself).

**Information Collected and Stored by a Network Tolling System**

Tolling a network of road facilities, such as was done during the Traffic Choices Study involves collecting detailed road use information for any applicable vehicles and associating that information with accountholders that are responsible for payment. In the case of a tolling system that relies upon global positioning system technology, the road use information that is collected may be as detailed as a trail of precise waypoints and time stamps at one second intervals. GPS tolling devices can calculate and store this level of detail about a vehicle’s location for an extended period of time. In the case of the Traffic Choices Study, the tolling meters could store up to approximately two weeks of positioning data before running out of allocated memory. When this level of detailed vehicle use data is associated with user account information, in a tolling back office, it is possible to determine the precise movements of vehicles and individuals.

Thus a principal aspect of privacy has very little to do with the data that is stored within the vehicle on the tolling meter, or on-board unit, but rather what data actually leaves the vehicle to be stored as part of the back office operations (facility use determination, violation processing, and billing) of the toll system. In this regard, a GPS toll system can be operated in a manner that either stores detailed road use information in the back office, or in a manner that stores only summary road use information that abstracts from the use of specific roadway facilities.

**Thick or Thin Client**

The two operating approaches have come to be reference according to the functionality of the in-vehicle tolling meter, as a thin or thick client. The thin client is an OBU (in-vehicle toll meter) concept where all raw data is transferred to the back office. In the back office, the data is processed and the road segments are recognized and matched with the toll rate table. This means that all information relevant for tolling is calculated in the back office. All information is retained at appropriate detail to meet evidentiary standards and for a period sufficient to cover dispute opportunities

In the thick client approach, the tolling process takes place in the OBU; the algorithm for the road section recognition is integrated in the OBU. After the road section is recognized, the toll rate is processed in the OBU according to the type of the road, time period, and vehicle class. The sections and driven distances can be sent to the back office in aggregate together with calculated road usage fee. Specific road use details are never stored in the toll system back office. If the fee is calculated in the OBU it is also possible to integrate a card slot (for usage of cash cards) into the OBU in order to achieve maximum privacy for the participants.

However a toll system is operated, it is important to remember that there is no absolute technical safeguard for personal information when road usage must be verified and processed for payment. Even if detailed data is stored only in the participant’s vehicle, it is vulnerable to discovery and misuse. But reasonable safeguards are an essential part of any business or government process that makes use of, or has access to, private information.

**Toll System Privacy Protections**

Addressing privacy concerns around toll system implementation can take many forms; the safeguards can be technical, institutional or legal but ultimately need to be a total package that are mutually supporting. Technical approaches might include thin versus thick client models, the use of anonymous proxies, and the purging or sanitization of data. Institutional approaches might limit the scope of information available to any single institution; separating personal data from road use data. But any approach will require a legal framework that ensures that privacy is adequately addressed with technology and institutional structures.

The table below itemizes some very general privacy protection principles and how these principles might be addressed in toll system design.

This report does not systematically inventory or assess approaches to addressing the dimensions of privacy that arise as a result of system level road charging. The fee system could result in significant concerns about the potential use of data regarding the location and movement of individuals. Authorities that are considering actual implementation of road charging through vehicle positioning, such as some in Europe, are able to take a much more considered approach to evaluating privacy concerns and designing practical solutions. Specific toll system proposals will require specific solutions; solutions that could not be designed into a field study such as the Traffic Choices study. However, Traffic Choices study participants did have a unique experience involving vehicle positioning tolling technology, and as such can provide some insights into the topic of privacy. A survey of participating households conducted at the end of the study asked for any additional comments households wished to advance regarding any aspect of the study. Such an open ended question resists systematic analysis but provides some general sense of what was on the minds of the participants after having spent considerable time involved in a research experiment. Concerns about privacy featured in the responses, but did not dominate. This can be seen in the Exhibit B.2 on the following page.

A specific question regarding privacy was also asked of the Traffic Choices Study participants during a “startup” and an “exit” survey.

