APPENDIX C

Demand Elasticities for Highway Travel

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An elasticity summarizes a large amount of information in a single number. Levels and distribution of incomes, price levels of the specific good and of substitute and complementary goods, preferences and tastes, transaction costs, etc., can, *ceteris paribus*, affect the measured value of any particular demand-price elasticity. The elasticity concept normalizes for the measurement scales (e.g., pounds or kilograms, dollars or pesos) and price levels (to the degree that the demand curve is constant elasticity), but other factors are ignored or implicitly averaged. Although the price elasticity of travel demand is frequently mentioned in discussion, there is no direct empirical measurement of elasticity with respect to the price of highway travel, and there are several alternatives about even what that price consists of.

The review and synthesis presented in this Appendix was conducted for the purpose of establishing values for use in the HERS model to represent the short run elasticity of demand on a given highway section, and to estimate the long run share parameter used for estimating induced demand, as described in Appendix B.

Theory

As an empirical measure, an elasticity is a microeconomic aggregate: it summarizes demand in a specific market at a point in time, at or near the prevailing price and quantity. A market could be a highway facility, a corridor, or an entire region. A point in time might be a peak hour, or a daily average. The basic concept can be represented as an arc elasticity between two demand points,

The Meaning of Elasticity

$$e \ = \ \frac{\%\Delta v}{\%\Delta p} \ = \ \frac{\Delta v}{\Delta p} \times \frac{p_0}{v_0} \tag{1}$$

where v_0 = initial traffic volume and p_0 = initial price. Elasticity can be thought of as a measure of slope normalized for the arbitrary measurement scales of p and v, and, indeed, the form to the right of the second equal sign is a slope multiplied by the initial demand point. If the derivative of the demand curve is substituted for the slope, the elasticity is instantaneous at the given point, rather than over an arc. For exposition, the arc form will be used, but the principles apply to either form.

Transferability

For a different time point on the same facility, a different group of users may respond differently to a change in price, because they have different incomes, demographic characteristics, and tastes. Moreover, prices in related markets (e.g., parallel facilities) may be different. If comparing different facilities, the above may be different, as well as differing substitute alternatives (routes, carpool and transit options, destinations, schedule options). Different days, seasons, regions, and forms of "price" all limit the transferability of an elasticity measured in one context to another context.

Hence -- unlike the speed of light or the age of a rock -- there is no underlying true number waiting to be discovered. Similar circumstances are likely to exhibit roughly similar elasticities, but the most important characteristics of these circumstances need to be made explicit. Given the nature of the empirical evidence, selecting appropriate values must rely heavily upon *a priori* reasoning.

Price, Output, and Market

The basic economic model of exchange reconciles supply and demand in a market, using price. The "price" is the market value of the resources given up by the buyer and received by the seller, accomplished in modern markets by means of some form of money that both parties agree to use as representing valuable resources. The market of interest in the present context is highway travel, measured as vehicle miles of travel (VMT). A single market has a single price, so a highway market could be a street length between intersections at a specific time of day. The concept of a market can be applied more broadly, however, to consist of a facility whose demand is averaged over the day, or a network of facilities. Elasticities will generally be larger (elastic) the more alternatives (route shift, time of day shift, add or forego trip) are available, and smaller (inelastic) the more broadly the market is defined (e.g., region versus facility). For present purposes, the focus is on a single facility, and its daily VMT.

Money Price

If the price measure were limited to the money price paid by the user to obtain the services of the highway, then such characteristics as travel time, pavement roughness, risk of accident, scenery, and curves and grades would be attributes of the service. Such a money price (assuming the user had access to a vehicle) would be a multi-part price consisting of vehicle registration fee, drivers' license fee, excise taxes on fuel and tires, and tolls.

This formulation of the highway market has limited usefulness for several reasons. Primarily, the fees paid are a small part of the total cost to the user of highway travel, and attributes of the good (such as travel time) dominate the choice rather than price. Because travel is a derived demand, at least some of the attributes can be thought of as part of the cost to be minimized, including time and operating costs as well as user fees.

Generalized Price and Its Components

Hence, an alternative formulation is to treat some of the attributes as disutilities, and translate them into a dollar price. Operation of the vehicle, travel delay, and tolls are thus all costs to the user, or components of the price. In practice, the only way to estimate the demand elasticity of highway travel is to build up total travel demand elasticity from elasticities of the components of user costs.

Three relationships are central to estimating total demand elasticities from component elasticities: the component's own-price elasticity, the correspondence of a change in the price of the component to a change in the price of travel, and the expansion from the component to the total elasticity.

Price Elasticity for a Component

If X is a component of the price of travel, and we observe its own price elasticity, then

$$e_X = \frac{\Delta q_X}{\Delta p_X} \times \frac{p_X}{q_X} \qquad \text{[2]}$$

where e_X is the demand price elasticity of good X, Δq_X is the change in the quantity of X that is consumed (e.g., gallons of fuel), Δp_X is the change in the price of the good (e.g., the price of gasoline at the pump), p_X is the initial price of the good, q_X is the initial quantity of the good, and $\Delta q_X/q_X$ is the percent change in the quantity of good X. This is a relationship between the price of the component and *its* consumption, not the consumption of the overall good of which X is a component.

Leakage from Component to Total

Higher fuel prices, for example, are partly absorbed in improved fuel mileage, so that the percentage reduction in fuel consumed is greater than the percentage reduction in VMT. The extent of this "leakage" between the component price elasticity and travel demand elasticity depends upon the component, and the possibilities for economizing on the component other than by reducing travel. A change in the price of a component of travel cost is not exactly an equivalent change in the price of travel, and less so in the long run. In general,

$$e_{T,X} = \sigma \times e_X, \quad \sigma \leq 1 \qquad \text{[3]}$$

where $e_{T,X}$ = elasticity of travel demand with respect to a change in the price of X, and σ = a shrinkage factor representing the share of a reduction (or change) in consumption of X that consists of reduction in travel. A $\sigma = 1$ implies that the component and travel are necessarily consumed in fixed proportions.

