CHAPTER 3

Estimating Transportation Demand

> *To go beyond is as wrong as to fall short.*
> *—Confucius (551–479 B.C.)*

INTRODUCTION

Transportation demand estimation is a key aspect of any transportation evaluation process because it provides a basis for predicting the needs for transportation in terms of passenger, freight, or vehicle volumes expected for a facility. Such forecasts are vital in evaluating alternative actions at every stage of the transportation development process. The decision to proceed with a project is often dictated by the levels of usage predicted for the proposed facility. Then at the facility design stage, the sizing of a proposed transportation facility and the scope of the proposed operational policies are influenced by the expected levels of demand. Furthermore, decision making to select and implement system policies is influenced by the expected levels of trip making. For example, the user benefits and costs, cash flow patterns, economic efficiency, effectiveness, and equity are all influenced by the volume of traffic using the facility. Finally, knowledge of the expected levels of demand in each future year is also useful for developing agency cost streams for preserving facilities whose deterioration and performance are influenced by the level of use.

As shown in Figure 3.1, the demand for transportation, which is derived from socioeconomic activities (e.g., commercial, industrial, educational, medical, and agricultural entities), is ultimately manifested in the form of traffic volume on the facility, such as the number of passengers and the freight tonnage. It is often appropriate to establish different levels of travel demand that correspond to different levels of supply attributes (cost, time, and so on).

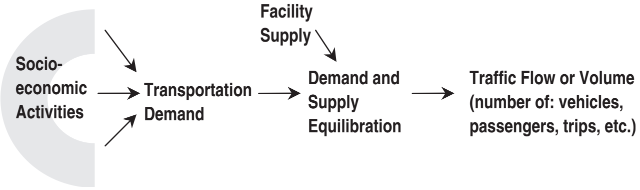

Figure 3.1 Relationships between demand, supply, and traffic volume.

The volumes of traffic observed or predicted at a system is therefore the interaction of travel demand and system supply.

It is thus important to be able to predict levels of transportation demand and system supply (performance) at any time in a facility's life or changes in these attributes in response to changes in socioeconomic characteristics, system price, system technology, and so on. Classical topics in transportation economics, such as demand modeling, supply functions, market equilibrium, price elasticity, production costs, and pricing, are therefore important in the evaluation of transportation system impacts.

In this chapter, we first discuss some basic concepts in economic demand theory and present methods for estimating aggregate project-level transportation demand. We then discuss the related topics of transportation supply and elasticity and explain how these concepts can help in estimating transportation demand or changes in demand.

3.1 TRANSPORTATION DEMAND

The demand for transportation is the number of trips that individuals or firms are prepared to make under a given set of conditions (i.e., trip time, cost, security, comfort, safety, etc.). The demand for transportation is often described as a *derived* demand because trips are typically undertaken not for the sake of simply traveling around but because of an expected activity at the end of a journey, such as work, shopping, returning home, or picking up or delivering goods. In this section we discuss methods for estimating travel demand.

3.1.1 Basic Concepts in Transportation Demand Estimation

The demand for any specific transportation facility or service depends on the characteristics of the activity system and the transportation system. An *activity system* is defined as the totality of social, economic, political, and other transactions taking place over space and time in a particular region (Manheim, 1979). Changes in an activity system may be represented by economic or

Transportation Decision Making: Principles of Project Evaluation and Programming. Kumares C. Sinha and Samuel Labi population growth, relocation of commercial, industrial, or other organizational entities into (or out of) an area, or increased (or decreased) scale of operations by entities already existing in an area. A *transportation system* is a collection of physical facilities, operational components, and institutional policies that enable travel between various points in a transportation network. The physical and operational components of a transportation system include the guideway, vehicle, transfer facilities, and facility management systems, while institutional components include pricing policies. The characteristics of a transportation network that are relevant to travel choice (and hence demand estimation) are termed *service attributes* and include travel time, travel cost (out-of-pocket expenses), safety and security, and comfort and convenience. *Demand functions* or *demand models* quantify the willingness of trip makers to “purchase” (i.e., undertake) a trip at various “prices” (i.e., levels of service attributes associated with the trip) under prevailing socioeconomic conditions. In its simplest formulation, a demand function is a two-dimensional model such as the classic demand–price curve. In a more complex formulation, demand is a multidimensional function of several explanatory variables (often including price) that represent the service attributes and trip-maker characteristics. These include a class of demand functions that estimate the expected total demand given the total trip-maker population and the probability that an individual (or group or individuals) will choose a particular transportation mode over another.

Figure 3.2(*a*) illustrates a simple aggregate function for transportation demand between a given origin and a destination at a specific time of day, for transit for a specific trip purpose (work trips), and for only one service attribute: trip price. The figure shows, for various trip prices, the associated levels of trip-making demand, and therefore provides an indication of the number of transit work trips that people are willing to undertake at various levels of the transit service attribute (in this case, trip fare).

Where the demand model predicts the shares of a travel alternative (such as mode, route, and so on), the service attributes that are specific to the alternative are termed *alternative-specific attributes*. These often include travel time, comfort, convenience, User attributes (income levels, household size, etc.), which describe socioeconomic characteristics and therefore do not vary by mode, are termed *generic attributes*. A demand function that estimates demand on the basis of more than one service attribute belongs to the class of *multiattribute demand functions*, and can be represented by a graph showing the relationship between demand and any single service attribute at constant levels of other service attributes. In such simplified cases, a change in the demand may be reflected as one of the following two situations:

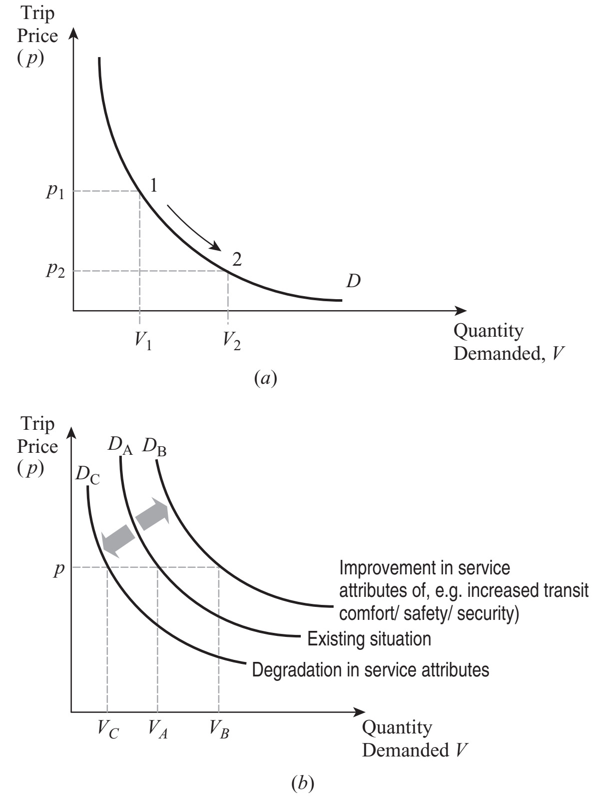

Figure 3.2 (*a*) Demand curve; (*b*) shifts in the curve.

1. A change in quantity demanded for a transportation service due to a change in the attribute selected (e.g., increase in trip fare). Demand changes in such cases are represented by an upward or downward *slide* along the demand curve (illustrated as 1 → 2 in Figure 3.2*a*). Demand curves of this nature apply primarily to competitive market conditions where travel demand is adequately responsive to changes in service attributes.
2. A *shift* in the single-attribute demand curve at a given level of the trip attribute in question (such as trip price) due to a change in the other trip or service attributes (such as trip time, comfort, accessibility, and security) of the transportation product or its rivals (Figure 3.2*b*).

For example, improvement of a transit system to reach more areas and to enhance passenger security and comfort would lead to an increase in transit demand even if the fare is kept the same—the single-attribute demand curve shifts to the right ($D_A \rightarrow D_B$). The same result would be obtained if there is decreased attractiveness of a rival good such as auto travel through for instance increased parking fees and tolls. By a similar reasoning, a reduction in the quality of transit service attributes, an increase in the attractiveness of auto travel, or a decrease in area employment would lead to reduced demand for transit travel even if transit fares remain the same ($D_{\mathrm{A}} \rightarrow D_{\mathrm{C}}$). In Section 3.1.2 we discuss factors that typically cause such shifts in the transportation demand curve.

In the example above, the single attribute (the variable on the ordinate axis of the demand function) is the trip price or fare. In a bid to simplify a multiattribute demand function, the ordinate could be expressed as a single composite cost variable that is an agglomeration of other *trip or service attributes*, such as trip fare, time, discomfort, safety and security, out-of-pocket expenses, and other "sacrifices" that each traveler incurs in making a trip. Therefore, various costs incurred by the trip maker can collectively represent the *user cost* that will be incurred by the trip maker.

3.1.2 Causes of Shifts in the Transportation Demand Curve

As explained in Section 3.1.1, there could be a change in the demand for a transportation facility even when its price remains the same, and this is reflected as a shift in the demand curve for that transportation facility. Factors that cause such demand shifts discussed below.

- *Sudden change in customer preference* (season, life style, etc.). For example, more people seem to ride transit in the winter season.
- *Change in the level of the attribute of interest* (*e.g., price increase*) *of related goods.* For complementary products, a decrease in the price of a product increases the demand for the other product, shifting the latter's demand curve to the right (e.g., parking spaces, automobile use). For rival products, an increase in price of a product increases the demand for its rival product, shifting the latter's demand curve to the right (e.g., transit and auto).
- *Change in regional income*. An increase in income shifts the demand curve for *normal* goods to the right. A normal good is one whose demand increases as a person's income increases.
- *Change in the number of potential consumers*. An increase in population or market size shifts the demand curve to the right.
- *Expectations of an impending change in the level of the attribute of interest.* For example, a news report predicting higher prices in the future can cause a shift in the demand curve at the current price as customers purchase increased quantities in anticipation of the price change.

3.1.3 Categorization of Demand Estimation Models

Demand models or functions can be either aggregate or disaggregate. *Aggregate demand functions* directly estimate the demand of a group of trip makers (such as a group of individuals, households, firms, or residents in a region or in a given class) in response to future changes in conditions. Alternatively, the decision processes of individual travelers or shippers can be modeled directly using *disaggregate demand functions*, and then summed up for all travelers and shippers to obtain the aggregate predicted demand. The disaggregate approach is based directly on the assumption that the trip makers seek to maximize their utility. It is also possible to develop demand models for a specific trip type and route and to estimate the probability that an individual or firm will undertake the trip given their characteristics and the attributes of the various modes of the transportation system. For the purpose of sketch planning, the aggregate approach, which estimates overall demand directly, is generally more appropriate than the disaggregate approach and has been used widely in past practice to estimate the predicted demand for transportation facilities.

Demand models may also be categorized by their stochastic nature. *Deterministic demand models* assume that the analyst has perfect information in order to predict travel demand, while *stochastic demand models* account for such lack of perfect information by introducing a random or probabilistic element into the demand model. This typically involves adding a random error variable in the demand model and implies that the utility assigned by the traveler to each travel alternative (and consequently, the precise choice of the traveler as to whether or not to travel) is unknown. Where data are available, it may be more appropriate to use stochastic demand models, particularly (1) when there exist some service attributes that are important to travelers but whose utilities are typically not explicitly represented in the demand modeling process, such as transportation security and safety, and convenience; (2) when travelers are not aware of all alternatives that are available to them or may not have correct or updated information on the levels of attributes of the alternatives; and (3) when a traveler's behavior is influenced by factors that change with time, such as weather.