Experience with the road tolling experiment appears to have helped individuals clarify their own views on the topic of privacy. Before the experiment a fair number of participants were ambivalent about the issue of privacy. After the project was complete, participants had become less ambivalent and were (as a group) both more and less concerned about privacy. This result points to a possible benefit of more refined research with a focus on addressing specific privacy aspects of the toll systems that remain a concern for individuals who have previously gained some tangible experience with the tolling technology.

**Exhibit B.1 Principles and Measures to Protect Privacy**

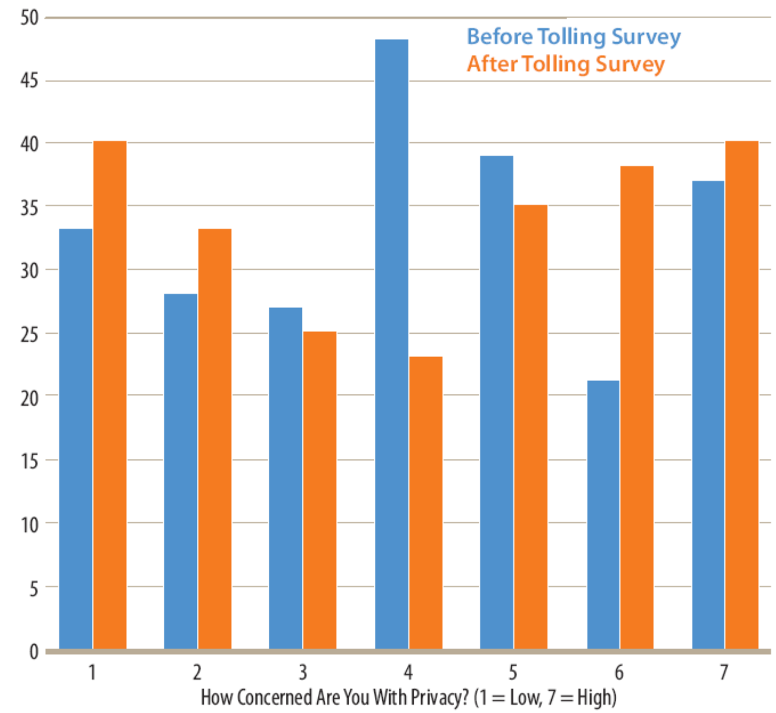
| Principles | Measures/Remarks |
|---|---|
| Capture only data necessary for the defined purpose | Define which data are captured for what purpose, and let the public know what data are collected and why |
| Don’t keep data longer than necessary | Ensure that obsolete data will be permanently deleted. |
| 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.<br>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 |

### Exhibit B.2. Household Survey – General Comment Categories

| Comment Topics | Number |
|---|---|
| Lack of flexibility to respond to tolls | 32 |
| Indicating some significant change in travel behavior | 17 |
| Found road use information useful/interesting | 11 |
| Roads should be free/objection to tolls | 8 |
| Expressing a need for better alternative modes of travel | 7 |
| Indicating support for tolling | 7 |
| Importance of focusing revenues on transportation | 4 |
| Concern about traffic diversion | 3 |
| Expressing the need for more roads | 1 |
| Preference for gas tax | 2 |
| Compliment about some aspect of the project | 9 |
| Complaint about some aspect of the project | 5 |
| Complaint about the tolling device (OBU) | 3 |
| Concern about privacy | 7 |
| Concern about fairness | 5 |
| Regarding some aspect of study design | 7 |
| Regarding study toll rates/rate policy | 5 |
| Misc. comment | 12 |
| Total comments | 145 |
| Percent of respondents that offered comments | 53% |

### Exhibit B.3. Household Survey – Privacy Concerns

*How concerned would you be about the privacy implications of a toll system that collects specific road use information for individual vehicles?*



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# APPENDIX C: TRAFFIC CHOICES 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.

Exhibit C.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.

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.