Expansion From Component to Total

If the elasticity of VMT with respect to a part of the price is known, then the elasticity of total travel demand is simply an expansion from the part to the whole,

$$e_T = \frac{e_{T,X}}{p_X/p_T} = \frac{\sigma e_X}{p_X/p_T}$$

[4]

where e_T = demand elasticity for travel (the overall good), p_T is the price of travel, and the component elasticity e_X is substituted using [3]. The bottom of the right-hand side is the share of the component in the total price of travel. For example, if the elasticity of gasoline consumption with respect to its own price is -0.25, and the shrinkage factor is 0.6 (from changes in fuel efficiency), then the elasticity of *travel* with respect to gasoline price is -0.15. If fuel is 20% of the cost of travel, then the implied demand elasticity is -0.75 with respect to the total price of travel.

Empirical Estimation of Price Components

From Evidence to Application

Because generalized price is being used rather than narrower money price, the analysis proceeds in two major steps: first, each of the components of generalized price (operating cost, time, etc.) is studied for what the empirical evidence says about the total vehicle price elasticity; and second, the total vehicle price elasticity is applied to specific contexts where various elasticity components (route change, forgo trip, etc.) may or may not be available as substitutes. The overall process is represented in Figure C-1.
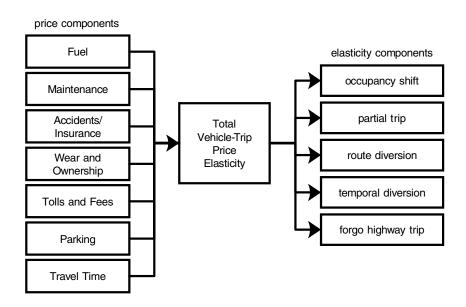

price components

| Fuel |
| Maintenance |
| Accidents/ Insurance |
| Wear and Ownership |
| Tolls and Fees |
| Parking |
| Travel Time |

Total Vehicle-Trip Price Elasticity

elasticity components

| occupancy shift |
| partial trip |
| route diversion |
| temporal diversion |
| forgo highway trip |

Figure C-1. Primary analytical steps in generating project-specific elasticities.

Empirical studies are mainly oriented toward changes in one component of price; these studies can be extrapolated to the full price. Once a total price elasticity is determined, then that value must be adjusted to apply to a specific context such as a highway section. If the section constitutes only a portion of the typical vehicle trip, then the elasticity with respect to a price change on the section will be lower than if the same percentage price change were applied to the entire trip. In contrast, if route diversion, occupancy changes, and changing the departure time of the trip are ways to escape the burden of a price increase, then the applicable elasticity will be higher than the total elasticity. If the only alternative is to forgo the trip, then the applicable elasticity will be at the low end of the range. Because the application under consideration here is to highway travel, a switch to bus is an occupancy change whereas a shift to rail transit is a trip forgone. The evidence and analysis presented here pertains primarily to passenger travel, although trucks can be expected to respond in similar ways.

It is important to remember that the analysis concerns vehicle-trips, not person-trips. Although persons make the decisions for vehicles, vehicle trips are more readily observed, and the price typically applies to vehicle travel rather than to person trips.

The methodological strategy for moving from information about the components of user cost or "price" to travel demand elasticity is represented in Figure C-2 and described below:

(1)   The first step is an accounting problem to define the user cost categories for which data have been collected and tabulated, matched with those for which elasticities have been or could be measured. The units are in dollars per vehicle mile of travel.

(2)   Because price per VMT -- even by component -- is an average of unlike conditions (large and small cars, urban and rural traffic), a more robust result is obtained by considering several different data sources and reconciling the numbers. Again, the choice of measure must match whatever is used or implied in empirical elasticity estimates.

(3)   A major source of uncertainty in expanding from component to total price is which components should be included in the "price" to the user. Possibilities range from using only short run variable out-of-pocket costs that the user "perceives," to all costs paid by the user including travel time.

(4)   Within this range of uncertainty, low and high percentage shares can be calculated for each of the price components.

(5)   Empirical estimates of any relevant elasticity estimates can be combed from the literature, formal or informal. Not all components are suitable for estimating elasticities empirically (e.g., accidents), and some that are suitable may not have been the subject of published estimates.

(6)   Given an own-price elasticity estimate for a component, and its share in the total price, the next problem to be resolved is the extent to which a change in

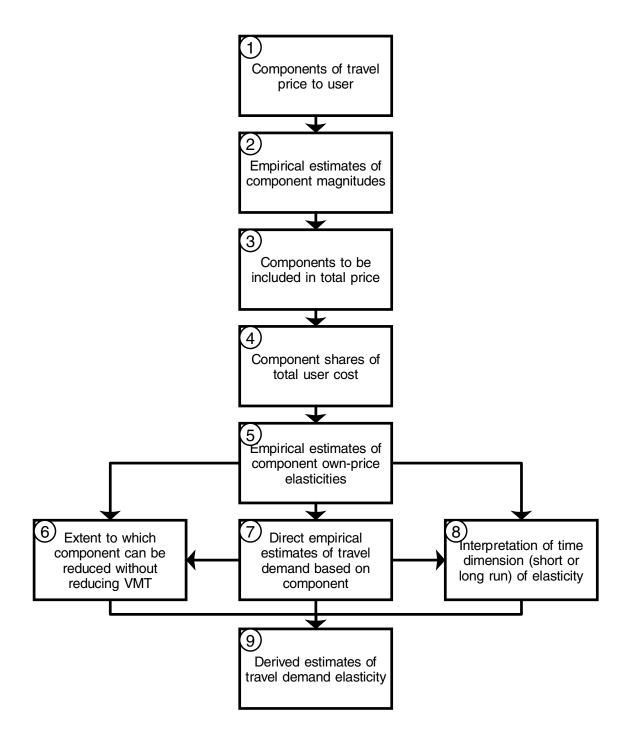**Construction of Travel Demand Elasticities from User Cost Components**

① Components of travel price to user

② Empirical estimates of component magnitudes

③ Components to be included in total price

④ Component shares of total user cost

⑤ Empirical estimates of component own-price elasticities

⑥ Extent to which component can be reduced without reducing VMT

⑦ Direct empirical estimates of travel demand based on component

⑧ Interpretation of time dimension (short or long run) of elasticity

⑨ Derived estimates of travel demand elasticity

Figure C-2. Method For Building Travel Demand Elasticities From Price Components.

the consumption of the component results in the same percentage change in VMT, i.e., the shrinkage factor.

