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Abstract

When cost-benefit analysis fails to account for peak-shifting the benefits of road improvement options are miscalculated. Using theory from transportation economics, we derive a simple model that disaggregates the average daily equilibrium into peak, counter-peak, and off-peak equilibria. This paper demonstrates how accounting for peak-shifting improves the performance of cost-benefit analysis.

JEL classifications: R41, D61, O21
Keywords: Transportation Demand, Transportation Supply, Congestion, Cost/Benefit Analysis, Planning Policy

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Abstract

When cost-benefit analysis fails to account for peak-shifting the benefits of road improvement options are miscalculated. Using theory from transportation economics, we derive a simple model that disaggregates the average daily equilibrium into peak, counter-peak, and off-peak equilibria. This paper demonstrates how accounting for peak-shifting improves the performance of cost-benefit analysis.

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1. Introduction

The use of cost-benefit analysis (CBA) in highway planning started in Britain during the late 1950s when Britain's Department of Transport completed the mainframe computer model COBA (COst-Benefit Analysis). COBA estimated the costs and benefits of alternative roadway designs and alignments for policy makers so that they could make socially optimal planning decisions. Since then other CBA models have been developed and steadily improved over the years, which include but are not limited to Highway Investment Analysis Program (HIAP), Highway Economic Requirements Model (HERS), Micro-computer Benefit Cost Analysis Model (MicroBENCOST), and the Strategic Benefit Cost Analysis Model (StratBENCOST).

The benefits to highway users are typically evaluated via consumer surplus. Reducing highway congestion lowers the cost of highway travel by reducing travel time, fuel and oil consumption, and accident rates. The alleviation of highway congestion can be accomplished by either increasing supply or reducing demand. McCarthy (2001, pp. 448-464) provides a detailed discussion of peak and off-peak demand in the presence of fixed and variable capacity. Kanafani (1983, pp. 57-74) discusses how variable capacity shifts highway supply. According to Henderson (1992), traditional CBA has indeed ignored peak shifting, which results in the miscalculation of road improvement benefits. This finding is *not* surprising. A CBA that operates under the assumption of annual daily demand and supply equations ignores peak-shifting because the peak and off-peak occur within a typical day.

Comparing Figures 1, 2 and 3 demonstrates what happens when CBA algorithms assume fixed daily highway demand and supply curves. In Figure 1 there is a single daily demand and supply curve, which we label *D* and *S*, respectively. Assuming there is only one of each of these curves results in an average daily price of travel and average annual daily traffic volume. Figure 2 shows why this assumption is not realistic. Sunday and Saturday highway traffic is characterized by a single long peak while weekday traffic is characterized by morning and evening peaks. Figure 3 illustrates how the price of travel is affected by peak and off-peak disaggregation of the single daily highway demand curve. The average daily price of travel (denoted p_e in both Figures 1 and 3) misrepresents the economic reality of highway usage. The average hourly prices of the peak and off-peak (labeled p_{peak} and p_{off} in Figure 3) tell a more realistic story. Ignoring peak-shifting lessens the impact of congestion, resulting in imprecise estimates of the price of travel and the benefits of road improvements.

The above analysis is widely understood in the congestion pricing and road traffic congestion literatures, which have long histories stemming all the way back to Pigou (1920) and Vickrey (1969), respectively (de Palma and Arnott, 1986; Cohen, 1987; Braid, 1989; Arnott, de Palma and Lindsey, 1990;). McCarthy (2001), Lin and Niemeier (1998), Henderson (1992), Kanafani (1983), and Morlok (1978) discuss the importance of accounting for shifting highway demand and supply. Wardman (1998) and Small et al. (1999) summarizes value-of-time (VOT) studies, while Gonzalez (1997) surveys the theory of consumer choice and its connection to VOT and choice modeling. Recently there has been a great deal of work done on the VOT and the value of reliability (VOR) (Brownstone and Small, 2005; Brownstone, Kazimi, Ghosh, and van Alemsfort, 2003; and Calfee and Winston 1998), and the short-run elasticity of highway demand (Harvey, 1994; Hirschman, McNight, Paaswell, Pucher, and Berechman, 1995; Gifford and

Talkington, 1996; Lawley Publications, 2000; Burris, Cain and Pendyala, 2001; and Matas and Raymond, 2003).

This paper integrates existing transportation and congestion theory and empirical estimates from transportation economics literature to construct a simple and easily understandable algorithm that disaggregates the daily highway equilibrium, like the one discussed in section two of this paper, into multiple within-day equilibria. In section four of this paper we review and compare results on VOT, VOR and the short-run elasticity of highway demand so that we can conduct a simulation of the disaggregation algorithm that we constructed in section three of this paper. Our algorithm not only allows for disaggregation down to the minute level, but also allows for variances in within-day short-run elasticity of highway demand, highway capacity and the VOT. In addition to these, it allows VOR to influence highway supply.[1] In section five we discuss the results of the simulation of our model, and check how sensitive it is to changes in the values of the model's parameters. As a result of our efforts, traffic planners will better understand peak shifting and be able to make better, more informed policy decisions, and as a consequence, commuters will be better served.

2. The Daily Equilibrium

The daily equilibrium occurs at the intersection of the short-run daily demand and supply curves. The supply curve we derive in this section is constructed from the expected average daily delay equation used by HERS—even though our methodology is based on this equation, our algorithm is general enough to be easily adapted into any CBA that assumes daily highway demand and supply.[2] The daily delay equation yields the number of hours delayed per 1000 vehicle miles given the average annual daily traffic volume and average hourly capacity. HERS selects an internally defined delay equation based on the attributes (number of lanes, traffic signs, traffic lights) of the section of highway under consideration for improvement.[3] For freeways or multilane rural highways, the following delay equation would be selected:[4]

$$D(A) = \begin{cases} 0.0797A + 0.00385A^2 & \text{if} \quad A < 8 \\ 12.1 - 2.95A + 0.193A^2 & \text{if} \quad 8 \leq A < 12 \\ 19.6 - 5.36A + 0.342A^2 & \text{if} \quad A \geq 12. \end{cases} \tag{1}$$

where A is the ratio of average annual daily traffic volume (V) and highway capacity (C) for a section of highway ($A = V/C$).[5] Equation (1) is referred to as the expected average daily delay equation in hours per 1000 vehicle miles.

