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Understanding Transport Demands and Elasticities

How Prices and Other Factors Affect Travel Behavior

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Abstract

Transport demand refers to the amount and type of travel that people would choose under specific conditions. This report describes concepts related to transport demand, investigates the influence that factors such as prices and service quality have on travel activity, and how these impacts can be measured using elasticity values. It summarizes research on various types of transport elasticities and describes how to use this information to predict the impacts of specific transport price and service quality changes.

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Executive Summary

Travel demand refers to the amount and type of travel that people would choose in particular situations. Various demographic, geographic and economic factors can affect travel demands, as summarized in Table 37. Models that reflect these relationships can predict how various trends, policies and projects will affect future travel activity, and therefore evaluate potential problems and transport system improvement strategies.

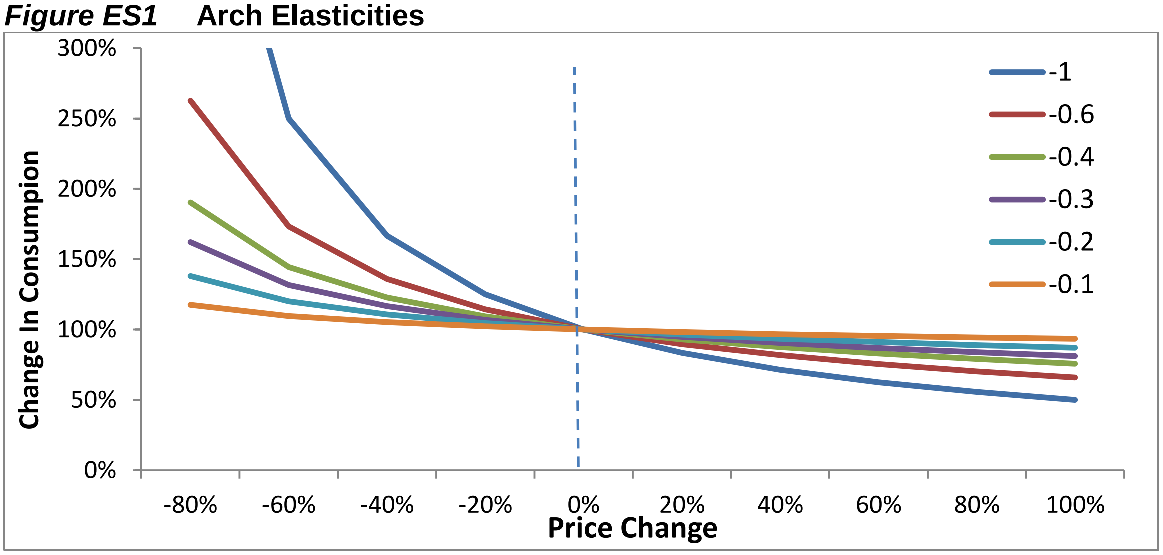
Table ES1 **Factors That Affect Transport Demand**

Demographics	Commercial Activity	Transport Options	Land Use	Demand Management	Prices
Number of people (residents, employees and visitors) Employment rate Wealth/incomes Age/lifecycle Lifestyles Preferences	Number of jobs Business activity Freight transport Tourist activity	Walking Cycling Public transit Ridesharing Automobile Taxi services Telework Delivery services	Density Mix Walkability Connectivity Transit service proximity Roadway design	Road use prioritization Pricing reforms Parking management User information Promotion campaigns	Fuel prices and taxes Vehicle taxes and fees Road tolls Parking fees Vehicle insurance Transit fares

Various factors that affect transport demands should be considered in policy analysis and planning.

Prices are the direct, perceived costs of using a good. Transport prices can include monetary (money) costs, plus travel time, discomfort and risk. Price changes can affect trip frequency, route, mode, destination, scheduling, vehicle type, parking location, type of service selected, and location decisions. Pricing impacts are commonly measured using elasticities, the percentage change in consumption (in this case, in travel activity) that results from each 1% change in price, as illustrated in Figure 11.

Figure ES1 **Arch Elasticities**



This graph illustrates how price changes affect consumption for various elasticity values.

Generalized cost refers to combined monetary and time costs of travel. For example, the generalized cost of automobile travel includes vehicle operating costs and the monetized value of motorists' travel time, and the generalized cost of transit travel include fares and monetized passenger travel time values. These values are used in transport models.

Although some travel is very beneficial, the travel demand curve appears to have a long tail, meaning that if prices (monetary, time, discomfort and risk costs) decline sufficiently people will tend to increase their travel, resulting in an increasing amount of marginal value travel that provides minimal user benefits, and if they impose external costs, their net benefits (total benefits are less than total costs) are likely to be negative. This lower-value travel tends to be quite sensitive to pricing.

A considerable body of research has analyzed how transport price changes affect transport activity, including changes in fuel prices, road tolls, parking fees, fares, and transport service quality, for various modes, user groups and travel conditions. Although these impacts vary widely, it is possible to identify certain patterns which allow these relationships to be modeled. For example:

- Transport pricing impacts can vary, including changes in trip generation, mode, destination, route, vehicle type and parking location. Pricing of one mode or service can affect demand of others.
- Pricing impacts tend to increase over time, and are typically triple over the long-run.
- Higher value travel, such as business and commute travel, tend to be less price sensitive than lower value travel.
- Wealthy people tend to be less sensitive to pricing and more sensitive to service quality than lower-income people.
- Travel tends to be more price sensitive if travelers have better travel options.
- Motorists tend to be particularly sensitive to road tolls and parking fees.
- How fees are promoted, structured and collected can affect their impacts.
- Motorists are more likely to accept vehicle price increases if presented as part of an integrated program that is considered fair and provides dispersed benefits.

A key factor in this analysis is the degree to which the demand factors and elasticity values collected in past studies are transferable to different times and places. The basic relationships that affect travel demands tend to be durable and therefore transferable, but it is important to take into account factors such as differences in employment rates, incomes, transport options and land use patterns when applying past experience in new areas. The values described in this report provide a reasonable starting point for travel demand modeling but the must be calibrated to reflect specific conditions. As transport planners, economists and modelers gain experience we will be better able to develop models for new locations, modes and pricing reforms.

In recent years there has been increasing interest in transportation demand management, including pricing reforms, to achieve planning objectives such as congestion, accidents and pollution reductions. Critics sometimes claim that vehicle travel is insensitive to pricing, citing studies of declining price elasticities and examples of fuel or toll price increases that caused little reduction in vehicle travel. This implies that pricing reforms are ineffective at achieving planning objectives and significantly harm consumers.

It is true that as normally measured, automobile use appears to be inelastic, meaning that price changes cause proportionately smaller changes in vehicle travel. However, this reflects how price impacts are normally evaluated. Short-run price effects are about a third of long-run effects, and most vehicle costs (depreciation, financing, insurance, registration fees and residential parking) are fixed. A -0.1 short-run elasticity of vehicle travel with respect to fuel price reflects a -0.3 long-run elasticity, which reflects a -1.2 elasticity of vehicle travel with respect to total vehicle costs, which implies that automobile travel is overall elastic.

Although automobile travel elasticities declined significantly in the U.S. during the last half of Twentieth Century, due to demographic and economic trends, including rising employment rates, increasing real incomes, declining fuel prices, highway expansion and sprawled land use development, and declining alternatives. Many of these trends are now reversing, resulting in peaking demand for automobile travel and increasing demand for alternative modes in most wealthy countries. These trends are increasing the price elasticity of automobile travel.

This has important implications for developing countries. Countries that implement policies that favor automobile travel during the early stages of their development, including low prices for fuel, roads and parking, will tend to create automobile dependent transportation systems, imposing greater economic, social and environmental costs. Developing countries that implement more efficient prices that test consumers' travel demands will have more efficient transport systems and fewer associated problems.

Improved transportation demand models, as described in this report, are an important tool to help policy makers and planners evaluate transport problems and potential solutions. It will be important for developing countries to establish data collection and capacity building programs to support model development.

Introduction

Life is full of trade-offs. People must choose how to spend scarce money and time. The decisions they make reflect their options, needs and preferences. Economists call these *demands*, which refers to the amount and type of goods people and businesses will consume under specific conditions.

Consumption is affected by *prices*, the direct, perceived costs of using a good. The term is often limited to monetary costs but can also include non-monetary factors. For example, the price of airline travel includes the ticket purchase price, flying time and risk, plus costs of getting to and from airports. Factors such as discomfort and risk can be incorporated into travel time unit costs: uncomfortable or unsafe travel costs more per minute or hour than comfortable and safe travel.

Price changes can affect consumption in various ways. You may consider a product too expensive at its regular price but buy it when discounted, and if its price increases you may shift brands or consume less. Such decisions are considered *marginal*: they are between similar alternatives (or *close substitutes*) and so may be influenced by small price changes. Although individually such decisions may seem variable (you might succumb to a sale today but ignore the same offer tomorrow), in aggregate they tend to follow a predictable pattern: price reductions usually increase consumption, and when prices increase consumption declines. This is called the *law of demand*.

Transport activities tend to follow this pattern. When transport prices decline, mobility tends to increase, and if prices increase, mobility declines. Transport price changes can affect trip frequency, route, mode, destination, scheduling, vehicle type, parking location and type of service selected. There has been conservable research on these relationships. Recent research is increasingly sophisticated, based on more and better data.

This information has many practical uses. Planners can use it to predict how demographic and economic trends will affect future travel activity. Policy makers and businesses can predict how fuel tax, parking fee, road toll and transit fare changes would affect travel activities and revenues. It can be used to evaluate various *transportation demand management* (TDM, also called *mobility management*) intended to change travel activity in order to achieve various planning objectives.

This report is an introduction to these issues. It describes concepts related to transport demands, investigates how prices and service quality affect transport activity, describes how these impacts can be measured, and summarizes various transport elasticity studies. It discusses how this information can be used for policy and planning analysis.

Transferability

A key factor in this report is the degree to which the transport demand factors and elasticity values it describes are transferable to other times and places. Many of the studies summarized in this report are many years or decades old, and most were performed in higher-income countries. Can they be applied to current conditions or developing country conditions? I believe that they can, provided it is done with care.

Certainly, when applying elasticity values in a particular situation, it is important to take into account factors such as differences in employment rates, incomes, transport options and land use patterns. However, the basic relationships that affect travel demands tend to be durable and therefore transferable. People have limited money and time to spend on transport, and so will respond similarly to changes in their money and time costs.

For example, a 20¢ per liter fuel price increase may have very different travel impacts in Houston, Texas and Delhi, India. However, if this price change is measured relative to travelers' incomes, the impacts are likely to be similar in these different areas. Described differently, a businessman who earns $100,000 annually and lives in an outlying neighborhood in Delhi, India will probably respond to a 20¢ per liter fuel price increase similarly to his colleague who earns a similar income and lives in a similar neighborhood in Houston, Texas. Although the portion of residents with this income may be smaller in Delhi than in Houston, resulting in different travel impacts for residents overall, among similar households impacts are likely to be similar.

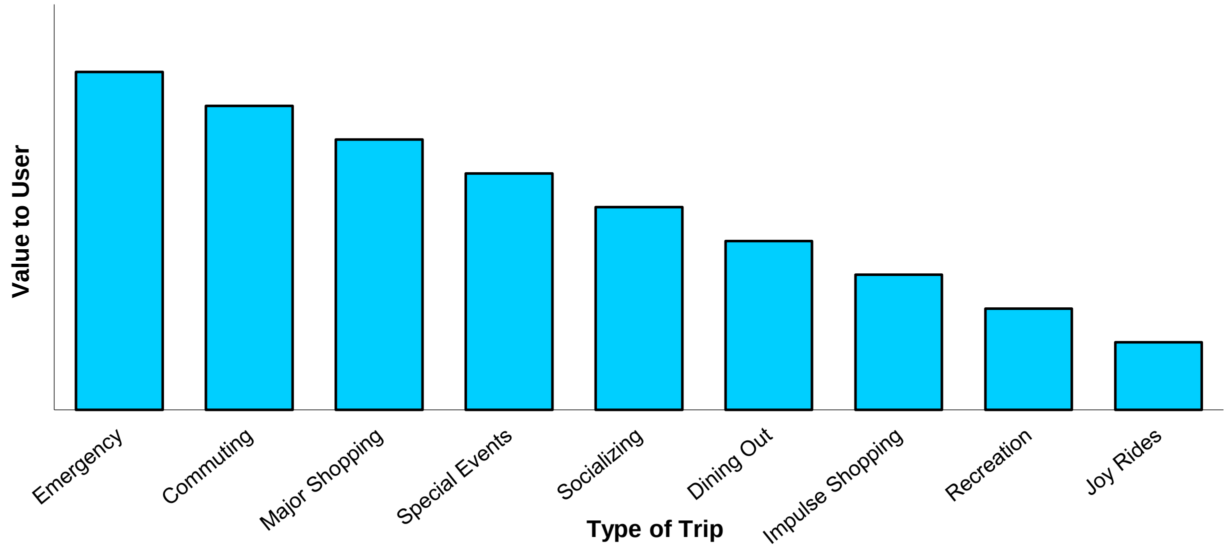
In some situation, increased fuel prices or road tolls may cause little vehicle travel reductions, suggesting that the elasticities in this report do not apply. However, this probably reflects factors such as high motorists' incomes and poor quality alternatives. If these factors are considered, by measuring price increases relative to incomes and considering examples where alternatives to driving are inferior, it is likely that elasticity values from other times and places will be transferable.

As a result, the values described in this report provide a reasonable starting point for travel demand modeling. As transport planners, economists and modelers gain experience we will be better able to predict travel activities in specific situations.

Travel Demands

To understand how prices affect travel decisions, think of all the trips you might make, as illustrated in Figure 1. Some trips are very important so you would take them even if their price is high, but others are lower value and so you will only take them if their price is low. For example, you might shop across town if travel is cheap and convenient, but shop locally or by Internet if financial or time costs increase.

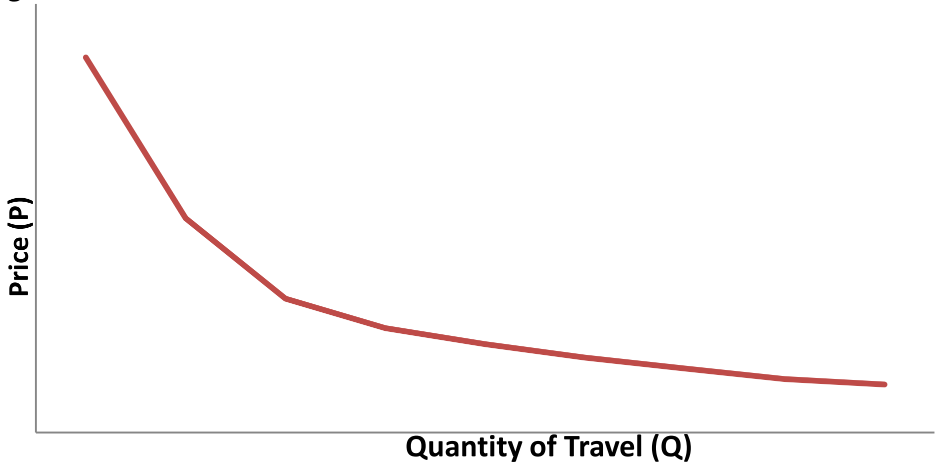
Figure 1 **Travel Ranked by User Value**



Trips range in value. High value trips will occur even if user costs are high. Some trips have relatively low value and will only occur if prices are low.

This is a *travel demand curve*, a graph of the relationship between prices and mobility. By convention the vertical axis indicates price, designated *P*, and the horizontal axis indicates quantity (number of trips or distance traveled) consumed, designated *Q*.

Figure 2 **Travel Demand Curve**



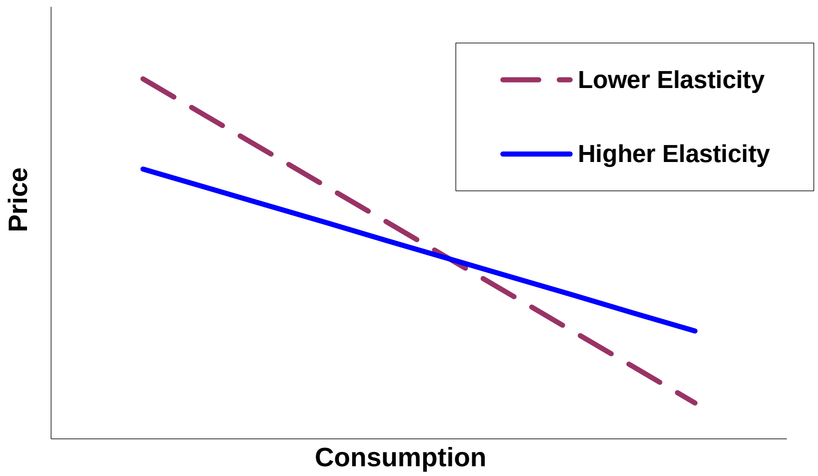
This travel demand curve indicates how changes in price affect the quantity of travel.

It is important to specify the geographic area, time and mode considered transport demand analysis. For example, some travel statistics only reflect commute travel, peak-period travel, or motor vehicle travel, which are subsets of total vehicle travel.

The value of travel is highly variable: some trips are very important but others may provide minimal benefit. Transport demand curves tend to have a long tail, meaning that if prices (money, time, discomfort and risk costs) are sufficiently low consumer will increase their travel. For example, some people might fly around the world to just eat at a popular restaurant or attend a party, or choose a home that requires very long commutes. Similarly, if vehicle travel prices are low, people will use automobiles for trips that could easily be made by other modes, for example, chauffeuring children by car rather than letting them walk or bicycle, and driving alone for urban trips that could be made efficiently by public transport. In that situation, an increasing portion of travel provides minimal user benefits, and so is likely to be price sensitive.

The demand curve's steepness indicates the price sensitivity of travel, measured using *elasticities*, as described later. A high sensitivity (a gradual curve) indicates that relatively small price changes cause relatively large changes in travel activity. A low sensitivity (a steep curve) indicates that price changes have relatively little impact on travel.

Figure 3 **Price Sensitivities**



A steeper demand curve (dashed red line) indicates that consumption is less price sensitive (low elasticity), implying that consumers find it difficult to change their consumption patterns. A more gradual demand curve (solid blue line) indicates that consumption is more price sensitive (higher elasticity), implying that consumers find it easy to change their consumption patterns.

Transport demand is a multi-variable function. Many factors can affect travel demands, including demographics, economics, prices and service quality, as discussed below. When considering a single factor's impacts we often say *ceteris paribus*, Latin for *holding all else constant*, to emphasize that other factors can affect results. The following section describes models that can be used to quantify travel demands and predict the impacts of transport system changes.

Transport Demand Statistics and Models

Transport demand analysis relies on various statistics and models. People involved in demand analysis should understand their weaknesses and biases (Litman 2007; Stopher and Greaves 2007; TRB 2007).

Transport statistics include demographic, travel activity, transport price and land use data. These statistics are often incomplete, inconsistent and outdated. For example, some surveys only collect data on peak-period trips between relatively large *traffic analysis zones* (TAZs), or commute trips. Surveys often overlook poor people and children. Definitions and methodologies often vary between surveys, making results difficult to compare. The resulting statistics tend to overlook or undercount off-peak travel, short trips (within TAZs), poor people's travel, children's travel, and non-motorized travel (May, et al. 2008).

Transport demand models are sets of formulas that predict the amount and type of travel people would choose in a particular situation, and the effects that transport system changes have on travel activity. For example, a model might predict the number and types of trips generated by a store or school, and how these would be affected by demographic, travel condition and price changes. Various statistical tests are used to calibrate a model for a particular situation. Most urban regions use four-step models to predict traffic volumes, congestion and pollution impacts. They follow these steps:

1. *Trip generation.* Predict number of trips originating in each TAZs based on factors such as number of residents and jobs in each zone, demographics, transport system conditions (roadway capacity, transit service quality, prices, etc.).
2. *Trip distribution.* Distribute trips between zone pairs based on the distance between them.
3. *Mode share.* Allocate trips among modes (walking, cycling, auto, transit, etc.).
4. *Route assignment.* Assign trips to specific roadway and transit system links.