(7) For those instances in which a travel demand elasticity has been estimated from changes in the price of the component, the component elasticity can be inflated directly to the total demand elasticity; this information can also be compared to any own-price elasticities to assess the "leakage" into non-VMT changes.

(8) All of the empirical elasticity estimates must be interpreted along several dimensions, the most important being whether it is a short run or long run estimate. Many published estimates are ambiguous regarding the time span covered.

(9) The above information, subject to its range of uncertainty, can be distilled into estimates of short run and long run travel demand elasticities based on generalized price.

These steps are explained and implemented in more detail below.

Seven categories of user cost are listed in Table C-1. They are intended to be non-overlapping and exhaustive. Fortunately, this set of categories is generally consistent with various estimates of user costs. The purpose of these categories is to be able to combine them in subsets that provide alternative measures of the "price," to distinguish fixed from variable costs as a means for defining the relevant costs, to match with empirical estimates of costs, and to match up with empirical elasticity estimates.

Accounting Framework for Price Components

Table C-1. User Cost Accounting Framework

Category	Scope
Fuel	gasoline, diesel fuel, or other fuel consumed by motor vehicles, including taxes
Maintenance	oil, parts, periodic maintenance, unscheduled maintenance, tires, excise taxes
Accidents and Insurance	costs of accidents (internal), insurance administration and profit
Vehicle Wear and Ownership	wear and tear, additional depreciation, financing, sales and excise taxes
Tolls and Fees	tolls, registration fees, license fees
Parking	cost of parking to the user at work, shopping or other
Travel Time	dollar value of time spent in traveling

Estimates of national averages for the cost components of highway travel are provided in Table C-2. All are intended to cover internal costs borne by users, omitting externalities, since elasticities necessarily must be based on internal costs. Four sources are presented, each of which offers a different orientation:

Estimates of Component Shares

Table C-2. **Estimates of Components of User Cost ($/VMT)**

Component	Back-of-Envelope	Delucchi	Runzheimer	FHWA
(1) Fuel	0.058	0.069	0.067	0.061
(2) Maintenance	0.087	0.073	0.052	0.053
(3) Accidents and Insurance	0.087	0.133	0.070	0.070
(4) Wear and Ownership	0.125	0.142	0.248	0.127
(5) Tolls, Fees	0.002	0.015	0.003	0.009
(6) Parking	0.022	0.004	0.019	0.013
(7) Time	0.306	0.344	0.344	0.344
Total Variable	0.232	0.275	0.189	0.184
Total Monetized	0.381	0.436	0.459	0.333
Total Variable w/ Time	0.538	0.620	0.495	0.490
Total Internal	0.687	0.780	0.765	0.639

Notes:

(1) Fuel -- BoE assumes $1.15 for fuel (including excise taxes) and 19.7 miles per gallon average fuel economy for all passenger vehicles (FHWA 1996 Highway Statistics); Delucchi value is sum of fuel costs, oil company producer surplus, and fuel taxes (Delucchi, 1998), divided by total 1991 US annual VMT of 2,172 billion (Highway Statistics); Runzheimer values are extracted by applying their 1998 percentage distribution of costs for and intermediate car to their estimates of annual fixed ($6,934) plus operating costs ($2,240) of a Ford Taurus (Runzheimer, 1997, 1998); FHWA values are for an intermediate sedan, including fuel taxes, at $1.196 per gallon (Jack Faucett Associates, 1991).

(2) Maintenance -- BoE based on assumed value of $1,000 per year for oil, tires, parts, and maintenance, and an average annual mileage for passenger vehicles in 1996 of 11,492 (Highway Statistics); Delucchi estimates national expenditures on maintenance, including in-house government and private fleet maintenance, and sales taxes, but excluding external property damage, divided by national VMT (see Fuel); Runzheimer and FHWA are same as for fuel.

(3) Accidents and Insurance -- BoE assumes $1,000 per year per vehicle for insurance and accidents, divided by average mileage (see Fuel); Delucchi's estimates include insurance administration, accidents paid by users, and pain and suffering "inflicted on oneself," but not external costs; Runzheimer and FHWA same as for Fuel.

(4) Wear and Ownership -- BoE assumes a capital cost of $12,000 over 5 years, and average passenger car mileage (see Fuel); Delucchi estimates private ownership costs, excluding sales tax, divided by total US VMT (see Fuel); Runzheimer and FHWA same as Fuel.

(5) Tolls and Fees -- BoE takes 1996 total toll payments nationally of $4 billion (Highway Statistics) divided by 1996 US VMT of 2,360 (Highway Statistics); Delucchi omits user fees as transfers, so a rate of 1.5 cents per VMT is inserted; Runzheimer estimates registration fees only; FHWA includes parking with tolls, but no adjustment is made here.

(6) Parking -- BoE assumes $1 per day per vehicle for 250 days per year, over 11,492 annual miles (see Maintenance); Delucchi's values combine paid private parking and public parking; Runzheimer provides only a residual "Other" category; FHWA includes tolls with parking.

(7) Time -- BoE uses 60% of US DOT (1997) "personal" wage rate of $17 and 1.2 persons per vehicle at an average speed of 40 mph; Delucchi values time in three categories -- paid time that is delay, paid uncongested time, and unpaid time whether delay or not; neither Runzheimer nor FHWA include time costs, so the Delucchi value is used.

(1) Back-of-Envelope: The value for the particular component is estimated from a few aggregate totals, rates, and averages. This approach provides a reality check on whether other results are plausible.

(2) Delucchi:[1] In his research, Delucchi has made original estimates of national totals for most of the components for 1991, broken down finely enough to permit aggregation along several dimensions. For each item, he provides a low and high estimate, which are averaged here. His estimates are unique for

including many imputed values, such as travel time, uncompensated accident costs borne directly by users, and accident costs paid from sources other than insurance.

(3) Runzheimer:[2] The Runzheimer International Corporation is a consulting firm that collects data on highway vehicle costs and other business expenses, and compiles these into planning and forecasting estimates for business use. Their "intermediate vehicle" is a full size sedan used 20,000 miles per year and traded in after three years.

(4) FHWA:[3] Up until 1991, the Federal Highway Administration intermittently contracted for tabulations of cost components for various types of highway passenger vehicles, and published the numbers. The most recent set is based on data collected in Maryland.