Equation (1) is converted into the daily supply curve with a sequence of operations. First, equation (1) is multiplied by the value of travel per hour (VOT), and then divided by 1000.[6] Next, hourly highway capacity C_0 is substituted into the resulting equation. These two operations yield "the price of delay," a function of traffic volume (V). The price of delay, shown in Figure 1, represents the implicit costs of congestion incurred by commuters given the average annual daily traffic volume, V, for the section of the highway under consideration. The supply curve results when the price without delay (p_{wod}) is added to the price of delay equation:[7]

$$P(V \mid C) = \tfrac{VOT}{1000} \cdot D(V \mid C = C_0) + p_{wod}\,, \tag{2}$$

labeled S in Figure 1. For the remainder of this paper, we refer to equation (2) as the highway supply curve.[8]

Short-run highway demand is assumed to exhibit constant elasticity. This allows the daily highway demand curve to be fit with a single initial point, which we denote (V_0, p_0).[9] The general form of the constant-elasticity highway demand curve is

$$V = \alpha\ p^{\varepsilon} \tag{3}$$

where α is some positive coefficient and ε is the short-run elasticity of demand.[10] Because ε is negative, the law of demand is satisfied, and demand is a rectangular hyperbola asymptotic to both the *V* and *p* axes. By assumption, equation (3) passes through the point V_0 and p_0. This means

$$\alpha = V_0 \cdot (p_0)^{-\varepsilon}$$

Substituting the above into equation (3) yields the short-run constant elasticity daily demand curve

$$P(V \mid V_0, p_0) = (V_0)^{-1/\varepsilon} \cdot p_0 \cdot V^{1/\varepsilon}\ . \tag{4}$$

The daily equilibrium (denoted V_e and p_e) is found by solving equations (2) and (4) simultaneously. The daily equilibrium is shown in Figure 1. Figure 1 graphs demand supply in units of average annual daily traffic (AADT). In Figure 3 we graph the hourly demand and supply curves corresponding to equations (2) and (4), respectively. They are the curves labeled *S* and *D*. Traffic volume in Figure 3 is in units of average hourly traffic (AAHT) *not* AADT. If *D* is disaggregated into hourly peak and off-peak demand curves (labeled D_{peak} and D_{off}), the result is a disaggregated equilibrium. According to Figure 3, the peak equilibrium exhibits much higher price and volume, denoted by p_{peak} and v_{peak}, than of that of the off-peak. Figure 3 also illustrates how heavily weighted the average daily equilibrium price of travel could be toward the off-peak price of travel.

3. The Disaggregation Algorithm

Because the peak, counter-peak, and off-peak periods occur within a one day period, the first step in disaggregating the daily equilibrium is to convert the daily delay equation, equation (1), into an hourly delay equation. By construction, using daily demand and supply curves unnecessarily holds hourly capacity, short-run price elasticity of demand and VOT constant throughout the day. Hourly, rather than daily, demand and supply curves allow for differences in these parameters that may exist between the peak and the off-peak. The hourly delay equation permits the highway supply curve to shift or rotate as hourly capacity or VOT to vary within the day. Hourly demands allow short-run demand elasticity to vary within the day.

3.1 Disaggregated Daily Highway Supply

The daily delay equation, equation (1), is a function of Average Annual Daily Traffic volume (*AADT*), which we denote as V for simplicity. To convert this equation into the hourly delay equation, we need delay to be a function of Average Annual Hourly Traffic volume (*AAHT*).[11] Let v denote average annual hourly traffic volume. For one-way traffic, average annual daily traffic volume V is divided into 24 one-hour periods, for two-way traffic V is divided into two 24 one-hour periods (or 48 one-hour periods). Let T be the traffic indicator variable that is assigned the value of one for one-way roads, 2 for two-way roads. When T equals one, there is no counter-peak demand because one-way roads experience only peak and off-peak traffic. Hence counter-peak equilibrium is derived only when T equals two.

Since $v = V/(24T)$, we can substitute $24Tv$ for V into $A = V/C$, resulting in $A = 24Tv/C$. Replacing A with $24Tv/C$ in equation (1) produces the expected average hourly delay equation for one-way and two-way roadways in hours per 1000 vehicle miles.[12] Thus equation (1) becomes

$$d(v \mid C,T) = \begin{cases} 0.0797\left(\frac{24Tv}{C}\right) + 0.00385\left(\frac{24Tv}{C}\right)^2 & \text{if} \quad \frac{v}{C} < \frac{1}{3T} \\ 12.1 - 2.95\left(\frac{24Tv}{C}\right) + 0.193\left(\frac{24Tv}{C}\right)^2 & \text{if} \quad \frac{1}{3T} \le \frac{v}{C} < \frac{1}{2T} \\ 19.6 - 5.36\left(\frac{24Tv}{C}\right) + 0.342\left(\frac{24Tv}{C}\right)^2 & \text{if} \quad \frac{v}{C} \ge \frac{1}{2T}. \end{cases} \tag{5}$$