These models are limited in the types of problems and solutions they can evaluate. Few are sensitive to nonmotorized travel conditions, public transit service quality, land use factors, and some pricing reforms. As a result they tend to exaggerate roadway expansion benefits and underestimate the benefits of walking, cycling and public transit service improvements, and transportation demand management strategies. Newer models are more multi-modal and integrated (Bartholomew and Ewing 2009; Dowling, et al. 2008; FHWA *Travel Model Improvement Program*), and so are able to evaluate more types of travel and more impacts. A few studies have investigated transport demands in developing countries (Gonzales, et al. 2009; Salon and Gulyani 2010; Venter, Vokolkova and Michalek 2007). Table 1 summarizes various transport statistic and model improvement strategies. These improvements are particularly important for evaluating demand management strategies and modeling in developing countries.

Table 1 **Statistics and Model Improvements** ("Model Improvements," VTPI 2011)

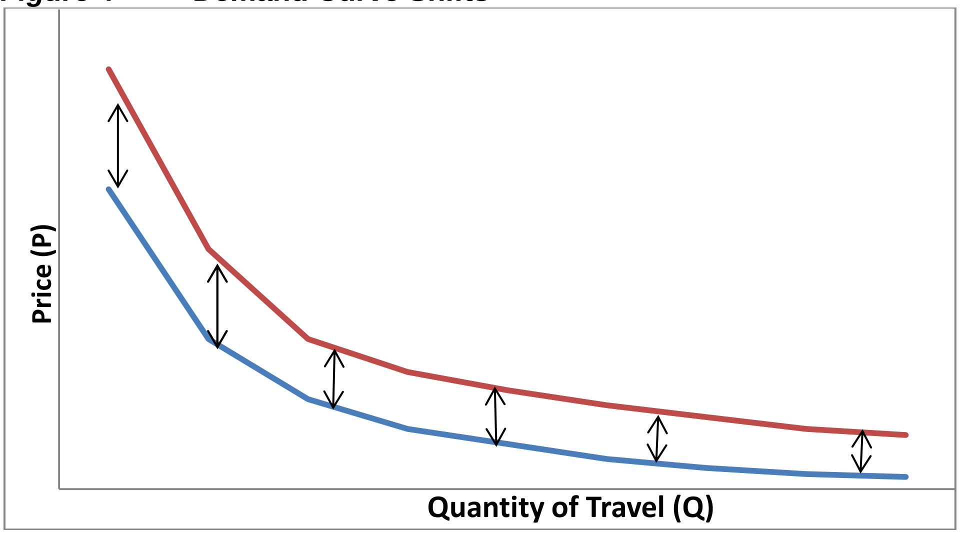
Factor	Current Problems	Appropriate Corrections
Definition of *transport*	Transport planning often assumes that *transport* refers primarily to automobile travel and so evaluates transport system performance based on driving conditions.	Define transport based on *accessibility* (people's ability to reach desired goods and activities). Considers multiple modes and land use factors when evaluating transport system performance.
Transport surveys	Travel surveys often undercount short trips, non-motorized travel, off-peak travel, travel by poor people and children, etc.	Improve travel surveys to provide more comprehensive statistics.
Consistency	Definitions and methodologies often differ between transport data sets, making it difficult to compare results.	Standardize transport statistics and survey methods.
Multi-modal performance indicators	Applies level-of-service ratings only to roadway conditions. Fails to evaluate the performance of other modes.	Incorporate multi-modal level-of-service ratings to evaluate problems and improvements to multiple modes.
Consumer Impacts	Economic evaluation models apply relatively crude consumer impacts analysis. They assume that faster is always better than slower travel.	Use more comprehensive consumer surplus analysis. Recognize that shifts to slower modes can provide net user benefits if they are more comfortable, enjoyable or affordable.
Travel time	Most models apply the same travel time value to all travel, regardless of conditions.	Vary travel time cost values to reflect travel conditions, such as discomfort and delay.
Generated traffic and induced travel	Few models account for all generate traffic impacts and induced travel (additional vehicle travel caused by roadway expansion).	Incorporate "feedback" into the traffic model to predict generated traffic and induced traffic.
Nonmotorized travel	Models undervalue nonmotorized improvements.	Improve models to better evaluate nonmotorized mode improvements.
Impacts Considered	Models consider few economic impacts (benefits and costs). Most primarily consider travel time and vehicle operating costs.	Use more comprehensive impact analysis, including parking, vehicle ownership, crashes, pollution and pedestrian delay costs.
Transit elasticities	Analyses often use short-run elasticities which understates long-term impacts	Use appropriate values when evaluating long-term impacts.
Self-fulfilling prophesies	Demand projections are often reported as if they are unavoidable. Demand management options are often ignored.	Rather than reporting demand as a fixed value ("traffic will grow 20%"), report it as a variable ("traffic will grow 20% if current policies continue; 10% if alternative modes are improved; and 0% if parking fees are also increased.").
Impacts on disadvantaged people	The travel demands of physically, economically and socially disadvantaged people often receive little consideration	Perform special analysis of disadvantaged groups' transport demands, and the impacts of transport system changes on them
Land use impacts	Models often fail to identify how transport decisions affect land use patterns, how this affects strategic planning objectives.	Develop integrated models which predict how transport decisions affect land use patterns and how land use decisions affect accessibility.

This table summarizes common problems with current transportation statistics and models, and ways to correct these problems. These improvements are particularly important for evaluating alternative modes and demand management strategies.

Factors Affecting Travel Demands

Various factors affect travel demands. Changing these factors can shift the demand curve, which changes the amount of travel consumed at a given price, as illustrated in Figure 4.

Figure 4 **Demand Curve Shifts**



Various factors affect travel demand. Changes in these factors can shift the demand curve, changing the amount and type of travel people will consume at a given price.

The following factors tend to affect transport demands.

Demographics

Different types of people have different travel demands. Travel, particularly automobile travel, tends to increase with employment and wealth. Walking, cycling and public transport demand tend to be higher for people who are younger, older, poor, have impairments, are immigrants, enjoy exercise, and live in urban areas.

Economic Activity

Commercial (business) activity has special travel demands, including heavy freight transport, local deliveries, service vehicles (plumbers vans and utility trucks), business travel, and tourist travel. This type of travel tends to have high value and may require special vehicles, including rail, large trucks and buses, delivery fleets, and air travel.

Transport Options

The quality of transport options affects travel activity. Improving walking and cycling conditions, and public transit service quality, tends to increase use of these modes and reduce automobile travel, although the relationships are complex. For example, some walking and cycling activity may be recreational and not reduce automobile travel. Conversely, in some situations, improving alternative modes may leverage additional motor vehicle travel reductions by helping to create communities where residents own fewer automobiles and drive less overall (ICF 2010; Litman 2010).

Geography and Land Use Patterns
Land use (also called *built environment* or *urban design*) factors such as density, mix, roadway connectivity, building design and parking supply can affect transport demand (Bartholomew and Ewing 2009; CARB 2010/2011; Litman 2008). Per capita vehicle ownership and travel tend to be higher in rural and automobile-dependent suburban areas, while walking, cycling and public transit travel tend to be higher in urban areas, particularly those developed prior to 1950, or more recently with transit-oriented or smart growth development policies.

Demand Management Strategies
Transportation demand management (also called *mobility management*) refers to various policies and programs specifically intended to affect travel activity, in most cases, to reduce urban-peak motor vehicle traffic. These strategies include improvements to alternative modes (walking, cycling, public transport, carsharing, etc.), pricing reforms and other incentives to reduce vehicle travel, and smart growth land use policies.

Prices (Monetary Costs)
As described in more detail later, vehicle, road, parking, fuel, insurance and public transport prices tend to affect travel activity. Increased prices for a particular type of travel tends to reduce its consumption and sometimes causes shifts to alternatives.

Summary
Table 2 summarizes factors that can affect travel demand.

Table 2 **Factors That Affect Transport Demand**

Demographics	Commercial Activity	Transport Options	Land Use	Demand Management	Prices
Number of people (residents, employees and visitors). Employment rate Wealth/incomes Age/lifecycle Lifestyles Preferences	Number of jobs Business activity Freight transport Tourist activity	Walking Cycling Public transit Ridesharing Automobile Taxi services Telework Delivery services	Density Mix Walkability Connectivity Transit service proximity Roadway design	Road use prioritization Pricing reforms Parking management User information Promotion campaigns	Fuel prices and taxes Vehicle taxes & fees Road tolls Parking fees Vehicle insurance Public transport fares

This table indicates various factors that affect transport demand, which should be considered in transport planning and modeling, and can be used to manage demand.

Measuring Price Impacts (Elasticities)

Price sensitivity is often measured using *elasticities*, defined as the percentage change in a good's consumption caused by each one-percent change in its price or other characteristics such as travel speed or transit service. A negative sign indicates the effect is opposite from the cause, so for example, a -0.5 elasticity of vehicle use *with respect to* (abbreviated *WRT*) vehicle operating expenses means that each 1% expense increase causes vehicle travel to decline 0.5%. Similarly, a transit service elasticity is defined as the percentage change in transit ridership resulting from each 1% change in transit service, such as bus-miles or frequency. This elasticity usually has a positive value since more service increases ridership. Elasticities can also be calculated based on ratios, such as between transit fares and automobile operating costs, or between vehicle costs and average incomes or wages.

Elasticity values are classified by their magnitude. *Unit elasticity* refers to a 1.0 absolute value (1.0 or -1.0) elasticity, meaning that price changes cause proportional consumption changes. Elasticities of less than 1.0 absolute value are called *inelastic*, meaning that prices cause less than proportional consumption changes. Elasticity values greater than 1.0 absolute value are called *elastic*, meaning that price changes cause more than proportional consumption changes. For example, both 0.5 and –0.5 values are considered *inelastic* because their absolute values are less than 1.0, while both 1.5 and –1.5 values are considered *elastic*, because their absolute values are greater than 1.0.

Several methods are used to compute elasticities, some more accurate than others (Beggs 2012; Pratt 2003, Appendix A; TRL 2004). A simplistic form, a linear function called a *shrinkage ratio* or *shrinkage factor*, is defined as the percentage change in consumption caused by a percentage change in price relative to the original consumption and price. For example, applying a -0.4 price elasticity to a 20% price increase predicts an 8% reduction on consumption (0.4 x 0.2 = 0.08). Although easy to use, this method is only accurate for relatively small price changes.

A more accurate method for calculating transportation elasticities (symbolized η) is the *arc elasticity* and its variation, the *mid-point arc elasticity*. The *arc* elasticity reflects the change in consumption (Q) resulting from each 1% change in price (P). Measured in this way, a price change consists of numerous incremental changes. For example, applying a –0.4 price elasticity applied to a 20% price increase is calculated as twenty 0.4% reductions in consumption. The first reduces current consumption by 0.4% to 99.6%, the second reduces this by another 0.4%, repeated a total of twenty times. Each step affects an incrementally smaller base, resulting in an exponential function. Arc elasticities can be calculated using a calculator or spreadsheet by raising the price change factor (the ratio of new to old price, such as 1.2 for a 20% increase) to the elasticity exponent. For example, if a good with a -0.4 price elasticity experiences a 20% price increase, the resulting consumption can be calculated as 1.2^(-0.4) times the old consumption, or 0.93, indicating a 7% reduction in consumption, which is slightly smaller than the 8% reduction calculated using the shrinkage ratio.

Arc elasticity calculations require both original and final price values. Free fares (price equals zero before or after the change) must be calculated using the mid-point formulation. Arc elasticity is a logarithmic formulation and, except for very large changes in price or service, and quantity demanded, is closely approximated by a mid-point formulation based on the average value of each independent variable (Pratt 1999).

Elasticity Equations

Arc Elasticity

$$\eta = \frac{\Delta \log Q}{\Delta \log P} \quad \text{or} \quad \eta = \frac{\log Q_2 - \log Q_1}{\log P_2 - \log P_1}$$

$$P_2 = P_1 \left(\frac{Q_2}{Q_1}\right)^{\frac{1}{\eta}} \quad \text{or} \quad Q_2 = Q_1 \left(\frac{P_2}{P_1}\right)^{\eta}$$

Mid-Point Arc Elasticity

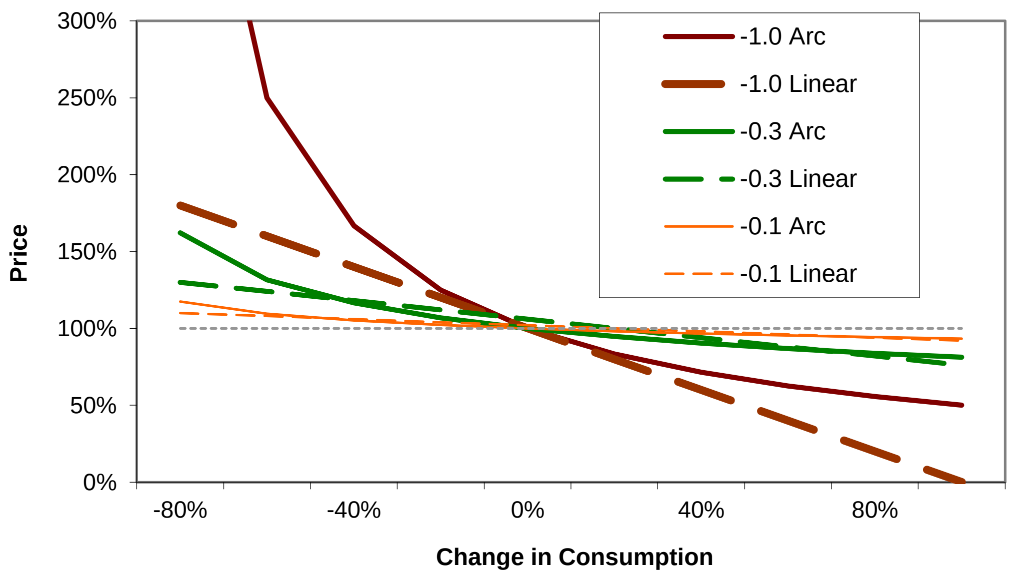
$$\eta = \left[\frac{\Delta Q}{\frac{1}{2}(Q_1+Q_2)}\right] \div \left[\frac{\Delta P}{\frac{1}{2}(P_1+P_2)}\right] \quad \text{or} \quad \eta = \left[\frac{\Delta Q}{P_1+P_2}\right] \div \left[\frac{\Delta P}{Q_1+Q_2}\right] \quad \text{or} \quad \eta = \frac{(Q_2-Q_1)(P_1+P_2)}{(P_2-P_1)(Q_1+Q_2)}$$

$$P_2 = P_1 \times \left[\frac{Q_1(\eta-1)+Q_2(\eta+1)}{Q_2(\eta-1)+Q_1(\eta+1)}\right] \quad \text{or} \quad Q_2 = Q_1 \times \left[\frac{P_1(\eta-1)-P_2(\eta+1)}{P_2(\eta-1)-P_1(\eta+1)}\right]$$

where η is the elasticity value, Q_1 and Q_2 are before and after consumption, and P_1 and P_2 are before and after price or service.

Figure 5 illustrates differences between linear and arc elasticities. These differences become significant when price changes exceed about 50%.

Figure 5 **Arc and Linear Elasticities** (Litman 2009)



This figure compares linear (or shrinkage values) and arc elasticities. Arc elasticities are based on an exponential function that is more accurate for evaluating larger price changes.

Cross-elasticities refer to the percentage change in the consumption of a good resulting from a price change in another, related good. For example, automobile travel is complementary to vehicle parking, and a substitute for transit travel. As a result, an increase in the price of driving tends to reduce demand for parking and increase demand for transit travel. To help analyze cross-elasticities it is useful to estimate *mode substitution* factors, such as the change in automobile trips resulting from a change in transit trips. These factors vary depending on circumstances.

For example, when bus ridership increases due to reduced fares, typically 10-50% of the added trips will substitute for an automobile trip, that is, one automobile trip is reduced for each two to ten additional transit trips. Other trips will shift from nonmotorized modes, ridesharing (which consists of vehicle trips that will be made anyway), or be induced travel (including chauffeured automobile travel, in which a driver makes a special trip to carry a passenger). Conversely, when a disincentive such as parking fees or road tolls causes automobile trips to decline, generally 20-60% shift to transit, depending on conditions. Pratt (1999) provides information on the mode shifts that result from various incentives, such as transit service improvements and parking pricing.

Elasticity analysis should use *real* (inflation adjusted) prices, as opposed to *nominal* or *current* prices (unadjusted for inflation). For example, if during a time period there is 10% inflation and nominal prices do not change, real prices will have declined by 10%. If during that time period prices increase by 10%, real prices will have stayed constant. If nominal prices increase 20% during that period, real prices will have increased by approximately 10%.

When comparing prices between different places and times, it is often best to evaluate changes relative to wages or incomes than absolute values. For example, when evaluating the impacts of transit fares on travel activity it may be best to measure the fee as a percentage of average passengers' hourly wages.

Although elasticities are often reported as single, point estimates, there are actually many factors that can affect the price sensitivity of a particular good. In other words, elasticities are actually functions with several possible variables, including the type of market, type of consumer and time period. For example, although the elasticity of vehicle travel with respect to fuel price may be defined as –0.3 (a single value), the actual value will vary between –0.1 and –0.8 depending on the type of trip (commercial, commute, recreational, etc.), the type of motorist (rich, poor, young, old, etc.), travel conditions (rural, urban, peak, off-peak), and the time period being considered (short-, medium- or long-run). These variables are discussed in more detail in the next section.

Factors Affecting Price Sensitivity

Various factors described below can affect how much a change in prices impacts travel activity.

Type of Price Change

Different types of charges can have different impacts on travel behavior. Vehicle taxes and fees can affect the number and type of vehicles purchased. Fuel prices and emission fees affect the type of vehicle used. A road toll may shift some trips to other routes and destinations, while congestion pricing (a time-variable fee, higher during congested periods) may shift travel times, as well as changing mode and the total number of trips that occur. These impacts depend on the specific type of pricing – for example, increased residential parking fees are most likely to affect vehicle ownership, and a time-variable parking fee can affect when trips occur. Because taxes are durable they tend to have higher elasticities than other fuel price changes.

Table 3 **Impacts of Different Types of Pricing**

Type of Impacts	Vehicle Fees	Fuel Price	Fixed Toll	Congestion Pricing	Parking Fee	Transit Fares
Vehicle ownership. Consumers change the number of vehicles they own.	✓				✓	✓
Vehicle type. Motorist chooses different vehicle (more fuel efficient, alternative fuel, etc.)	✓	✓				
Route Change. Traveler shifts travel route.			✓	✓	✓	
Time Change. Peak to off-peak shifts.				✓	✓	
Mode Shift. Traveler shifts to another mode.		✓	✓	✓	✓	✓
Destination Change. Motorist shifts trip to alternative destination.		✓	✓	✓	✓	✓
Trip Generation. People take fewer total trips (including consolidating trips).		✓	✓	✓	✓	
Land use changes. Changes in location decisions, such as where to live and work.			✓		✓	✓

Different price changes have different impacts on travel behavior.

Research on *mental accounting* (how consumers perceive expenditures) indicates that price impacts are affected by factors such as how prices compare with what is considered *normal* and *good value*, whether a financial incentive is presented as a discount or a surcharge, and the frequency of fee collection. Consumers tend to measure prices with respect to what they perceive as their *endowment* (what they consider theirs), and place a greater value on losses than on gains. Some studies indicate that losses from an original endowment are valued at 2.25 times gains (Thaler 1999). For example, a typical motorist could be expected to respond 2.25 times as much to a new parking fee (they pay more if they use a parking space) than a parking *cash out* incentive (they receive a rebate for reducing their use of parking spaces) of the same amount (Shoup 1997).