3.1.4 Aggregate Methods for Project-Level Transportation Demand Estimation

Transportation improvements are typically carried out for a specific facility in a network, such as links (e.g., highway segments, rail corridors, air travel corridors) or nodes (e.g., airports, water ports, bus terminals, transit stations). Analysts may seek to estimate aggregate transportation demand at a link between two nodes (population or activity centers ranging from small areas that differ by land use to large cities), for a segmental facility within the link, or for a nodal facility. There are two general ways of doing this: The first involves the use of network methods that simultaneously estimate the demand for all links in the parent regional or urban network of that facility type on the basis of the trip productions and attractions and trip distributions at various points in the network. This approach yields demand models with predictive capabilities that account for any changes that may occur at other facilities in the network and affect demand at the facility in question. The second approach considers only the data for a link or nodal facility and yields total demand for the facility only. A discussion of each approach is presented here.

(*a*) *Demand Estimation Based on the Attributes of the Entire Parent Network* The four-step transportation planning model (TPM), shown in Figure 3.3, is currently the cost widely used model for estimating the link-by-link for an urban or regional network demand. Besides its applicability to entire networks rather than just a single origin–destination route, the attractiveness of the TPM framework lies in its ability to estimate not only overall demand but also demand with respect to trip type, mode, and route. In recent years, this framework has been extended to statewide transportation planning involving passengers and freight. The TPM estimates expected demand on the basis of the attributes of the activity system (such as employment and population) that generates such demand and the characteristics of the transportation system (that serves this demand). The end product of TPM is the demand on each link in a network at “equilibrium” conditions.

Step A1: Establish the Market Segmentation This step provides a basis for carrying out demand estimation separately for different attributes, such as flow units (passenger vs. freight) and commodity types. Other segmentation criteria (e.g., trip purpose, or mode) could be considered at this stage or may be accounted for in subsequent steps of the framework. It is essential to design a market segmentation process so as to enable the analyst to predict the new demand patterns reliably and ultimately to capture the expected effects of the new system or policy.

Step A2: Establish Traffic Analysis Zones Trip makers are typically classified by certain characteristics. Urban travelers, for example, can be classified by income, automobile availability, household size, and trip purpose, and most commonly, geographical location. The common procedure involves dividing the study area into traffic analysis zones and then characterizing each zone by each attribute of the entities that demand transportation.

Step A3: Estimate the Number of Generated Trips This step estimates the total passenger or freight transportation demand for all modes and routes into and out of each zone. This process is carried out on the basis of trip productions and trip attractions. For passenger transportation, variables in trip production equations typically include residential and household characteristics, while variables in trip attraction equations typically include employment types and levels, and floor space by business type (e.g., educational, commercial, or industrial). Analysts may determine the expected number of trips to be generated using information available in ITE’s *Trip Generation Handbook* (ITE, 2003). This publication presents average rates and regression equations for each land-use category, such as ports and terminals, industrial area, residential area, institutions, medical facilities, offices, lodging, retail, services, and recreational facilities. For freight, trip generation rates developed by Cambridge Systematics (1996) may be used.

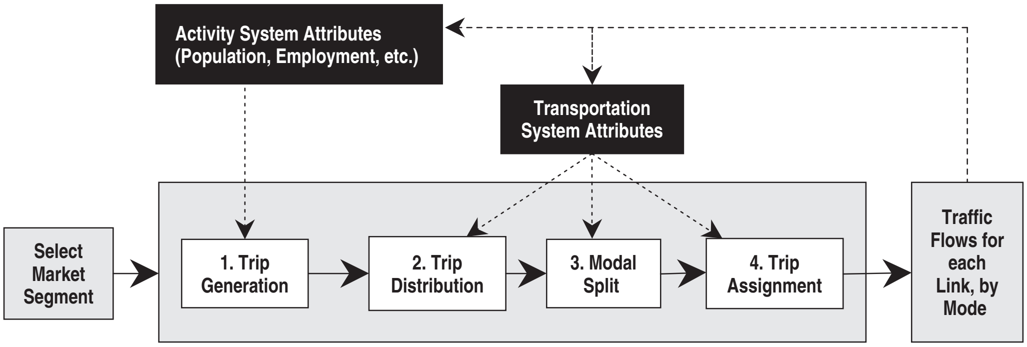

Figure 3.3 Four-step transportation planning model.

Step A4: Estimate Trip Distribution This step identifies specific origins and destinations of trips generated. Trips can be distributed using any of several methods. However, the most common method is the gravity model, which estimates trip making between two points directly as a function of the trip generation potential of any two points and indirectly as some measure of trip-making impedance (such as distance or travel time) between the two points. Such impedance, referred to as the *friction factor*, should be calibrated for the area of interest, time of day, and so on. The number of trips between any pair of zones i and j is given by

$$T_{ij} = P_i \frac{A_j F_{ij} K_{ij}}{\sum_{j=1}^{n} A_j F_{ij}} \tag{3.1}$$

where P_i are the trip productions from zone i, A_j the trip attractions to zone j, K_{ij} is an adjustment factor for trip interchanges between zone i and j, and F_{ij} is the friction factor, a measure of travel impedance between i and j given by $F_{ij} = t_{ij}^{-\alpha}$, where t_{ij} is the travel time between i and j and α is a coefficient.

Step A5: Determine the Modal Split These models predict the shares of overall demand taken by each available mode and may be carried out before or after the trip distribution step. The most common modal split models are of the logit or probit forms.

Step A6: Assign the Traffic For each bundle of demand associated with an origin–destination pair and mode, this step predicts, the route to be undertaken by that bundle. Traffic assignment can be carried out either on the basis of various techniques associated with user or system equilibrium.

Example 3.1 A transportation improvement program is planned in a metropolitan area for implementation in year 2020. Figure E3.1 shows the main corridors in the area. You are asked to estimate the passenger travel demand along the corridors. Instead of a simple trend analysis or two-point gravity model, it is preferred to use a network demand model and to incorporate supply characteristics. Three neighborhoods or population centers (1, 2, and 3) are considered for the network. The tables below provide the following information: zone-to-zone person-trips for the base year, zone-to-zone travel times and costs (for auto and transit, at the base and horizon years); and utility functions for auto and transit, zonal socioeconomic characteristics, and trip generation models. The trips shown in all tables are person-trips in hundreds.

1. *Base year* (2000) Table E3.1.1 shows the base year zone-to-zone person-trips, travel times, and friction factors.

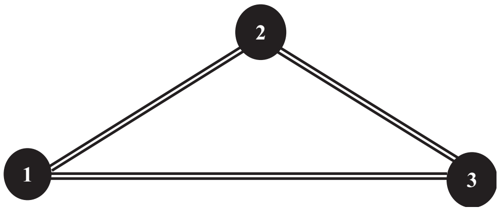

Figure E3.1 A simple network example.

Table E3.1.1 Base-Year Zone-to-Zone Person Trips, Travel Time, and Friction Factors[a]

From Zone:	To Zone: 1	To Zone: 2	To Zone: 3	Total Trip Productions
1	TT = 1 NT = 40 FF = 0.753	TT = 9 NT = 110 FF = 1.597	TT = 4 NT = 150 FF = 0.753	300
2	TT = 11 NT = 50 FF = 0.987	TT = 2 NT = 20 FF = 0.753	TT = 17 NT = 30 FF = 0.765	100
3	TT = 6 NT = 110 FF = 1.597	TT = 12 NT = 30 FF = 0.765	TT = 3 NT = 10 FF = 0.753	150
Total trip attractions	199	161	190	

[a] TT, travel time in minutes; NT, number of trips; FF, friction factor ($\alpha = 2$).

2. *Horizon year* (2020) Provision of the transit service Trip generation models (from the trip generation phase):

Productions: $P_i = -10 + 2.0X_1 + 1.0X_2$, where X_1 = number of cars and X_2 = number of households.

Attractions: $A_j = -30 + 1.4X_3 + 0.04X_4$, where X_3 = employment and X_4 = area of commercial area in hectares.

Table E3.1.2 shows the socioeconomic characteristics of each zone in terms of the number of cars, number of households, employment, and area of commercial activity; the travel time and friction factors between zone centroids for the year 2020 are shown in Table E3.1.3, and the zone-to-zone travel times and costs for auto and transit are given in Table E3.1.4.

Table E3.1.2 Zonal Socioeconomic Characteristics (Projected) in Horizon Year

Zone	Cars, X_1	Households, X_2	Employment, X_3	Commercial Area, X_4
1	280	200	420	4100
2	220	150	560	800
3	190	110	220	600

Table E3.1.3 Horizon Year Zone-to-Zone Person Trips, Travel Time, and Friction Factors

From	To Zone:		
Zone:	1	2	3
1	TT = 2 FF = 0.753	TT = 12 FF = 0.987	TT = 7 FF = 1.597
2	TT = 13 FF = 0.987	TT = 3 FF = 0.753	TT = 19 FF = 0.765
3	TT = 9 FF = 1.597	TT = 16 FF = 0.765	TT = 4 FF = 0.753

The utility functions for auto and transit, which are used in the mode choice models, are as follows:

Auto: $U_{\text{auto}} = 2.50 - 0.5\text{CT}_\text{A} - 0.010\text{TT}_\text{A}$

Transit: $U_{\text{transit}} = -0.4\text{CT}_\text{T} - 0.012\text{TT}_\text{T}$

where CT_A and TT_A are the cost and travel time for auto travel, respectively, and CT_T and TT_T are the cost and travel time for transit travel, respectively, where TC = travel costs in dollars and TT = travel time in minutes.

SOLUTION

1. *Trip generation*. The projected trip productions P_i and attractions A_j for each zone for the year 2020 are shown in Table E3.1.5.

$$\begin{aligned}\text{Total number of trips produced}\\ &= \text{total number of trips attracted}\\ &= 1810 \text{ (trip balancing)}\end{aligned}$$

2. *Trip distribution*. Calculate the zone-to-zone trips for the base year 2000 with the use of the gravity model. (Assume that $K_{ij} = 1.0$ for all zones and use zonal trip productions and attractions, and friction factors from Table E3.1.1.)

Table E3.1.4 Horizon Year Zone-to-Zone Travel Time and Cost for Auto and Transit[a]

From	To Zone:					
	1		2		3	
Zone:	Auto	Transit	Auto	Transit	Auto	Transit
1	TT = 3 CT = \$0.5	TT = 5 CT = \$1.0	TT = 12 CT = \$1.0	TT = 5 CT = \$1.5	TT = 7 CT = \$1.4	TT = 12 CT = \$2.0
2	TT = 13 CT = \$1.2	TT = 15 CT = \$1.8	TT = 3 CT = \$0.8	TT = 6 CT = \$1.2	TT = 19 CT = \$1.2	TT = 26 CT = \$1.9
3	TT = 9 CT = \$1.7	TT = 20 CT = \$2.0	TT = 16 CT = \$1.5	TT = 21 CT = \$2.0	TT = 4 CT = \$0.7	TT = 8 CT = \$1.1

[a] TT, travel time in minutes; CT, travel cost in dollars.

Table E3.1.5 Trip Productions and Attractions for Year 2020

	Zone		
	1	2	3
Trip productions, P_i	750	580	480
Trip attractions, A_j	722	786	302

Table E3.1.6 Calculated Trip Table (2000) Using the Gravity Model [equation (3.1)]

	To Zone:			
From Zone:	1	2	3	P_i
1	85	111	104	300
2	39	19	42	100
3	75	31	44	150
A_j	199	161	190	550

Table E3.1.6 shows the trip interchanges calculated between the various zones after row and column factoring. The adjustment factors K_{ij} are calculated as follows:

$$K_{ij} = \frac{T_{ij}(\text{observed})}{T_{ij}(\text{calculated})}$$

T_{ij}(observed) and T_{ij}(calculated) are determined from Tables E3.1.1 and E3.1.6, respectively. Apply the gravity model [equation (3.1)] to estimate zone-to-zone trips for the horizon year 2020. Friction factors are obtained from Table E3.1.3. The K_{ij} values are used from Table E3.1.7. The final trip interchange matrix for the horizon year is shown in Table E3.1.8.