This is the hourly delay equation. Notice that we use d to denote the hourly delay equation rather than D. We do this to distinguish the hourly delay equation from its daily counterpart, equation (1). To derive "hourly price with delay" curve, we do to equation (5) what we did to equation (1). The result is

$$P(v \mid C,T) = \frac{VOT}{1000} \cdot d(v \mid C,T) + p_{wod}\,. \tag{6}$$

For the remainder of this paper, we refer to equation (6) as the hourly highway supply curve. Notice the subtle differences between equations (2) and (6). Equation (2) is a function of average annual daily traffic volume (V) given C, while equation (6) is a function of annual hourly traffic volume (v) given C and T. To verify that equation (6) is the hourly equivalent of equation (2) substitute the average hourly daily equilibrium traffic volume, $V_e/(24T)$, into equation (6) and simplify:

$$\begin{aligned} P\left(\frac{V_e}{24\cdot 2}\middle| C = C_0, T = 2\right) &= \frac{VOT}{1000} \cdot d\left(\frac{V_e}{24\cdot 2}\middle| C = C_0, T = 2\right) + p_{wod} \\ &= \frac{VOT}{1000} \cdot D\left(\frac{24\cdot 2}{C_0} v_e\right) + p_{wod} \\ &= \frac{VOT}{1000} \cdot D\left(\frac{24\cdot 2}{C_0}\frac{V_e}{24\cdot 2}\right) + p_{wod} \\ &= \frac{VOT}{1000} \cdot D\left(V_e\right)\Big|_{C=C_0} + p_{wod} \\ &= p_e \end{aligned}$$

Figure 3 graphs the peak and off-peak highway demand curves, unknown at this point, with the hourly supply curve, equation (6). Figure 3 illustrates the relationship between these curves and the annual average hourly equilibrium volume $V_e/(24T)$, denoted as v_e. The hourly supply curve shown in Figure 3 assumes capacity is the same in the peak as it is in the off-off peak, this is not necessarily true. Relaxing this assumption is easily done because equation (6) permits hourly capacity to change throughout a given day. Figure 4 shows how changes in hourly capacity shift the highway supply curve. An interstate equipped with reversible lanes is an example of a road with variable short-run capacity. Reversible lanes increase the number of lanes during a peak commute, while simultaneously decreasing the number of lanes for counter-peak traffic. Another example of varying highway capacity is the use of no parking zones on lanes nearest to curbs of downtown streets during peak hours.

Since traffic monitoring equipment is generally available to a traffic planner in urban areas, volumes and capacities of the peak, counter-peak and off-peak are known. We let v_{peak}, v_{cntr} and v_{off} denote the equilibrium average annual hourly traffic volumes that correspond to the peak, counter-peak and off-peak.[13] Similarly, we let C_{peak}, C_{cntr} and C_{off} denote corresponding hourly capacities. Figure 4 assumes $C_{peak} \geq C_{cntr} \geq C_{off}$, which would typically be the case since traffic planners vary capacity to accommodate congestion. The hourly supply curve for the peak, counter-peak, and off-peak are defined by

$$P(v \mid C_i, T = 2) = (VOT_i / 1000) \cdot d(v \mid C_i, T = 2) + p_{wod} \tag{7}$$

for i = *off*, *counter*, or *peak*, where VOT_i is the VOT for period *i*. The hourly delay equations corresponding to C_{peak}, C_{cntr} and C_{off} are shown in Figures 4 and 5.

3.2 Disaggregated Daily Highway Demand

If v_{off}, v_{cntr}, and v_{peak} are known values of the annual average hourly off-peak, counter-peak, and peak traffic volumes of a given section of highway, the price of travel for each of these periods is given by

$$p_i = (VOT_i / 1000) \cdot d(v_i \mid C_i, T = 2) + p_{wod}$$

where $i = off, cntr,$ or $peak$. The resulting equilibriums would then be (v_{off}, p_{off}), (v_{cntr}, p_{cntr}) and (v_{peak}, p_{peak}). Because the equilibrium represents the point where demand crosses supply, demand curves can be fit using these equilibria. To fit these demand curves to their respective equilibriums, we follow the same procedure that we used in constructing equation (4). Because these are hourly demand equation, short-run demand elasticities of the peak, counter-peak, and off-peak (ε_{off}, ε_{cntr}, and ε_{peak}) can be used to fit each curve. This allows for a more realistic estimation of the benefit calculations of road improvements because these elasticities are most likely not all equal. The highway periodic short-run highway demand curves are defined by

$$v(p) = \alpha_i p^{\varepsilon_i} \tag{8}$$

where $\alpha_i = v_i p_i^{-\varepsilon_i}$ and $i = off, cntr,$ or $peak$. We plot each of these demand curves with their corresponding supply curves in Figure 5.

According to Figure 5, p_{off} is only slightly higher than the flat sections of all three hourly supply curves. Recall from Figure 1 that the vertical axis intercept in Figure 5 is the price without delay, p_{wod}. Thus, according to our disaggregation model, $p_{wod} \approx p_{off}$, which is exactly what we should expect. Also, the price of the off-peak is smaller than the price of the counter-peak, and the counter-peak price is less than the peak price. Again, what we should expect. Traffic volumes and the slopes of the demand and supply curves vary at the three equilibriums as well.

3.3 The Disaggregation Algorithm

The discussions above yield the simple four-step algorithm below. Subscript i is used in the steps that follow to identify off-peak, counter-peak, or peak period.

Step 1: The user is asked to input values for the following variables:

T = an indicator variable that is equal to one if the section of road accommodates one-way traffic, 2 for two-way traffic.

C_i = the hourly capacity for the i th period.

ε_i = the short-run demand elasticities of the i th period.

v_i = the average annual hourly daily traffic volume for the i th period.

VOT_i = the VOT of the i th period, which could include the VOR.