The sources and methods for tabulating the various price components are described in the notes to the table.

Several criteria might be considered for guiding the definition of total price:

(1) Out-of-pocket costs: These include fuel, maintenance, parking, tolls, vehicle wear, variable insurance, and other variable costs to the user that are affected by whether a given trip is taken or not.

(2) Full, average, or long run costs: Ownership costs and the annual portion of insurance might be added to out-of-pocket costs.

(3) Generalized cost or generalized price: All variable and fixed costs, plus travel time, can be included.

(4) Perceived cost: Costs might be limited to those the user explicitly recognizes in making the decision to take a trip or use a vehicle.

Components Included in the "Price"

Generalized price is preferred from a theory standpoint, because it allows all components of cost to be fused into a single dimension. Pragmatically, the relevant price is also affected by (a) how other elasticities have been measured empirically, for comparison, and (b) how elasticity is used in the model or analytic procedure into which the parameter is inserted.[4] With proper interpretation, different measured elasticities can be used to estimate a model parameter that is defined or based differently from the empirical sources.

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[1] Delucchi (1997).

[2] Runzheimer International (199, 1998)

[3] Jack Faucett Associates (1991)

[4] The HERS model uses a generalized price including time, operating costs, and accidents, but not user fees; demand is aggregated over peak and off-peak (therefore no time diversion) and applies to a single facility (therefore the elasticity includes route diversion).

Perceived price is an attempt to identify the components of price that are consciously recognized by the user, as a basis for predicting user behavior. Whether making this intermediate variable explicit adds anything to predictive accuracy is doubtful, and, in any event, it does not provide much guidance for which costs to include. Consumers tend to respond, as a group, to attributes and magnitudes that have some significant impact on their well-being, whether consciously perceived or not.

This means that the user response depends upon what decisions are at stake. If ownership is not in question, then only variable costs may be considered, and more so in the short run. Four alternative definitions for total price are given in Table C-2, ranging from short run monetary costs to full long run costs including travel time. The distinction between variable and fixed is not clean: vehicle wear is variable, while ownership is fixed. Insurance is typically paid annually and has a large fixed component, although most exposure to risk is from operation.

Component Shares of Total User Cost

The several definitions of total cost yield a range of component shares, shown in Table C-3. Obviously, the range of values is quite large, depending more upon which total is used than upon the source of data. With travel time being roughly half the cost, its inclusion makes a big difference.

Table C-3. Component Shares in Total Price.

Component	Low Share	High Share
Fuel	8%	36%
Maintenance	9%	48%
Accidents and Insurance	7%	37%
Vehicle Wear and Ownership	18%	54%
Tolls and Fees	0%	10%
Parking	1%	10%
Travel Time	40%	62%

Empirical Estimates of Own-Price Elasticities

The number of categories drops when considering which components are suitable for empirical estimation, and more so when actual estimates are tabulated. The cost of maintenance is difficult to keep track of, and either controlled or natural experiments are hard to imagine; no such studies were found. User responses to the risk of accident based on equipment such as air bags has been used to estimate users' implicit valuation of life, but users cannot be observed reducing either their travel or their rate of accidents in response to changes in risk. Tolls, fees, and parking are clearly candidates, but apply to very specific circumstances. Direct estimates of time elasticities have been made, and indirect estimates can be derived from changes in traffic induced by changes in capacity.

Income elasticities are regarded as exogenous for purposes of estimating travel demand elasticities, by assuming that price changes are not large enough or general enough to result in a significant change in income for the average traveler.

The size of the shrinkage factor for fuel can be seen in Goodwin's (1992) review of elasticity estimates. Table C-4 summarizes his result for studies based on fuel price changes. The numbers are juxtaposed to permit comparison of elasticities of fuel consumption (average of over 100 separate empirical values) versus elasticities of travel (about a dozen numbers), stratified by whether a time series model or a cross-sectional model was used and whether the intent was short term, long term, or ambiguous.

Magnitudes of the Leakages

Table C-4. **Goodwin's Review of Fuel Price Elasticities.**

Method	Fuel or Travel	Short Run	Long Run	Uncertain
Time-series	**fuel consumption**	-.27	-.71	-.53
	travel demand	-.16	-.33	-.46
Cross-section	**fuel consumption**	-.28	-.84	-.18
	travel demand	-	.29	-0.5
Source: Goodwin (1992).				

Fuel elasticities are higher than travel demand elasticities, and long term elasticity estimates are at least twice as large as short term values, as might be expected. For fuel, the shrinkage from fuel consumption to travel consumption seems to be about 0.5-0.9, meaning that half to ninety percent of the reduction in fuel expenditure is the result of less travel.

For other price components, the shrinkage factor is more speculative. Increases in insurance and vehicle ownership costs might result in fewer vehicles but more mileage per vehicle, with the latter less than fully offsetting the former. Increases in road roughness increase wear and tear, reduce fuel mileage, and reduce speeds. Increases in tolls directly affect the cost per vehicle mile, but, depending upon how the tolls are graduated, could alter the mix of vehicles and the time-of-day distribution.

The largest user response is likely to come from those users for whom the price change is relatively largest. A fuel price or tax increase will affect long trips and vehicles with low fuel efficiency; insurance costs deter ownership in urban areas thereby shifting the geographic distribution of vehicles; high parking costs deter short trips more than long ones; high ownership or insurance costs deter vehicles with low annual utilization.

Some responses occur within days or weeks, while others may take five or ten years to reach equilibrium. To usefully interpret an empirical elasticity estimate, the time dimension must be known. If the statistical measure for an empirical estimate includes all VMT or other changes that occurred within a year of the price change, then a short run elasticity has been estimated. Longer lag periods for the same price changes yield longer run elasticities, but separating behavioral responses from background variation gets harder with longer lags.

Durations of the Short and Long Run Adjustment Periods

Several studies reviewed by Cairns, et al. (1998) reveal the degree to which individuals change their travel patterns on a daily basis. Two studies, summarized in Table C-5, are illustrative. Of a group of commuters passing a given point on a road on a given day,

Table C-5. **Travel Behavior Variability**

Location: Time Lag: Type of Travel:	Leeds 1 Week commuting	Southampton 4 months regular trips
Same behavior[a]	60%	49%
Different time	7%	5%
Different route	14%	7%
Different mode	8%	1%
Different destination	5%	13%
No trip/different trip	6%	25%

Source: Cairns, et al. (1998).