Table E3.1.7 Adjustment Factors (K_{ij})

	To Zone:		
From Zone:	1	2	3
1	0.47	0.99	1.45
2	1.27	1.06	0.72
3	1.47	0.98	0.23

Table E3.1.8 Calculated Trip Table (2020) Using the Gravity Model [equation (3.1)]

	To Zone:			
From Zone:	1	2	3	P_i
1	105	396	249	750
2	288	247	45	580
3	329	143	9	480
A_j	722	786	303	1810

3. Mode choice. Use the utility functions to estimate the utilities for auto and transit (Table E3.1.9). The logit model for finding the auto share is

$$P(\text{auto}) = \frac{e^{U_{\text{auto}}}}{e^{U_{\text{auto}}} + e^{U_{\text{transit}}}}$$

Use the logit model to determine the fraction of zone-to-zone trips by auto and transit, as shown in Table E3.1.10. The trip interchange matrix obtained from trip distribution in step 2 and the modal share yield Table E3.1.11.

Table E3.1.9 Utility Values by Mode[a]

	To Zone:		
From Zone:	1	2	3
1	$U_{\text{auto}} = 2.23$	$U_{\text{auto}} = 1.88$	$U_{\text{auto}} = 1.73$
	$U_{\text{transit}} = -0.46$	$U_{\text{transit}} = -0.78$	$U_{\text{transit}} = -0.94$
2	$U_{\text{auto}} = 1.77$	$U_{\text{auto}} = 2.07$	$U_{\text{auto}} = 1.71$
	$U_{\text{transit}} = -0.90$	$U_{\text{transit}} = -0.55$	$U_{\text{transit}} = -1.07$
3	$U_{\text{auto}} = 1.56$	$U_{\text{auto}} = 1.59$	$U_{\text{auto}} = 2.11$
	$U_{\text{transit}} = -1.04$	$U_{\text{transit}} = -0.05$	$U_{\text{transit}} = -0.54$

[a] U_{auto}, auto utility; U_{transit}, transit utility.

Table E3.1.10 Fraction of Trips by Mode

	To zone:		
From zone:	1	2	3
1	P(auto) = 0.94 P(transit) = 0.06	P(auto) = 0.93 P(transit) = 0.07	P(auto) = 0.94 P(transit) = 0.06
2	P(auto) = 0.94 P(transit) = 0.06	P(auto) = 0.93 P(transit) = 0.07	P(auto) = 0.94 P(transit) = 0.06
3	P(auto) = 0.93 P(transit) = 0.07	P(auto) = 0.93 P(transit) = 0.07	P(auto) = 0.93 P(transit) = 0.07

Table E3.1.11 Trip Interchanges by Mode (2020)

	To Zone:		
From zone:	1	2	3
1	Auto trips = 98 Transit trips = 7	Auto trips = 370 Transit trips = 26	Auto trips = 233 Transit trips = 16
2	Auto trips = 269 Transit trips = 19	Auto trips = 230 Transit trips = 17	Auto trips) = 42 Transit trips = 3
3	Auto trips = 307 Transit trips = 23	Auto trips = 133 Transit trips = 10	Auto trips) = 8 Transit trips = 1

4. *Traffic assignment*. The minimum path (all-or-nothing) method is used for loading the trips on each link to yield Table E3.1.12. These trips reflect expected demand for given levels of service. By changing trip time and cost (representing supply functions), demand can be estimated for all or individual links.

Example 3.2 This example illustrates the use of a statewide travel model to estimate the transportation impacts of proposed major corridor improvements on a selected transportation network. The study corridor is the 122-mile corridor (U.S. 31) between Indianapolis and South Bend, Indiana. U.S. 31 is the primary north/south route through north-central Indiana. The proposed major corridor improvement concept for U.S. 31 is for an upgrade of the corridor to Interstate design standards and also includes construction of a new east-side bypass of Kokomo and a new freeway-to-freeway interchange with I-465, as shown in Figure E3.2. The overall study was carried out by Cambridge Systematics, Inc. and Bernardin, Lochmueller & Associates, Inc. (CSI-BLA, 1998).

Table E3.1.12 Auto and Transit Volumes by Link (2020)

Route	Auto and Transit Travel Time[a]	Auto and Transit Trips
1–2	12* (15*)	374 (22)
1–3	7* (12*)	236 (13)
1–2–3	31 (41)	
1–3–2	23 (33)	
2–1	13* (15*)	271 (17)
2–3	19* (26*)	42 (3)
2–3–1	28 (46)	
2–1–3	20* (27*)	
3–1	9* (20*)	309 (20)
3–2	16* (21*)	134 (9)
3–2–1	29 (36)	
3–1–2	21 (35)	

[a] An asterisk indicates the travel time of paths with least travel time. Transit travel time and trips are shown in parentheses.

SOLUTION The Indiana Statewide Travel Model (ISTM) was used to generate projections of traffic volumes and travel times on the highway network in the corridor, as well as in the entire state. Developed

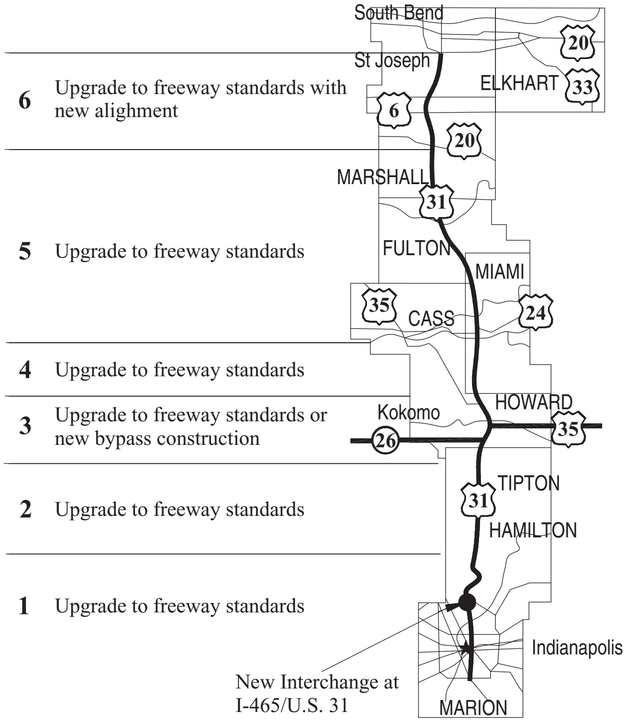

Figure E3.2 Proposed U.S. 31 corridor improvement.

in 1998 for INDOT to support statewide transportation planning activities, ISTM includes both passenger and freight movements on the 11,300-mile statewide highway network. The model includes 651 internal and 110 external traffic analysis zones. Two future-year (2020) traffic forecasts were developed and compared—one assuming the U.S. 31 improvements are implemented and one assuming they do not occur, as shown in Table E3.2.1.

The transportation network analysis suggested that at the horizon year (2020) the average daily traffic (ADT) is expected to increase significantly along most segments of U.S. 31, with an average increase of approximately 45% for the entire corridor. In absolute number of trips, the largest increase in trips would be seen at the southern end of the corridor.

Over the past two decades, there have been efforts to improve the TPM using *individual choice* (or *random utility*) *models* and *activity-based models* (Hensher and Button, 2000). Individual choice models try to capture the decision process of individual trip makers given the assumption that the trip maker is rational, has full knowledge, and therefore seeks to choose a transportation alternative mode, route, destination, and so on, that maximizes their utility (utility is measured implicitly or explicitly in terms of travel time, out-of-pocket costs, comfort and security, and other nonmonetary costs). Depending on the number of travel alternatives and the statistical assumptions associated with the demand data, model types include logit, probit, and dogit models. Unlike trip-based demand estimation approaches, activity-based approaches capture the scheduling of and participation in activities that directly generate the need to travel. Also, activity-based methods are considered more responsive to evolving policies oriented toward management rather than facility expansion. A new generation of demand models has been advocated to overcome the limitations of the currently used models (McNally, 2000).

The TPM method has seen wide applications in transportation demand for modes other than highways (such as air and rail) and for flow entities other than passengers (e.g., freight). In freight demand analysis involving spatial interactions of facilities, commodity surpluses and deficits at various geographical points on a transportation network are established and commodities are made to flow from centers of excess supply to those of excess demand. Such flow is governed by trip distribution techniques such as the gravity model.

Table E3.2.1 Estimated Demand along U.S. 31 (2020)

		Number of Trips (ADT)		
U.S. 31 Link	Length (miles)	No-Build	Build	Difference
I-465 to SR 431	10	78,800	122,200	43,400
SR 431 to SR 26	23	39,800	61,400	21,600
SR 26 to U.S. 35 (north leg)	9	36,400	41,900	5,500
U.S. 35 (north leg) to U.S. 24	11	23,800	37,000	13,200
U.S. 24 to U.S. 30	52	18,500	30,700	12,200
U.S. 30 to U.S. 20 bypass	19	35,200	42,900	7,700
Corridor Total	**122**	**36,100**	**52,600**	**16,500**

Another demand estimation method that involves spatial interaction is *network optimization*, where the demand for each link is determined on the basis of minimized total transportation cost expended in the network. Compared to the traffic assignment method, the optimization method may have serious limitations because (1) it implies that there is only one central decision-making entity for travel in the network and therefore fails to account for the different adaptations of individual users to network changes, and (2) the objective (total cost) function may be rendered concave due to scale economies, and therefore infeasible (Hensher and Button, 2000).

(*b*) *Demand Estimation Based Only on the Attributes of a Corridor or Project or Its Endpoints* The estimation of aggregate transportation demand for a specific link or node of a network based on the facility data has been discussed extensively. Kanafani (1983) provided models that estimate travel demand for a link between two nodes (ranging from small areas that differ by land use to large cities or major population centers), for a segment within the link, or for a nodal facility. Such estimation can be carried out using either one of two approaches. The first is a *multimodal approach* that recognizes the relationships that exist between modes and thus carries out the estimation in a simultaneous fashion. The structure of models that estimate multimodal intercity demand is similar to that of the TPM approach in that there are several alternative modes, several destinations, and several routes. It has been recommended that because trip distribution analysis (estimation of various demands for various modes at various alternative links) may be limited by the intrinsic characteristics of the cities, demand estimation should be done separately for each pair of cities. The second approach, a *mode-specific approach*, assumes that the modal demands are independent and therefore estimates these demands separately. Steps that could be used for estimating demand between two major population centers based only on the attributes of a corridor or its endpoints are presented next.

Step 1: Establish the Market Segmentation Demand estimation may be carried out separately for freight and passenger transportation, for work trips and nonwork trips, or for trips that otherwise differ by some attribute. The entire trip-making market could therefore be divided into different segments, the demand estimated for each segment, and the demands summed to yield the overall demand.

Step 2: Select the Demand Function In this step, data are collected for the project and models are developed to estimate demand as a function of the attributes of the endpoints of the proposed project, such as population or employment. The analyst could use one of many forms of demand functions, depending on the type of data being used, whether the demand is for a link or a node, whether it is sought merely to estimate demand changes in response to changes in service attributes, and so on. Where only historical data on demand are available, the analyst may estimate future demand on the basis of projections of past trends using time series–based trend lines. Where socioeconomic data are available to derive trip productions and attractions of the endpoints, the gravity models may be more appropriate.