ℓ_i = the average length of the i th period.[14]

Step 2: Calculate the average hourly prices corresponding to the peak, counter-peak and off-peak using definition $V_i \equiv 24 \cdot T \cdot v_i / C_i$:

$$p_i = (VOT_i / 1000) \cdot D\left(\frac{24 \cdot T \cdot v_i / C_i}{C_i}\right) + p_{wod}$$

Step 3: Fit the hourly demand equations of the peak, off-peak, and counter-peak periods using the prices calculated in Step 2:

$$v_i(p) = \left(v_i p_i^{-\varepsilon_i}\right) p^{\varepsilon_i} .$$

Step 4: Compute the lengths of the peak and consumer surplus for the peak, off-peak, and counter-peak periods:

$$\ell_{cntr} = (T - 1) \cdot \ell_{peak}$$

$$\ell_{off} = 24 \cdot T - (T - 1) \cdot \ell_{cntr} - \ell_{peak}$$

$$CS_i = \ell_i \int_{p_i}^{\infty} v_i(p)\,dp \ .$$

Step 4 of the disaggregation algorithm has not been discussed nor is it the focus of this paper. We include this step because we want to show how the consumer surplus calculation must be modified as a result of disaggregating from a daily equilibrium to an hourly equilibrium. Since the benefit of a road improvement is computed by calculating the change in average *daily* consumer surplus, the inclusion of Step 4 ensures that the algorithm computes average *daily*, rather than *hourly*, consumer surplus.

4. Empirical Results

In this section we review and compare results on the short-run elasticity of highway demand, VOT and VOR. These parameters have received much attention in the literature, and since VOT and short-run elasticity enter our model via highway demand and supply, respectively, it is worthwhile to discuss the empirical ranges of these parameters.

There is a general consensus in the literature that, on average, the short-run price elasticity of highway demand is fairly inelastic. Table 1 provides selected results. According to this table, elasticity estimates range from –0.03 to –0.83. The lowest values of toll elasticities are typically associated with heavy congestion. For example, bridges in highly congested U.S. metropolitan and the peak are generally associated with low elasticities. Wuestefeld and Regan (1981)'s findings suggest elasticities vary according to the purpose, length and frequency of the trips, and the existence of a toll-free alternative. Hirschman et al. (1995) find that tolled highway demand is more sensitive when untolled alternative roads are available. According to Burris et al. (2001)'s results, travelers responded to off-peak toll discounts in Florida. Thus, CBA should allow for within day variations in short-run elasticity.

Table 2 reports selected results of several recent studies on the VOT.[15] The revealed preference studies report higher medians than the stated preference studies, which is consistent with Wardman (2001)'s meta-analysis findings. Stated preference studies make use of survey instruments while revealed preference studies rely on the real-time decisions of commuters faced with congestion. The revealed preference studies listed in Table 2 use micro data from commuters' account information and electronic transponders, which are located in their cars. Thus the choice models in revealed preference studies such as Brownstone et al. (2003) mimic the real-time decisions commuters are faced with, suggesting that stated preference studies underestimate the VOT. Traffic congestion influences VOT as well. Results from the literature suggest that VOT during the peak is 30 percent higher than it is during the off-peak (Bradely et. al, 1986 and Bates et al., 1987). Thus CBA should also allow for within day variations in VOT.

VOR measures the willingness to pay for reductions in day-to-day variability in the lengths of commutes. VOR studies are not as common as VOT studies, and are estimated with revealed preference data. Small, Winston and Yan (2002) estimate the median VOR to be about $20 per hour. Lam and Small (2001) were able to disaggregate the median VOR into male and female components. The female median VOR was estimated to be about $30 per hour, which was about twice that of the male median VOR.

By simply replacing VOT_i with $VOT_i + \rho VOR_i$ in equation (7), where ρ is some measure of the propensity for traffic delaying incidences on a given section of highway, our model could permit the VOR to influence the disaggregated supply curve. This could be an important improvement in CBA because some sections of highways exhibit higher propensities for delay than others.

5. Numerical Simulation and Sensitivity Analysis

In this section we demonstrate how dramatically our algorithm improves CBA. We use simulation to calculate the increase in consumer surplus that results when an improvement is made to a hypothetical section of highway. The freeway section under consideration is assumed to be the one-way portion of an interstate having multiple lanes. Therefore equation (1) is selected and T is set equal to one. The road under consideration is currently equipped with reversible lanes, and as a result the hourly capacities of this section of roadway during peak and off-peak hours are 20,000 and 10,000, respectively. Upon completion of the improvement project the capacity of this section of highway increases by 25 percent, *ceteris paribus*. Traffic planners have estimated the price without delay, the average hourly peak and off-peak traffic volumes, and average length of the peak in hours to be 0.56, 20,000 3,000, and 6 respectively.

The results of our simulations are reported in Table 3. We conducted two sets of simulations to compute the increases in consumer surplus that results from the highway improvement mentioned above. A comparison of the two sets of results demonstrates how our model improves CBA at various values of VOT, VOR and demand elasticity. The first set of simulation results are from the daily highway demand and supply model, equations (2) and (4). Columns (1.a) through (4.a) report these results. The second set of results was computed using our disaggregation algorithm. We report these results in columns (1.b) through (5.b). Columns (1.a), (1.b), (2.a) and (2.b) correspond to simulations based on stated preference studies, while the remaining columns are the results of simulations based on revealed preference studies. The top row of each pair of rows under columns (1.b) – (5.b) corresponds to the peak, while the rows below each of these correspond to the off-peak. Column (x.b) reports the results of disaggregating the results from column (x.a) where x = 1, 2, 3, 4. Notice that the daily CBA model drastically underestimates the benefit of the improvement for each set of assumptions. Column (5.b) shows how further disaggregation via hourly VOT improves the benefit calculation over columns (3.b) and (3.a).