Type of Trip and Traveler

Elasticities tend to vary by type of trip and traveler:

- Commercial (business) travel tends to be less price sensitive than personal travel.
- Commute trips tend to be less elastic than shopping or recreational trips.
- Higher income travelers tend to be less price sensitive than lower-income travelers.
- Weekday trips may have very different elasticities than weekend trips.
- Urban peak-period trips tend to be price inelastic because congestion discourages lower-value trips, leaving only higher-value automobile trips.

Quality and Price of Alternatives

Price sensitivity tends to increase with the quality and affordability of alternative routes, modes and destinations. For example, highway tolls tend to be more price sensitive if there are parallel untolled roadways. Driving is less price sensitive in automobile-dependent areas where the quality of alternatives is poor. Transportation elasticities can often be measured as ratios, such as:

- The elasticity of automobile mode share with respect to the ratio of automobile and transit travel time for a particular type of trip.
- The elasticity of automobile mode share with respect to the ratio of automobile operating costs and transit fares.
- The elasticity of household vehicle ownership and per capita vehicle ownership with respect to the quality of transit service in a community.

This information can be used to help identify problems and solutions. For example, increased automobile mode share can often be explained by factors such as the increased ratio of automobile travel speeds relative to the speed of alternative modes, and efforts to shift travel to other modes can be evaluated by setting targets for improving their relative quality and affordability.

Scale and Scope of Pricing

In general, narrowly defined transport is more elastic than broadly defined transport, because consumers have more alternatives. For example, demand for *peak-period automobile travel on a certain road* is usually more elastic than *total personal travel along a corridor*, since a higher price for driving at a particular time at a particular road may shift travel to alternative routes, destinations, modes and travel times.

Individual price components (fuel, parking, tolls) tend to be less elastic because they each represent a small portion of total user costs. For example, driving is inelastic with respect to fuel costs, but since fuel only represents about 20% of total vehicle costs, a -0.25 elasticity of driving with respect to fuel price represents about a -1.25 elasticity with respect to total financial costs.

Time Period

Transportation elasticities tend to increase over time as consumers have more opportunities to take prices into effect when making long-term decisions. For example, if consumers anticipate low automobile use prices they are more likely to choose an automobile dependent suburban home, but if they anticipate significant increases in driving costs they might place a greater premium on having alternatives, such as access to transit and shops within convenient walking distance. These long-term decisions affect the options that are available. For example, if consumers are in the habit of shopping in their neighborhood, local stores will be successful. But if they always shop at large supermarkets, the quantity and quality of local stores will decline.

For this reason, the full effects of a price change often take many years. Short-term elasticities (usually defined as less than two years) are typically one-third of long-term elasticities (more than 10 years) (Dargay and Gately 1997). Large price changes tend to be less elastic than small price changes, since consumers make the easiest accommodations first. Dargay and Goodwin (1995) argue that the common practice of using static rather than dynamic elasticity values overestimate welfare losses from increased user prices and congestion by ignoring consumers' ability to respond to changes over time. Static elasticities skew investments toward increasing highway capacity, and undervalues transit, TDM, and "No Build" options.

Analysis by Shell International (2011) indicates that much higher per capita vehicle travel in the U.S. compared with peer countries results from decades of lower fuel prices which result in more dispersed and automobile-oriented urban development patterns. They conclude, "This result indicates that the quality of urban mobility infrastructure development can hard-wire either energy profligacy or energy efficiency into the system for decades. It also highlights the pernicious impact on long-term demand of low energy prices such as those driven by subsidies, particularly in emerging markets."

Large and Cumulative Price Changes

Extra care should be used when calculating the impacts of large price changes, or when summing the effects of multiple changes, because each subsequent change impacts a different base, as explained earlier in the discussion of *arc elasticities*. As a result, travel reductions are multiplicative, not additive. For example, if prices increase 10% on a good with a –0.5 elasticity, the first one-percent of price change reduces consumption by 0.5%, to 99.5% of its original amount. The second one-percent of price change reduces this 99.5% by another 99.5%, to 99.0%. The third one-percent of price change reduces this 99.0% by another 99.5% to 98.5%, and so on for each one-percent change. Thus, the reduction in consumption of a 10% price increase is calculated as $(1\text{-}0.005)^{10}$ (one minus 0.005, or 0.995, to the tenth power), which is 4.9%, not a full 5% that would be calculated by simply multiplying –0.5 x 10. Similarly, if three strategies are proposed for implementation, which individually provide a 5%, 6% and 7% reduction in vehicle travel, the total predicted reduction is 17%, calculated as (1-0.05) x (1-0.06) x (1-0.07) = 17.0, not 18% (5 + 6 + 7 = 18).

Price Structure
Transport prices can be structured in various ways, taking into account different rates, categories of users, vehicles, travel conditions, time periods, and special discounts or surcharges. Consumers tend to prefer simple price structures that minimize their *cognitive effort* (the need to make complex decisions), but are often willing to respond to special incentives. In a detailed study of how price structures affect consumer response to road pricing, Bonsall, et al. (2006) found the following:

- The method and timing of payments influences purchasing behaviour.
- A significant proportion of consumers "disengage" if they perceive cost structures to be too complex. This may lead them to avoid that expenditure.
- Perceived fairness is a key factor in consumers' preferences for different price structures and their response to prices.
- Attitudes to motoring costs appear to differ from other expenses. Drivers rarely consider the costs of individual journeys - motoring expenses are widely perceived as unavoidable periodic events.
- Most people have very limited spatial knowledge or ability to estimate distances.
- There appear to exist various consumer types who share distinct attitudes, preferences and behaviors, and these 'types' reflect age and gender more than income.

Transportation Elasticity Estimates

This section summarizes the results of various transportation elasticity studies reflecting various analysis scopes and perspectives.

Numerous studies have investigated transport elasticities (see summaries in BTE *Transport Elasticities Database*; Dahl 2012; Goodwin, Dargay and Hanly 2004; Pratt 2004; TRACE 1999; Wardman and Shires 2011; Wardman, et al. 2018 and 2022). They measure various types of transport, prices, users and travel conditions, and used various analysis methods. Some simply measure how changes in a single variable, such as fuel prices or transit fares, affect a single outcome, such as fuel consumption or transit riders, but more recent studies tend to apply more sophisticated evaluation techniques, considering a variety of variables and statistical analyses.

Some literature reviews and meta-analyses have evaluated and summarized the results of various studies, often resulting in recommended "generic" elasticity values that can be used in typical situations. Examples of these are summarized below.

Summaries

The tables below summarize some transport elasticity studies. The elasticities of various types of price changes are described in individual sections in this report.

Table 4 **Estimated Long Run Elasticities** (Johansson and Schipper 1997, p. 209)

Estimated Component	Fuel Price	Income	Taxation (Other than Fuel)	Population Density
Car Stock (vehicle ownership)	-0.20 to 0.0 (-0.1)	0.75 to 1.25 (1.0)	-0.08 to -0.04 (-0.06)	-0.7 to -0.2 (-0.4)
Mean Fuel Intensity (fuel efficiency)	-0.45 to -0.35 (-0.4)	-0.6 to 0.0 (0.0)	-0.12 to -0.10 (-0.11)	-0.3 to -0.1 (-0.2)
Mean Driving Distance (per car per year)	-0.35 to -0.05 (-0.2)	-0.1 to 0.35 (0.2)	0.04 to 0.12 (0.06)	-0.75 to 0.0 (-0.4)
Car Fuel Demand	-1.0 to -0.40 (-0.7)	0.05 to 1.6 (1.2)	-0.16 to -0.02 (-0.11)	-1.75 to -0.3 (-1.0)
Car Travel Demand	-0.55 to -0.05 (-0.3)	0.65 to 1.25 (1.2)	-0.04 to 0.08 (0.0)	-1.45 to -0.2 (-0.8)

Summarizes various studies. Numbers in parenthesis indicate original authors' "best guess" values.

After a detailed review of international studies, Goodwin (1992) produced the average elasticity values summarized in Table 5.

Table 5 **Transportation Elasticities** (Goodwin 1992)

	Short-Run	Long-Run	Not Defined
Petrol consumption WRT petrol price	-0.27	-0.71	-0.53
Traffic levels WRT petrol price	-0.16	-0.33	
Bus demand WRT fare cost	-0.28	-0.55	
Railway demand WRT fare cost	-0.65	-1.08	
Public transit WRT petrol price			0.34
Car ownership WRT general public transport costs			0.1 to 0.3

Summarizes various studies of long-run price effects. ("WRT" = With Respect To).

Table 6 **Consumer Demand Elasticities, European Data** (Mayeres 2000)

	Price, Peak	Price, Off-Peak	Income
Vehicle travel - essential trips	-0.16	-0.43	0.70
Vehicle travel - optional trips	-0.43	-0.36	1.53
Bus, Tram, Metro passenger-kms	-0.19	-0.29	0.59
Rail passenger-kms	-0.37	-0.43	0.84

This table summarizes elasticities from European studies. It indicates greater price elasticities for essential and peak-period travel compared with optional and off-peak travel.

Some countries have adopted standard elasticity values to be used consistently in official models and demand evaluations. The table below illustrates values used in Australia.

Table 7 **Australian Travel Demand Elasticities** (Luk and Hepburn 1993)

Elasticity Type	Short-Run	Long-Run
Petrol consumption and petrol price	-0.12	-0.58
Travel level and petrol price	-0.10	
Bus demand and fare	-0.29	
Rail demand and fare	-0.35	
Mode shift to transit and petrol price	+0.07	
Mode shift to car and rail fare increase	+0.09	
Road freight demand and road/rail cost ratio	-0.39	-0.80

This table shows elasticity values adopted by the Australian Road Research Board.

Table 8 **European Travel Elasticities** (de Jong and Gunn 2001)

Term/ Purpose	Car-Trips WRT Fuel Price	Car-Kms. WRT Fuel Price	Car-Trips WRT Travel Time	Car-Kms. WRT Travel Time
Short Term				
Commuting	-0.20	-0.12	-0.62	
HB business	-0.06	-0.02		
NHB business	-0.06	-0.02		
Education	-0.22	-0.09		
Other	-0.20	-0.20	-0.52	
Total	-0.16	-0.16	-0.60	-0.20
Long Term				
Commuting	-0.14	-0.23	-0.41	-0.63
HB business	-0.07	-0.20	-0.30	-0.61
NHB business	-0.17	-0.26	-0.12	-0.53
Education	-0.40	-0.41	-0.57	-0.76
Other	-0.15	-0.29	-0.52	-0.85
Total	-0.19	-0.26	-0.29	-0.74

WRT = "With Respect To" HB = "Home Based" NHB = "Not Home Based"

Dahl (2012) summarized the income and price elasticities of gasoline and diesel fuel from various countries with different incomes and prices. She found that gasoline price elasticities typically range from -0.11 to -0.33, and diesel price elasticities range from 0.13 to 0.38; and gasoline income elasticities that range from 1.26 to 0.66, and diesel elasticities that may be as high as 1.34 but are probably lower. Dargay (2010) developed a model for predicting long-distance car, train, bus and air travel which provides detailed elasticity values for various trip types, distances and users.

Table 9 **Summary of Elasticity Studies** (Goodwin, Dargay and Hanly 2003)

Dependent Variable	Short term	Long term
Fuel consumption (total)		
Mean elasticity	-0.25	-0.64
Standard deviation	0.15	0.44
Range	-0.01, -0.57	0, -1.81
Number of estimates	46	51
Fuel consumption (per vehicle)		
Mean elasticity	-0.08	-1.1
Standard deviation	N/A	N/A
Range	-0.08, -0.08	-1.1, -1.1
Number of estimates	1	1
Vehicle kilometres (total)		
Mean elasticity	-0.10	-0.29
Standard deviation	0.06	0.29
Range	-0.17, -0.05	-0.63, -0.10
Number of estimates	3	3
Vehicle kilometres (per vehicle)		
Mean elasticity	-0.10	-0.30
Standard deviation	0.06	0.23
Range	-0.14, -0.06	-0.55, -0.11
Number of estimates	2	3
Vehicle stock		
Mean elasticity	-0.08	-0.25
Standard deviation	0.06	0.17
Range	-0.21, -0.02	-0.63, -0.10
Number of estimates	8	8

This table summarizes numerous elasticity studies.

Based on a major review of studies Goodwin, Dargay and Hanly (2004) conclude that:

- Fuel consumption elasticities are greater than traffic elasticities, mostly by factors of 1.5 to 2.
- Long run elasticities are greater than short run, mostly by factors of 2 to 3.
- Income elasticities are greater than price, mostly by factors of 1.5 to 3.

They predict that a 10% real (inflation adjusted) fuel price increase will cause:

- Traffic volumes to fall about 1% within a year and 3% over the longer run (five years).
- Fuel consumption to fall about 2.5% within a year and 6% over the longer run.

- Vehicle fuel economy to increase about 1.5% within a year and 4% over the longer run.
- Total vehicle ownership to fall less than 1% in the short run and 2.5% in the longer run.

They also predict that if real income increases 10%, the following occurs:

- Number of vehicles, and the total amount of fuel they consume, will both rise by nearly 4% within about a year, and by over 10% in the longer run.
- Traffic volume (i.e., total vehicle travel) increases about 2% within a year and 5% in the longer run, indicating that the additional vehicles are driven less than average mileage.

Small and Winston (1999) estimate price and travel time elasticities for U.S. urban and intercity passenger transport by four modes, as summarized in the following table.

Table 10 **Passenger Transport Elasticities** (Small & Winston 1999, Table 2-2)

	Auto	Bus	Rail	Air
Urban Passenger, Price	-0.47	-0.58	-0.86	
Urban Passenger, In-Vehicle Time	-0.22	-0.60	-0.60	
Intercity Passenger, Price	-0.45	-0.69	-1.20	-0.38
Intercity Passenger, Travel Time	-0.39	-2.11	-1.58	-0.43

This table summarizes price and travel time elasticities for various types of passenger transport.

Burt and Hoover (2006) estimate the following vehicle travel elasticities. They indicate, for example, that each 1% increase in the portion of national population living in urban areas reduces per capita annual light truck mileage about 5.0% and car travel about 2.4%.

Table 11 **Light Duty Vehicle Travel Demand Coefficients** (Burt and Hoover 2006)

Factor	Light Truck Travel	Car Travel
The share of national population living in urban areas	–4.984	–2.413
Vehicles per person of driving age	1.097	1.010
Real per capita disposable income	0.721	0.705
Vehicle-kilometres traveled per driving age person	0.163	0.220
The price of gasoline relative to the price of local transit	–0.195	–0.080
The lane-kilometres of road network per person of driving age	0.490	0.267

This table indicates how some geographic and economic factors affect car and light-truck travel.

The Louis Berger Group (2004) provides recommended elasticity values for vehicle travel with respect to numerous transportation and land use factors including regional accessibility, land use density and mix, lane-miles, travel time, transit service, sidewalks and other pedestrian facilities. Bento, et al (2003) identify the following factors affecting household vehicle travel, based on analysis of data from 113 U.S. cities:

Table 12 **Factors Affecting Household Vehicle Travel** (Bento, et al. 2003)

	Annual VMT		Annual VMT
Additional working adult male	6,070	10% increase in education	1,239
Additional working adult female	4,779	10% increase in income	588
Additional working child	8,461	10% increase in central location	-281
		10% increase in accessible city shape	-84
		10% increase in road density	127
		10% increase in bus service	-1
		10% increase in rail service	-40
		10% increase in jobs-housing imbalance	107
		10% increased distance to nearest bus stop	151

This table summarizes how various factors affect average household vehicle mileage in U.S. cities. Employment and income have the greatest impacts, but land use factors can also affect vehicle travel.

Using a detailed travel survey integrated with a sophisticated land use model, Frank, et al. (2008) found that a 10% fuel or parking price increase reduces automobile mode share by 0.7%, increases demand for carpooling 0.8%, transit 3.71%, biking 2.7% and walking 0.9%. Using data from U.S. cities between 1982 and 2008, McMullen and Eckstein (2011, Table 5.6) found long-run elasticities of vehicle travel with respect to (WRT) lane-miles to be 0.2524, WRT income to be 0.2630, WRT population density to be -0.0431, WRT fuel price to be -0.1542, and WRT transit ridership to be -0.0228.

In a detailed analysis of transport and land use factors, Buehler (2010) found that fuel price is the largest factor explaining differences in travel activity (per capita walking, cycling, public transit and automobile travel) between the U.S. and Germany. He found that, although increased land use density and mix tend to reduce automobile travel in both countries, at any population density Americans drive 60% to 80% more than Germans. The analysis also found that vehicle travel is more sensitive to fuel prices in the U.S. than in Germany. For example, the 2008 gasoline price spike caused a 0.05% vehicle travel decline in Germany compared with a 3.6% decline in the U.S., since low U.S. fuel taxes cause wholesale oil price increases to result in proportionately larger retail fuel price increases, and leads to more lower-value, discretionary vehicle travel than in Germany.

Barla, et al. (2010) used panel analysis to estimate the price and income elasticities, and rebound effects of Canadian light-duty vehicle travel and fuel consumption using provincial level data from 1990 to 2004. They found the long-term fuel price elasticity to be -0.2, and a 0.2 to 0.3 elasticity of vehicle travel with regard to income. Estimates of the short- and long-term rebound effects are approximately 8% and 20% respectively.

Boilard (2010) used two methods to quantify Canadian fuel price and income elasticities for the 1970-1989 and 1990-2009 periods. The *dynamic partial adjustment model* explains per capita gasoline consumption as a function of average real gasoline prices, real disposable income per capita during each quarter, a seasonal effect and per capita gasoline consumption during the preceding quarter. This method is commonly used because it is relatively simple and can easily distinguish between short- and long-term elasticities, but it can bias results if the series are not stationary (i.e., risk of spurious correlation) or due to other confounding factors. A second approach, an *estimation of an error correction model* (ECM), can avoid these pitfalls. The table below summarizes the results. They indicate that price elasticities declined during the 1990 to 2009 period.

Table 13 **Factors Affecting Household Vehicle Travel** (Boilard 2010)

Approach	Elasticity	1970-1989		1990-2009	
		Short Term	Long Term	Short Term	Long Term
Dynamic Model	Price	-0.093	-0.762	-0.091	-0.256
	Income	0.046	0.377	0.249	0.699
Cointegration Model	Price	-0.193	-0.450	-0.046	-0.085
	Income	0.209	0.428	0.169	0.423

This analysis indicates that fuel price sensitivity declined between 1970-1980s and 1990-2009.

Analyzing the 2009 U.S. National Household Travel Survey, Blumenberg and Pierce (2012) identified factors that affect vehicle ownership and passenger travel, including income, age, gender, race-ethnicity, employment status (student, work, retiree, homemaker), children in household, geographic location (density and urban region), vehicle insurance costs and vehicle ownership (as it affects personal travel). The results indicated that as household incomes rise from low to medium levels, vehicle ownership and travel tend to increase proportionately faster than incomes. Vehicle ownership and travel increase for workers and if a household has children, decline with land use density.

A study titled, [The Future of Driving in Developing Countries] (Ecola, et al. 2014) identified various factors that affect motor vehicle ownership and use, including demographics (the portion of residents who work), incomes, geography (development density and travel distances), vehicle infrastructure (the quality and price of using roads and parking facilities), fuel price, vehicle ownership policies (such as vehicle taxes and registration fees), quality of alternatives to driving, the political influence of domestic oil and vehicle production industries, and the favorability of car culture (whether popular culture, attitudes toward the environment and consumer attitudes, and perceptions) favor automobile travel over other modes.