Specific mathematical forms for demand estimation may include the elasticity-based form that is typically used where the analyst is faced with data and time limitations and seeks to estimate changes in demand from an existing or base situation. Common generic mathematical forms for demand estimation are:

$$\textit{Linear:}\quad V = b_0 + b_1 x$$

$$\textit{Multiplicative:}\quad V = b_0 x^{b_1}$$

$$\textit{Exponential:}\quad V = b_0 e^{b_1 x}$$

$$\textit{Power:}\quad V = (b_0)^x$$

$$\textit{Logistic:}\quad V = \frac{b_0}{b_1 + e^{b_2 x}}$$

$$\textit{Logistic-product:}\quad V = \frac{\alpha}{1 + \gamma x^{\beta}}$$

For simple trend analysis, the x variable simply represents time (years). For other types of demand estimation models, x is a vector of multiple variables, such as socioeconomic system attributes.

Demand Estimation Using Trend Analysis: Future demand can be estimated simply on the basis of past data. The functional form typically selected is one that best fits the historical data (the S-curve has often been used). Obviously, the use of trend analysis to estimate future demand implicitly assumes that the levels of the other factors affecting travel (as well as their relationships) will remain unchanged over time—this can be a rather restrictive assumption. Also, trend analysis does not account for possible future changes in the trip-generating characteristics of the area served by the facility or the wider network areas, or for possible future changes in the service attributes of the facility in question, of other links in the network, or of other competing modes. Given such limitations, trend analysis is generally considered to be more appropriate as a *diagnostic* rather than a *predictive* tool in the estimation of demand (Meyer and Miller, 2001).

Example 3.3 The demand for a certain rail transit system shows stable growth over the past decade, as shown in Table E3.3.1. An analyst seeks to estimate the expected demand at year 2008 when the system is due for improvement. Use the linear and exponential functional forms to predict the expected demand in that year. What assumptions should be made in using the predicted value of demand for evaluation? What are the limitations in using trend analysis for demand estimation?

SOLUTION The expected demand in the year 2008 can be determined using the mathematical functional forms of the linear and exponential curves as follows:

Linear form:

$$V = 0.089(\text{year} - 1990) + 1.1408 \qquad R^2 = 0.95$$

Thus, the projected demand in 2008 on the basis of linear trends is

$$(0.089)(2008 - 1990) + 1.1408 = 2.74 \text{ million}$$

Exponential form:

$$V = 1.2106e^{0.0499(\text{year}-1990)} \qquad R^2 = 0.98$$

Thus, the projected demand in 2008 on the basis of exponential trends is

$$1.2106e^{0.0499(2008-1990)} = 2.97 \text{ million}$$

While the exponential form gives a higher value of R^2, both forms provide good fits. Consequently, it may be desirable to use both estimates to yield a range of expected demand in 2008.

The underlying assumption in trend analysis is that all demand-contributing factors in the study area are constant over the period of projection. Furthermore, the supply of this mode and that of competing modes (e.g., private automobile or bus transit) are assumed to be constant. A limitation of the trend analysis method of demand estimation is that these assumptions are not always realistic. Changes in socioeconomic characteristics (such as relocation of new businesses, construction of schools, hospitals, etc.) and improvements or degradations in the supply attributes of this mode or its rival modes are always imminent. Such changes violate the foregoing assumption and can render the demand predictions inappropriate.

Elasticity-Based Models for Demand Estimation: Transportation improvements typically result in changed levels of service, such as trip cost and/or time. Elasticity-based demand models help estimate the new demand levels for a particular transportation mode in response to changes in service attributes, such as trip cost and time. The assumption is that the preimplementation demand level is known. In Section 3.4 we present the concept of elasticity and in Section 3.4.5 we discuss how it can be used for demand estimation.

Gravity-Based Models for Demand Estimation: The concept of gravity model used in TPM (discussed in Section 3.1.4) can be used for direct estimation of demand between two population or employment centers. In its classic formulation the gravity model is analogous to Newton's law of universal gravitation:

$$V_{\text{AB}} = N_{\text{A}}N_{\text{B}}I_{\text{AB}} \tag{3.2}$$

where V_{AB} is the demand for transportation between zones A and B; N_{A} and N_{B} are the measure of trip attractiveness, such as employment at zones A and B, respectively; I_{AB} and is the travel "impedance" between A and B (i.e., some characteristic or attribute of the transportation system that either impedes or facilitates travel between zones A and B, such as travel distance, time, speed, comfort, security, or out-of-pocket cost). The formulation above shows that the gravity model incorporates demand and supply characteristics by using parameters for trip attractiveness and impedance, respectively.

Most mode-specific travel demand estimation is carried out on the basis of the gravity model. The gravity model used in the traditional four-step transportation planning model (TPM), represents interzonal distribution of trips. Equation (3.1) gives a ratio of the travel propensity for each link relative to the sum of all link travel propensities, in terms of their respective impedances. Thus the gravity

Table E3.3.1 Annual Ridership of a Rail Transit System

Year	1990	1992	1994	1996	1998	2000	2002	2004
Demand (millions of passengers per year)	1.25	1.37	1.45	1.58	1.72	1.95	2.31	2.48

model determines the relative competitiveness of alternative destinations and estimates the shares of travel destinations. Compared to passenger transportation demand, commodity transportation demand is more consistent with economic demand theory and analysis because (1) the reason behind travel decisions are mostly economic (e.g., cost minimization), and (2) the demand for commodity transportation is derived completely from the various demands for the commodities at the points of consumption that are geographically distinct from the points of production—as such, the nature of the demand function can be found by identifying the patterns of production, distribution, and consumption in the network.

Example 3.4 The total air traffic (thousands of passengers per week) between a certain pair of cities, V_{ij}, can be given by

$$V_{ij} = \mathrm{INC}_{ij}^{0.38} \times \mathrm{POP}_{ij}^{0.25} \times \mathrm{TIME}_{ij}^{-1.51}$$

where INC_{ij} is the per capita income averaged across both cities i and j, in tens of thousands; POP_{ij} the average population between the two cities, in millions; and TIME_{ij} the average flying time between the two cities, in hours. Determine the demand when the average per capita income is \$30,000, the average of the two populations is 2 million, and the average flying time is 1.5 hours.

SOLUTION

$$V_{ij} = (3^{0.38})(2^{0.25})(1.5^{-1.51}) = 979 \text{ passengers per week}$$

Other variables that could be used in such models include the distance between the cities, average ticket price, and availability of other modes. However, in developing or using models of this type, the analyst should be careful to ascertain whether the predictive power of the model could be compromised by high correlations between the independent variables. For example, flight distance, ticket price, and flying time may be highly correlated.

(*c*) *General Comments on Demand Estimation Methods* As with most other real-world models, the main weakness of transportation demand estimation models is that they are often developed on the basis of historical data that may not be adequately representative of the future. Furthermore, transportation planning models are often based on the hypothesized travel patterns of travelers, and such patterns can be validated empirically by observing the trip behavior of passengers. If it were possible to carry out controlled experiments that incorporate specific levels of the transportation system and activity system attributes, the behavior of travelers under each set of conditions could be ascertained more reliably and used as a basis for future demand prediction. Unfortunately, it is not feasible to carry out such controlled experiments, therefore, past and current transportation and activity system conditions offer the only setting upon which future predictions can be made. As such, demand models are typically most valid when they are applied to future conditions that are not very different from those under which such models were developed. Second, demand models tend to be most reliable in the short term, as they typically fail to incorporate the long-term impacts of changes in trip patterns.

3.2 TRANSPORTATION SUPPLY

3.2.1 Concept of Transportation Supply

The supply of a transportation product or service represents the level of performance of the product or service that a provider is willing to offer at a given level of a service attribute (such as trip price). There are basically two aspects of transportation supply: quantity and quality.

1. *Quantity* refers to the amount of a product or service that the provider makes available or the capacity of a transportation system. For a transit system, for example, quantity may refer to the number of buses or rail cars per hour; and for a highway system, quantity may refer to the number of lanes. In the quantity context, a performance (supply) model estimates the quantity expected to be supplied at a given level of the service attribute, such as trip cost or travel time, at a given period of time.
2. *Quality* refers to the level of service. Examples for transit are cleanliness, security, lack of passenger congestion, and vehicle and track condition. For the highway system, examples are the level of traffic congestion and the pavement surface condition. In the quality context, performance (supply) models typically estimate the rate of deterioration of the transportation product or service over time. For example, the quality of rail tracks decreases with time as accumulated climate and use take their toll.

A specific supply curve represents the supply–price relationship given a set of conditions specific to the transportation product or service in question (referred to as *alternative-specific attributes*, such as travel time, comfort, convenience), and also specific to the producers or service providers (such as technology, policy, and governmental intervention through policies and regulations). Changes in such conditions often result in changes in the levels of transportation supply, even at a fixed price of that service or product. When such changes in conditions (other than price) occur, they are represented as a shift in the supply curve.

In the context of quantity and quality as discussed above, increases in transportation supply may be thought of not only in terms of increasing the fleet size of a transit company, building new roads, or adding lanes to existing roads, but also in terms of investments that are not physical and capital-intensive in nature. For instance, the use of intelligent transportation systems, ramp metering, and managed lanes (high-occupancy vehicle, or high-occupancy and toll lanes, truck-only lanes, etc.) could lead to an increased level of service without any physical enlargements of the road network.

3.2.2 Causes of Shifts in the Transportation Supply Curve

The supply of a transportation service may change even if price remains the same, for reasons such as:

- *Prices of rival transportation services.* The supply of a service may decrease if there is a decrease in the price of a competing transportation service, causing providers to reallocate resources to provide larger quantities of the more profitable service. This may apply more to toll roads, where profit is the primary motive, and to a lesser extent, non-toll roads.
- *Number of transportation modes*. An increased number of modes, such as construction of a subway in a city that already has buses and light rail transit and facilities for autos, indicates an increase in supply, shifting the supply curve to the right (downwards).
- *Prices of relevant inputs*. If the cost of resources used to produce a transportation service increases, the transportation agency would be less capable of supplying the same quantity at a given price, and the supply curve will shift to the left (upwards).
- *Technology*. Technological advances that increase facility capacity or efficiency cause the supply curve to shift to the right (downwards).

3.3 EQUILIBRATION AND DYNAMICS OF TRANSPORTATION DEMAND AND SUPPLY

3.3.1 Demand–Supply Equilibration

At equilibrium conditions, the quantity of trips demanded is equal to the quantity supplied. The equilibrium state is essentially fixed at a given point in time and is often analyzed as such. However, over a period of time, several short- and long-term equilibrium states can occur in response to changes in system supply or system demand, and each equilibrium state can be analyzed separately. The traffic assignment step in TPM discussed in Section 3.1.4 represents the equilibrium state, typically for a peak period.

Example 3.5 The following equations represent the demand and supply functions associated with a given passenger railway route for a particular season.

Demand function:

$$V = 5500 - 22p$$

Supply function:

$$p = 1.50 + 0.0003V$$

where V is the daily passenger trips along the route and p is the fare in dollars. Determine the equilibrium demand and price and comment on the threshold demand and fare.

SOLUTION Solving the two equations simultaneously yields the following equilibrium values: $V = 5431$ daily passenger trips and $p = \$3.13$. The equilibrium point can also be obtained graphically by plotting the two equations simultaneously and determining the point of intersection. Several other observations can be made: The maximum daily demand along the route is 5500 trips, and the minimum ticket price is $1.50 per trip.