[a] travelled the same route by car within the same 2-hour time period.

60% could be found a week later within the same 2-hour block; the rest were doing something slightly or completely different. A similar study with a longer time lag showed a smaller share doing the same thing. Other studies reinforce the same conclusion: individual travel variability is high on a day-to-day basis, and more so over longer time spans. This is without any significant changes in either exogenous or endogenous factors.

One implication is that -- if stability is much higher in the aggregate than in the microscopic -- attempting to predict individual travel behavior is less fruitful than using aggregate elasticities for endogenous changes. Another is that, with so many individuals making changes within a short time span, the responses of travelers to changed conditions is likely to be rapid. There is not a lot of inertia in travel patterns. According to Cairns, et al. (1998), roughly 50% of the response to a change takes place within 1-3 years, and 90% within 5-10 years. Hence, long run elasticities tend to be about twice as large as 1-year or short run elasticities.

Conversion to Total Price Elasticity

The results of the above process are displayed in Table C-6, showing empirical estimates of component travel elasticities, along with their implied short and long run total travel demand elasticities. The range of possible values is wide, extending from -0.22 to -3.7 for short run demand and -0.57 to -5.1 for long run demand. The most plausible numbers, however, lie in the -0.5 to -1.0 range for short run demand, and -1.0 to -2.0 for long run demand. These elasticities apply to *vehicle* travel, not person travel, which can be considerably less elastic and still be consistent with these vehicle elasticities due to changes in vehicle occupancy and other adaptations.[5] The "low" values come from using the full generalized price, and reinforce the preference for full cost rather than subsets such as variable costs.

Table C-6. **Component and Total Travel Demand Elasticities**

User Cost Component	Component Elasticities		Implicit Total Travel Elasticities			
			Low		High	
	SRE	LRE	SRE	LRE	SRE	LRE
Fuel	-0.17	-0.33	-0.48	-0.93	-2.0	-3.9
Wear and Ownership	-0.12	-0.31	-0.22	-0.57	-0.6	-1.7
Tolls	-0.10	-0.19	-0.33	-0.63	-1.0	-1.9
Parking	-0.15		-1.17	-1.61	-3.7	-5.1
Time	-0.38	-0.68	-0.60	-1.07	-0.9	-1.7

Fuel Price Elasticities

Numerous empirical studies have estimated the price elasticity of gasoline, and a few have measured the travel elasticity with respect to fuel price. The review and summary by Goodwin described above reflects the results of these studies, and subsequent studies have tended to confirm his conclusions. Thus a value of -0.16 for short run travel impacts and -0.33 for long run impacts are used, with **[4]**, in Table C-6.

Ownership Elasticity

Holding exogenous factors constant, an increase in the real price of vehicles of the same quality causes a reduction in the purchases of vehicles, especially new ones. The most likely behavior response is to defer purchase of a new or better vehicle, and keep using the old one. If, however, the response is measured in the aggregate as total vehicle ownership, then fewer vehicles means less VMT, offset by the extent to which vehicles are shared.

Dargay (1998) compared several ownership and operation elasticities between the UK and France, including price elasticity and income elasticity. Converting the price elasticities to VMT elasticities, using a shrinkage factor of 0.9 and the values from Table C-3 in **[4]**, gives the results shown in Table C-6. The source of imprecision in applying ownership elasticities is the uncertain share of total cost per VMT comprised by ownership and wear-and-tear costs.

Toll Elasticities

Studies based on toll variations are somewhat inconsistent and not easily interpreted. A useful study is one by Gifford and Talkington (1996) that provides elasticity estimates for the Golden Gate Bridge in San Francisco of -0.187, based on toll variations over the days of the week as well as changes in the fee structure over several years.[6] They also review other toll elasticity studies. Because most trips are not tolled, national averages of tolls per VMT are not useful. Of trips that are tolled, $1.25 might be about average,

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[5] Cairns, et al. (1998) provide an illuminating list of examples that illustrate the many ways in which individuals and households can satisfy their travel requirements while reducing vehicle miles of travel.

[6] Harvey (1994) provides examples that are roughly consistent with Gifford and Talkington's. Peter Samuel uses a phased-in toll increase on the Ohio Turnpike to make a back-of-the envelope calculation of trip elasticity of -0.23 and VMT elasticity of -0.15, in his *Toll Roads Newsletter* for February, 2000.

yielding a share of total costs on a 15-mile trip ranging from 10-30%. This range is used in Table C-6 instead of the range shown in Table C-3.

Elasticities in response to tolls are difficult to impute because the quality of travel, in delay time, often changes when the toll changes. For measuring elasticity, an ideal experiment is one in which travel time is constant while tolls change. Under even moderately congested conditions, a toll change results in trade-offs between money and time (value of time) as well as money and travel (price elasticity), not to mention time and travel (time elasticity). Separating these seems difficult.

Parking Price Elasticities

Shoup (1994), and Willson and Shoup (1990) review more than a dozen studies of parking pricing, including their own as well as Shoup and Pickrell (1980). From these studies it is possible to extract five case studies that provide sufficient data to construct ordinary price elasticities. In all of these examples, the price of parking was zero for the base alternative in the comparison, so the calculations in Table C-7 base the elasticity estimates on an assumed total price for travel, rather than for parking alone. The elasticity magnitudes are large even when the price change is measured against only a small share of long run cost.

Table C-7. Parking Total Price Elasticities

Before/After Case Studies:	Trip Rate[a]		Parking Price[b]		Total Price Elasticity[c]	
	Free	Priced	Free	Priced	Low	High
Mid Wilshire, LA	48	30	0	58	-1.05	-3.33
Warner Center, LA	92	64	0	30	-1.65	-5.23
Ottawa CBD, Canada	94	80	0	30	-0.81	-2.56
Average					-1.17	-3.70
With/Without Case Studies:						
Century City, LA	39	32	0	23	-1.27	-4.02
Civic Center, LA	78	50	0	30	-1.95	-6.16
Average					-1.61	-5.09

Notes:

a Autos driven per 100 employees.

b Price in dollars per month.

c Full vehicle "backward" arc (low price to high) price elasticity based on 35-mile round trip average for LA reported in Willson and Shoup (1990), at an average user cost of $.22 per VMT for variable costs only (=$163 per month for the Low estimate) or $.70 for all costs including time but excluding parking (=$515 for the High estimate). Backward elasticities are lower than midpoint or forward arc elasticities for downward-sloping demand curves.