This analysis framework is used to develop a predictive model of motorization. The results indicate that although motor vehicle ownership and use tend to increase as during a country's period of motorization, as incomes increase from very low to moderate, at high incomes they tend to saturate, and the level of saturation varies significantly depending on geographic factors and public policies. This explains why, for example, per capita vehicle travel has saturated at about 4,000 annual kilometers in Japan, 7,000 annual kilometers in Germany, 10,000 annual kilometers in Australia and 15,000 kilometers in the United States.

Individual Elasticities

The elasticities of different types of transport prices found in various studies are discussed below.

Vehicle Ownership

Whelan (2007) identified various factors that affect vehicle ownership, including household demographics, income and location. Comparing UK and US travel patterns Giuliano and Dargay (2006) find that UK residents own fewer automobiles and make fewer and shorter motor vehicle trips due to a combination of lower real incomes, higher vehicle fees (particularly fuel taxes) and better travel options (better walking and cycling conditions, better public transport services, and more local shops). Johansson and Schipper (1997) conclude that per capita vehicle ownership is affected by fuel prices (elasticity -0.1), income (elasticity 1.0), other taxes (elasticity -0.06), and population density (elasticity -0.4). Goodwin, Dargay and Hanly (2003) estimate that a 10% fuel price increase reduces vehicle ownership 1.0 in the short-run and 2.5% over the long-run.

Income

As household incomes rise from poverty their vehicle ownership tends to increases, but at a declining rate (Blumenberg and Pierce 2012). International data indicate that between $3,000 to $10,000 annual income (2002 U.S. dollars), per capita automobile ownership and mileage tend to increase about twice as fast as income growth, but at higher incomes growth rates levels off and eventually saturate (Dargay, Gately and Sommer 2007; IEA 2004; Millard-Ball and Schipper 2010). Dargay (2007) finds asymmetry in these impacts: household vehicle ownership rates increase with employment and incomes but are less likely to decline if employment and incomes are reduced. Kopits and Cropper (2003) find that vehicle ownership rates level off at about $16,000 (2003 dollars) per capita annual income. Karlaftis and Golias (2002) find that a household's purchase of its first vehicle is primarily dependent on socioeconomic factors (employment and income), but the purchase of additional vehicles depends primarily on local travel conditions. If walking and cycling conditions are poor and driving is faster and cheaper than transit, households tend to own more automobiles. Small and Van Dender (2005 and 2007) found that fuel price rebound effects (increased annual vehicle travel from increased vehicle fuel economy) declines significantly with income.

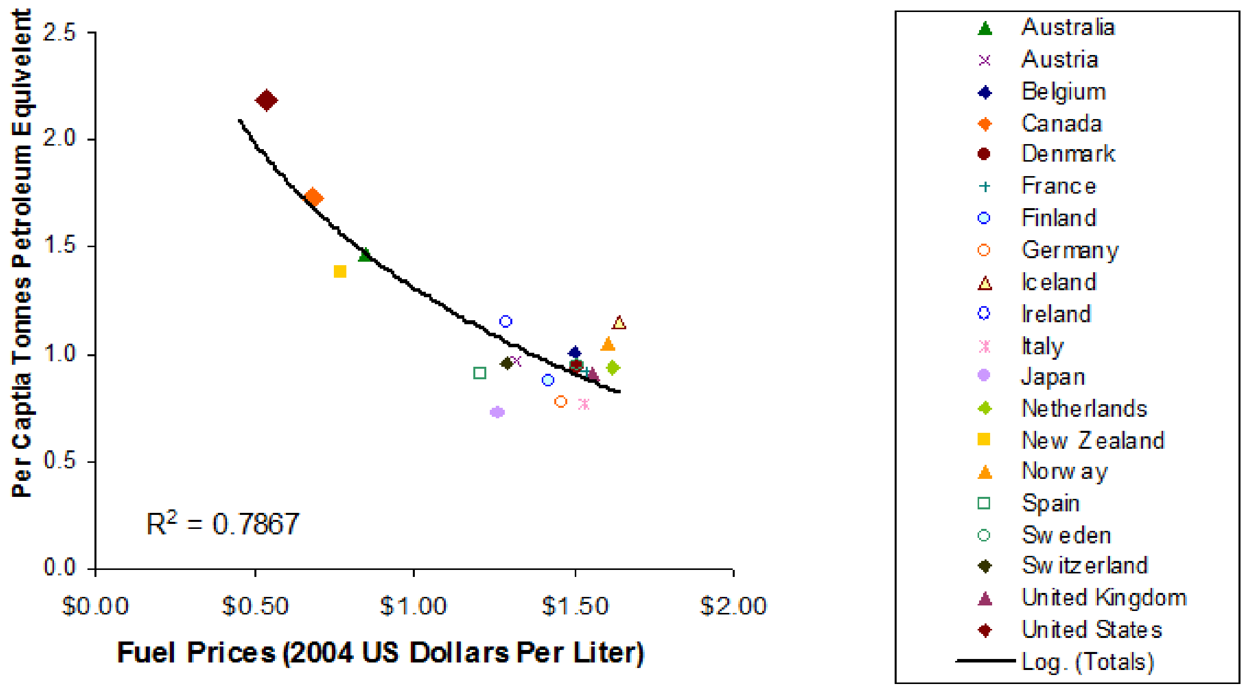
Glaister and Graham (2002) conclude that the long-run elasticity of vehicle fuel consumption with respect to income is 1.1 to 1.3, and the long-run elasticity of vehicle travel with respect to income is 1.1 to 1.8, with lower short-run values. Using data from U.S. cities between 1982 and 2008, McMullen and Eckstein (2011, Table 5.6) found 0.263 long-run elasticities of vehicle travel with respect to income. Based on their review, Goodwin, Dargay and Hanly (2003) conclude that if real income increases 10%:

- Vehicle ownership and fuel consumption will increase nearly 4% within a year, and over 10% in the longer run.
- Traffic volumes will increase 2% within a year and about 5% in the longer run. Much of the increase in fuel consumption will result from reduced fuel efficiency.

Fuel Consumption With Respect to Fuel Price

Fuel price increases tend to cause fuel consumption to decline, in the short-term by reducing total vehicle mileage and traffic speeds, and shifting travel to more fuel-efficient vehicles in multi-vehicle households, and in the long-term by increasing vehicle fuel economy (distance traveled per unit of fuel consumed), and more accessible land use patterns (Institute for Transport Studies 2004; Sterner 2006; Lipow 2008; CBO 2008; Sivak and Schoettle 2009; UKERC 2009). Where fuel prices are low, motorists tend to use improvements in vehicle energy *efficiency* (power per unit of fuel consumed) to increase vehicle performance (power and size) rather than improving fuel economy (Lutsey and Sperling 2005) Figure 6 illustrates the relationship between national fuel prices and fuel consumption.

Figure 6 **Fuel Price Versus Per Capita Transport Energy Consumption** (OECD Data)



As fuel prices increase, per capita transportation energy consumption declines.

Using 1982-1995 U.S. data, Agras and Chapman (1999) find short-run fuel price elasticities of -0.15 for vehicle mileage and 0.12 for fuel economy, summing to an overall short-run gasoline price elasticity of –0.25, and long-run elasticities of –0.32 for vehicle travel and 0.60 for fuel economy, summing to –0.92 in the long run. This means that a 10% fuel price increase typically reduces driving 1.5% and improves fuel economy by 1.2% in the short-run, and over the long run mileage declines 3.2% and fuel efficiency increase 6%, leading to a 9.2% overall reduction in fuel consumption.

Glaister and Graham (2002) review international studies on fuel price and income impacts on vehicle travel and fuel consumption. They find short run fuel price elasticities from –0.2 to –0.5, and long run elasticities from –0.24 in the U.S. (ranging from –0.24 to –0.8) up to –1.35 in the OECD overall (ranging from –0.75 to –1.35). They identify factors that affect fuel price elasticities including functional form, time span, geography and what other factors are included in a model (such as vehicle ownership), and find that long-term gasoline demand appears to be getting more elastic. They conclude that short-run elasticities are –0.2 to –0.3, and long-run elasticities are –0.6 to –0.8. Summarizing international research, Goodwin (1992) estimates gasoline price elasticity to be -0.27 in the short run and -0.7 in the long run. He predicts that a 10% vehicle fuel price increase will have the following effects:

- In the short run vehicle travel declines about 1.5% and fuel consumption 2.7%, due in part to shifts to more fuel efficient vehicles in multi-vehicle households and reduced speeds.
- In the long run vehicle travel declines 3-5%, split between reduced car ownership and per-vehicle use. Petroleum consumption declines 7% or more, due in part to the purchase of more fuel-efficient vehicles.

In a major review, Goodwin, Dargay and Hanly (2003) conclude that a durable, 10% real (inflation adjusted) fuel price increase causes the following adjustment process:

A. Vehicle travel declines by approximately 1% within about a year and about 3% in the longer run (about five years).

B. Fuel consumption declines approximately 2.5% within a year and 6% in the longer run.

Fuel consumed declines more than vehicle travel because motorists purchase more fuel-efficient vehicles and drive more carefully. As a result, price increase cause:

C. Vehicle fuel efficiency increases approximately 1.5% within a year and approximately 4% over the longer run.

D. Total vehicle ownership declines less than 1% in the short run and 2.5% in the longer run.

The results indicate that fuel price affect vehicle purchase decisions, which affects total vehicle travel. However, many studies only assess vehicle ownership, per vehicle mileage or traffic, but not at the same time or using the same data. Their analysis suggests that (A) and (B) effects are more robust than (C) and (D) effects.

Dargay (1992) reports higher fuel price elasticities averaging -0.67 when price increases and decreases are calculated separately. DeCicco and Gordon (1993) calculate the medium-run U.S. vehicle fuel price elasticity to be -0.3 to -0.5. Eltony (1993) finds the Canadian fuel price elasticity to be approximately -0.3 in the short term and rises to approximately 1.0 after a decade. Hagler Bailly (1999) conclude that the fuel price elasticity for gasoline is –0.15 in the short run and –0.6 in the long run, with separate estimates for air, freight and transit transport. Table 14 summarizes the price elasticities of various types of transportation fuel. Using 1980-2000 U.S. data, Zupan (2001) finds little relationship between fuel price and VMT in the short-term, but a relationship is found if price changes are evaluated with a 6-month lag, indicating that approximately 25% of VMT changes can be accounted for by fuel price.

Table 14 **Estimated Fuel Price Elasticities** (Hagler Bailly 1999)

	Short Run Elasticity			Long Run Elasticity		
	Low	Base	High	Low	Base	High
Road Gasoline	-0.10	-0.15	-0.20	-0.40	-0.60	-0.80
Road Diesel - Truck	-0.05	-0.10	-0.15	-0.20	-0.40	-0.60
Road Diesel – Bus	-0.05	-0.10	-0.15	-0.20	-0.30	-0.45
Road Propane	-0.10	-0.15	-0.20	-0.40	-0.60	-0.80
Road CNG	-0.10	-0.15	-0.20	-0.40	-0.60	-0.80
Rail Diesel	-0.05	-0.10	-0.15	-0.15	-0.40	-0.80
Aviation Turbo	-0.05	-0.10	-0.15	-0.20	-0.30	-0.45
Aviation Gasoline	-0.10	-0.15	-0.20	-0.20	-0.30	-0.45
Marine Diesel	-0.02	-0.05	-0.10	-0.20	-0.30	-0.45

This table summarizes Canadian price elasticities for various vehicle fuels.

Meta-analysis by Espey (1996) evaluated price and income elasticity estimates in 101 U.S. gasoline demand studies. It found the gasoline price-elasticity of averages -0.26 short-run (one year or less), and -0.58 the long-run (longer than 1 year). Among the explanatory variables considered in the meta-analysis included functional form, lag structure, time span, and geographic scope. Including vehicle ownership in gasoline demand studies was found to result in lower estimates of income elasticity, data sets which pool U.S. and foreign data result in larger (absolute) estimates of both price and income elasticity, and the small difference between static and dynamic models suggests that lagged responses to price or income changes are relatively short. This study found that elasticity estimates appear relatively robust across estimation techniques.

Sipes and Mendelsohn (2001) surveyed motorists concerning their response to fuel price increases. They find an elasticity of -0.4 to -0.6 in the short-run and -0.5 to -0.7 in the long run, with greater price sensitivities for larger and poorer households. Kennedy and Wallis (2007) calculate that the price elasticity of fuel in New Zealand is –0.15 in the short run (less than two years) and –0.20 in the medium run (2-4 years).

Analyzing 1971-1997 OECD energy and price data, Gately and Huntington (2001) find the long-run price elasticities of 64% for petroleum and 24% for all energy. They report a long-run income-elasticity of 55-60% for oil and energy, indicating that 3% GDP growth would increase energy use less than a 2%, all things equal (i.e., constant prices). Sterner (2006) estimates the long-term vehicle fuel price elasticity to be -0.8, and calculates the carbon emission reductions that would have resulted if during the last three decades all OECD countries had high fuel taxes (about 44%), and the additional emissions if all countries had low fuel taxes (about 40%). Wadud, Graham and Noland (2008) find heterogeneity in price and income elasticities for different demographic and income groups; elasticities are higher in multi-vehicle, multi-wage earner, urban households, and are lower in single car, single (or no) wage earner, and rural household.

Lee, Han and Lee (2009) found long-run elasticities of vehicle travel with respect to fuel prices to average -0.59 in Korea between 2000 and 2008. This is a relatively high value possibly reflecting low average incomes or high quality travel alternatives.

Santos and Catchesides (2005) evaluate the equity and travel impacts of fuel taxes using U.K. consumer and travel survey data. They find the most price sensitivity among lower-income urban households, who show an elasticity of -0.93 (a 1% fuel price increase reduces vehicle travel 0.93%), and the lowest price sensitivity among middle-income rural residents, who show an elasticity of -0.75. Elasticity values decline with income, from -0.63 for lower-income urban households to -0.07 for the richest rural residents. Their analysis indicates the following factors affecting vehicle travel:

- *Real cost per mile:* Real cost per mile has a negative and statistically significant effect on mileage, such that an increase in the real cost per mile causes a drop in mileage.
- *Real household income:* Real income has a positive and statistically significant effect on mileage, but the rate of increase of mileage declines with income.
- *Age of head of household:* Age has a positive and statistically significant effect on mileage, but the rate of increase of mileage declines with age.
- *Number of children:* The number of children in the household has a positive and significant effect on mileage.
- *Employment status of head of household:* All categories have lower mileage compared to full-time workers, although the effect is statistically significant only for the retired.
- *Occupational class:* Professionals have increased mileage, and skilled manual workers reduced mileage, compared to an unskilled manual worker. The difference for non-manual workers is not statistically significant.
- *Availability of public transport:* Available and frequent public transport services have a statistically significant negative impact on mileage.
- *Population density:* Households in the least densely populated areas have significantly increased mileages compared to those in the most densely populated areas.

Bomberg and Kockelman (2006) surveyed motorists' to evaluate their responses to the 2005 fuel price spike. They found that motorists use a combination of reduced driving speeds, increased trip chaining, and mode shifting. These responses varied by geography, with more mode shifting by urban residents and more trip chaining by suburban residents.

Using California 2005-08 emission inspection odometer readings Gillingham (2010a and 2010b) found the medium-run elasticity of vehicle travel to fuel price to be -0.15. Responses vary by income, demographics and location. Elasticities are U-shaped with regard to income, with higher values in the lowest and highest income brackets, which probably reflects lower-income motorists' greater financial constraints and better public transit availability, and higher-income motorist greater total mileage and therefore more marginal-value vehicle travel, and shifts to air travel. Elasticities are higher in urban than rural areas. Vehicles registered in counties with higher average commute times tend to be less elastic than those with lower commute times, probably reflecting fewer alternatives to driving. Vehicles in zip codes with a higher percentage of residents over 64 years tend to have higher elasticities than those with fewer seniors, possibly reflecting retirees' greater travel flexibility. Vehicles in zip codes with more under 18 year-olds tend to have a lower elasticity, which may reflect travel inflexibility by families with children.

Sivak and Schoettle (2011) found that new vehicle fuel economy is influenced by the unemployment rates and gasoline prices. Their model shows that U.S. new vehicle miles-per-gallon = 16.58 + (0.39 x unemployment rate) + (0.62 x gasoline price). Anas and Hiramatsu (2010) develop a spatial computable general equilibrium (CGE) model of the Chicago region called RELU-TRAN2, which indicates that the long-run elasticity of gasoline demand is -0.081, of which 79% is from changes in vehicle travel and 21% from increased fuel economy per vehicle-mile.

Spiller and Stephens (2012) developed a comprehensive model using data from the 2009 National Household Travel Survey, U.S. Census, and monthly state-level gasoline prices to estimate household-level fuel price elasticities. They found the mean elasticity of demand for gasoline is -0.67, with significant variation across location and income. They found that higher income households, households with more vehicles, and households that drive more annual VMT tend to have higher fuel-price elasticities, and since rural households tend to drive relatively high annual miles and have relative low annual incomes, they tend to be more price elastic than urban households.

North American fuel price elasticities declined between 1980 and 2005 (CBO 2008). Using U.S. state-level data, Hughes, Knittel and Sperling (2006) found short-run elasticities from -0.21 to -0.34 during 1975-80, but only -0.034 to -0.077 during 2001-06. Using more comprehensive data, Small and Van Dender (2005 and 2007) found the gasoline price elasticities were -0.09 in the short run and -0.40% in the long run during the 1997 to 2001 period, about half the values observed from 1966 to 1996. They implied that these trends will continue, resulting in ever declining price sensitivity.

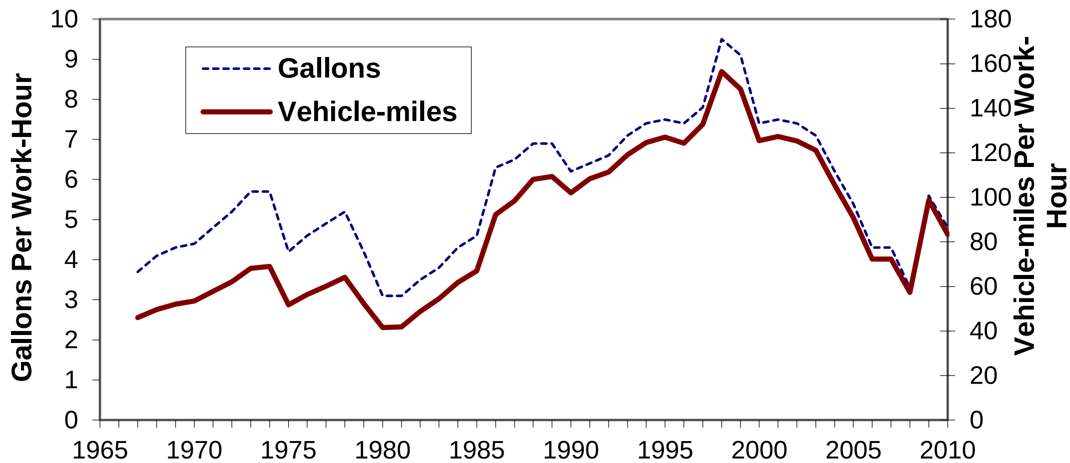
Similarly, Hymel, Small and Van Dender (2010) and Hymel and Small (2015) used U.S. state-level cross-sectional time series data for 1966 through 2009 to evaluate the effects of various factors including incomes, fuel price, road supply and traffic congestion on vehicle travel. They find the elasticity of fuel consumption with respect to fuel price (based on 2004 conditions for factors such as vehicle ownership and incomes) from 1966-2004 was -0.055 in the short run and -0.285 over the long run (a 10% increase in fuel price causes fuel consumption to decline by 0.55% in the short run and 2.85% over the long run), but increased in 2005-2009. Their analysis indicates that long-run travel elasticities are typically 3.4–9.4 times the short-run elasticities.