Table 4 reports the results of sensitivity analyses we performed on our disaggregation algorithm using column (5.b) as the baseline. Each of the variables in the first column was increased by 10 percent, holding all other parameters and variables in the model constant. The rest of the columns report the percent change in the off-peak, peak and overall benefit calculation. The off-peak variables have very little impact on overall benefit. This is because the off-peak demand curve intersects the flat section of the supply curve, and so improvements in supply have very small price effects. The peak variables, however, have much larger impacts on overall benefit. Accounting for peak shifting in CBA will allow policy makers to more accurately calculate road improvement benefits.

6. Conclusions

Our simple disaggregation model demonstrates how accounting for peak shifting improves benefit calculations in CBA. Our model makes four major improvements to CBA. For one, it allows highway supply to shift when capacity is varied to alleviate congestion during a given day. Second, it permits VOT to be adjusted for each period of disaggregation, and allows planners to include VOR into the benefit calculations as well. Third, our algorithm permits peak-shifting of the highway demand curve resulting from changes in the number of commuters throughout the day. Finally, traffic planners can specify short-run price elasticities of periodic highway demand. Our algorithm allows traffic planners to make better and more viable economic decisions, and as a consequence, commuters will be better served.

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[1] Currently, HERS does not use VOR to compute cost-benefit ratios. Including VOR should improve the performance of any CBA that does not account for day-to-day variability in travel times.

[2] See Department of Transportation publication DOT-VNTSC-FHWA-99-6. HERS calculates the net present value of the benefit-cost ratios of various highway improvements such as resurfacing, reconstruction, lane widening, shoulder widening, increasing the number of lanes, and highway realignment. HERS makes these computations with its six internal computer models: speed, pavement deterioration, travel forecast, fleet composition, widening feasibility, and capacity. The transportation literature refers to this equation as the daily user cost function; HERS refers to this as the daily price with delay function. To be consistent with HERS, we refer to this equation as the price with delay function for the remainder of this paper.

[3] Table 6-3 of DOT-VNTSC-FHWA-99-6 shows the delay equation assigned to sections with stop signs, Table 6-4 shows the delay equation assigned to sections with traffic signals, Table 6-5 shows the delay equation assigned to free-flow sections with one lane in each direction, and Table 6-6 shows the delay equation for freeways and multilane rural highways.

[4] This delay equation is shown in Table 6-6 of DOT-VNTSC-FHWA-99-6, p. 6-11.

[5] HERS denotes the ratio of the average annual daily traffic volume and highway capacity with *ACR*. For simplicity, we use *A*.

[6] The HERS expected daily delay equation is in hours per 1000 vehicle miles. To get the average delay per vehicle mile, HERS divides the delay equation by 1000.

[7] The price without delay (p_{wod}) includes travel time cost without delay, operating costs, property damage, injury cost, fatality cost, and cost of delays due to crashes. All of the components of p_{wod} are in dollars per vehicle mile traveled.

[8] HERS refers to equation (2) as the highway supply equation, while the Transportation Economics literature refers to it as link supply (Kanafani, 1983). We refer to it as the supply curve to be consistent with the HERS manual.

[9] V_0 and p_0 are inputs to HERS. DOT-VNTSC-FHWA-99-6 refers to V_0 and p_0 as the initial volume and price without delay. For a more detailed discussion on this point, see DOT-VNTSC-FHWA-99-6 section 6.3.3.

[10] Since there is no direct empirical estimate of the short-run price elasticity of highway demand, it is typically assumed by many traffic planners to be –1. For a more detailed discussion, see Appendix C of DOT-VNTSC-FHWA-99-6.

[11] For demonstration purposes we disaggregate to the hourly level. However, further disaggregation down to the minute level is possible. This level of disaggregation would require us to have delay be a function of Average Annual Minute Traffic volume (*AAMT*).

[12] If delay is a function of *AAMT*, then we would have to replace A with $1440Tv/C$ in equation (1). This would disaggregate the expected average daily delay equation for one-way and two-way roadways in hours per 1000 vehicle miles down to the minute level.

[13] If disaggregation goes all the way down to the minute level, these traffic volumes would be in average annual traffic volumes per minute.

[14] Planners that have use average peak, off-peak and counter-peak traffic volumes would define l_i to be equal to the length of the peak in hours. However, planners that have hourly traffic volumes would define l_i to equal to 1 hour. Disaggregation down to the minute level means l_i to equal to 1 minute.

[15] Each estimate in Table 1 represents a weighted median across the study's samples.

REFERENCES

Arnott, R., A. de Palma and R. Lindsey (1990): “Economics of a Bottleneck.” *Journal of Urban Economics*, 27(1): 111-130.

Braid, R. (1989) “Uniform versus Peak-Load Pricing of a Bottleneck with Elastic Demand.” *Journal of Urban Economics*, 26(3): 320-327.

Bates, J., Dix, M. and May, A. (1987): “Travel time variability and its effect on time of day choice for the journey to work.” Proceedings of the PTRC Summer Annual Meeting, Seminar C: Transportation Planning Methods, pp, 293-311. PTRC Education and Research Services, London.

Bradley, M., Marks, P. and Wardman, M. (1986): “A summary of four studies into the value of travel time savings.” Proceedings of the PTRC Summer Annual meeting, Seminar M: Transportation Planning Methods, pp. 271-285. PTRC Education and Research Services, London.

Brownstone, D. and K. Small (2005): “Valuing Time and Reliability: Assessing the Evidence from Road Pricing Demonstrations.” *Transportation Research: Part A: Policy and Practice* 39(4): 279-293.

Brownstone, D., A. Ghosh, T. F. Golob, C. Kazimi, D. Van Amelsfort (2003) "Drivers’ Willingness-to-Pay to Reduce Travel Time: Evidence from the San Diego I-15 Congestion Pricing Project.” *Transportation Research – Part A*, 37(4): 373-387.