In the before/after cases, the price of parking changed at a particular work site, and the behavior responses were tracked for up to a year after parking became priced. Some of the employers had ridesharing incentive programs, which were ineffective so long as parking was free. These examples are interpreted as representative of short run demand elasticities. The with/without cases compare similar work sites, one priced and one not. These are interpreted here as long run elasticities, on the rationale that commuters had sufficient time to make long run adjustments. These elasticities would be higher if all

employee parking were priced, because more people at more sites would be seeking ridesharing or transit arrangements.

Because parking is free to the user for 99% of all trips (over 90% of urban work trips), the average share of parking in the cost of travel to the user is not a valid base value for these elasticities. As Shoup (1994) states,

> "It is important to remember that the elasticity estimates [average -0.15] refer to commuter response to changes in only the parking price of their trip and are therefore smaller than the elasticity of demand with respect to changes in the full price of automobile trips."(p. 159)

He gives other reasons why these estimates are low, including the likely availability of cheaper parking nearby and the inelasticity of work trip demand.[7]

Time Cost Elasticities

Several studies have tabulated traffic volumes subsequent to an increase in capacity, or occasionally in response to a decrease in capacity or change in travel time. For those based on change in capacity, the measure of elasticity is

$$e_{T,\,capacity} = \frac{\%\Delta VMT}{\%\Delta cap} \qquad [5]$$

where $\%\Delta cap$ = percent change in capacity, with capacity measured in lane miles. Hansen et al. (1993) estimate this elasticity for eighteen highway sections in California, and include controls for trend VMT. To transform this measure into a price elasticity requires substituting a price measure for the capacity measure, such that

$$e_T = \frac{\%\Delta VMT}{\%\Delta p} = \frac{\%\Delta VMT}{\%\Delta cap} \times \frac{\%\Delta cap}{\%\Delta p} = e_{T,\,capacity} \times \frac{\%\Delta cap}{\%\Delta p} \qquad [6]$$

i.e., a conversion factor is needed from the Hansen elasticity to a price elasticity, consisting of the ratio of an increase in capacity to its corresponding reduction in price. Taking time as the only component affected, the question is what are the time savings from a given added capacity? Most of Hansen's expansions are from four to six lanes or six to eight lanes; if it is assumed that two lanes in the same direction are congested, and that adding a third will increase average speed from 40 to 60 mph[8] for at least a few years, then a 50% capacity increase is equivalent to a 33% time savings (neither the value of time nor occupancy affect this result), for a conversion factor of -1.5. Thus Hansen's low

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[7] Harvey (1994) offers examples from San Francisco and Boston airport parking, which are consistent with Shoup's summary if Harvey's elasticities measure the number of vehicles parking. This does not necessarily equate, however, to the same percentage reduction in VMT, because some of the deterred parking is shifted to taxi trips.

[8] This speed change implies an average savings of 0.50 minutes per VMT. Using the HERS (Camus and Weinblatt, 1999) delay equations for expressways, which model average daily delay per VMT as a function of AADT/c(apacity), a 50% increase in capacity at an AADT/c of 15 (fairly high) results in delay savings of 0.855 minutes per mile, whereas an initial AADT/c of 12 yields a savings of 0.255 per mile.

or short run value of about 0.25 becomes -0.375 and his high or long run value of 0.45 becomes -0.675.

Cohen (1995) reviews several time-travel elasticity studies. The results are somewhat erratic, but generally consistent with the above. Often, some types of induced traffic are counted (e.g., new travel by users already in the market) and others omitted (e.g., route diversions). Unlike other components of user price, time cannot be economized by sharing the cost among additional vehicle occupants. Therefore, elasticity with respect to time cost should be lower than for the other components.

Adjustment from Total to Section Elasticities

The total price elasticity reflects the change in vehicle miles of travel in response to the generalized price of travel. For application to the specific context of evaluating improvement alternatives for a section of highway, the price elasticity for price changes on the section or link may require several adjustments. In this context, the price is the generalized price per vehicle mile of travel, and the quantity is the volume of vehicle travel on the facility, per hour or per day.

Occupancy

Any price component that applies to the vehicle and can be divided among occupants creates an incentive to increase occupancy; such monetary components include tolls, excise taxes, wear and ownership costs, parking, and operating costs except for some portion of accidents.[9] The remaining non-divisible non-monetary price components are time and collective accident costs. Thus empirical evidence should show higher observed elasticities for monetary components than non-monetary, other things being equal. A strong pattern is not evident from Table C-6, although at the high end the time elasticity is lower than all but for wear-ownership.[10]

Conceptually, the overall total price elasticity has two components, one derived from the divisible portion of the price, the other from the indivisible portion. Using Figure C-3, the elasticity at a point p_0, v_0 can be represented as the slope of a demand curve.[11] The less elastic demand is labeled D_{nd} (although we are dealing with point elasticities, the explanation is easier if we imagine them as arc elasticities).

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[9] Insurance rates are often higher for carpool drivers, but the component is probably shareable in the same way operating costs can be shared. Damages to the vehicle and other property can be divided, but all occupants are exposed to risk of personal injury and fatality if the vehicle is involved in a crash.

[10] An increase in the money share of the generalized price -- assuming a mix of travelers with differing values of time -- will shift the mix of travelers toward those with higher time values. We do not know, however, if the demand elasticity of high income travelers with respect to the *generalized* price is higher or lower than that of low income travelers.

[11] Holding constant the initial point, the elasticity varies directly with the slope, as can be seen in **[1]**.
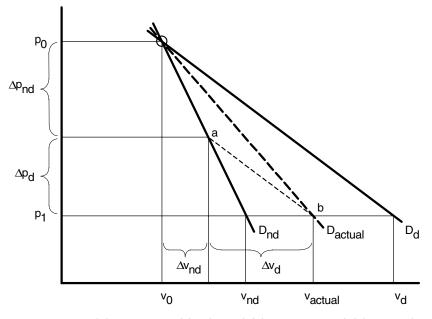
Figure C-3. Elasticity decomposition into divisible and non-divisible portions.