Those results likely reflect unique factors during those years, including increased per-capita vehicle ownership, increasing female employment rates, peak Baby Boom driving years, declining real fuel prices and rising real incomes (which reduced fuel prices relative to incomes), highway expansion and sprawling development. Recent studies suggest that fuel price elasticities increased after 2006 (Litman 2013; Williams-Derry 2010). In 2007 and 2008, per capita fuel consumption and vehicle travel declined due to high fuel prices (CERA 2006; Williams Derry 2011). Komanoff (2008-2011) estimates that short-run U.S. fuel price elasticities reached a low of -0.04 in 2004, but increased to -0.08 in 2005, -0.12 in 2006, -0.16 in 2007 and -0.29 in 2011. Brand (2009) found that the 20% U.S. fuel price increase between 2007 and 2008 caused a 4.0% reduction in fuel consumption, indicating a short-run price elasticity of -0.13. However, this does not account for the long-term trends. Between 1983 and 2004 VMT increased about 2.9% annually and gasoline consumption increased about 1.2% annually, reflecting growth in population, incomes and GDP. Accounting for these base trends Brand estimate that the 10-month fuel consumption price elasticity increases to about -0.17.

Li, Linn and Muehlegger (2011) used data on U.S. gasoline consumption, vehicle travel, vehicle ownership, and new vehicle purchases to evaluate how price changes affected transport activity and fuel consumption between 1968 and 2008. They find that fuel tax increases, which are considered durable, have a greater effect on fuel consumption than oil market fluctuations. They estimate the elasticity of gasoline demand with respect to fuel price is -0.235, with greater elasticities for taxes than for tax-exclusive price fluctuations. This analysis suggests that the declining elasticities of fuel consumption with respect to price during the last quarter of the Twentieth Century may reflect, in part, the decline in the tax share of fuel prices, a factor not generally considered in elasticity studies. This study suggests that increases in motor vehicle operating costs that consumers consider durable (fuel taxes, road tolls, parking fees and distance-based insurance and registration fees) are likely to cause much greater reductions in vehicle travel and fuel consumption than indicated by conventional models which use elasticity value based on responses to price changes that consumers considered temporary.

Various factors can help explain these changes in fuel price sensitivity. Fuel costs have increased relative to incomes. For example, in 1967 a median work-hour could purchase 3.7 gallons (14.2 liters) of fuel and 46 vehicle-miles (74 kilometers). In 2000 the same effort could purchase about twice as much fuel (7.4 gallons or 28.1 liters) and nearly three times as much vehicle travel (126 vehicle-miles or 202 kilometers), due to higher incomes and fuel economy. But these trends subsequently reversed. In 2010, a median work-hour only purchased 4.7 gallons (17.9 liters) and 83 vehicle-miles (133 kilometers), more than in 1967 but a third less than in 2000. Figure 7 illustrates these trends.

Figure 7 **U.S. Fuel and Vehicle-Travel Purchased Per Median Work-Hour** (Litman 2012)



The amount of fuel and vehicle travel that consumers could purchase increased significantly between 1967 and 2000, but declined since.

Other factors that may have increased vehicle travel demand and reduced the price sensitivity of driving during the second half of the Twentieth Century included extensive roadway expansion, and more dispersed, automobile-oriented land use development patterns (Litman 2006). An extensive body of literature indicates that roadway expansion induces vehicle travel (Litman 2001). Hymel, Small and Van Dender (2010) found that the elasticity of vehicle use with respect to road lane-miles is 0.037 in the short run and 0.186 in the long run. Both Gillingham (2010) and Guo, et al. (2011) found that vehicle travel is more price sensitive for residents of urban, transit-accessible areas than for comparable households in automobile dependent areas.

Although price elasticities generally decline with income (wealthy people tend to be less price sensitive than poor), based on analysis of the 2009 National Household Travel Survey, Wang and Chen (2014) found fuel price elasticities to be −0.41 and −0.35 for the two highest quintile income groups, much higher than the −0.24 for the lowest income group. This may reflect higher income household's ability to respond to fuel price increases by purchasing more fuel efficient vehicles (since they tend to purchase new vehicles), and the greater portion of their travel that is optional.

There is also evidence that vehicle travel demand has peaked in most industrialized countries (Millard-Ball and Schipper 2010; Metz 2012), and demand for alternatives is increasing (Litman 2006; Pearce 2011). This may make vehicle travel more price sensitive, particularly if the quality of alternative modes improves.

For this analysis it is also interesting to compare U.S. conditions with other countries. Most economically developed countries have much higher fuel prices than the U.S. For example, in 2010, gasoline prices averaged $0.76 per liter in the U.S., $1.60 in Japan, $1.90 in Germany, $1.92 in the U.K., and $2.12 in Norway (GIZ 2011). Since elasticities are normally calculated based on percentage changes, fuel price elasticities will appear larger in these countries than in the U.S. For example, a $0.25 per liter price increase represents a 33% change in the U.S. but only 13% in the U.K., although the cost burden relative to consumers' incomes is similar in both countries (it is somewhat larger in the U.K. due to somewhat lower incomes). This creates an illusion that U.S. motorists are less sensitive to fuel prices than motorists in other countries. For example, if a $0.25 per liter fuel price change caused a 10% reduction in vehicle travel in both U.S. and the U.K., this would indicate an elasticity of -0.3 in the U.S. but -0.77 in the U.K.

Evaluating effects of the British Columbia carbon tax, Rivers and Schaufele (2015) find that a five cent carbon tax causes an 8.4% gasoline demand reduction, about four times higher than the 2.1% reduction caused by an identical five cent increase in other market prices fluctuations.

Table 15 summarizes the major results of these fuel price elasticity studies.

Table 15 **Summary of Fuel Price Elasticity Studies**

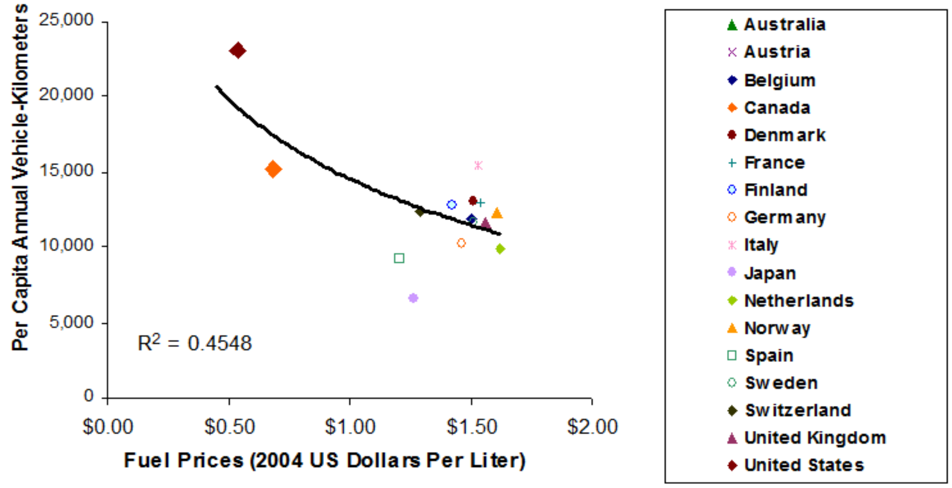
Study	Study Type	Scope	Major Results
Goodwin, Dargay and Hanly (2004)	Summarized various fuel price and income elasticity studies	1929 to 1991. Mostly North America and Europe.	-0.25 short run -0.6 long run
Espey (1996)	Review of 101 gasoline price elasticity studies.	1936 to 1986, U.S.	-0.26 short-run -0.58 long-run
Glaister and Graham (2002)	Review of various fuel price and income elasticity studies.	Second half of the Twentieth Century. Mostly North America and Europe.	–0.2 to –0.3 short run –0.6 to –0.8 long-run
Lipow 2008	Review of selected energy price elasticity studies.	Second half of the Twentieth Century. Mostly North America and Europe	-0.17 short run, -0.4 long run
Small and Van Dender (2005)	State-level cross-sectional time series of gasoline price elasticities. Comprehensive model.	U.S. State Data, 1966-2001	*1966-2001* –0.09 short run –0.41% long run *1997 to 2001* –0.07 short run –0.34% long run
Hymel, Small and Van Dender (2010)	Comprehensive state-level cross-sectional time series gasoline price model	1966 to 2004, U.S.	–0.055 short run –0.285 long run
Agras and Chapman (2001)	Gasoline price elasticity.	1982-1995, U.S.88	–0.25 short-run –0.92 long run
Li, Linn and Muehlegger (2011)	Comprehensive, with separate analysis of fuel tax increases and price fluctuations	1968-2008, U.S. 88	-0.235
Hughes, Knittel and Sperling (2006)	Gasoline price elasticities. Comprehensive model.	1975 to 2006, U.S.	*1975-1980* –0.21 to –0.34 short-run *2001-2006* –0.034 to –0.077 short-run
Boilard (2010)	Fuel price elasticities. Comprehensive model.	1970 to 2009, Canada	*1970-1989* -0.093 to -0.193 short run -0.762 to -0.45 long run *1990-2009* -0.046 to -0.091 short run -0.085 to -0.256 long run
Komanoff (2008-2011)	Short run fuel price elasticity. Simple model.	2004 to 2011 U.S. data	-0.04 in 2004 -0.08 in 2005 -0.12 in 2006 -0.16 in 2007 -0.29 in 2011

Various types of studies covering various times and geographic areas have measured fuel price elasticities. Some of these are reviews of previous studies.

Vehicle Travel With Respect To Fuel Prices

As mentioned above, about a third of the fuel savings caused by fuel price increases result from vehicle travel reductions, and increased fuel economy tends to increase vehicle travel, a *rebound effect*. For example, increasing vehicle fuel economy from 20 to 30 miles per gallon (MPG) reduces per-mile fuel costs by 33%, from 10¢ to 6.7¢ per mile when fuel is $2.00 per gallon and from 20¢ to 13.3¢ per mile at $4.00 per gallon. This effect is typically estimated at 10-30% over the long run, so each 10% fuel economy gain increases vehicle mileage 1-3%, resulting in 7-9% net fuel savings (UKERC 2007).

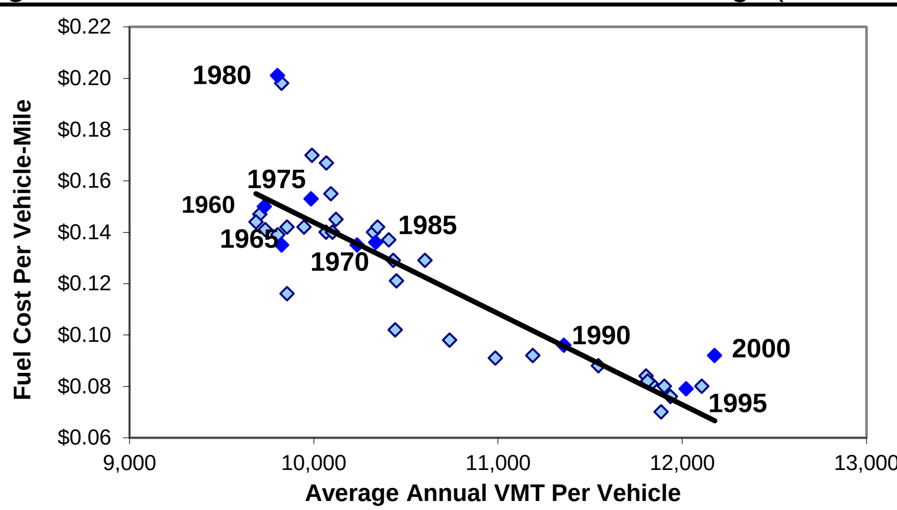
Figure 8 **Fuel Price Versus Per Capita Vehicle Travel** (VTPI 2007)



Higher fuel prices tend to reduce per capita vehicle travel.

Figures 8 and 9 illustrate how changes in real fuel prices (adjusted for inflation and currency exchange) affect per capita annual vehicle travel.

Figure 10 **Fuel Costs Versus Annual Vehicle Mileage** (BTS 2001)[1]



Per capita vehicle mileage tends to increase when real (inflation-adjusted) fuel costs decline.

[1] VTPI (2011), *U.S. Fuel Trends*, Victoria Transport Policy Institute; at www.vtpi.org/fueltrends.xls.

A meta-analysis of 74 primary studies found that rebound effects (the additional vehicle travel resulting from increased vehicle fuel economy) average about 10–12% in the short-run and 26–29% over the long-run (Dimitropoulos, Oueslati and Sintek (2018), with relatively higher effects associated with lower incomes, higher gasoline prices and higher population densities, and declining rebound effect over time. Nehiba (2022) measured how fuel price variations by location and time affect vehicle traffic using the fast network of traffic sensors on U.S. roads during 2013 to 2016, accounting for other factors that affect vehicle travel activity including weather, economic conditions, day of week and month of the year. The results indicate that a 10% price increase causes traffic counts fall by 3.3% with smaller reductions (just 1%) in rural counties and larger (4% in the most urbanized counties. This probably reflects the greater mobility and accessibility options in urban areas.

Using French household travel data, Catherine and Alejandra (2019) found that a third of energy savings from vehicle fuel economy (efficiency) increases are offset by increased vehicle-kilometres, and a positive relationship between income and driving distance until households reach a monthly income of 3,453 €, beyond which it becomes negative.

Kilian and Zhou (2020) and Litman (2013) conclude that the very low fuel price elasticities reported by Hymel, Small and Van Dender (2010) during the latter part of the Twentieth Century probably reflected unique conditions (low fuel prices, rising employment, incomes and sprawl) and data biases; more recent, technically sophisticated studies find higher elasticities, typically -0.27 to -0.37. The study, "Anticipation, Tax Avoidance, and the Price Elasticity of Gasoline Demand," published in the *Journal of Applied Econometrics*, (Coglianese, et al. 2017) exploited variations in fuel taxes across states to calculate that the short-run price elasticity of gasoline demand is -0.37 in the aggregate. The study, "High Frequency Evidence on the Demand for Gasoline" published in the *American Economic Journal* (Levin, Lewis and Wolak 2017), used U.S. credit card fuel purchase data to calculate that the price elasticity of gasoline demand ranging from -0.27 to -0.35. Using fuel price and consumption for individual Japanese motorists Knittel and Tanaka (2019) estimated a -0.37 short-run elasticity of fuel consumption to price, which includes -0.30 for the price elasticities of miles driven and -0.07 on-road fuel economy.

Taiebat, Stolper and Xu (2019) developed a microeconomic model to estimate vehicle travel elasticities with respect to fuel and time costs. Their central estimate of the combined elasticity of VMT demand is −0.4. They find that most households are more sensitive to time than to fuel costs, and that wealthier households have more elastic demand. They use these estimates to predict the VMT and energy use impacts of connected and autonomous vehicle adoption scenarios, and forecast a 2–47% increase in travel for an average household, resulting in net increases in energy us, especially in higher income groups. Using data from the National Household Travel Survey and the American Time Use Survey, Alberini, Di Cosmo and Horvath (2022) found that fuel prices affect vehicle travel and time spent travelling. They find that a 25₵ per gallon gasoline price increase (about 10%) reduces vehicle travel and emissions by 1–5%.

Linn (2013) found a higher elasticity of vehicle travel with respect to vehicle fuel economy (miles per gallon or liters of fuel per 100 kilometers) than for fuel price, indicating significant rebound effects from vehicle fuel efficiency standards. He estimates the rebound effect ranges between -0.2 and -0.4 (each 1% increase in vehicle fuel economy increases vehicle travel 0.2% to 0.4%, resulting in 0.6% to 0.8% net fuel savings), which are substantially larger values than recent rebound effect estimates using aggregate fuel price data (e.g., Small and van Dender 2007).

Using data from U.S. cities between 1982 and 2008, McMullen and Eckstein (2011, Table 5.6) found long-run elasticities of vehicle travel with respect to fuel price to be -0.1542. Li, Linn and Muehlegger (2011) find that the elasticity of vehicle travel with respect to gasoline prices ranges from -0.24 to -0.34, depending on time period and model specifications, with no significant difference between taxes and other price changes.

Hymel, Small and Van Dender (2010) used U.S. state-level cross-sectional time series data for 1966 through 2004 to evaluate the effects of income, fuel price, road supply and traffic congestion on vehicle travel. They find the elasticity of vehicle travel with respect to per-mile fuel cost is -0.026 in the short run and -0.131 in the long run. Their elasticity values tend to decline with income, and increase as fuel prices rise relative to incomes. They also find that the elasticity of vehicle travel with respect to total road mileage is 0.037 in the short run and 0.186 in the long run (a 10% increase in lane miles causes VMT to increase 0.37% in the short run and 1.86% over the long run), and the elasticity of vehicle use with respect to congestion over the entire time period is -0.045, and increases with income, and so is estimated to be 0.078 at 2004 income levels. Their analysis indicates that long-run travel elasticities are typically 3.4–9.4 times the short-run elasticities.

Brand (2009) found that the 20% U.S. fuel price increase between 2007 and 2008 caused a 3.5% reduction in VMT, indicating a short-run price elasticity of -0.17 for the four-month July to October period of 2007 is compared with the same months in 2008, and about -0.12 went the first ten months of 2007 are compared with those of 2008. However, this does not account for the long-term trends. Between 1983 and 2004 VMT increased about 2.9% annually and gasoline consumption increased about 1.2% annually, reflecting growth in population, incomes and GDP. Accounting for these base trends the short-run VMT fuel price elasticity for the four months of July through October 2008 versus 2007 is about -0.30, and for the first ten months of 2008 versus 2007 it is -0.21. Salon (2014) found the elasticity of household VMT with respect to fuel price is -0.1 overall but a much larger -0.20 in “Urban High Transit Use” neighborhoods.

Using odometer readings taken during California vehicle smog checks 2005 to 2008, Gillingham (2010b) found statistically significant medium-run (two-year) elasticities of vehicle travel with respect to gasoline price to be -0.15 to -0.20, with variations by geographic location, income and vehicle type. These price effects appear to increase over time. For urban and suburban residents, higher fuel economy cars have a lower elasticity than SUVs and pickups, suggesting that multi-vehicle households respond to price increases by shifting mileage to more efficient vehicles. Rural low income residents driving pickups and SUVs appear to have low elasticities.

INRIX (2008) evaluated the effects of fuel prices on U.S. vehicle travel and traffic congestion, using the *Smart Dust Network* of GPS-enabled vehicles. Their results indicate that increased prices in the first half of 2008 significantly reduced VMT and highway traffic congestion. Two-thirds of consumers indicated that increased gas prices caused them to decrease their driving, including 23% reporting a significant decrease. This reduction in driving significantly reduced traffic congestion. The largest congestion reductions occur at Friday afternoons, the time most impacted by vacation driving, and areas with the greatest congestion reduction from fuel price increase have significant vacation travel such as Las Vegas, Miami and Orlando. These congestion reductions occurred every peak hour of the day and every day of the week.

A Congressional Budget Office study (CBO 2008) found that increased fuel prices reduce urban highway traffic speeds and volumes. For each 50¢ per gallon (20%) gasoline price increase, traffic volumes on highways with parallel rail transit service declined by 0.7% on weekdays and 0.2% on weekends, with comparable increases in transit ridership, (no traffic reductions were found on highways that lack parallel rail service), and reduces median uncongested highway traffic speeds about one percent.

Small and Van Dender (2005 and 2007) used cross sectional data from U.S. states from 1966-2001 to estimate rebound effects. Their model accounts for endogenous changes in fuel efficiency, distinguishes between autocorrelation and lagged effects, includes a measure of the stringency of fuel-economy standards, and interacts the rebound effect with income. They estimate rebound effects of 4.7% in the short run and 22.0% over the long run (a 10% fuel efficiency gain will increase VMT 0.47% in the short run and 2.2% over the long-run) with values that declined with income: with variables at 1997- 2001 levels they become 2.6% and 12.1% (a 10% fuel efficiency gain will increase VMT 0.26% in the short run and 1.2% over the long-run).