**Exhibit C.1. Candidate Links for Tolling**

| V/C Ratio | AM Peak Links | PM Peak 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% |

# APPENDIX D: TRAFFIC CHOICES BACK OFFICE DATA MANAGEMENT FUNCTIONS

## GENERAL 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

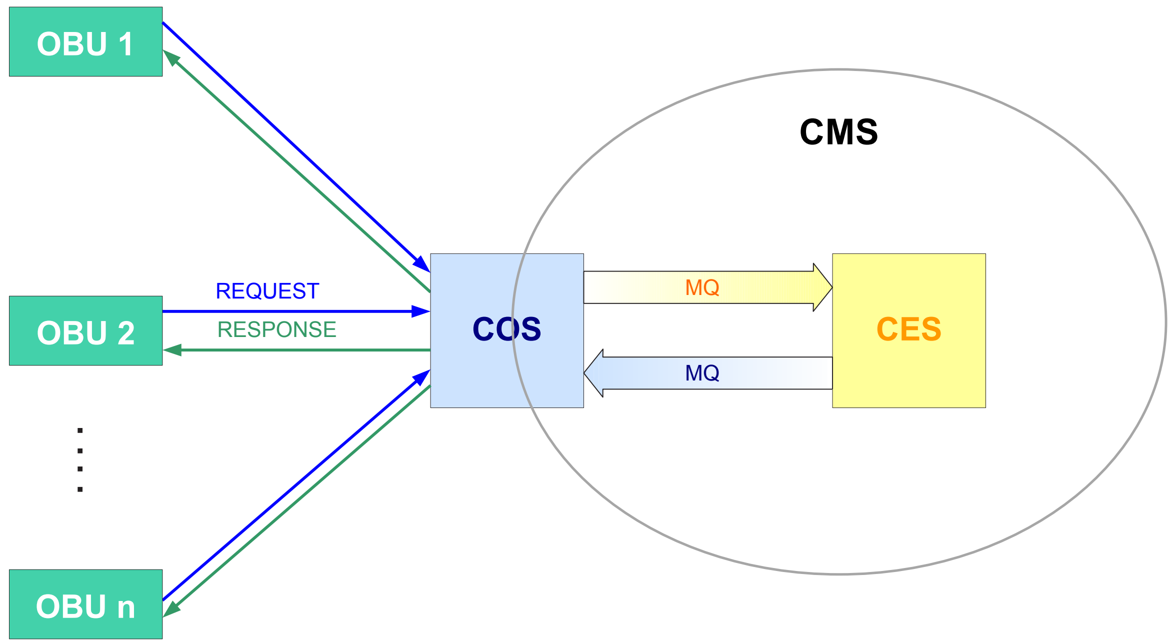
The study contracted for local wireless telephone and data communication services to allow communication between the OBU and the CMS. The wireless service provider issued SIM chipsets for each OBU used in the project. Exhibit D.1 illustrates the system.

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

**Exhibit D.1. Communications between System Components**




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

## TARIFF MODEL

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. The project team based the range of tariff structures and toll schedule options on composite measures of facility use. 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.

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 (Exhibit D.2). 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.

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 Exhibit D.3 below. Other logic checks were supported by the system, such as consistency of direction of travel.

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.