Burris, M.W., A. Cain, and R.M. Pendyala (2001): “Impact of Variable Pricing on Temporal Distribution of Travel Demand.” *Transportation Research Record* 1747: 36-43.

Calfee, J. and C. Winston (1998): “The Value of Automobile Travel Time: Implications for Congestion Policy.” *Journal of Public Economics*, 69(1): 83-102.

Cohen, Y. (1987): “Commuter Welfare Under Peak-Period Congestion Tolls: Who Gains and Who Loses?” *International Journal of Transport Economics*, 14: 238-266.

de Palma, A. and R. Arnott (1986): “Usage-Dependent Peak-Load Pricing,” *Economics Letters*, 20(2): 101-105.

Gifford, J.L. and S.W. Talkington (1996): “Demand Elasticity Under Time-Varying Prices: Case Study of Day-of-Week Varying Tolls on the Golden Gate Bridge.” *Transportation Research Record* 1558: 55–59

Gonzalez, R. M. (1997): “The Value of Time: A Theoretical Review.” *Transport Reviews* 17, 245-266.

Harvey, G. (1994): “Transportation Pricing Behavior. Curbing Gridlock: Peak-Period Fees To Relieve Traffic Congestion,” Transportation Research Board Special Report 242. Washington, DC: National Academy Press: 89–114

Henderson, J. V. (1992): “Peak Shifting and Cost-Benefit Miscalculations.” *Regional Science and Urban Economics*, 22(1): 103-21.

Highway Economic Requirements System Version 3.26, U.S. Department of Transportation publication DOT-VNTSC-FHWA-99-6, 2000.

Hirschman, I., C. McNight, R.E. Paaswell, J. Pucher, and J. Berechman (1995): “Bridge and Tunnel Toll Elasticities in New York: Some Recent Evidence.” *Transportation* 22: 97–113.

Jones, P. and A. Hervik (1992): “Restraining Car Traffic in European Cities: An Emerging Role for Road Pricing.” *Transportation Research – Part A*, 26(2): 133–145.

Kanafani, A. (1983) *Transportation demand analysis*, New York: McGraw-Hill.

Lam, T.C. and K. Small (2001): “The value of time and reliability: measurement from a value pricing experiment.” *Transportation Research – Part E*, 37(2/3): 213-251.

Lawley Publications (2000): “Traffic Responses to Toll Increases Remain Inelastic.” *The Urban Transportation Monitor*, 14(10):

Lin, K. and D. Niemeier (1998): “Temporal Disaggregation of Travel Demand for High Resolution Emissions Inventories,” *Transportation Research – Part D*, 3(6): 375-387.

Matas, A. and J. Raymond (2003): “Demand Elasticity on Tolled Motorways.” *Journal of Transportation and Statistics*, 6(2/3): 91-108.

Mauchan, A. and P. Bonsall (1995): “Model Predictions of the Effects of Motorway Charging in West Yorkshire.” *Traffic, Engineering and Control*, 36: 206–212

May, A.D. (1992): “Road Pricing: An International Perspective.” *Transportation*, 19: 313–333.

McCarthy, P. S. (2001): *Transportation Economics: Theory and Practice: A Case Study Approach*, Malden, MA: Blackwell Publishers.

Morlok, E. (1978): *Introduction to Transportation Engineering and Planning,* New York: McGraw-Hill.

Oum, T.H., W.G. Waters, and J.S. Yong (1992): “Concepts of Price Elasticities of Transport Demand and Recent Empirical Estimates.” *Journal of Transport Economics and Policy*, 26(2): 139–154

Pigou, A. C. (1920): *The Economics of Welfare*, London: Macmillan.

Ribas, E., J.L. Raymond, and A. Matas (1988): Estudi Sobre la Elasticitat Preu de la Demanda de Tràfic per Autopista. Departament de Política Territorial i Obres Públiques, Generalitat de Catalunya, Barcelona, Spain

Small, K., C. Winston and J. Yan (2002): “Uncovering the Distribution of Motorists’ Preferences for Travel Time and Reliability: Implications for Road Pricing. Working Paper 546, UCTC: http://www.uctc.net/papers/546.pdf.

Small, K., R. Noland, X. Chu, and D. Lewis (1999): “Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation.” National Cooperative Highway Research Program Report 431, National Academy Press, Washington, DC.

TRACE Consortium (1998): Outcomes of Review on Elasticities and Values of Time. The Hague, Netherlands.

Vickery, W. (1969): “Congestion Theory and Transport Investment,” *The American Economic Review*, 59(2): 251-260.

Wardman, M. (1998): “The value of travel time: A review of British evidence.” *Journal of Transportation Economics and Policy*, 32(3): 285-316.

Wuestefeld, N.H. and E.J. Regan (1981): “Impact of Rate Increases on Toll Facilities.” *Traffic Quarterly* 34: 639–55