3.3.2 Simultaneous Equation Bias in Demand–Supply Equilibration

Traditional methods for estimating transportation demand and supply implicitly assume that the supply characteristics are exogenous and fixed, implying that demand and supply functions exist as single independent equations. In reality, one or more of the supply variables may not be exogenous, but rather, may depend on the endogenous variable representing traffic volume, thus introducing a two-way causality problem best known as *simultaneity*. An example is the use of time-series analysis in modeling air travel demand; the issue of simultaneity arises because observed trends in traffic (a representation of demand) and price and capacity (representations of supply) are actually not independent. In such cases, a system of equations needs to be specified to estimate the model parameters reliably. Simultaneity may be ignored if the value of the supply variable at each demand level is assumed to be fixed and exogenous. Where such simultaneity cannot be ignored, it becomes difficult to reliably calibrate the demand and supply models, and the problem of *identification* (which gives rise to such difficulty) needs to be addressed. Several standard econometric texts provide methodologies to identify or address simultaneity (Wooldridge, 2000; McCarthy, 2001; Washington et al., 2003).

3.3.3 Dynamics of Transportation Demand and Supply

Assume that at the same price, there is increased demand due to factors exogenous to the transportation system, such as increasing population, rising employment, or business growth. This causes the demand curve to shift from D_{old} to D_{new} while the supply stays the same; the equilibrium point shifts from (V_0, p_0) to (V_1, p_1). Then, if there is an improvement in the quantity or quality of the transportation system, such as additional highway lanes, congestion mitigation techniques, or an intelligent transportation system (ITS), the supply (performance) function shifts from S_{old} to S_{new} and the system reaches yet another new equilibrium (V_2, p_2). The increase in system performance may then lead to further shifts in demand for the system. For example, the construction of a new interchange or added lanes may be accompanied by increased business activity (such as an increased number of shopping malls or restaurants, or increased sales by existing businesses). There will thus be a new equilibrium point. These demand and supply shifts and resulting changes in equilibrium positions are illustrated in Figure 3.4. In reality, transportation systems undergo such changes constantly, moving from one equilibrium point to another.

3.4 ELASTICITIES OF TRAVEL DEMAND

Analysts involved in transportation system evaluation may often need to adjust their demand forecasts to reflect changed socioeconomic or transportation system characteristics. Knowledge of demand elasticities enable analysis of the impacts of changes in factors that influence transportation demand. In cases where elasticity values are known, changes in demand from an existing level can be estimated using the methods that are presented in Section 3.4.5.

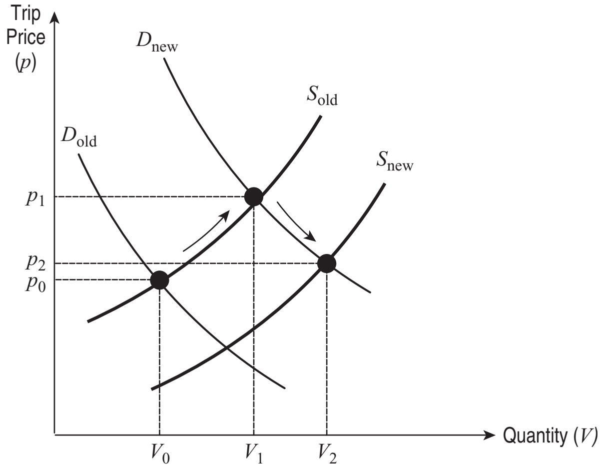

Figure 3.4 Instances of demand and supply equilibration.

Elasticity, defined as percentage change in demand for a 1% change in a decision attribute, helps to obviate the dimensionality problems associated with other concepts of demand sensitivity, such as derivatives. The elasticity of travel demand V, with respect to an attribute x can be expressed as.

$$e_x(V) = \frac{x}{V}\frac{\partial V}{\partial x} \tag{3.3}$$

Table 3.1 presents the elasticity functions for selected mathematical forms of the demand model. The interpretation of elasticity values, methods of computation, and applications are discussed in a subsequent section of this chapter. Demand elasticities can be influenced by factors such as mode type, trip purpose, time of day, trip length, trip-maker characteristics, and existing level of factor. Because the trip maker's decision is typically associated with combined utility maximization, a specific elasticity value cannot be considered while explicitly considering the existing levels of the other factors. As such, the transportation service attributes are important determinants of trip-maker sensitivity to price changes. For example, for a high level of service, the impact of a fare increase will be

Table 3.1 Elasticity Functions for Standard Mathematical Forms of Aggregate Demand

	Elasticity Function: $(x/V)(\partial V/\partial x)$
Linear	
$V = \alpha + \beta x$	$\frac{\beta x}{V} = \frac{1}{1 + (\alpha/\beta x)}$
Product	
$V = \alpha x^{\beta}$	$e = \beta$
Exponential	
$V = \alpha e^{\beta x}$	$e = \beta x$
Logistic	
$V = \frac{\alpha}{1 + \gamma e^{\beta x}}$	$\left(1 - \frac{V}{\alpha}\right) = -\frac{\beta_{\gamma} x e^{\beta x}}{1 + \gamma e^{\beta x}}$
Logistic-product	
$V = \frac{\alpha}{1 + \gamma^{x\beta}}$	$\left(1 - \frac{V}{\alpha}\right) = -\frac{\beta \gamma x^{\beta}}{1 + \gamma x^{\beta}}$

Source: Adapted from Manheim (1979).

relatively small (as is the case for the peak-period operations of many rail transit systems). On the other hand, for a poor level of service, a fare increase would probably cause a significant drop in demand.

It has been determined that the overall value of demand elasticity with respect to rail transit fares is much lower than that for bus transit, and suburban bus transit shows higher fare elasticity than bus service. Also, demand-fare elasticities for short trips are likely to exceed those of long trips by a factor of 2. In most cases, the magnitude of demand elasticity for fare decrease is lower than that for fare increase. The elasticities of demand with respect to transportation service attributes (such as travel time) generally exceed those with respect to trip price, and long-run service elasticities typically exceed those of the short run.

Elasticities can be classified by the method of computation, source of the elasticity, and relative direction of response. These are discussed in the next sections.

3.4.1 Classification of Elasticities by the Method of Computation

Two elasticity computation methods can be illustrated using Figure 3.5.

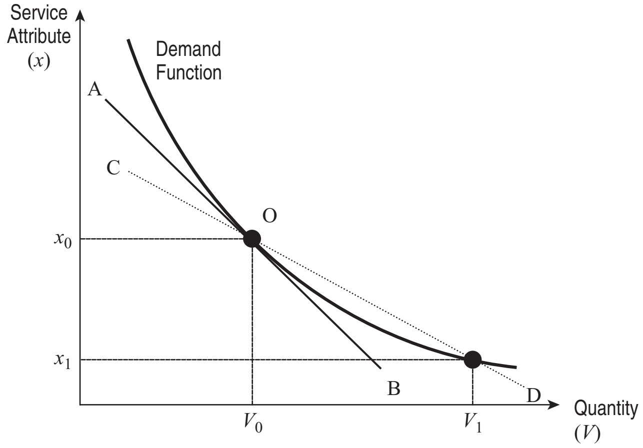

Figure 3.5 Point and arc elasticities.

Point elasticity, expressed as equation (3.3), is proportional to the slope of the tangent (AOB) to the demand curve at (x_0, V_0), where V is the quantity demanded and x is the attribute of the transportation system, such as the out-of-pocket costs associated with a trip.

Arc elasticity, on the other hand, is computed over the arc between (x_0, V_0) and (x_1, V_1) and is proportional to the slope of the line (COD). It is expressed as

$$e_x(V) = \frac{\Delta V/V}{\Delta x/x} = \frac{\Delta V x}{\Delta x V} = \frac{(V_1 - V_0)(x_1 + x_0)/2}{(x_1 - x_0)(V_1 + V_0)/2} \tag{3.4}$$

where V_0 is the quantity demanded when the attribute value is x_0 and V_1 is the quantity demanded when the attribute value is x_1.

It can be seen from the equations above that as Δx approaches zero, the value of arc elasticity becomes equal to that of point elasticity. Typically, specific values of the attribute x and travel demand V can be measured to permit estimation of the arc elasticity, while data for the computation of point elasticities are not so easily available. When the value of elasticity is lower than -1 or greater than 1, the demand is described as being elastic with respect to the attribute (Figure 3.6). However, when elasticity is between -1 and 1, the demand is described as being inelastic or relatively insensitive.

If the demand for a given mode is elastic with respect to the price of travel on that mode, a change in the price is likely to lead to a change in the revenue associated with that mode. This is most readily observed for transit modes and also for highway modes involving a toll. Similarly, significant cross-elasticities across modes influence the level of revenue generated.

Example 3.6: Point Elasticity An aggregate demand function for a rail transit service from a suburb to a downtown area is represented by the equation $V = 500 - 20p^2$, where V is the number of trips made per hour and p is the trip fare. At a certain time when the price was \$1.50, 2000 trips were made. What is the elasticity of demand with respect to price?

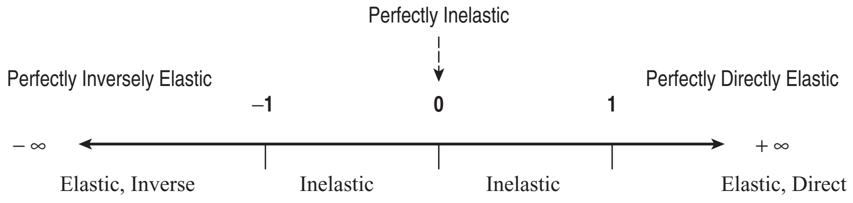

Figure 3.6 Elastic and inelastic regions.

SOLUTION

$$\text{Point price elasticity, } e_p(V) = \frac{\partial V/V}{\partial p/p} = \frac{\partial V}{\partial p}\frac{p}{V}$$

$$= (-20)(2)(1.50)\left(\frac{1.50}{2000}\right)$$

$$= -0.045$$

Example 3.7: Arc Elasticity Two years ago, the average air fare between two cities was \$1000 per trip and 45,000 people made the trip per year. Last year, the average fare was \$1200 and 40,000 people made the trip. Assuming no change in other factors affecting trip making (e.g., security, state of the economy), what is the elasticity of demand with respect to the price of travel?

SOLUTION

$$\text{Arc price elasticity, } e_p(V)$$

$$= \frac{\Delta V(p_1 + p_2)/2}{\Delta p(V_1 + V_2)/2}$$

$$= \frac{(40{,}000 - 45{,}000)(1{,}200 + 1{,}000)/2}{(1200 - 1000)(40{,}000 + 45{,}000)/2}$$

$$= -0.647$$

3.4.2 Classification of Elasticities by the Attribute Type

Attributes that affect travel demand include characteristics of the transportation system, such as the price and level of service associated with a given mode, the price and level of service of competing modes, and the characteristics of the socioeconomic system (i.e., income, level of employment, household size, car ownership, etc.). Among these factors, price and income are of particular interest. The elasticities of demand in response to price and income can be termed price elasticity and income elasticity, respectively.

(*a*) *Demand Elasticities with Respect to the Trip Maker's Income* Transportation planners often seek to predict the impact of changing socioeconomic characteristics on the demand for various modes of transportation. A major indicator of economic trends is income. *Income elasticity* is generally defined as the percent change in travel demand in response to a one percent change in income. In transportation economics, a good or service is considered *normal* if there is a direct relationship between the demand for the transportation service and the income of the consumer (trip maker). Besides, if the demand for a good decreases with increasing income, the good is described as *inferior*. Automobile travel is generally considered superior, and mass transit is considered to be an inferior good.

(*b*) *Demand Elasticities with Respect to Trip Price* A study of price elasticities is important because it is often used to assess the impact of the changing prices of a transportation mode (or its rival modes) on the demand for the mode. The level of price elasticity depends on factors such as the price of the rival modes, the income share of the mode, the scope of definition of the mode, and whether the mode is considered a luxury or a necessity.

(*c*) *Demand Elasticities with Respect to Other Attributes* It is also useful to have knowledge of the elasticity of transportation demand with respect to attributes other than price and income. Such other attributes may include the service reliability of the transportation system and the backgrounds of the system users (for example, household auto availability). This knowledge can help the analyst to make any needed adjustments in future demand in response to changes in such attributes so that more reliable demand predictions can be obtained.