Schimek (1997) found that the elasticity of vehicle travel with respect to fuel price in the U.S. to be -0.26 using 1950 to 1994 time series data. TRACE (1999) provides detailed estimates of the elasticity of various types of travel (car-trips, car-kilometers, transit travel, walking/cycling, commuting, business trips, etc.) with respect to fuel price under various conditions (level of vehicle ownership, transit use, type of trip, etc.). Table 16 summarizes fuel price elasticities of kilometers traveled in areas with high vehicle ownership.

Table 16 **Elasticities WRT Fuel Price** (TRACE 1999, Tables 8 & 9)

Term/Purpose	Car Driver	Car Passenger	Public Transport	Slow Modes
Trips				
Commuting	-0.11	+0.19	+0.20	+0.18
Business	-0.04	+0.21	+0.24	+0.19
Education	-0.18	+0.00	+0.01	+0.01
Other	-0.25	+0.15	+0.15	+0.14
Total	*-0.19*	*+0.16*	*+0.13*	*+0.13*
Kilometers				
Commuting	-0.20	+0.20	+0.22	+0.19
Business	-0.22	+0.05	+0.05	+0.04
Education	-0.32	+0.00	+0.00	+0.01
Other	-0.44	+0.15	+0.18	+0.16
Total	*-0.29*	*+0.15*	*+0.14*	*+0.13*

Slow Modes = Walking and Cycling WRT = With Respect To

This table shows the estimated elasticities and cross-elasticities of urban travel in response to fuel or other vehicle operating costs. For example, a 10% fuel price increase is predicted to reduce automobile trips by 1% and increase transit ridership by 2%.

Table 18 summarizes the major results of these travel price elasticity.

Table 18 **Summary of Vehicle Travel Price Sensitivity Studies**

Study	Study Type	Scope	Major Results
Brand (2009)	Gasoline price elasticities.	2007-2008, U.S.	-0.12 to -0.17 short run -0.21 to -0.3 long run
Coglianese, et al. (2017)	Analyzed fuel prices, taxes and vehicle travel.	U.S.	-0.37 short run
Gillingham (2010)	Odometer and fuel consumption data.	2005-2008, California	-0.15 to -0.20 medium run, varies by vehicle type and location
Goodwin, Dargay and Hanly (2004)	Summarized results of various studies	1929 to 1991, mostly North America and Europe.	-0.1 short run -0.3 long run
Hymel, Small and Van Dender (2010)	State-level cross-sectional time series.	1966 to 2004, U.S.	-0.026 short run -0.131 long run
Johansson and Schipper (1997)	Summary of various studies.	International	-0.2 long run
Kilian and Zhou (2020)	Research summary	U.S. and Japan	-0.27 to -0.37 short run
Knittel and Tanaka (2019)	Individual motorists fuel consumption and price	Japan	-0.37 short-run
Levin, Lewis and Wolak (2017)	Credit card fuel purchase data.	U.S.	-0.27 to -0.35 short-term
Li, Linn and Muehlegger (2011)	Vehicle travel wrt fuel price. Comprehensive model.	1968-2008, U.S.	-0.24 to -0.34
Linn (2013)	Comprehensive model of households' vehicle economy and mileage	2009 U.S. travel survey data	-0.2 to -0.4 long-run, vehicle travel wrt fuel economy
Schimek (1997)	Elasticity of vehicle travel with respect to fuel price	1950-1994 time-series and 1988-1992 pooled data, U.S.	-0.26
Small and Van Dender (2010)	Vehicle travel elasticity with respect to fuel price. Comprehensive model.	2001, U.S.	*1966- 2001* -0.047 short run -0.22 Long run *1997- 2001* –0.026 short run –0.121% long run
Taiebat, Stolper and Xu (2019)	Vehicle travel wrt fuel and time costs.	U.S.	Combined elasticity of VMT demand is −0.4.

Various types of studies covering various times and geographic areas have measured the elasticity of vehicle travel with respect to fuel prices.

Road Pricing and Tolls

Road pricing means that motorists pay a toll for using a particular roadway or driving in a particular area. *Congestion* or *decongestion pricing* refers to tolls that are higher during peak compared with off-peak periods to reduce traffic congestion.

Motorists tend to be relatively sensitive to road pricing compared with other price changes (Evans, Bhatt and Turnbull 2003; Lake and Ferreira 2002). Spears, Boarnet and Handy (2010) summarize recent road pricing experience. They conclude that the elasticity of traffic volumes to tolls is typically -0.1 to -0.45, so a 10% toll increase reduces traffic on that road 1.0% to 4.5%. Roads with fewer essential trips, more viable alternatives or lower congestion levels tend to have higher elasticities. They find that cordon tolls have reduced traffic volumes 12% to 22% in various cities, indicating a -0.2 to -0.3 elasticity, so each 10% increase in the cordon charge reduces traffic volumes 2% to 3%. Similarly, Beaty, Burris, and Geiselbrecht (2013) estimate that on Texas highways, the elasticity of traffic volume to toll prices is -0.35.

Although impacts vary depending on specific factors including the types of travellers and quality of alternative routes and modes, examples indicate that cost-recovery pricing (tolls that repay the costs of building and maintaining a road or bridge) typically reduces traffic volumes 30-50%. For example, after tolls ($2.21 per trip or $1.10 for frequent users) were imposed on the I-65 Ohio River bridges at Louisville, Kentucky in 2017, traffic declined by more than half, from 135,000 to 60,000 average daily vehicles (Cortright 2021). Similarly, after tolls (CA$3.15 for cars and CA$9.45 for large trucks) were eliminated on bridges in Vancouver, Canada in 2017, traffic increased about a third on the Port Mann Bridge, from 112,000 to 150,000 average daily trips, and increased 38% on the Golden Ears Bridge, from about 40,000 to 55,000 average daily trips.

Axhausen, et al. (2021) tested how 3,700 Swiss motorists respond to information and pricing incentives equal to their estimated congestion, crash risk and pollution external costs. They found that pricing causes significant shifts in route choice, departure time choice, and mode choice, reflecting a short-term price elasticity of -0.31. Giving motorists information caused much smaller vehicle travel reductions.

Matas and Raymond (2003) developed a tollroad demand model using data from Spain, 1980-1998. They found that demand varies depending on economic activity (GDP), tourist activity, fuel prices, and travel conditions on parallel roads. Their short-term toll road price elasticities range from -0.21 to -0.83. Since February 2003 a congestion pricing fee has been charged for driving in downtown London during weekdays, which reduced private automobile traffic 38% and total vehicle traffic (including buses, taxis, and trucks) by 18%, a greater reduction than planners predicted indicating a higher price elasticity than economists expect (Litman 2003). Parsons Brinckerhoff (2012) found significant bias against tolls, equivalent to 15-20 minutes of travel time. This reluctance reduced traffic volumes and revenue below what was predicted for many toll road projects (NCHRP 2006; Prozzi, et al. 2009; Williams-Derry 2011).

Odeck and Brathan (2008) found elasticities at 19 Norwegian toll roads averaging -0.54 in the short run and -0.82 in the long run, and public attitudes toward tolls tend to become more favorable when people understand how revenues will be used. A survey of Tappan Zee Bridge users found that most travelers would respond to congestion pricing by changing travel timing, route or mode (Adler, Ristau and Falzarano 1999). Luk (1999) estimates that Singapore toll elasticities are –0.19 to –0.58, with an average of –0.34.

The Puget Sound *Traffic Choices Study* measured the responses of 275 volunteer motorists to road pricing (PSRC 2005). Each participant was given a $1,016 debit account. A meter installed in their car tracked where and when they drive and subtracted tolls that varied depending on time and location. Vehicle travel declined about -0.12 overall. The elasticity of Home-to-Work travel averaged approximately -0.04 overall, but was four times higher (-0.16) for workers with the best public transit service, indicating that the cross-elasticity of vehicle travel with respect to price is affected by transit service quality. Guo, et al. (2011) found that given financial incentives, households in denser, mixed use, transit-accessible neighborhoods reduced their peak-hour and overall vehicle travel significantly more than comparable households in automobile dependent suburbs.

Arentze, Hofman and Timmermans (2004) surveyed traveler to determine their expected response to congestion pricing. They found that for commute trips, pricing primarily affects route and departure time changes, with smaller shifts to public transit and working at home. For non-commute trips, shifts to cycling also occur. They conclude that the price elasticity of traffic on a particular roadway is -0.35 to -0.39, including shifts in route and time, and -0.13 to -0.19 for total vehicle travel on a corridor. A CA$5.00 (US$3.00) round-trip road toll would reduce automobile commuting 25%, and a CA$5.00 daily parking fee would reduce automobile commuting 20%.

Hirschman, et al. (1995) find that New York area bridge and tunnel toll elasticities for automobiles average -0.1. Mekky found toll elasticities as high as -4.0 for Toronto’s Highway 407, and that traffic volumes and trip lengths decline significantly if tolls exceed 10¢ per vehicle kilometer (1999). Holguín-Veras, Ozbay and de Cerreño (2005) investigated automobile and truck travel responses to E-ZPass tolls, which provide discounts for off-peak travel. The car short-term elasticities range from –0.31 to –1.97 for weekday and –0.55 and –1.68 for weekends depending on time of day, with modest shifts from peak to off-peak periods.

Harvey and Deakin (1997) modeled the effect of congestion pricing on transportation impacts in four major urban regions in California. Table 19 summarizes their results for the year 2010. It indicates, for example, that in the South Coast (Los Angeles) region, an a congestion fee averaging 19¢ per mile driven in congested conditions would reduce total vehicle trips by about 3.3%, but congestion delay would decline by 32%.

Table 19 **Congestion Pricing Impacts, Year 2010** (Harvey and Deakin 1998, Table B.6)

Region	Avg. Fee	VMT	Trips	Delay	Fuel	ROG	Revenue
Bay Area	13¢	-2.8%	-2.7%	-27.0%	-8.3%	-6.9%	$2,274
Sacramento	8¢	-1.5%	-1.4%	-16.5%	-4.8%	-3.9%	$443
San Diego	9¢	-1.7%	-1.6%	-18.5%	-5.4%	-4.2%	$896
South Coast	19¢	-3.3%	-3.1%	-32.0%	-9.6%	-8.1%	$7,343

Avg. Fee = average congestion fee per mile applied to vehicle travel on congested roads. VMT = change in total vehicle mileage. Trips = change in total vehicle trips. Delay = change in congestion delay. Fuel = change in fuel consumption. ROG = a criteria air pollutant. Revenue = annual revenue in millions of 1991 dollars. See report for additional notes and data.

Road pricing impacts and benefits depend on the price structure. Ubbels and Verhoef (2006) predict that road pricing in The Netherlands would reduce car trips 6% to 15%. A flat kilometre fee primarily affects social trips and tends to cause total trips to decline and shifts to nonmotorized modes. A peak-period fee primarily affects commute trips, and tends to cause a combination of shifts in time and mode, and working at home. May and Milne (2000) used an urban traffic model to compare cordon tolls, distance pricing, time pricing and congestion pricing impacts. They found significant differences in the effects that different fee structures would have in achieving TDM objectives. The table below shows the estimated price level required to achieve a 10% reduction in regional vehicle trips. They conclude that time-based pricing provides the greatest overall benefits, followed by distance-based pricing, congestion pricing and cordon pricing.

Table 20 **Estimated Fee To Reduce Vehicle Trips 10%** (May and Milne 2000)

Type of Road Pricing	Fee Required to Reduce Trips 10%
Cordon (pence per crossing)	45
Distance (pence per kilometer)	20
Time (pence per minute)	11
Congestion (pence per minute delay)	200

Mileage and Emission Charges

Various pricing reforms impose distance-based vehicle fees, including per-mile/kilometer road use and emission fees, and distance-based vehicle insurance and registration fees which prorate existing fixed fees by mileage (for example, a $1,200 annual insurance premium becomes 10¢ per vehicle-mile).

Harvey and Deakin (1998) model the effect of a 2¢ per vehicle-mile fee on transportation impacts in four major urban regions in California. Table 21 summarizes their results for the year 2010. It indicates, for example, that in the South Coast (Los Angeles) region, a 2¢ per mile fee would reduce total vehicle trips by 4.1%, but reduces congestion delay 10.5%. INFRAS (2000) estimates kilometer fees have elasticities of –0.1 to –0.8, depending on the trip purpose, mode and price level.

Table 21 **Impacts of 2¢ Per Mile Fee, Year 2010** (Harvey and Deakin 1998, B.9)

Region	VMT	Trips	Delay	Fuel	ROG	Revenue
Bay Area	-3.9%	-3.7%	-9.0%	-4.1%	-3.8%	$1,122
Sacramento	-4.4%	-4.1%	-7.5%	-4.4%	-4.3%	$349
San Diego	-4.2%	-4.0%	-8.5%	-4.2%	-4.1%	$629
South Coast	-4.3%	-4.1%	-10.5%	-5.2%	-4.2%	$3,144

VMT = change in total vehicle mileage. Trips = change in total vehicle trips. Delay = change in congestion delay. Fuel = change in fuel consumption. ROG = a criteria air pollutant. Revenue = annual revenue in millions of 1991 U.S. dollars. See report for additional notes and data.

Table 22 shows the predicted change in travel by income class, based on 1991 dollars. The last column adjusts average reductions to 2006 dollars. This indicates an elasticity of vehicle travel with respect to VMT fees to be -0.2 to -0.25 (Deakin & Harvey, 1998).

Table 22 **VMT Fee Travel Reduction by Income Quintile** (USEPA 1998, Table B21)

VMT Fee	Q1	Q2	Q3	Q4	Q5	Overall	2006
1¢	-7.0	-4.2	-2.6	-1.5	-0.5	-2.3	-1.6
2¢	-13.3	-8.2	-5.1	-3.1	-1.0	-4.5	-3.1
3¢	-19.1	-12.0	-7.5	-4.6	-1.6	-6.6	-4.6
4¢	-24.3	-15.6	-10.0	-6.2	-2.2	-8.7	-6.0
5¢	-29.1	-19.1	-12.4	-7.7	-2.8	-10.7	-7.4
6¢	-33.5	-22.4	-14.7	-9.3	-3.5	-12.6	-8.7
7¢	-37.4	-25.6	-17.0	-10.8	-4.1	-14.5	-10.0
8¢	-41.0	-28.7	-19.2	-12.4	-4.8	-16.3	-11.2
9¢	-44.2	-31.5	-21.4	-13.9	-5.5	-18.0	-12.4
10¢	-47.2	-34.3	-23.5	-15.4	-6.3	-19.7	-13.6

A quintile is one-fifth of the population. Values are based on 1991 dollars, except the last column, labeled 2006, which takes into account inflation between 1991 and 2006.

O'Mahony, Geraghty and Humphreys (2000) found that congestion fees averaging €6.40 per trip for 20 volunteer motorists reduced peak period trips 21.6% and total trips 5.7%, peak mileage 24.8% and total mileage 12.4%. Table 23 indicates impacts of two types of emission fees: a per-mile charge based on each vehicle model-year average emissions, and a fee based on actual emissions measured when a vehicle is operating. Distance based emission charges averaging about 0.5¢ per mile are estimated to reduce VMT by 1-7% and emissions by 14-35% (ICF 1997). The in-use pricing options has much greater emission reducing impacts, because it discourages driving of high-emitting vehicles.

Table 23 **Impacts of Emission Charges, Year 2010** (Harvey and Deakin 1998, B.10)

Region	Fee Basis	VMT	Trips	Delay	Fuel	ROG	Revenue
Bay Area	Vehicle Model	-2.2%	-1.9%	-3.5%	-3.9%	-5.4%	$384
	Vehicle Use	-1.6%	-1.4%	-2.5%	-6.6%	-17.7%	$341
Sacramento	Vehicle Model	-2.6%	-2.3%	-4.5%	-4.0%	-5.7%	$116
	Vehicle Use	-2.3%	-2.1%	-5.0%	-7.4%	-20.2%	$102
San Diego	Vehicle Model	-2.5%	-2.2%	-3.5%	-4.1%	-5.5%	$211
	Vehicle Use	-1.9%	-1.7%	-3.5%	-7.1%	-19.5%	$186
South Coast	Vehicle Model	-2.5%	-2.3%	-5.5%	-3.9%	-5.5%	$1,106
	Vehicle Use	-2.1%	-1.9%	-6.0%	-7.2%	-18.9%	$980

Vehicle Model Fee = a per-mile fee based on vehicle model and year. Vehicle Use Fee = a fee based on measured tailpipe emissions of individual vehicles using electronic instrumentation. VMT = change in total vehicle mileage. Trips = change in total vehicle trips. Delay = change in congestion delay. Fuel = change in fuel consumption. ROG = a criteria air pollutant. Revenue = annual revenue in millions of 1991 U.S. dollars. See report for additional notes and data.

Parking Price

Motorists tend to be particularly sensitive to parking price because it is such a direct charge. Compared with other out-of-pocket expenses, parking fees are found to have a greater effect on vehicle trips, typically by a factor of 1.5 to 2.0 (USEPA 1998). For example, a $1.00 per trip parking charge is likely to cause the same reduction in vehicle travel as a fuel price increase averaging $1.50 to $2.00 per trip.

Concas and Nayak (2012); Lehner and Peer (2019), Spears, Boarnet and Handy (2010a), and Vaca and Kuzmyak (2005) summarize various studies of parking price impacts on travel behavior, taking into account demographic factors and travel conditions, and type of trip; including changes in the magnitude and structure of prices, elimination of employee parking subsidies, rideshare vehicle parking discounts and park-and-ride facility pricing. Kuzmyak, Weinberger and Levinson (2003) describe how parking supply affects parking and travel demand, but this may actually reflect price impacts (reduced supply increases prices). These studies indicate that the elasticity of vehicle trips with regard to parking prices is typically –0.1 to –0.3, with significant variation depending on demographic, geographic, travel choice and trip characteristics. A study of downtown parking meter price increases, Clinch and Kelly (2003) find that the elasticity of parking frequency is smaller (–0.11) than the elasticity of vehicle duration (-0.20), indicating that some motorists respond to higher fees by reducing how long they stay.

Frank, et al. (2011) evaluated the impacts of urban design factors on vehicle travel and carbon emissions. They found that increasing parking fees from approximately $0.28 to $1.19 per hour (50th to 75th percentile) reduced VMT 11.5% and emissions 9.9%. Barla, et al. (2012) measure the impact of travel time, financial costs and attitudes on commute mode share in Laval University. They find that elasticities with respect to time and cost parameters are relatively low, but their impacts are synergist, so combining several policy interventions is most effective at reducing automobile trips.

Farrell, O'Mahony and Caulfield (2005) survey university employees to determine how they would respond to parking pricing and cash out. They found that most employees would reduce their automobile trips in response to a €5 daily fee, and one third would reduce their trips in response to parking cash out. Shiftan (1999) surveyed motorists driving to a commercial district in Haifa, Israel to determine how they would respond to higher fees. Of 200 motorists surveyed there, 78% currently parked for free (67% on-street, 11% at employee off-street parking lots). Their predicted reduction in vehicle trips is summarized below. Non-work trips tended to be more price-sensitive than work trips.

New Israeli Shekels (NISs)/U.S. dollars per hour	Parking Demand Decline
5 NIS/$1.00	29%
10 NIS/$1.00	50%
10 NIS/$1.00	58%

Washbrook, Haider and Jaccard (2006) surveyed Vancouver, British Columbia region commuters to determine how they would respond to various incentives. Table 24 shows how various road and parking fees would affect their drive alone rates. For example, with unpriced roads and parking, 83% of commuters drive alone, but this declines to 75% if there is a CA$1.00 ($0.64 US) parking charge and a CA$1.00 daily road toll. A $9.00 ($5.72 US) parking fee and a $9.00 road toll together reduce automobile commute mode share to 17%, which equals a total reduction in drive alone demand of 80%.