FIGURE 1 The H.E.R.S. All-Day Equilibrium

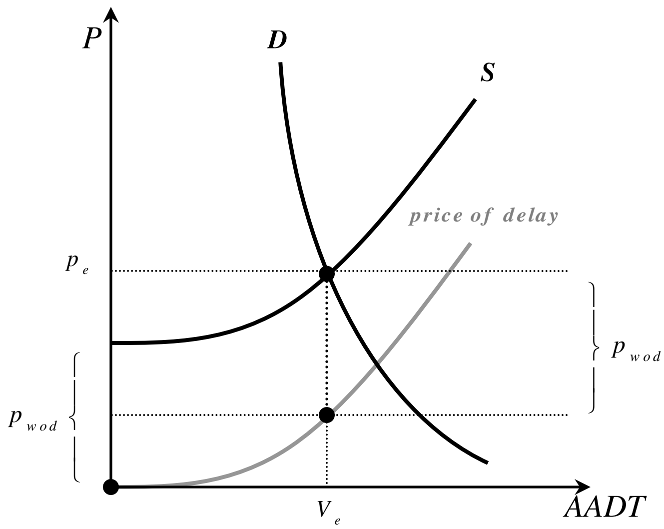
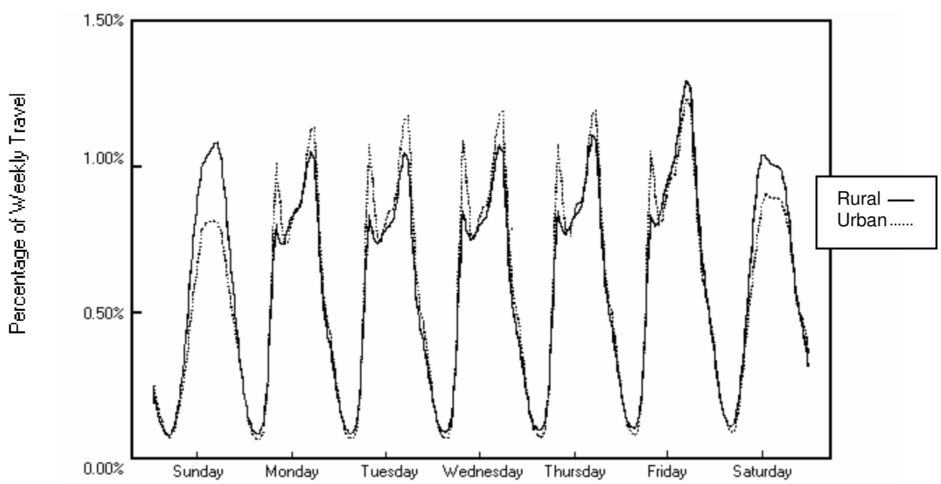


FIGURE 2 Example of Daily Variation in Traffic flow by Type of Route



Source: FHWA, Office of Highway Information Management, *Summary of National and Regional Travel Trends 1970-1995, Washington, D.C.: FHWA, U.S. Department of Transportation, 1996.*

FIGURE 3 The Average Hourly Equilibria (when there is no counter-peak)