3.4.3 Classification of Elasticities by the Relative Direction of Response: Direct and Cross-Elasticities

Direct elasticity is the effect of the change in an attribute (e.g., price) of a transportation service on the demand for the *same* service. For example, when the transit fare increases, it is likely that transit travel will decrease, depending on the extent of the fare increase. *Cross-elasticity* refers to the effect of a change in an attribute of a transportation service on the demand for an alternative transportation service. Applications of cross-elasticity can be found in the case of substitute services or complementary services. In the case of substitute services, when consumers patronize more of service A in response to an increase in the price of service B, service A is generally described as a perfect substitute for service B. An example is rail freight demand and highway freight demand. An increase in the price of rail transportation causes an increase in the demand for truck transportation. In this case, cross-elasticity is positive. For complementary goods such as auto travel and gasoline, an increase in the price of gasoline results in decreased demand for gasoline and consequently, a decreased demand for auto travel. In this case, the cross-elasticity is negative.

Example 3.8 A 20% increase in downtown parking costs resulted in a 5% reduction in downtown auto trips and a 20% increase in transit patronage for downtown routes. Determine the elasticities of auto and transit demand with respect to parking costs.

SOLUTION Let p_1 and p_2 represent the initial and new parking fee, respectively. A_1 is the auto travel demand before the parking fee increase, A_2 the auto travel demand after the parking fee increase, T_1 the transit travel demand before the parking fee increase, and T_2 the transit travel demand after the parking fee increase. The percent change in auto use with respect to an increase in parking costs is a direct elasticity, while the percent change in transit use with respect to an increase in parking costs is a cross-elasticity:

$$\begin{aligned}\text{initial parking price} &= p_1,\\ \text{final parking price} &= p_2 = 1.20p_1\\ \text{initial transit demand} &= V_{\text{T1}},\\ \text{final transit demand} &= V_{\text{T2}} = 1.20V_{\text{T1}}\\ \text{initial auto demand} &= V_{\text{A1}},\\ \text{final auto demand} &= V_{\text{A2}} = 0.95V_{\text{A1}}\end{aligned}$$

Arc elasticity of transit demand with respect to parking costs,

$$e_{Tp} = \frac{\Delta V(p_1+p_2)/2}{\Delta p(V_1+V_2)/2} = \frac{(V_{\text{T2}}-V_{\text{T1}})(p_1+p_2)/2}{(p_2-p_1)(V_{\text{T1}}+V_{\text{T2}})/2} = 1$$

Arc elasticity of auto demand with respect to parking costs,

$$e_{Tp} = \frac{\Delta V(p_1+p_2)/2}{\Delta p(V_1+V_2)/2} = \frac{(V_{\text{A2}}-V_{\text{A1}})(p_1+p_2)/2}{(p_2-p_1)(V_{\text{A1}}+V_{\text{A2}})/2} = -0.25$$

3.4.4 Examples of Elasticity Values Used in Practice

Demand can be expressed in terms of the amount of travel [vehicle-miles traveled (VMT)], ton-miles of freight, car ownership or vehicle stock, fuel consumption, and so on, and elasticity values have been developed for many of these forms of demand. The concept of elasticities has broad applications in many areas of transportation systems management such as physical changes that increase supply, policy changes that change trip prices and out-of-pocket costs, parking costs, selective road pricing, and so on, as well as changes in the economic environment outside the control of the system planner, such as fuel price changes.

Demand elasticity values may vary by the temporal scope of the analysis and the type of demand measure selected (VTPI, 2006). Short run is typically less than two years, medium run is two to 15 years, and long run is 15 years or more, although these temporal definitions may vary from agency to agency (Litman, 2005). Studies by Button (1993) suggest that long-run elasticities are mostly greater than those of the short run by factors of 2 to 3. Also, Goodwin et al. (2003) determined that the elasticities of demand expressed in terms of fuel consumption generally exceed elasticities expressed in terms of vehicle travel by factors of 1.5 to 2.

(*a*) *Demand Elasticity with Respect to General Out-of-Pocket Expenses* Out-of-pocket expenses or the trip price for automobile travel include fuel, road tolls, and parking fees. For transit the trip price includes mainly the fare charged (VTPI, 2006). The elasticity of automobile travel with respect to trip price was found to be −0.23 and −0.28 in the short and long run, respectively (Oum et al., 1992). In another study in Europe (VTPI, 2006), the elasticities for urban peak period travel with respect to trip price were found as follows: −0.384 for automobile and −0.35 for public transit; elasticity values were higher for off-peak travel. Also, elasticity values with respect to out-of-pocket expenses on the basis of automobile trip type are given in Table 3.2.

(*b*) *Demand Elasticity with Respect to Parking Price* Several studies, such as Clinch and Kelly (2003), Kuzmyak et al. (2003), Pratt (2005), and Vaca and Kuzmyak (2005), provide information on demand elasticities with respect to parking price. Kuzmyak et al. (2003) indicated a range of demand elasticities with respect to parking prices as follows: −0.1 to −0.3, depending on trip type, demographics, location, and other factors. Table 3.3 provides the elasticities of demand for various travel modes with respect to parking price for relatively automobile-oriented urban regions. Hensher and King (2001) determined that a 10% increase in prices at preferred central business district (CBD) parking locations in Sydney, Australia, would cause a 5.41% reduction in demand at those locations, a 3.63% increase in "park-and-ride" trips, a 2.91% increase in public transit trips, and a 4.69% reduction in total CBD trips.

Some researchers have cautioned that the use of parking price elasticities can be misleading, particularly where parking is currently free. It is meaningless to measure a percentage increase from a zero price (VTPI,

Table 3.2 Elasticity of Road Travel with Respect to Out-of-Pocket Expenses

Trip Type	Elasticity
Urban shopping	−2.7 to −3.2
Urban commuting	−0.3 to −2.9
Interurban business	−0.7 to −2.9
Interurban leisure	−0.6 to −2.1

Source: VTPI (2006).

Table 3.3 Demand Elasticities with Respect to Parking Price by Mode

Trip Purpose	Car Driver	Car Passenger	Public Transportation	Walking and Cycling
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

Source: TRACE (1999), VTPI (2006).

2006). Policy shifts from free to priced parking typically reduce drive-alone commuting by 10 to 30%, particularly when implemented with improvements in transit service and ride-share programs and other TDM strategies (Litman, 2005).

(*c*) *Demand Elasticity with Respect to Fuel Price* Road users generally react to increased fuel prices by reducing the amount of driving (typically in terms of vehicle-miles) in the short run, and by purchasing or leasing more-fuel-efficient vehicles in the long run (VTPI, 2006). On the basis of international studies, Goodwin (1992) estimated elasticity values as −0.15 and −0.3 to −0.5 for the short and long run, respectively. Higher values were found by Dargay (1992), who carried out an analysis separately for fuel price increases and decreases. Johansson and Schipper (1997) estimated a long-run car travel demand elasticity of −0.55 to −0.05 with respect to fuel price. Using U.S. data spanning the early 1980s to the mid-1990s, Agras and Chapman (1999) determined that the short- and long-run elasticities of VMT with respect to fuel price were −0.15 and −0.32, respectively. From country to country, there is some variation in demand elasticity with respect to fuel price (Glaister and Graham, 2000).

Some studies have used, implicitly or explicitly, fuel consumption as a surrogate for travel demand. Dahl and Sterner (1991) estimated the elasticity of fuel consumption with respect to fuel price to be −0.18 in the short run and −1.0 in the long run. DeCicco and Gordon (1993) estimated that the medium-run elasticity of vehicle fuel in the United States ranges from −0.3 to −0.5. Hagler Bailly (1999) established fuel consumption elasticities with respect to fuel price in the short run and long run, with separate estimates for various fuel types and transportation modes (Table 3.4).

Table 3.4 Estimated Fuel Price Elasticities by Mode and Fuel Type

Mode and Fuel Type	Short-Run Elasticity	Long-Run Elasticity
Road gasoline	−0.10 to −0.20	−0.40 to −0.80
Road diesel truck	−0.05 to −0.15	−0.20 to −0.60
Road diesel bus	−0.05 to −0.15	−0.20 to −0.45
Road propane	−0.10 to −0.20	−0.40 to −0.80
Road compressed natural gas	−0.10 to −0.20	−0.40 to −0.80
Rail diesel	−0.05 to −0.15	−0.15 to −0.80
Aviation turbo	−0.05 to −0.15	−0.20 to −0.45
Aviation gasoline	−0.10 to −0.20	−0.20 to −0.45
Marine diesel	−0.02 to −0.10	−0.20 to −0.45

Source: Hagler Bailly (1999), VTPI (2006).

(*d*) *Demand Elasticity with Respect to Road Pricing and Tolling* Short-term toll road price elasticities in Spain range from −0.21 to −0.83 (Matas and Raymond, 2003.) Litman (2003) reported that the recent congestion pricing fee in downtown London during weekdays led to a 38% and an 18% reduction in private automobile and other traffic (buses, taxis, and trucks), respectively, in that area. Luk (1999) estimated that toll elasticities in Singapore range from −0.19 to −0.58 (average of −0.34).

(*e*) *Demand Elasticity with Respect to Travel Time* Goodwin (1992) estimated that the elasticity of vehicle travel demand at urban roads with respect to travel time is −0.27 and −0.57 in the short and long run, respectively (the values for rural roads were −0.67 and −1.33, respectively). The elasticities of demand with respect to auto travel times, by trip type and mode, are summarized in Table 3.5. These are long-term elasticities in areas of high vehicle ownership: over 0.45 vehicle per person (TRACE, 1999). Also, demand elasticities with respect to travel time were presented by SACTRA (1994) and separately for auto and

Table 3.5 Elasticity of Demand with Respect to Travel Time by Mode and Trip Purpose

Mode/ Purpose	Auto Driver	Auto Passenger	Public Transport	Walking and Cycling
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

Source: TRACE (1999), VTPI (2006).

bus in-vehicle time, and for transit-related walking and waiting times, by Booz Allen Hamilton (2003).

(*f*) *Demand Elasticity with Respect to Generalized Travel Costs* The generalized cost of transportation can include the costs associated with travel time, safety, vehicle ownership and operation, fuel taxes, tolls, transit fares, and parking, among others (VTPI, 2006). NHI (1995) provides an elasticity of demand of −0.5 with respect to the generalized cost. Booz Allen Hamilton (2003) estimated the elasticity of demand with respect to the generalized cost of travel in the Canberra, Australia region by time of day: −0.87 for peak, −1.18 for off-peak, and—1.02 overall (peak and off-peak combined). In the United Kingdom, TRL (2004) estimated generalized cost elasticities as follows: 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) estimated the elasticity of vehicle travel demand with respect to generalized cost (fuel, vehicle wear and mileage-related ownership costs, tolls, parking fees and travel time, etc.) as follows: −0.5 to −1.0 in the short run and −1.0 to −2.0 in the long run.

(*g*) *Transit Elasticities* The elasticity of demand with respect to transit fare (Pham and Linsalata, 1991) is generally higher for small cities than for large cities and is also higher for off-peak hours (Table 3.6). Similar values were obtained by TRL (2004), which estimated that (1) metro rail fare elasticities were −0.3 in the short run and −0.6 in the long run; (2) bus fare elasticities were approximately −0.4 in the short run, −0.56 in the medium run, and 1.0 over the long run; and (3) bus fare elasticities were relatively low (−0.24) in the peak period compared to the off-peak period (−0.51).

Kain and Liu (1999) summarized transit demand elasticity estimates from previous studies and determined the elasticity values with respect to various attributes as follows: regional employment, 0.25; central city population, 0.61; service (transit vehicle miles), 0.71; and fare, −0.32. For example, a 10% increase in fare would be expected to decrease ridership by 3.2%, all other factors remaining the same.