Table 24 **Automobile Commute Mode share** (Washbrook, Haider and Jaccard, 2006)

Road Toll	Free Parking	$1 Parking	$3 Parking	$6 Parking	$9 Parking
$0	83%	80%	74%	62%	49%
$1	78%	75%	68%	55%	42%
$3	68%	65%	56%	43%	30%
$6	56%	52%	43%	31%	21%
$9	50%	46%	37%	26%	17%

This table indicates the automobile commute mode share that can be expected from various combinations of road tolls and parking fees in the Vancouver region.

Hensher and King (2001) model the price elasticity of CBD parking, and predict how an increase in parking prices in one location will shift cars to park at other locations and drivers to public transit (Table 25). Harvey (1994) finds that airport parking prices range from -0.1 for less than a day to -2.0 for greater than 8 days.

Table 25 **Parking Elasticities** (Hensher and King 2001, Table 6)

	Preferred CBD	Less Preferred CBD	CBD Fringe
Car Trip, Preferred CBD	-0.541	0.205	0.035
Car Trip, Less Preferred CBD	0.837	-0.015	0.043
Car Trip, CBD Fringe	0.965	0.286	-0.476
Park & Ride	*0.363*	*0.136*	*0.029*
Ride Public Transit	*0.291*	*0.104*	*0.023*
Forego CBD Trip	0.469	0.150	0.029

This table shows elasticities and cross-elasticities for changes in parking prices at various Central Business District (CBD) locations. For example, a 10% increase in prices at preferred CBD parking locations will cause a 5.41% reduction in demand there, a 3.63% increase in Park & Ride trips, a 2.91% increase in Public Transit trips and a 4.69% reduction in total CBD trips.

Hess (2001) assesses the effect of free parking on commuter mode choice and parking demand in Portland's (Oregon) CBD. He found that where parking is free, 62% of commuters drive alone, 16% carpool and 22% ride transit; with a $6.00 daily parking charge 46% drive alone, 4% carpool and 50% ride transit. The $6.00 parking charge results in 21 fewer cars driven for every 100 commuters, a daily reduction of 147 VMT per 100 commuters and an annual reduction of 39,000 VMT per 100 commuters. Using a stated response survey, Kuppam, Pendyala and Gollakoti (1999) predict that about 35% of drive-alone commuters would likely switch modes in response to $20 per month parking fees, even if offset by a transport vouchers. They found that mode shifting increases for lower income, and if transit, ridesharing and sidewalks are available. Trip Reduction Tables, such as illustrated below, predict travel reductions resulting from parking fees and other financial incentives ("Trip Reduction Tables," VTPI 2011).

Table 26 **Commute Trip Reductions from Daily Parking Fees** (Comsis Corp. 1993)

	$1	$2	$3	$4
Suburb	6.5%	15.1%	25.3%	36.1%
Suburban Center	12.3%	25.1%	37.0%	46.8%
Central Business District	17.5%	31.8%	42.6%	50.0%

This table indicates automobile commute trip reductions from daily parking fees. (1993 U.S. dollars)

TRACE (1999) provides detailed estimates of the elasticity of various types of travel (car-trips, car-kilometers, transit travel, walking/cycling, commuting, business trips, etc.) with respect to parking price under various conditions (e.g., level of vehicle ownership and transit use, type of trip, etc.). Table 27 summarizes long-term elasticities for relatively automobile-oriented urban regions.

Table 27 **Parking Price Elasticities** (TRACE, 1999, Tables 32 & 33)

Term/Purpose	Car Driver	Car Passenger	Public Transport	Slow Modes
Trips				
Commuting	-0.08	+0.02	+0.02	+0.02
Business	-0.02	+0.01	+0.01	+0.01
Education	-0.10	+0.00	+0.00	+0.00
Other	-0.30	+0.04	+0.04	+0.05
Total	*-0.16*	*+0.03*	*+0.02*	*+0.03*
Kilometres				
Commuting	-0.04	+0.01	+0.01	+0.02
Business	-0.03	+0.01	+0.00	+0.01
Education	-0.02	+0.00	+0.00	+0.00
Other	-0.15	+0.03	+0.02	+0.05
Total	*-0.07*	*+0.02*	*+0.01*	*+0.03*

This table indicates how parking fees affects various types of trips. For example, a 10% increase in commuter parking prices will reduce automobile trips and parking demand 0.8%, and increase car passenger, public transport, and slow mode travel (walking and cycling) 0.2% each.

Parking fees affect trip destinations as well as vehicle use. An increase in parking prices can reduce use of parking facilities at a particular location, but this may simply shift vehicle travel to other locations. Increased parking prices may result in spillover parking problems, as motorists find nearby places to park for free illegally ("Parking Management," VTPI, 2005). However, if parking prices increase throughout an area, there is effective enforcement of parking regulations, and there are good travel alternatives, parking price increases can reduce total vehicle travel. For some types of trips, pricing can affect parking duration, such as how long shoppers stay at a store.

The use of parking price elasticities can be confusing since most parking is currently free, so it is meaningless to measure percentage increases from zero price. The table below summarizes the commute mode shifts occurring at worksites that changed from free to priced parking. Other case studies find similar impacts. Shifting from free to priced parking typically reduces drive alone commuting by 10-30%, particularly if implemented with improvements in transit service and rideshare programs and other TDM strategies.

Table 28 **Changes in Workplace Travel Due to Parking Pricing**

	Canadian Study			Los Angeles Study		
	Before	After	Change	Before	After	Change
Drive Alone	35%	28%	*-20%*	55%	30%	*-27%*
Carpool	11%	10%	*+9%*	13%	45%	*+246%*
Transit	42%	49%	*+17%*	29%	22%	*-24%*
Other	12%	13%	*-8%*	3%	3%	*0%*

(Feeney, 1989, cited in Pratt, 1999)

Shoup (1992) finds that charging employees for parking reduces solo commuting by 20-40%. A study by ICF (1997) indicates that a $1.37 to $2.73 increase in parking fees (1993 U.S. dollars) reduces auto commuting 12-39%, and if matched with transit and rideshare subsidies, can reduce total auto trips by 19-31%. Parking supply can affect travel behavior by affecting parking convenience, parking price and walkability (Morrall and Bolger, 1996). Increased parking supply tends to increase automobile commuting and reduce transit and ridesharing (Mildner, Strathman and Bianco 1997). How parking prices are structured also affects travel patterns. Large discounts for long-term parkers (e.g., lower-priced monthly leases) encourages automobile commuting, while pricing that discounts short-term use (e.g., "First-Hour-Free" rates) favor shoppers and business trips. Rate increases of $1-2 per day directed at commuters are found to reduce long-term parking demand by 20-50%, although much of this may consist of shifts to other parking locations rather than alternative modes (Pratt 1999).

Travel Time

Increased travel speed and reduced delay (by congestion or transfers) tends to increase travel distance, and increased relative speed for a particular mode tends to attract travel from other modes on a corridor. Some research supports the *constant travel time budget* hypothesis, which means the amount of time people devote to travel tends to remain constant (typically averaging 70-90 daily minutes), implying the elasticity of travel with respect to speed is 1.0 (Mokhtarian and Chen 2004). Leading U.K. transport economists concluded the elasticity of travel volume with respect to travel time is -0.5 in the short term and -1.0 over the long term (SACTRA 1994), so increasing traffic speeds 20% typically increases traffic volumes 10% in the short term and 20% over the long term. Another study found the elasticity values for vehicle travel with respect to travel time shown in Table 29. Pratt (1999) estimates the effects of service speed, frequency and reliability on public transit use, including the effects of HOV facilities.

Table 29 **Vehicle Travel Elasticities With Respect to Travel Time** (Goodwin 1996)

	Short Run	Long Run
Urban Roads	-0.27	-0.57
Rural Roads	-0.67	-1.33

Taiebat, Stolper and Xu (2019) developed a microeconomic model to estimate vehicle travel elasticities with respect to fuel and time costs. Their central estimate of the combined elasticity of VMT demand is −0.4, which is higher than values found in the previous studies they review. They find higher elasticities for time than fuel costs, particularly for higher-income households.

TRACE (1999) provides detailed estimates of the elasticity of various types of travel (car-trips, car-kilometers, transit travel, walking/cycling, commuting, business trips, etc.) with respect to car travel times under various conditions (e.g., level of vehicle ownership and transit use, type of trip, etc.). Table 30 summarizes elasticities of kilometers traveled with respect to travel time in areas with high vehicle ownership (more than 450 vehicles per 1,000 population). Litman (2007 and 2009) discusses the valuation of travel time costs, including adjustments for qualitative factors such as comfort and convenience.

Table 30 **Long Run Travel Elasticities With Respect to Car Travel Time** (TRACE 1999)

Term/Purpose	Car Driver	Car Passenger	Public Transport	Slow Modes
Commuting	-0.96	-1.02	+0.70	+0.50
Business	-0.12	-2.37	+1.05	+0.94
Education	-0.78	-0.25	+0.03	+0.03
Other	-0.83	-0.52	+0.27	+0.21
Total	-0.76	-0.60	+0.39	+0.19

This table summarizes the effects of changes in car travel time on travel demand for other modes for various types of trips. (Slow Modes = walking and cycling)

Dowling Associates (2005) estimate the elasticity of travel with respect to travel time for various modes and time periods, based on Portland, Oregon data. For example, it indicates that each 1% increase in AM Peak Drive Alone travel time reduces vehicle travel 0.225% and increases demand for Shared Ride travel 0.037% and transit 0.036%.

Table 31 **Travel Time Elasticities and Cross Elasticities** (Dowling Asso. 2005)

		Am Peak			Pm Peak		
		DA	SR	TR	DA	SR	TR
AM Peak	DA	-0.225	0.030	0.010	-0.024	0	0
	SR	0.037	-0.303	0.032	0	-0.028	0
	TR	0.036	0.030	-0.129	0	0	-0.007
PM Peak	DA	-0.124	0	0	-0.151	0.015	0.005
	SR	0	-0.109	0	0.019	-0.166	0.016
	TR	0	0	-0.051	0.018	0.015	-0.040
Off-Peak	DA	-0.170	0	0	-0.069	0	0
	SR	0	-0.189	0	0	-0.082	0
	TR	0	0	-0.074	0	0	-0.014

DA = Drive Alone, SR = Shared Ride, TR = Transit
This table indicates the change in demand by three modes from changes in travel time by that mode and other modes during morning peak, afternoon peak and off-peak periods.

Frank, et al. (2008) find that relative that the travel time between different modes significant affects mode choice. Increasing drive alone commute time by 10% was associated with increases in demand for transit by 3.1%, bike demand by 2.8% and walk demand by 0.5%. Transit riders are found to be more sensitive to changes in travel time, particularly waiting time, than to cost of transit fares. Increasing transit in-vehicle travel times for non-work travel by 10% was associated with a 2.3% decrease in transit demand, compared to a 0.8% reduction for a 10%

fare increase. Non-work walking trips increased in more walkable areas with increased density, mix and intersection density. Increasing auto travel time for non-work trips by 10% was associated with a 2.3% increase in transit ridership, a 2.8% increase in bicycling, and a 0.7% increase in walking. Walking and biking are used for shorter trips, such as travel to local stores and mid-day tours from worksites if services are nearby.

Various studies have used the elasticity of travel with respect to travel time to calculate the amount of induced travel that results from roadway improvements that increase travel speeds and reduce delays, particularly expansion of congested urban roadways (Litman 2001). Schiffer, Steinvorth and Milam (2005) summarize recent publications on this subject in the transportation modeling literature.

Generalized Costs

Generalized cost refers to combined monetary and time costs of travel. For example, the generalized cost of automobile travel includes vehicle operating costs and the monetized motorists' travel time, and the generalized cost of transit travel include fares and monetized passenger travel time values. Generalized cost values are used in transport models.

These are usually determined empirically for a specific conditions based on local travel behavior and user survey data. A typical value is -0.5 (NHI 1995). Booz, Allen, Hamilton (2003) estimate generalized travel cost elasticities in the Canberra, Australia region to be -0.87 for peak, -1.18 for off-peak, and –1.02 overall (peak and off-peak combined). TRL (2004) calculates generalized cost elasticities to be -0.4 to -1.7 for urban bus transit, -1.85 for London underground, and -0.6 to –2.0 for rail transport. Lee (2000) estimates the elasticity of vehicle travel with respect to Total Price (including fuel, tolls, parking fees, vehicle wear and travel time, which is equivalent to generalized costs) is -0.5 to -1.0 in the short run, and -1.0 to -2.0 over the long run.

Transport Pricing and Development Patterns

Households often make tradeoffs between transportation costs (time and money) and locations decisions: larger lot homes at the urban fringe generally require more motor vehicle travel and therefore costs. It is therefore likely that changes in vehicle operating costs will affect the desirability of automobile-dependent locations and therefore the amount of urban fringe development that occurs.

Sextony, Wu and Zilbermanx (2012) found that unanticipated fuel price increase tend to reduce the value of homes away from the city center and increasing foreclosure rates. A U.S. Federal Reserve Board study found that, after a four year lag, each 10% fuel price increase leads to a 10% decrease in demand for homes in locations with longer average commute relative to locations closer to jobs (Molloy and Shan 2011). Tanguay and Gangias (2011) found that, controlling for variables such as income and population growth, a 1% fuel price increase causes a 0.32% increase in inner city populations and a 1.28% decline in lower-density housing development in Canadian urban regions.

Transit Elasticities

Several factors can affect public transit elasticities (Dunkerley, et al. 2018; Lane 2012; Litman 2004; Iseki and Ali 2014; McCollom and Pratt 2005; Pratt and Evans 2004; Taylor et al. 2009; TRL 2004; Wang 2011; Wardman and Shires 2011; Wardman et al. 2018 and 2022):

- *User Type.* Transit dependent riders are generally less price sensitive than *discretionary* (also called *choice*) riders, people who could drive for that trip). People with low incomes, disabilities, young and old age tend to be more transit dependent. In most communities transit dependent people are a relatively small portion of the total population but a large portion of transit users, while discretionary riders are a potentially large but more price sensitive market segment.

- *Trip Type.* Non-commute trips tend to be more price sensitive than commute trips. Elasticities for off-peak transit travel are typically 1.5-2 times higher than peak period elasticities, because peak-period travel largely consists of commute trips.

- *Mode and route.* Rail and bus elasticities often differ. In major cities, rail transit fare elasticities tend to be relatively low, typically in the –0.18 range due to users relatively high incomes. For example, the Chicago Transportation Authority found peak bus riders have an elasticity of -0.30, and off-peak riders -0.46, while rail riders have peak and off-peak elasticities of -0.10 and -0.46, respectively. Fare elasticities tend to be lower on routes that serve more people who are transit dependent and higher on routes where travelers have viable alternatives, such as for suburban rail systems.

- *Geography.* Large cities tend to have lower price elasticities than smaller cities and suburbs, probably reflecting differences in the portion of transit-dependent residents.

- *Type of Price Change.* Transit fares, service quality (service speed, frequency, coverage and comfort) and parking pricing tend to have the greatest impact on transit ridership. Fuel price tends to have relatively little impact. Elasticities appear be somewhat higher for higher fare levels (i.e., when the starting point of a fare increase is relatively high).

- *Direction of Price Change.* Transportation demand models often apply the same elasticity value to both price increases and reductions, but there is evidence that some changes are non-symmetric. Fare increases tend to cause a greater reduction in ridership than the same size fare reduction will increase ridership. A price increase or transit strike that induces households to purchase an automobile may be somewhat irreversible, since once people become accustomed to driving they often continue using that option.

- *Time Period.* Price impacts are often categorized as short-term (typically, within one year), medium-term (within five years) and long-term (more than five years). Elasticities increase over time, as consumers take price changes into account in more decisions (such as where to live or work). Long-term transit elasticities tend to be two or three times as large as short-term elasticities.

- *Transit Type.* Bus and rail often have different elasticities because they serve different markets. Although car ownership has a negative impact on rail demand, it is less than for bus and, although there are quite large variations between market segments and across distance bands, the overall effect of income on rail demand is often positive.

Transit Elasticity Studies

Taylor, et al. (2009) evaluated how various geographic, demographic, pricing and transit supply factors affect per capita transit ridership rates in U.S. cities. They found an aggregate (all types of transit) fare elasticity of -0.51, and service hours elasticities of 1.1 to 1.2.

Dunkerley, et al. (2018) evaluated bus fare and journey time elasticities and cross elasticities based on analysis of numerous studies. Similarly, Holmgren (2007) used meta-regression to explain the wide variation in elasticity estimates obtained in previous demand studies. He calculated short-run U.S. elasticities with respect to fare price (−0.59), level of service (1.05), income (-0.62), price of petrol (0.4) and car ownership (−1.48). The analysis indicates that commonly-used elasticity estimates treat transit service quality as an exogenous variable, which reduces analysis accuracy, and recommends that demand models include car ownership, price of petrol, own price, income and some measure of service among the explanatory variables, and that the service variable be treated as endogenous. Based on a literature review, APTA (2011) estimated the elasticity of transit ridership with respect to fuel prices to range from a low of 0.14, an average value of 0.185, and a high value of 0.23.

The study, *Declines in Transit Ridership: Analysis of Recent Trends* (Watkins, et al. 2021) evaluated factors that affected U.S. transit ridership between 2012 and 2018. During that period, bus ridership declined 15% and rail ridership declined 3%. These losses are widespread and in contrast to trends in other countries. The study found that expanded transit service and land-use changes increased bus ridership 4.7% and rail ridership 10.7%, and transit operators that restructured their bus networks on average achieved 4.7% bus ridership increases above other service expansion gains. However, these increases were offset by other factors. Increased ride-hailing caused bus ridership, and rail ridership in mid-sized metropolitan areas to decline by 10%, but much smaller declines in larger cities. Lower gas prices, higher fares, higher incomes and car ownership and increased teleworking also contributed to transit ridership declines.

Mattson (2008) analyzed the effects of rising fuel prices on transit ridership in U.S. cities from 1999 through 2006. He found longer-run elasticities of transit ridership with respect to fuel price to be 0.12 for large cities, 0.13 for medium-large cities, 0.16 for medium-small cities, and 0.08 for small cities. Responses are quicker in larger cities, mostly occurring within one or two months, while for medium and small cities, the effects take five to seven months.

Dargay and Hanly (1999) studied the effects of UK transit bus fare changes over several years using sophisticated statistical techniques to derive the elasticity values summarized in Table 32. They found that demand is slightly more sensitive to rising fares (-0.4 in the short run and –0.7 in the long run) than falling fares (-0.3 in the short run and –0.6 in the long run). The cross-elasticity of bus patronage to automobile operating costs is negligible in the short run but increases to 0.3 to 0.4 over the long run, and the long run elasticity of *car ownership* with respect to transit fares is 0.4, while the elasticity of *car use* with respect to transit fares is 0.3.

Table 32 **Bus Fare Elasticities** (Dargay and Hanly 1999, p. viii)

Elasticity Type	Short-Run	Long-Run
Non-urban	-0.2 to –0.3	-0.8 to –1.0
Urban	-0.2 to –0.3	-0.4 to –0.6

This table shows elasticity values from a UK study.

Based on extensive research, TRL (2004) calculates that bus fare elasticities average approximately –0.4 in the short-run, -0.56 in the medium run and 1.0 over the long run, while metro rail fare elasticities are –0.3 in the short run and –0.6 in the long run. Bus fare elasticities are lower (-0.24) during peak than off-peak (-0.51). Lee, Lee and Park (2003) surveyed motorists to determine factors that affect their willingness to shift to public transit. Motorists are more sensitive to parking fees, travel time and crowding, indicating that transit service improvements can increase discretionary users ridership.