**Exhibit D.2. Example Road Segment**

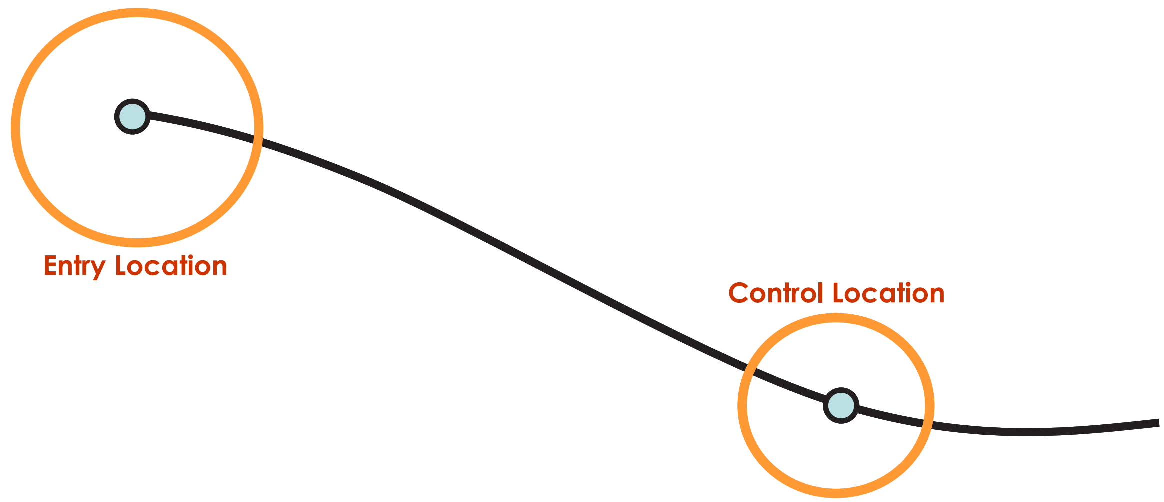
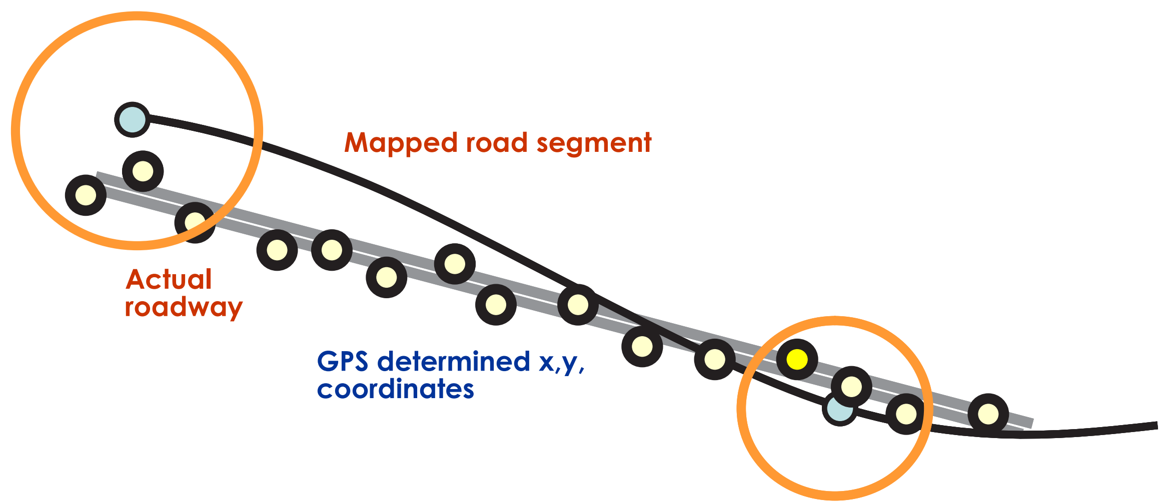



**Exhibit D.3. Map Matching Concept**



# APPENDIX E: SAMPLE DESIGN FOR THE TRAFFIC CHOICES STUDY

Pilot projects that aim to understand consumer behavior must also adhere to scientific standards that allow for useful analysis to be performed at the conclusion of the study operation. Sample size is a key issue for any experiment. The sample for a study of road users should be grouped by households, as 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, it is generally 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.

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 XX.**

### 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 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. Exhibit E.1 shows the basic recruitment goals and constraints.

**Exhibit E.1. 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 |

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# APPENDIX F: EXAMPLE 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.

**Exhibit F.1. Congestion Pricing Business Processes**


The business processes of the network tolling system are shown in Exhibit F.1 and summarized below.

## 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 Exhibit F.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.