If all price components were indivisible, there would be no incentive for increased occupancy, so elasticity would be relatively low; for a given price change from p_0 to p_1, the additional traffic would be from v_0 to v_{nd}. Alternatively, if all price components were monetized to the vehicle and divisible among occupants, the applicable demand curve would be D_d and the induced traffic would be from v_0 to v_d. More generally, where the components are mixed, the demand curve is a weighted average, represented by the dashed demand D_{actual}. The end result at point b can be decomposed into a movement along D_{nd} for the non-divisible portion, plus a movement along line ab (parallel to D_d) for the divisible portion. Hence the incremental volume from v_0 to v_{actual} is comprised of a portion Δv_{nd} from non-divisible price components, plus a portion Δv_d from the divisible components. The share of movement along D_{nd} versus D_d is determined by the shares of price components, Δp_{nd} and Δp_d.

In elasticity terms, the actual or combined elasticity is simply a weighted average of the two component elasticities,

$$e = \eta e_{nd} + (1 - \eta)e_d \qquad \textbf{[7]}$$

where η = share of generalized price that consists of non-divisible components, e_{nd} = elasticity for non-divisible components, e_d = elasticity for divisible components, and e = combined or "actual" elasticity.

Neither of the "pure" (all non-divisible or all money) demand curves can be observed directly, and although there may be enough variation in the distribution η to extract the

two elasticities econometrically, whatever evidence has been acquired has not been studied in this way.[12] If it can be assumed that e_{nd} and e_d are proportionally related, then

$$e_d = (1 + x)e_{nd} \qquad \text{[8]}$$

where x = fraction by which the more elastic divisible-price demand is greater in magnitude than the non-divisible demand.

In responding to a change in the generalized price of highway travel, the total price elasticity incorporates changes in vehicle trips due to changes in mode or occupancy, change in destination or trip chaining that alter trip length, and adding or deleting person-trips (it omits route and temporal diversion). Using Table C-2 and averaging values, the share of existing price that is monetary is about one-half.[13] The portion of total elasticity that is due to occupancy is unknown, but might likely be around one-third, for a value of x of 0.5. This is enough information to calculate the two divisible/non-divisible elasticities, given an initial overall elasticity, as shown in Table C-8.

If the share of the price that consists of divisible components remains fixed, nothing is gained by this decomposition. If, however, specific sections are priced differently from the overall average, or the intent is to test a different pricing policy, then the component elasticities can be recalculated based on price components that pertain to the particular section. The example shown in Table C-8 might represent a shift to congestion pricing, such that delay is almost eliminated but the money price is much higher. The result is a large decline in the non-divisible costs, but only a modest increase in average elasticity.

Section Length

Most traffic on a given section of highway can be assumed to be using more than that section to accomplish its trips. If, for example, the price for the section being evaluated will decrease by 20% if the improvement is implemented, and the section constitutes 60% of the complete vehicle trip, then the price for the trip will decline by 20% times 60%, or 12%. If total elasticity for the vehicle trip is -1.0, the elasticity for the section is 60% of the total, or -0.6; the 20% price decrease will thus result in a 12% reduction in volume, same as if the price change were calculated for the full trip and applied to the -1.0 elasticity. Specifically,

$$e_s = e\frac{L_s}{L_T} \qquad \text{[9]}$$

where e_s = section elasticity, e = total price elasticity, adjusted for occupancy, L_s = section length, and L_T = average trip length for vehicles using the section.

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[12] Average vehicle occupancies vary by trip purpose from barely one to over three, as evidenced by FHWA (1992) or MTC(1998); the effect on average occupancy of current variations in the divisible money price is likely to be much smaller in magnitude, thus hard to detect empirically.

[13] This result gives half as much weight to the Runzheimer column, on the assumption that these data apply primarily to business travel.

Table C-8. **Occupancy Elasticity Based on Divisible Price Components**

total vehicle price elasticity (base elasticity)	-1.00
Occupancy elasticity:	
share of base price that is nondivisible (%) (η)	50%
elasticity increment for divisible price (%) (x)	50%
elasticity for nondivisible price components (e_{nd})	-0.8
elasticity for divisible price (e_d)	-1.2
section-specific data:	
money price	0.20
operating costs	0.26
accidents	0.10
normal travel time	0.30
delay	0.02
Total	0.88
nondivisible portion of price (η)	0.37
base elasticity adjusted for divisible/nondivisible components	-1.05

If the section is longer than the average trip length, then the multiplier should be one, meaning no change from the total price elasticity, assuming that the price change on the section applies to the full trip for the average traveler. Individual trips that use only part of the section would show a lower elasticity (approaching zero), but there would be several or many of them in each average daily VMT across the entire section, giving the same result as if a single trip used the entire section.

Route Diversion

For most of the components of the generalized price of vehicle travel, route diversion is not an available substitute (e.g., fuel price, operating cost). For the parking studies, employee parking at a substitute destination is not feasible. Toll elasticities of major facilities such as the Golden Gate Bridge incorporate very few alternative route possibilities, and time elasticities based on facility expansion allow for some indeterminate amount of diversion in the empirical values. Thus the elasticity for a single facility or section will be higher than the value derived from empirical estimates for total price elasticity, because travelers can divert to parallel routes.

The magnitude of an elasticity is greater if there are many close substitutes. A route diversion elasticity will be high if there are alternative routes that are only slightly "worse" in the sense of having a higher generalized price. For example, a simplified representation of route diversion is shown in Figure C-4. The section being considered for improved is S_0. In the base case, the preferred path for a trip between A and B uses the section S_1, but an alternative route uses S_{a1}, S_0, and S_{a2}. The alternate might become preferred if S_0 were improved to the extent that the total trip price were lower via the alternative route, i.e., if

$$p_{a1} + p_0 + p_{a2} < p_1 \qquad\qquad \text{[10]}$$

where p_i = generalized price on section S_i. Sections S_{a1} and S_{a2} are "access" sections that would be used to get to and from the improved section. For a given primary section of interest, S_0, there might be many trip ends such as A and B that do not use S_0 as their preferred route, but might choose to do so if the price on S_0 were lower, e.g., faster.
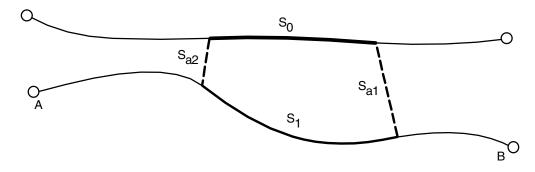

Figure C-4. Generic example of route diversion.