Table 3.6 Transit Elasticities by Time of Day and City Size

	Large Cities (more than 1 million population)	Smaller Cities (less than 1 million population)
Average for all hours	−0.36	−0.43
Peak hour	−0.18	−0.27
Off-peak	−0.39	−0.46
Off-peak average	−0.42	
Peak-hour average	−0.23	

Source: Pham and Linsalata (1991), VTPI (2006).

(*h*) *Freight Elasticities* In a study in Denmark, the price elasticity of highway freight demand was found to be as follows (Bjorn, 1999):

- *Freight volume* (in terms of tonnage distance): −0.47
- *Freight traffic* (in terms of truck trip distance): −0.81

In response to increases in highway freight prices, shippers may utilize existing truck capacity more efficiently or may shift to rail freight modes (Litman, 2005). For freight transportation by rail and road, Hagler Bailly (1999) established the long-run elasticity of demand with respect to price as −0.4, but could be lower or higher, depending on the freight type and other factors. Small and Winston (1999) reviewed various estimates of freight elasticities, a summary of which is provided in Table 3.7.

(*i*) *Final Comments on Elasticity* The value of travel elasticity to be used in any situation depends on the characteristics of the area, the existing level of demand, the trip type, the existing level of the elasticity attribute, the location, and other factors. For example, transit-dependent individuals are generally less sensitive to changes in trip price or other transit service attributes. Litman (2005) found that as the per capita income, drivers, vehicles, and transport options increase, the transit elasticities are likely to increase. Also, in using elasticity values for demand analysis, analysts must consider conditions under which the elasticity values were developed. Elasticity values that are from studies performed many decades ago may be misleading in the current time. For transit demand analysis, for instance, it should be realized that real incomes have increased over the years, and a relatively smaller percentage of the population is transit dependent. Furthermore, the temporal lag of the response must be given due consideration. For example, Dargay and Gately (1997) state that approximately 30% of the response to a price change takes place within one year, and virtually 100% takes place within 13 years.

The common practice of using static rather than dynamic elasticity values overestimates welfare losses from increased user prices and congestion because it ignores society's ability to respond to changes over time (Dargay and Goodwin, 1995). Static elasticities skew investments toward increasing highway capacity and undervalue transit, TDM, and "no build" transportation

Table 3.7 Freight Transportation Elasticities with Respect to Price and Transit Time

Model Type	Attribute	Rail	Truck
Aggregate mode split model	Price	−0.25 to −0.35	−0.25 to −0.35
	Transit Time	−0.3 to −0.7	−0.3 to −0.7
Aggregate model, cost function	Price	−0.37 to −1.16	−0.58 to −1.81
Disaggregate mode choice model	Price	−0.08 to −2.68	−0.04 to −2.97
	Transit time	−0.07 to −2.33	−0.15 to −0.69

Source: Small and Winston (1999), VTPI (2000).

alternatives (Litman, 2005). Evidence of the variation of travel demand elasticities across nations is found in a study by the World Bank (1990) that published values of price elasticities of travel demand in several developing and developed countries.

3.4.5 Application of the Elasticity Concept: Demand Estimation

Elasticity-based demand models help estimate the new demand levels for a particular transportation mode in response to implementation of service attribute changes, such as trip cost increases and travel-time decreases. For this, it is assumed that the preimplementation demand level is known.

(*a*) *Nonlinear Demand Function* For a demand function of the form $V = kx^{a}$, where x is an activity or transportation system attribute, the elasticity of demand with respect to the attribute x can be calculated on the basis of two data points (x_1, V_1), and (x_2, V_2) as

$$e_x = a = \frac{\log V_1 - \log V_2}{\log x_1 - \log x_2}$$

The new demand, V_{new}, corresponding to a change in the attribute x, can therefore be estimated as

$$V_{\text{new}} = V_1 \left(\frac{x_{\text{new}}}{x_1} \right)^{e_x} \tag{3.5}$$

(*b*) *Linear Demand Function* A variation to this method of demand estimation is when the demand function is assumed to be linear over the range of interest. In this case, the elasticity can be determined using equation (3.3):

$$e_x = \frac{\partial V/V}{\partial x/x} = \frac{\Delta V/V}{\Delta x/x}$$

$e_x = (\Delta V/V_1)/(\Delta x/x_1)$ when x_1 is used as a base point, and $e_x = (\Delta V/V_2)/(\Delta x/x_2)$ when x_2 is used as a base point. Clearly, the value of elasticity will depend on which coordinate is used as a base point. If coordinate (x_k, V_k) is used as the base point, the new demand (V_{new}) corresponding to a change in the attribute x can be estimated using equation (3.5):

$$V_{\text{new}} = V_k \left(1 + e_x \frac{x_{\text{new}} - x_k}{x_k} \right) \tag{3.6}$$

Example 3.9 A commuter system involves two modes to the downtown area: rail transit and bus transit. When the average bus travel times are 2 and 2.5 hours, respectively, bus riderships are 7500 and 5000, respectively. A new high-occupancy-vehicle lane is being evaluated for implementation, and it is expected that this would reduce the bus travel time to 1 hour from the existing travel time of 2 hours. What is the expected demand of bus transit after the project is implemented assuming (a) a linear demand function and (b) a nonlinear demand function?

SOLUTION (a) (x_1, V_1) is (2, 7500), and (x_2, V_2) is (2.5, 5000). Assuming that the demand function is linear over the range of interest, the elasticity of demand with respect to travel time can be calculated as follows:

$$\begin{aligned} e_x &= \frac{\partial V/V}{\partial x/x} = \frac{\Delta V/V}{\Delta x/x} \\ &= \frac{V_2 - V_1}{x_2 - x_1} \frac{x_1}{V_1} \qquad [\text{using}(x_1, V_1)\text{as the base point}] \\ &= \left(\frac{5000 - 7500}{2.5 - 2.0} \right) \left(\frac{2.0}{7500} \right) = -1.33 \\ e_x &= \frac{\partial V/V}{\partial x/x} = \frac{\Delta V/V}{\Delta x/x} \\ &= \frac{V_2 - V_1}{x_2 - x_1} \frac{x_2}{V_2} \qquad [\text{using}(x_2, V_2)\text{as the base point}] \\ &= \left(\frac{5000 - 7500}{2.5 - 2.0} \right) \left(\frac{2.5}{5000} \right) = -2.5 \end{aligned}$$

Therefore, the new demand can be calculated using equation (3.6) as follows:

$$V_{\text{new}} = V_k\left(1 + e_x\frac{x_{\text{new}} - x_k}{x_k}\right) = (7500)\left(1 - 1.33\frac{1-2}{2}\right)$$

$$= 12{,}487 \qquad \text{[using an elasticity value of} -1.33]$$

$$V_{\text{new}} = V_k\left(1 + e_x\frac{x_{\text{new}} - x_k}{x_k}\right) = (7500)\left(1 - 2.5\frac{1-2}{2}\right)$$

$$= 16{,}875 \qquad \text{[using an elasticity value of} -2.5]$$

(b) Assuming a nonlinear demand function, the elasticity can be calculated as follows:

$$e_x = a = \frac{\log(V_1/V_2)}{\log(x_1/x_2)}$$

$$= \frac{\log(7500/5000)}{\log(2/2.5)} = \frac{0.1761}{-0.0969} = -1.82$$

In Example 3.9, where the bus travel time is reduced from 2 hours to 1 hour, the new demand (bus ridership) can be calculated using equation (3.5) as follows:

$$V_{\text{new}} = V_1\left(\frac{x_{\text{new}}}{x_1}\right)^{e_x} = (7500)\left(\frac{1}{2}\right)^{-1.82} = 26{,}481$$

Therefore, assuming a nonlinear demand function, it is estimated that the bus ridership will increase by 253% if the travel time is reduced by 50%.

It has often been cautioned that demand estimation using elasticity-based models are prone to *aggregation bias* because elasticities are typically computed from aggregate data with little segmentation. Also, there are issues of the transferability of models from one area to another, as the elasticity of individual travelers actually depends on the specific characteristics of the activities and transportation systems at each area. Also, the elasticities assume that all other factors besides the factor in question are constant (which may be true only in the short run); therefore, the elasticity-based method may be unsuitable for long-term demand predictions. Furthermore, demand estimation based on elasticity models typically assumes that elasticities are constant or that demand is linear: Both assumptions may be valid only for small changes in the system attributes.

3.4.6 Consumer Surplus and Latent Demand

Analysis of the impact of changes in the market price of a transportation service helps establish whether the consumer's position is better or worse. Such traditional analysis fails to quantify changes in consumer satisfaction due to these price changes. One method used to address this gap is the use of a concept known as *consumer surplus*. This method compares the *value* of each unit of a commodity consumed against its *price*. In other words, consumer surplus is the difference between what consumers are willing to pay for a good or service (indicated by the position on the demand curve) and what they actually pay (the market price). For example, for a certain air transportation route where the average traveler pays \$600 per trip but would be willing to pay an average of \$650 per trip, the consumer surplus is \$50. Consumer surplus measures the net welfare that consumers derive from their consumption of goods and services, or the benefits or satisfaction they derive from the exchange of goods. The total consumer surplus is shown by the area under the demand curve and above the ruling market price ($p^* p_w W$) as shown in Figure 3.7.

Consumer surplus or changes in consumer surplus are typically obtained from structural demand estimation, from which estimates of willingness to pay are derived and compared to expenditures. The total value of willingness to pay is the sum of consumer surplus and consumer expenditure.

Maximization of consumer surplus is the maximization of the economic utility of the consumer. The use of the consumer surplus concept is common in the area of the evaluation of transportation systems. In Figure 3.7, the area enclosed by $p^* O V_w W$ represents the *total community benefit of the transportation service*, and the area enclosed by $p_w O V_w W$ represents the *market value of* (*or total consumer expenditure for*) *the service.* It can also be observed that travelers between V_w and V^* do not make

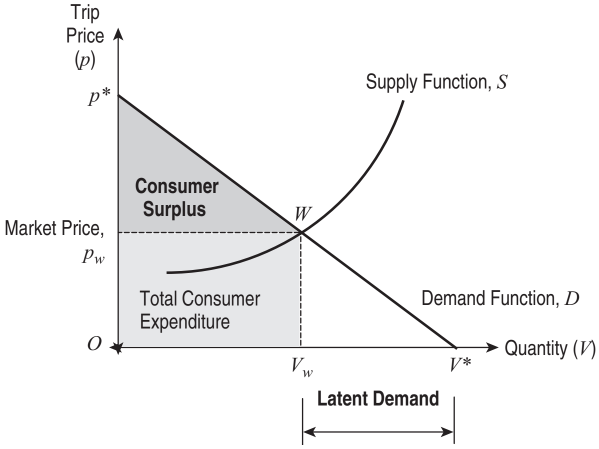

Figure 3.7 Consumer surplus and latent demand.

trips given the prevailing circumstances, but would do so if the price per trip were lower than the equilibrium price. The total of such potential trips is termed *latent demand* (represented by $V^* - V_w$ along the x-axis) and refers to the difference between the maximum possible number of trips and the number of trips that are actually made. An application of the latent demand concept is travel demand management, such as transit fare reduction and other incentives for non–peak hour travel. From Figure 3.7, it is seen that if a zero fare is charged, consumers will demand transit trips up to the point where the demand curve cuts the x-axis.