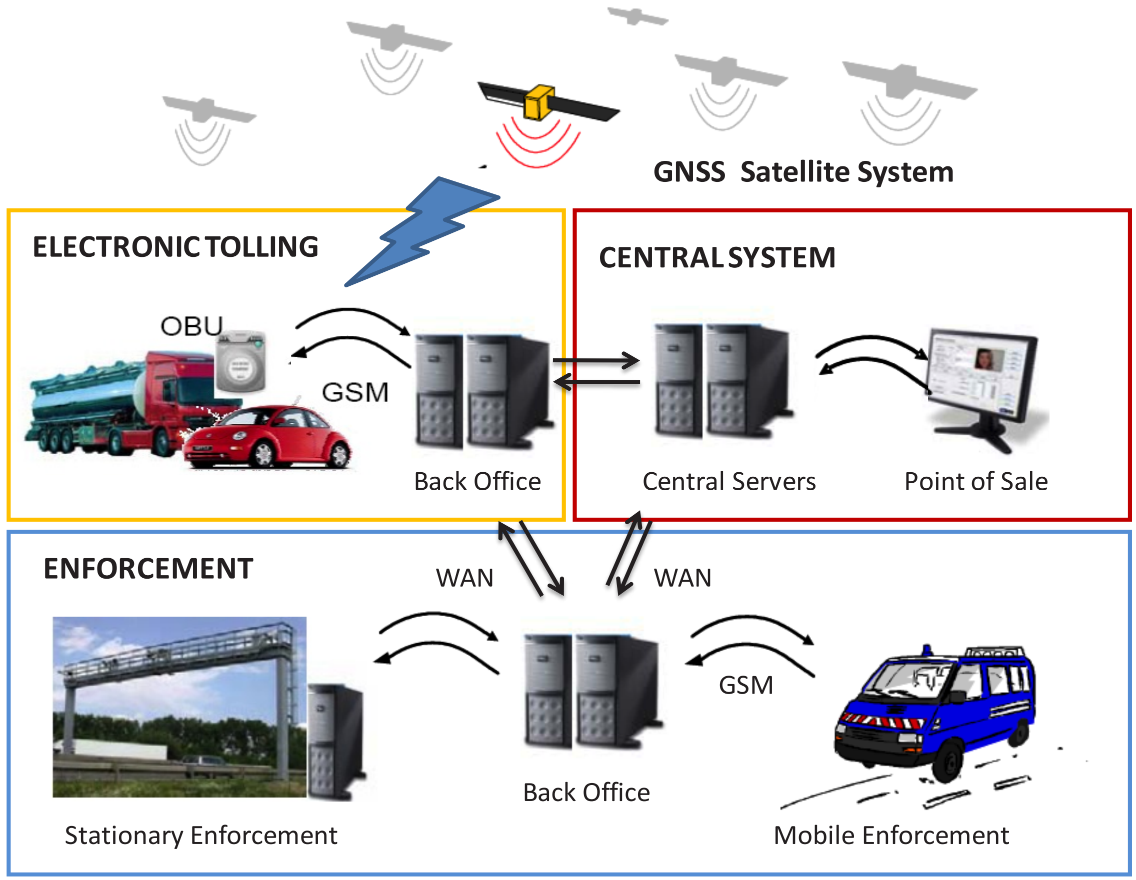
## ELECTRONIC TOLLING SYSTEM

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

**Exhibit F.2. High Level Architecture for Road Network Tolling System**




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.

Exhibit F.3 summarizes the main advantages and disadvantages of both approaches.

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

**Exhibit F.3. Advantages of Thin and Thick Client**

| | **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 | High - 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 |