METS (MEtropolitan Transport Simulator) is a simulation model of transport supply and demand. It uses default values that simulate transport in London, but it can be modified for any large urban region. METS was built in the early 1980s to evaluate the effects of London transit fare changes. It is a large computer program which represents London's transport system as a series of inter-related equations. For example, there is an equation that describes the demand for bus trips as a function of the cost of the journey and the costs of alternative modes such as cars or the tube, and similar equations for the tube, trains, cars and taxis. Table 33 summarizes elasticities used in the METS model.

Table 33 **METS Cost Elasticities**

	Car	Bus	Underground
Car	-0.30	0.09	0.057
Bus	0.17	-0.64	0.13
Underground	0.056	0.20	-0.50

Source: Grayling and Glaister p.35.

Booz Allen Hamilton (2003) used stated preference survey data to estimate own and cross-elasticities for various costs (fares, travel time, waiting time, transit service frequency, parking fees) modes (automobile, transit, taxi) and trip types (peak, off-peak, work, education, other) in the Canberra region. They developed generalized costs and travel time cost values, including estimates of the relative cost of walking and waiting time for transit users. Table 34 shows their estimated price and cross fare elasticities.

Table 34 **Australian Travel Demand Elasticities** (Booz, Allen Hamilton 2003)

Mode	Peak	Off-Peak	Total
Bus	-0.18	-0.22	-0.20
Taxi	0.03	0.08	0.07
Car	0.01	0.01	0.01

This table shows elasticity and cross-elasticity values. It means, for example, that a 10% peak-period transit fare increase (decrease) will reduce (increase) peak-period transit ridership by 1.8%, and will increase (reduce) taxi travel by 0.3% and car travel by 0.1%.

Vanpool Elasticity Studies

York and Fabricatore (2001) estimate the price elasticity of vanpooling at about 1.5, meaning that a 10% reduction in vanpool fares increases ridership by about 15%. For example, if vanpool fares that are currently $50 per month are reduced to $40 (a 20% reduction), ridership is likely to increase by about 30% (20% x 1.5). Concas, Winters and Wambalaba (2005) find that the elasticity of vanpool ridership with respect to fees is -14.8%, indicating that a one dollar decrease (increase) in vanpool fares is associated with a 2.6% to 14.8% increase (decrease) in the predicted odds of choosing vanpool rather than drive alone. The same study found the elasticity of vanpooling with respect to price to be 13.4%, meaning that for each 10% increase in vanpool price there is a 13% decrease in vanpool choice relative to auto.

Transit Service Elasticities

Service elasticity refers to how changes in transit service mileage, service-hours, frequency, and service quality (such as comfort) affect transit ridership. Transit ridership tends to be more responsive to service improvements than to fare reductions (Pratt concludes that "ridership tends to be one-third to two-thirds as responsive to a fare change as it is to an equivalent percentage change in service"), particularly by discretionary travelers (people who could drive). Evans (2004) provides various transit service elasticities. The elasticity of transit use to service expansion is typically 0.6 to 1.0, meaning that each 1% increase in transit vehicle-miles or -hours increases ridership 0.6-1.0%. The elasticity of transit use with respect to service frequency (called a *headway elasticity*) averages 0.5. There is a wide variation in these factors, depending on specific conditions. Higher service elasticities often occur with new express transit service, in university towns, and in suburbs with rail transit stations to feed. It usually takes 1 to 3 years for ridership on new routes to reach its full potential.

Pratt (1999) finds that completely new bus service in a community that previously had no public transit service typically achieves 3 to 5 annual rides per capita, with 0.8 to 1.2 passengers per bus mile. Improved schedule information, easy-to-remember departure times (for example, every hour or half-hour), and more convenient transfers can also increase transit use, particularly in areas where service is less frequent.

Mackett (2000 and 2001) identifies a number of positive incentives that could reduce short (under 5 mile) car trips, including improved transit service, improved security, reduced transit fares, pedestrian and cycling improvements. Of those, transit improvements are predicted to have the greatest potential travel impacts.

Parking Pricing Impacts on Transit

Several studies indicate that parking prices (and probably road tolls) tend to have a greater impact on transit ridership than other vehicle costs, such as fuel, typically by a factor of 1.5 to 2.0, because they are paid directly on a per-trip basis. Kuzmyak, Weinberger and Levinson (2003, p. 18-18) find that each 1% increase in downtown parking supply reduces transit ridership by 0.77%. Hensher and King (1998) calculate elasticities and cross-elasticities for various forms of transit fares and automobile travel in the Sydney, Australia city center.

Cross Elasticities

Cross-elasticity refers to the changes in demand for a good that results from a change in the price of a substitute good. This includes changes in automobile travel due to transit fare changes, changes in transit ridership due to changes in automobile operating costs, and changes in one type of transit (such as bus) in response to price changes in another type of transit (such as rail). Hensher developed a model of elasticities and cross-elasticities between various forms of transit and car use, illustrated in Table 35.

Table 35 **Direct and Cross-Share Elasticities** (Hensher 1997, Table 8)

	Train Single Fare	Train Ten Fare	Train Pass	Bus Single Fare	Bus Ten Fare	Bus Pass	Car
Train, single fare	-0.218	0.001	0.001	0.057	0.005	0.005	0.196
Train, ten fare	0.001	-0.093	0.001	0.001	0.001	0.006	0.092
Train, pass	0.001	0.001	-0.196	0.001	0.012	0.001	0.335
Bus, single fare	0.067	0.001	0.001	-0.357	0.001	0.001	0.116
Bus, ten fare	0.020	0.004	0.002	0.001	-0.160	0.001	0.121
Bus, pass	0.007	0.036	0.001	0.001	0.001	-0.098	0.020
Car	0.053	0.042	0.003	0.066	0.016	0.003	-0.197

This table indicates how transit fare and car operating cost changes affects transit and car travel demand. For example, a 10% increase in single fare train tickets will reduce the sale of those fares 2.18% and increase single fare bus ticket sales 0.57%.

Using data from U.S. cities between 1982 and 2008, McMullen and Eckstein (2011) found -0.0228 long-run elasticities of per capita vehicle travel with respect to transit ridership (as transit ridership increase, automobile travel declines). Currie and Phung (2008) found that in Australia, the cross elasticity of transit ridership with respect to fuel prices are 0.22, with higher values for high quality transit (rail and bus rapid transit) and for longer-distance travel, compared with basic bus service and shorter-distance trips. TRACE (1999) provides detailed estimates of transit ridership with respect to fuel and parking prices for various types of travel and conditions (see data in sections on fuel and parking price elasticities). It estimates that a 10% fuel price increase causes transit ridership to increase 1.6% in the short run and 1.2% over the long run (this declining elasticity value is unique to fuel, due to motorists purchasing more efficient vehicles when fuel prices rise). The Congressional Budget Office found that a 20% gasoline price increase reduces traffic volumes on highways with parallel rail transit service by 0.7% on weekdays and 0.2% on weekends, with comparable increases in transit ridership, but find no traffic reductions on highways that lack parallel rail service (CBO 2008).

Air Travel

A major study by the International Air Transport Association (IATA) concluded that air travel demand is both price and income elastic (InterVISTAS 2007) and price elasticities vary by market segments. There is a high elasticity for an individual airline or route, since consumers can often choose other carriers, routes and destinations but demand is less price elastic for overall air travel. The study identified the following patterns:

- Business travellers tend to be less price elastic than leisure travellers.
- Fare elasticities were generally higher on shorter- than long-haul routes due to more inter-modal substitution opportunities (e.g., to rail or automobile).
- The demand elasticity faced by individual air carriers is higher than that faced by the whole market.

- Virtually all studies estimate income elasticities to be above one, generally between +1 and +2. This indicates air travel increases with higher incomes.

The price elasticity of air travel is about -1.0, and fuel costs represent about 10% of total operating costs, so doubling fuel costs or comparable fees would reduce air travel mileage about 10% (Davidson, Wit and Dings 2003). Dargay (2010) developed a model for predicting long-distance travel demand which provides detailed elasticity values for various trip types, distances and users.

Taxi and Ridesharing Service Elasticities

Schaller (1999) finds that in New York City, the elasticity of taxi demand with respect to fares is – 0.22, the elasticity of service availability with respect to fares is 0.28, and the elasticity of service availability with respect to total supply of service is 1.0. Based on these values he concludes that fare increases tend to increase total industry revenues and service availability, and that the number of taxi licenses can often be expanded without reducing the revenue of existing operators.

The report, *Analysis of Travel Choices and Scenarios for Sharing Rides* (Middleton, et al. 2021) analyzed factors that affect travellers' willingness to share taxi and ridehailing rides, and the potential effectiveness of incentives. It found that financial and time incentives can both be effective: a price difference of $1.16 per mile or a time savings of 18 seconds per mile would each individually increase the probability of sharing trips by 10 percentage points (from roughly 30% to roughly 40% of trips), although changes were found with much smaller incentives. It also identified the types of trips and travellers that are most amenable to ridesharing.

Commute Trip Reduction Programs

Models are now available which can predict the travel impacts of a specific Commute Trip Reduction program, taking into account the type of program and worksite. These include the *CUTR_AVR Model* (www.cutr.usf.edu/tdm/download.htm), the *Business Benefits Calculator* (BBC) (www.commuterchoice.gov) and the *Commuter Choice Decision Support Tool* (www.ops.fhwa.dot.gov/PrimerDSS/index.htm).

Travel impacts are affected by the magnitude of the benefit and the quality of travel options available. Mode shifts tend to be greatest if current transit use is low. In New York City, where transit commute rates are already high, transit benefits only increased transit use 16% to 23%, while in Philadelphia, transit commuting increased 32% (Schwenk, 1995). Similarly, only 30% of employees who received transit benefits who work in San Francisco increased their transit use, while 44% of those in other parts of the region commuted by transit more (Oram Associates 1995). These probably represent the lower range of mode shifts since they are marketed primarily as an employee benefit and are therefore most attractive to firms with high current levels of transit commuting.

A stated preference survey calculated the effects of changes in travel prices and speeds on commutes at the University of Laval, Quebec (CDAT 2012). It found that:

- Making public transit free would reduce total automobile commutes 18% (staff -20%; students -17% and professors -12%).

- Increasing annual parking fees from the current $660 to $1,056 (a 60% increase) would reduce automobile trips 10% (students -12%, staff -10%, and professors -3%).
- Improving public transit service so bus travel became as fast as automobile travel would reduce automobile trips 10% (students -12%, staff -8% and professors -3%).
- Implied values of travel time are much lower than commonly assumed in travel time valuation studies.
- Combining strategies increased the effects. For example, if public transit becomes free and the parking cost is increased 60%, automobile trips would decline 42%, which is more than the sum of the effects of each measure taken separately).

Table 36 **Laval University Commute Elasticities** (CDAT 2012)

Elasticity With Respect To	Complete sample	Students	Professors	Staff
Travel time by car	-0.15	-0.18	-0.03	-0.12
Travel time by bus	0.21	0.29	0.04	0.12
Price of parking	-0.15	-0.19	-0.04	-0.09
Bus fare	0.09	0.10	0.02	0.07
Value of time-car ($/hour)	$4.50	$4.60	$4.90	$4.20
Value of time-bus ($/hour)	$5.90	$6.60	$5.80	$4.60

Freight Elasticities

The price elasticity of freight transport (measured in ton-miles) in Denmark is calculated to be –0.47, while the elasticity of freight traffic (measured in truck-kilometers) is –0.81, and the elasticity of freight energy consumption is only about –0.1 according to a study by Bjørner (1999). A 10% increase in shipping costs reduces truck traffic by 8%, but total shipping volume by only 5%. Some freight is shifted to rail, while other freight is shipped using existing truck capacity more efficiently. Hagler Bailly (1999) estimate the long-run price elasticity of rail and truck freight transport at –0.4, with a wide range depending on the type of freight. Small and Winston summarize various estimates of freight elasticities, as summarized in the table below.

Table 37 **Freight Transport Elasticities** (Small and Winston 1999, Table 2-2)

	Rail	Truck
Aggregate Mode share Model, Price	-0.25 to –0.35	-0.25 to –0.35
Aggregate Mode share Model, Transit Time	-0.3 to –0.7	-0.3 to –0.7
Aggregate Model from Tanslog Cost Function, Price	-0.37 to –1.16	-0.58 to –1.81
Disaggragate Mode Choice Model, Price	-0.08 to -2.68	-0.04 to –2.97
Disaggragate Mode Choice Model, Transit Time	-0.07 to –2.33	-0.15 to –0.69

These elasticities vary depending on commodity group.

Conclusions and Recommendations

Travel demand refers to the amount and type of travel that people would choose in particular situations. Various demographic, geographic and economic factors can affect travel demands, as summarized in Table 38. Models that reflect these relationships can predict how various trends, policies and projects will affect future travel activity, and therefore evaluate potential problems and transport system improvement strategies.

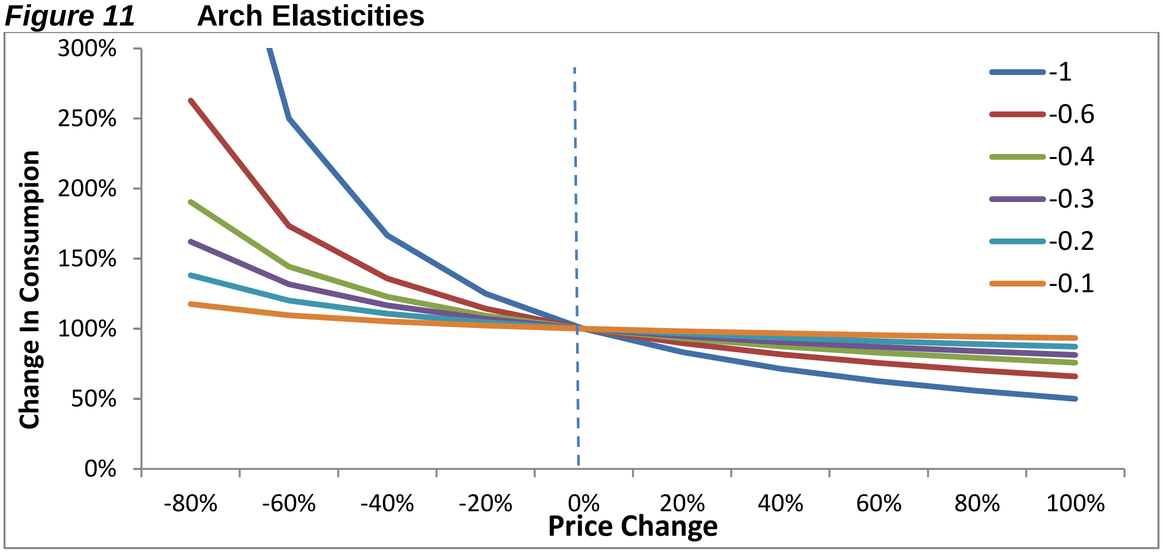
Table 38 **Factors That Affect Transport Demand**

Demographics	Commercial Activity	Transport Options	Land Use	Demand Management	Prices
Number of people (residents, worker and visitors) Employment rate Wealth/incomes Age/lifecycle Lifestyles Preferences	Number of jobs Business activity Freight transport Tourist activity	Walking Cycling Public transit Ridesharing Automobile Taxi services Telework Delivery services	Density Mix Walkability Connectivity Transit service proximity Roadway design	Road use prioritization Pricing reforms Parking management User information Promotion campaigns	Fuel prices and taxes Vehicle taxes and fees Road tolls Parking fees Vehicle insurance Transit fares

Various factors that affect transport demands should be considered in policy analysis and planning.

Prices are the direct, perceived costs of using a good. Transport prices can include monetary (money) costs, plus travel time, discomfort and risk. Price changes can affect trip frequency, route, mode, destination, scheduling, vehicle type, parking location, type of service selected, and location decisions. Pricing impacts are commonly measured using elasticities, the percentage change in consumption (in this case, in travel activity) that results from each 1% change in price, as illustrated in Figure 11.

Figure 11 **Arch Elasticities**



This graph illustrates how price changes affect consumption for various elasticity values.

Although some travel is very beneficial, the travel demand curve appears to have a long tail, meaning that if prices (monetary, time, discomfort and risk costs) decline sufficiently people will tend to increase their travel, resulting in an increasing amount of marginal value travel that provides minimal user benefits, and if they impose external costs, their net benefits (total benefits are less than total costs) are likely to be negative. This lower-value travel tends to be quite sensitive to pricing.

A considerable body of research has analyzed how various types of price changes affect transport activity. The types of travel impacts that result can vary, including changes in trip generation, mode, destination, route, vehicle type and parking location. Changing the price of one mode or service can affect demand of others modes and services (cross elasticities). Although impacts vary widely, it is possible to identify certain patterns:

- Higher value travel, such as business and commute travel, tend to be less price sensitive than lower value travel.
- Wealthy people tend to be less sensitive to pricing and more sensitive to service quality than lower-income people.
- Prices tend to affect consumption in proportion to their share of household budgets.
- Consumers tend to be more responsive to price changes they consider durable, such as fuel tax increases, compared with oil market fluctuations perceived as temporary.
- Pricing impacts tend to increase over time. Short-run (first year) effects are typically a third of long-run (more than five year) effects.
- Travel tends to be more price sensitive if travelers have better options, including different routes, modes and destinations.
- Travelers tend to be particularly sensitive to visible and frequent prices, such as road tolls, parking fees and public transit fares.
- How fees are promoted, structured and collected can affect their impacts.

A key factor in this analysis is the degree to which the demand factors and elasticity values collected in past studies are transferable to different times and places. The basic relationships that affect travel demands tend to be durable and therefore transferable, but it is important to take into account factors such as differences in employment rates, incomes, transport options and land use patterns when applying past experience in new areas. The values described in this report provide a reasonable starting point for travel demand modeling but the must be calibrated to reflect specific conditions. As transport planners, economists and modelers gain experience we will be better able to develop models for new locations, modes and pricing reforms.

In recent years there has been increasing interest in transportation demand management, including pricing reforms, to achieve planning objectives such as congestion, accidents and pollution reductions. Critics sometimes claim that vehicle travel is insensitive to pricing, citing studies of declining price elasticities and examples of fuel or toll price increases that caused little reduction in vehicle travel. This implies that pricing reforms are ineffective at achieving planning objectives and significantly harm consumers.

It is true that as normally measured, automobile use appears to be inelastic, meaning that price changes cause proportionately smaller changes in vehicle travel. However, this reflects how price impacts are normally evaluated. Short-run price effects are about a third of long-run effects, and most vehicle costs (depreciation, financing, insurance, registration fees and residential parking) are fixed. A -0.1 short-run elasticity of vehicle travel with respect to fuel price reflects a -0.3 long-run elasticity, which reflects a -1.2 elasticity of vehicle travel with respect to total vehicle costs, which implies that automobile travel is overall elastic.

Although automobile travel elasticities declined significantly in the U.S. during the last half of Twentieth Century, due to demographic and economic trends, including rising employment rates, increasing real incomes, declining fuel prices, highway expansion and sprawled land use development, and declining alternatives. Many of these trends are now reversing, resulting in peaking demand for automobile travel and increasing demand for alternative modes in most wealthy countries. These trends are increasing the price elasticity of automobile travel.

This has important implications for developing countries. Countries that implement policies that favor automobile travel during the early stages of their development, including low prices for fuel, roads and parking, will tend to create automobile dependent transportation systems, imposing greater economic, social and environmental costs. Developing countries that implement more efficient prices that test consumers' travel demands will have more efficient transport systems and fewer associated problems.

Improved transportation demand models, as described in this report, are an important tool to help policy makers and planners evaluate transport problems and potential solutions. It will be important for developing countries to establish data collection and capacity building programs to support model development.

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