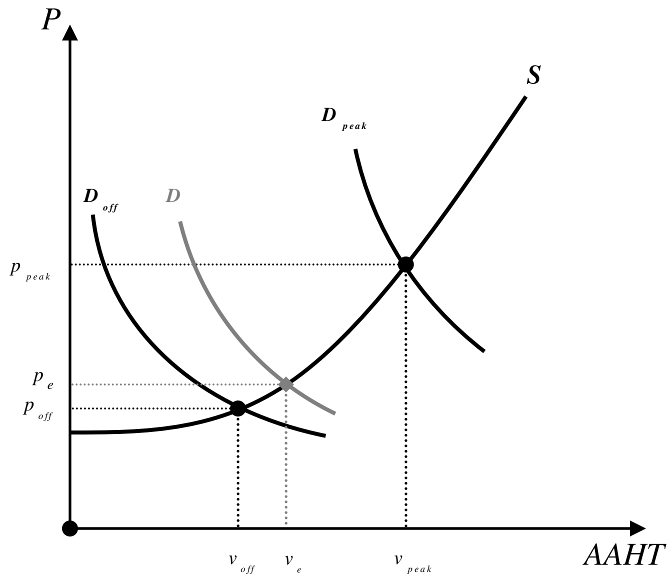


FIGURE 4 The Peak, Counter-peak and Off-peak Supply Curves

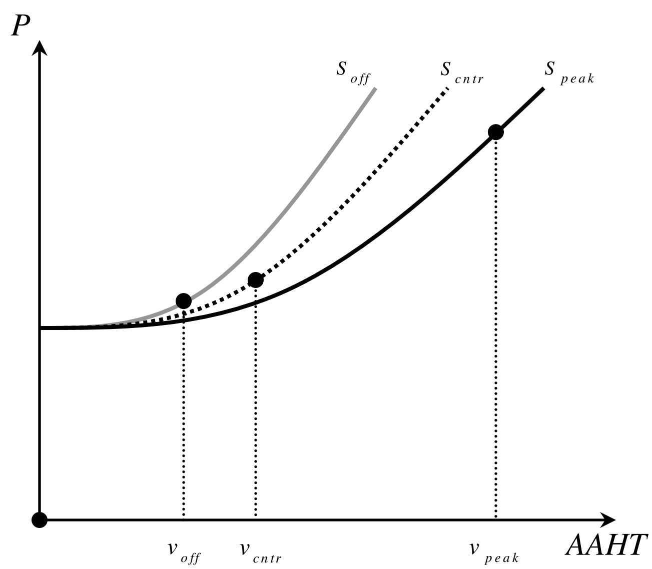


FIGURE 5 The Peak, Counter-peak and Off-peak Equilibriums

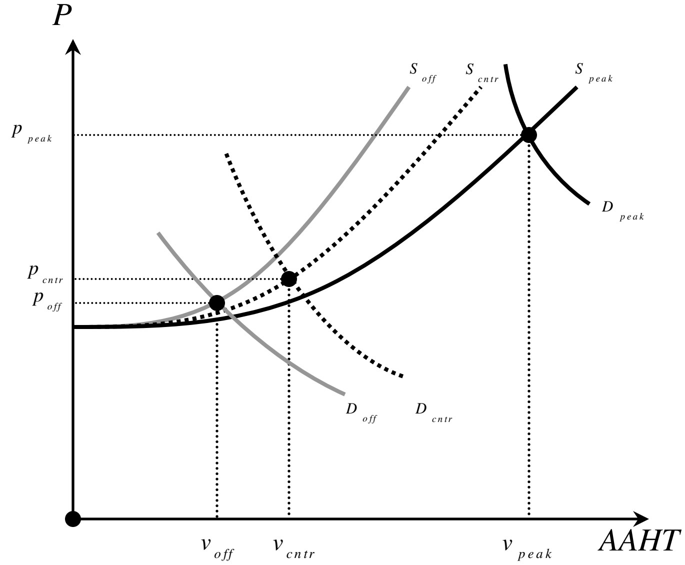


Table 1—Elasticity of Highway Demand From Recent Select Studies

Study	Data Source	Type of Elasticity	Low	High
Wuestefeld and Regan (1981)	16 tolled roadways in U.S.	Roads	-0.03	-0.31
		Bridges	–0.15	–0.31
White (1984)	Southampton, UK	Peak	-0.21	-0.36
		Off-peak	-0.14	-0.29
Ribas, Raymond, and Matas (1988)	3 intercity roadways, Spain		-0.15	-0.48
Jones and Hervik (1992)	Oslo, Norway	Metro	-0.22	
	Alesund, Norway	Tourist	-0.45	
Harvey (1994)	Golden Gate Bridge, San Francisco Bay Bridge, and NH Everett Turnpike	Roads	-0.1	
		Bridges	-0.05	-0.15
Hirschman et al. (1995)	6 bridges and 2 tunnels in the NYC area		-0.09	-0.5
Mauchan and Bonsall (1995)	Simulation model of West Yorkshire, UK	Highway System	-0.4	
		Intercity Highways	-0.25	
Gifford and Talkington (1996)	Golden Gate Bridge, San Francisco, U.S.	Weekend (own price)	-0.18	
		Week Day (x price)	-0.09	
INRETS (1997)	French roadways for trips longer than 100 km		-0.22	-0.35
Lawley Publications (2000)	New Jersey Turnpike		-0.2	
Burris, Cain, and Pendyala (2001)	Lee County, Florida	Off-peak	-0.03	-0.36
Matas and Raymond (2003)	Spanish tolled roads between 1981 and 1998	Short-Run	-0.21	-0.83

Table 2—Median VOT Estimates from Select Recent Studies

	Preferences	Data	Median VOT ($/hour)
Lam & Small (2001)	Revealed	SR91[1]	23-24
Small, Winston & Yan (2002)	Revealed	SR91	20-25
	Stated	SR91	9
Brownstone et al. (2003)	Revealed	I-15[2]	30
Steimetz and Brownstone (2005)	Revealed	I-15	22-45
Ghosh (2001)	Revealed	I-15	21-40
	Stated	I-15	13-16
Calfee, Winston & Stempski (2001)	Stated	Survey[3]	4

[1] California State Route 91 in Orange County includes four regular freeway lanes and two express lanes in each direction. Commuters that used these express lanes had to carry electronic transponders to pay tolls which vary by hour.
[2] The San Diego 1-15 Congestion Pricing Project was set up on 8.5 mile section. It allowed solo drivers to pay to use reversible HOV lanes. Commuters carried electronic transponders to pay tolls which varied to maintain free flow speed.
[3] The survey was conducted by Alison-Fisher, Inc. in December 1993.

Table 3—Simulation Results

	Daily Supply and Demand				Disaggregated Hourly Model				
	(1.a)	(2.a)	(3.a)	(4.a)	(1.b)	(2.b)	(3.b)	(4.b)	(5.b)[1]
VOT	10	10	30	30	10	10	30	30	44
					10	10	30	30	30
Elasticity[2]	-0.5	-0.05	-0.5	-0.05	-0.8	-0.08	-0.8	-0.08	-0.8
					-0.4	-0.04	-0.4	-0.04	-0.4
Initial Price	0.64	0.67	0.72	0.86	1.44	1.44	3.20	3.20	4.43
					0.57	0.57	0.58	0.58	0.58
Final Price	0.59	0.59	0.63	0.65	1.22	1.03	2.66	2.01	3.67
					0.57	0.57	0.58	0.58	0.58
%Δ Price	-7.9	-11.4	-12.3	-24.3	-15.1	-28.5	-16.9	-37.0	-17.3
					-0.33	-0.32	-0.95	-0.95	-0.95
%Δ Traffic	4.2	0.6	6.8	1.4	14.0	2.7	16.0	3.8	16.4
					0.13	0.01	0.38	0.04	0.38
Benefit	8340	13152	14024	35904	27978	49971	70244	144587	99152

[1] Column (5.b) allows VOT, VOR, elasticity, and capacity to very over the peak and off-peak. According to the empirical results, VOT is about 30 percent greater in the peak than it is in the off-peak. Thus we assumed peak VOT was equal to (30)(1.3) = 39 dollars per hour. Also, we assumed the VOR was 5 dollars per hour.
[2] Daily elasticities equal the average of peak and off-peak elasticities weighted by length of peak (L = 6 hours).

Table 4—Sensitivity Analysis[1]

	Percent Change in Benefit		
10% Increase in Variable	Off-peak	Peak	Overall
VOT peak	0	8.127	8.103
VOT off-peak	9.931	0	0.030
VOR[2]	0	1.042	1.039
Elasticity of the peak	0	-5.593	-5.577
Elasticity of the off-peak	-0.095	0	-0.0003
Length of the peak	-3.333	10.000	9.960
Capacity of the peak	0	41.657	41.531
Capacity of the off-peak	34.629	0	0.104
Price without delay	0.142	0.829	0.822

[1] The analysis here uses column (5.b) of Table 3 as a baseline.
[2] Since the off-peak is rarely affected by traffic delaying incidents, the VOR is assumed to affect only peak travel.