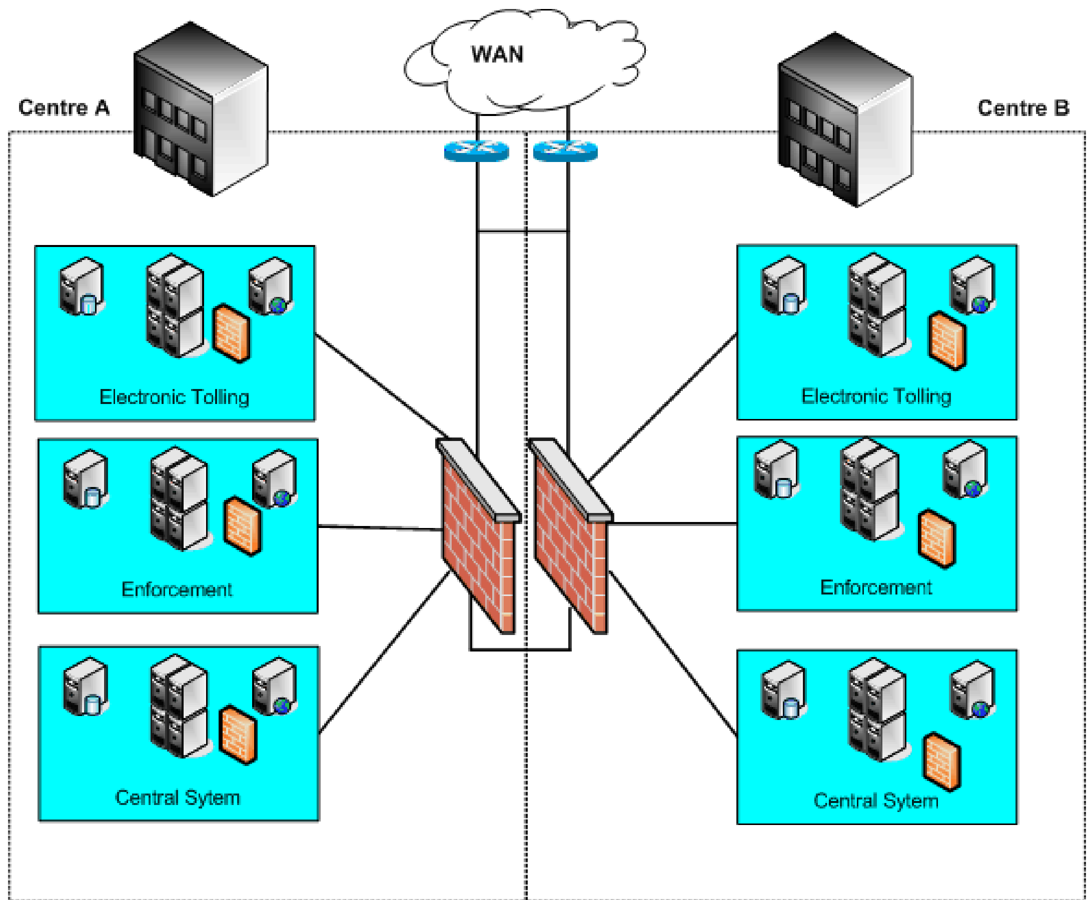
### Central System / Back Office

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 physiczal interfaces have redundancy built into each data center. The data centers themselves are connected over redundant lines (Exhibit F.4). 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.

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.

### Exhibit F.4 Central System Architecture




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 - Scurity mechanisms for access control, history logging, encryptionintrusion 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. Exhibit F.5 summarizes some of the principles and measures to protect privacy.

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.

**Exhibit F.5. 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.<br>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. |

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 (Exhibit F.6). 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.

**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.

Exhibit F.7 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 (Exhibit F.8). Classification detection is not included for the arterial assemblies.

**Exhibit F.7. Schematic of Stationary Enforcement Assembly**

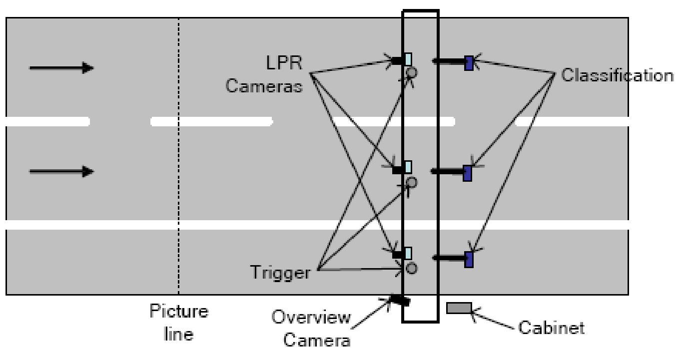



**Exhibit F.6. London Summary Record from ALPR**

### 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 (Exhibit F.9). 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

**Exhibit F.8. Pole-Based ALPR / Enforcement Installation 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.[12] 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 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.

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

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.

**Exhibit F.9. Mobile Enforcement Vehicle in London**


### 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.