The demand elasticity on S_0 with respect to route diversion only depends upon the relative volumes of traffic on the two routes (as well as other alternate routes) and the difference in the price between them. If v represents the volume on all routes such as S_1 that do *not* use S_0 but could, stated as a ratio to the volume on S_0, then

$$\text{diversion elasticity } (S_0) \; = \; -\left(\frac{s \times v \times V_0 / V_0}{r / a}\right) \; = \; -\frac{sva}{r} \qquad \textbf{[11]}$$

where s = share of corridor traffic not using S_0 for which the price of S_0 is $r\%$ greater than their preferred route, a = the access share of the alternative route that incorporates S_0, and V_0 is the volume on S_0. The numerator is the percent change in volume on S_0 from a change in price of on S_0, and the denominator is the percent change in the price of the alternate route from a change of $r\%$ on S_0.

None of these parameters is readily observable, although they could be extracted from traffic assignment simulations. As an example, parameter values have been entered into Table C-9 and the diversion elasticity calculated. There exists some distribution of the share of traffic in the corridor according to the percentage by which the price of the preferred path differs from the path that incorporates S_0, and an example distribution is shown in its cumulative form. Because its shape is unknown, it is possible (and likely) that the elasticity on S_0 varies by the magnitude of the percentage price change on S_0, i.e., the diversion elasticity is not a constant. In general, it might be expected that network redundancy is higher in urban areas, implying that route diversion elasticities are higher (in absolute magnitude) in urban areas.

The diversion elasticity can be added to the previous total elasticity that has been adjusted for section length and occupancy. Because the section length relative to the total trip length is corrected for separately, section length does not need to be considered for route diversion.[14] Also, because speed-volume or delay functions account for the

Table C-9. **Construction of route diversion elasticity**

% by which route with section S_0 is worse than preferred path (r)	0.05	0.1	0.2	0.4	0.5
cumulative share of ROTC within % of trip cost (urban) (s)	0.10	0.25	0.50	0.85	0.95
ratio of ROTC volume to section AADT (trips) (v)	0.60				
access share of price (a)	0.50				
percent increase on section S_0	0.06	0.15	0.30	0.51	0.57
diversion elasticity	-0.60	-0.75	-0.75	-0.64	-0.57

ROTC = trips in the rest of the corridor that do not use the primary section but could.

increase in price from congestion, the capacity of S_0 does not need to be considered in diversion.

Time-of-day Diversion (Peak Spreading)

A price component that applies only to the peak should have a higher elasticity than that for the total price as estimated from the empirical evidence, considering only the peak period, because some travel will be diverted to the off-peak. If diurnal demand periods are modeled separately (i.e., two or more demand periods per day), then the interrelationships among the demand periods must be explicitly modeled. This is more than just a problem of elasticities.[15] Of narrower interest here is whether peak-offpeak price differentiation alters the overall -- or daily-- elasticity. The bottleneck model provides an example of a substitution of price for queuing delay, without any change in overall traffic, but the model does not include the option of changing the total number of trips.

If the price varies over the time of day according to the level of demand, then overall delay will be reduced (relative to no differentiation) by redistributing traffic from congested periods to time periods with lower v/c ratios. This suggests that total traffic levels will be higher because the average price is lower. If, however, we hold average price constant as well as the share that is monetary, it is not obvious that the demand elasticity is changed by altering the price between peak and offpeak.

Two effects can be separated: first, the change in volumes between a differentiated price and a constant price; and second, whether the elasticity is different for total demand if the price is differentiated or constant.

Because the share of the price that is paid in money is recognized in the occupancy factor, for purposes of peak spreading the price can be considered homogenous. The empirical evidence applies to a context in which peak and offpeak prices are differentiated by the amount of delay. If we imagine a case with the same demand curves but constant price across all (both) periods, and the same average price, then more demand will occur

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[14] A very short section might have negligible impact on generating new trips but still have a large diversion impact. If the section were isolated, then the access portions of the diversion would neutralize any diversion, but if the access were easy (e.g., turn right on one block rather than the next), the amount of diversion could be large. The benefits from this diversion might be small in absolute terms, but so might the costs. Incremental consumer surplus would be made up almost entirely of diverted (rather than new) trips.

[15] Some of the difficulties are described in Cambridge Systematics (1997).

in the peak and less in the offpeak. If elasticities differ between the two periods, then total volume will be higher if peak elasticity is greater then offpeak, and lower if the reverse.

If we then ask what difference this makes for total price elasticity, the simplest answer is that it makes no difference if the two elasticities are the same. If we use constant elasticity demand curves, located at different volume points but having the same elasticity, then the overall elasticity is not affected by the differentiation of price between the two periods, for the same average price.

If the elasticities are different between the two periods, then the amount of differentiation between peak and offpeak prices may cause the aggregate elasticity to be greater or lesser than the case where the price is constant, but the effect seems to be relatively small.[16]

Conclusions

Despite the widely varying orientations, data sources, and scope of applicable empirical studies, and the fact that none was attempting to estimate total travel elasticity, the results are roughly consistent. Users respond to changes in any of the components of travel cost that are measurable, and the response starts immediately and continues over many years.

Taking the short run to be approximately a year or less, vehicle demand-price elasticity tends to fall in the range of -0.5 to -1.0, with -0.7 to -0.8 being the most likely for typical conditions. The long run may occur over twenty years, but five years is enough to cover most of the effects. Long run elasticities are about twice as high as short run, with a range of about -1.0 to -2.0. Response to variable and obvious money costs such as parking and fuel show higher elasticities than for fixed and more hidden costs. These elasticities apply to vehicle-trips, not person-trips.

These total price elasticities can be applied to specific highway sections, adjusting for changes in the share of divisible price components, the section length, and possibilities for route diversion. The elasticity values are somewhat uncertain, due to the fact that every context is different, but the uncertainty could be reduced with focused data collection and research.

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[16]These generalizations are based on informal numeric experiments.

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