Figure 3.8 shows how the user impact of a transportation system improvements could be evaluated in terms of consumer surplus by representing such improvement as the resulting area under a transportation demand curve due to a shift in the transportation supply curve. In the figure, the demand curve (as a function of trip price) for a transportation system is depicted by the line D. An improvement in supply, such as increased quantity (e.g., number of guideway lines, highway lanes, transit frequency) or improved quality of service (e.g., increased comfort, safety and security) causes the supply curve to shift from S_{old} to S_{new}. The new consumer surplus is given by the area enclosed by $p^* p_{\text{new}} W_{\text{new}}$. Thus, change in consumer surplus is represented by the shaded area enclosed by $p_{\text{old}} p_{\text{new}} W_{\text{new}} W_{\text{old}}$ and has a magnitude of $(p_{\text{old}} - p_{\text{new}})(V_{\text{old}} + V_{\text{new}})/2$.

- *Consumer surplus in cases of perfect elasticity*. When demand for a transportation service is perfectly elastic, the level of consumer surplus is zero since the price that people pay matches the price they are willing to pay. There must be perfect substitutes in the market for this to be the case.

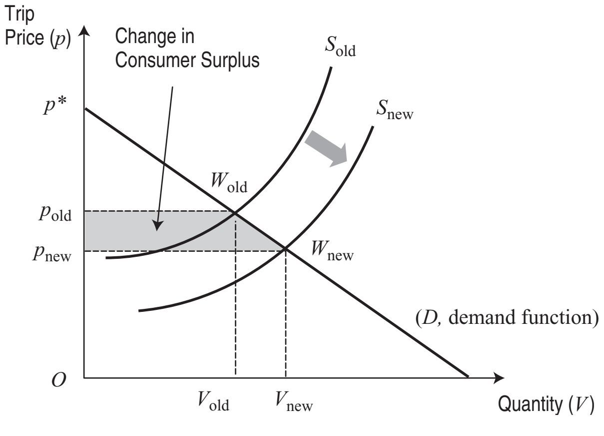

Figure 3.8 Change in consumer surplus.

- *Consumer surplus in cases of perfect inelasticity*. When demand is perfectly inelastic (demand is invariant to changes in price), the amount of consumer surplus is infinite.

Example 3.10 The demand for a transit service between a city and its largest suburb during an off-peak hour, V, is given by $2500 - 350t$ where t is the travel time in minutes. At the current time, the transit trip takes an average of 5 minutes. Determine (a) the time elasticity of demand and (b) the latent demand at this travel time.

SOLUTION

(a) $$e_t(V) = \frac{\partial V/V}{\partial t/t} = \frac{\partial V}{\partial t}\frac{t}{V} = (-350)\left[\frac{5}{2500 - (350 \times 5)}\right] = -2.3$$

(b) At $t = 5$ min, the demand $V = 750$. Therefore, the latent demand is $2500 - 750 = 1750$.

Example 3.11 It is estimated that the demand for a newly constructed parking facility will be related to the price of usage as follows: $V = 1500 - 25P$, where V is the number of vehicles using the parking lot per day and P is the average daily parking fee in dollars. For the first month of operation, parking at the facility is free. (a) How many vehicles would be expected to park at the facility during the first month? (b) After the second month, when a \$10 daily fee is charged, how many vehicles would be expected to use the facility, and what would be the loss in consumer surplus?

SOLUTION

(a) During the first month, when $p_1 = 0$, $V_1 = 1500$ vehicles/day.
(b) After the second month, when $p_2 = \$10$, $V_2 = 1500 - (25 \times 10) = 1250$ vehicles/day. Using Figure 3.7, the loss in consumer surplus is given by

$$\tfrac{1}{2} \times (p_2 - p_1)(V_1 + V_2) = (0.5)(10 - 0)(1500 + 1250) = \$13{,}750$$

3.5 EMERGING ISSUES IN TRANSPORTATION DEMAND ESTIMATION

Over the past two decades, increasing availability of detailed travel data has encouraged faster development of disaggregate demand models that seek to predict the travel choices of individual travelers. Developments that have added impetus to such efforts include: (1) the consideration of travelers as *rational* units who seek to maximize their utility associated with the trips they undertake, (2) the quantification of travelers' perceptions of demand and supply, and (3) recognition of the probabilistic nature of travel decisions. Using the disaggregate function directly—given the characteristics of each consumer in the market—the overall demand can be estimated from disaggregate demand models developed for each consumer within each market segment. Further information on disaggregate transportation demand modeling may be obtained from Bhat (2000) and other literature.

Another issue is that of organizational travel demand. Hensher and Button (2000) stated that while demand modeling for passenger travel is important, it is becoming increasingly clear that travel demand by businesses and other organizations needs to be addressed fully. In the past, the latter has received less than the attention deserved because the public sector provided most transportation services, and the purpose of transportation demand modeling had been to allow this component of transportation to interface with users. However, this situation has changed in light of recent and continuing developments, such as deregulation and large-scale privatization. Also, the capacities of transportation networks in the past were defined by peak-volume commuter traffic, but this is no longer the case in the current era.

SUMMARY

An important step in the transportation project development process is the evaluation of alternative policies and regulations for transportation systems operations and use, which depend heavily on transportation demand and supply and interaction between the two parameters. In presenting this material, we recognize that travel demand is not direct but derived, is subject to governmental policies, has a consumption that is unique in time and space, and can be undertaken by several alternative modes that differ by technology, operating and usage policies, and extents of scale economies. We presented a background for transportation demand analysis in the context of transportation supply (or changes thereof). To provide the analyst with some working numbers useful for estimating expected changes in demand in response to changing attributes such as travel time, trip price, income, and parking, we provided recent values of demand elasticities.

EXERCISES

3.1. The demand and supply models for travel between Townsville and Cityburg during a particular season are represented by the following equations:

Demand function:

$$V = 4200 - 29p$$

Supply function:

$$p = 3.10 + 0.02V$$

where V is the number of tickets purchased per month and p is the price of a ticket in dollars. Provide a graphical illustration of the supply and demand functions, and determine the equilibrium demand and price.

3.2. The aggregate demand for a bus transit service serving a newly developed suburban area is represented by the equation $V = 300 - 40p^2$, where V is the number of trips made per month and p is the average price of a ticket for the trip. In a given month, the average price was \$0.75. What is the point elasticity of demand of the bus transit service with respect to price?

3.3. A $w\%$ increase in downtown parking costs resulted in a $f\%$ reduction on downtown auto trips and a $g\%$ increase in transit patronage for downtown routes. Derive expressions for the arc elasticities of auto and transit demand with respect to parking costs.

3.4. The number of automobile trips per hour (V) between two midwestern cities has the following function:

$$V = aT_{\mathrm{A}}^{-2.0}T_{\mathrm{T}}^{0.15}C_{\mathrm{A}}^{-0.5}C_{\mathrm{T}}^{0.6}$$

where T_{A} and T_{T} are the travel time for auto and transit, respectively; C_{A} and C_{T} are the out-of-pocket costs for auto and transit, respectively; and a is a constant that reflects the size and average income of the population.

- **(a)** At the current time, there are 50,000 automobile trips between the cities every day. If a new parking policy results in an increase of out-of-pocket auto costs from \$5 to \$6, what will be the change in demand?
- **(b)** In addition to part (a), if transit facility improvements lead to a reduction in transit time from 1 hour to 45 minutes, what would be the new demand for automobile travel between the two cities?

3.5. The Kraft demand model can be expressed in the following general form:

$$k\prod_{i=1}^{n} X_i^{c_i}$$

where X is a vector of variables representing the socioeconomic system (such as population and income) and the transportation system (such as travel costs and time) and n is the number of variables. Show that for any variable in the Kraft model, the elasticity of travel demand with respect to each variable is constant.

3.6. For input in evaluation of an improvement project for rail service between cities A and B in a certain state, it is desired to determine the volume of demand. The intercity travel demand is given by the following demand function:

$$Q_{ijm} = 28\mathrm{POP}_i^{0.81}\mathrm{POP}_j^{1.24}\mathrm{PCI}_i^{1.5}\mathrm{PCI}_j^{1.75}\mathrm{PCR}_i^{-0.62} \times \mathrm{PCR}_j^{-0.87}\mathrm{RTT}_m^{-1.85}\mathrm{BTT}^{-0.90}\mathrm{RTC}_m^{-2.97}\mathrm{BTC}^{0.57}$$

where POP = average population of the city (millions)
PCI = average per capita income of the city (tens of thousands)
PCR = share of retail in total employment in the city (a fraction)
RTT_m = travel time by mode m relative to the travel time of the fastest mode
BTT = travel time by the fastest mode (min)
RTC_m = travel cost by mode m relative to the cost of the cheapest mode
BTC = travel cost by the cheapest mode (cents)

Estimate the expected level of demand for the rail facility given the following post-implementation data:

City A: population = 1.2 million, average per capita income = \$37,900, share of retail in total employment = 20%

City B: population = 0.8 million, average per capita income = \$45,000, share of retail in total employment = 15%

Table EX3.7.1 Input Information for Exercise 3.7

(a) Dependent Variables in Regression Models

Zone	Cars X_1	Households X_2	Employment X_3	Commercial Area (Acres) X_4
1	370	235	880	5230
2	220	180	495	1200
3	190	136	300	550

(b) Travel Time (min) (2000)

	To Zone:		
From Zone:	1	2	3
1	10	25	40
2	27	12	29
3	45	24	13

(c) Expected Travel Time (min) (2020)

	To Zone:		
From Zone:	1	2	3
1	12	28	42
2	29	15	34
3	46	27	16

(d) Trip Interchange Matrix (2000)

	To Zone:			
From Zone:	1	2	3	P_i
1	680	256	135	1071
2	383	200	121	704
3	210	211	156	577
A_j	1273	667	412	2352

Table EX3.7.2 Travel Times and Travel Costs for Auto and Transit: 2020

(a) Travel Time (Travel Costs) by Auto

	Destination		
Origin	1	2	3
1	12 (\$4.5)	28 (\$2.9)	42 (\$3.5)
2	29 (\$5.3)	15 (\$2.5)	34 (\$4.1)
3	46 (\$3.6)	27 (\$3.4)	16 (\$2.3)

(b) Travel Time (Travel Costs) by Transit

	Destination		
Origin	1	2	3
1	15 (\$3.0)	35 (\$1.8)	52 (\$2.2)
2	38 (\$4.5)	22 (\$1.1)	40 (\$2.7)
3	55 (\$2.8)	35 (\$2.3)	24 (\$1.4)

Expected travel time by rail upon improvement
= 35 minutes

Travel time by fastest mode(auto)
= 28 minutes

Expected travel cost of rail upon improvement
= 75 cents

Travel cost by cheapest mode(bus transit)
= 65 cents

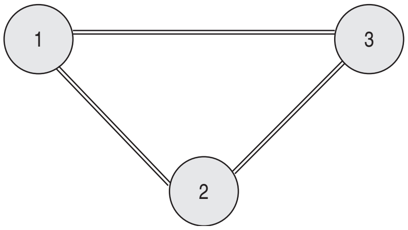

Figure EX3.7

3.7. Use the four-step travel demand modeling procedure to calculate the travel demand on the three links in a three-zone transportation network shown in Figure EX3.7. Use the information in Table EX3.7.1. The following horizon year (2020) trip production and attraction models are given:

$$P_i = 10 + 2.2x_1 + 1.3x_2$$

$$A_j = 30 + 1.27x_3 + 0.035x_4$$

The impedance function is given as $t_{ij}^{-0.5}$, where t_{ij} is the travel time between zones i and j. The calibrated utility functions for auto and transit are given as (time in minutes and cost in dollars)

$$U_{\text{auto}} = 3.45 - 0.8\text{Cost} - 0.025\text{Time}$$

$$U_{\text{transit}} = 1.90 - 0.26\text{Cost} - 0.028\text{Time}$$

The expected travel times and travel cost for auto and transit in 2020 are given in Table EX3.7.2.

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