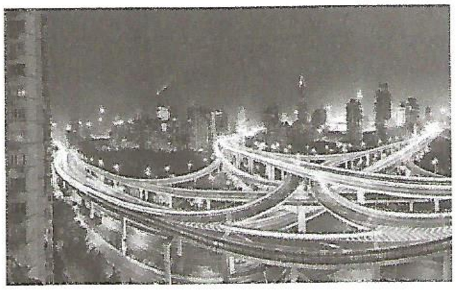
CHAPTER 12



Forecasting Travel Demand

Travel demand is expressed as the number of persons or vehicles per unit time that can be expected to travel on a given segment of a transportation system under a set of given land-use, socioeconomic, and environmental conditions. Forecasts of travel demand are used to establish the vehicular volume on future or modified transportation system alternatives. The methods for forecasting travel demand can range from a simple extrapolation of observed trends to a sophisticated computerized process involving extensive data gathering and mathematical modeling. The travel demand forecasting process is as much an art as it is a science. Judgments are required concerning the various parameters—that is, population, car ownership, and so forth—that provide the basis for a travel forecast. The methods used in forecasting demand will depend on the availability of data and on specific constraints on the project, such as availability of funds and project schedules.

CHAPTER OBJECTIVES:

- Understand the difference between urban and intercity travel demand forecasting.
- Calculate trip generation forecasts using the cross-classification and activity unit method.
- Apply the gravity model and growth factor equations to compute trip distributions between zones.
- Learn how to use the three types of transit estimating procedures to compute modal choice.
- Learn how to predict the number of autos and transit trips on roadway segments using three basic procedures of traffic assignment.
- Describe forecasting models other than the 4-step process, including trend analysis and demand elasticity.

12.1 DEMAND FORECASTING APPROACHES

There are two basic demand-forecasting situations in transportation planning. The first involves travel demand studies for urban areas, and the second deals with intercity travel demand. Urban travel demand forecasts, when first developed in the 1950s and 1960s, required that extensive databases be prepared using home interview and/or roadside interview surveys. The information gathered provided useful insight concerning the characteristics of the trip maker, such as age, sex, income, auto ownership, and so forth; the land use at each end of the trip; and the mode of travel. Travel data then could be aggregated by zone to formulate relationships between variables and to calibrate models.

In the intercity case, data are generally aggregated to a greater extent than for urban travel forecasting, such as city population, average city income, and travel time or travel cost between city pairs. The availability of travel data improved considerably with the formation of the Bureau of Transportation Statistics, now within the Research and Innovative Technology Administration (RITA) of the U.S. DOT. The availability of data from the Census Bureau's American Community Survey is another positive development. This chapter describes the urban travel forecasting process. The underlying concepts may also be applied to intercity travel demand.

The databases that were established in many urban transportation studies have been used for the calibration and testing of models for trip generation, distribution, mode choice, and traffic assignment. These data collection and calibration efforts involved a significant investment of money and personnel resources, and consequent studies are based on updating the existing database and using models that had been previously developed.

12.1.1 Factors Influencing Travel Demand

The three factors that influence the demand for urban travel are: (1) the location and intensity of land use; (2) the socioeconomic characteristics of people living in the area; and (3) the extent, cost, and quality of available transportation services. These factors are incorporated in most travel forecasting procedures.

Land-use characteristics are a primary determinant of travel demand. The amount of traffic generated by a parcel of land depends on how the land is used. For example, shopping centers, residential complexes, and office buildings produce different traffic generation patterns.

Socioeconomic characteristics of the people living within the city also influence the demand for transportation. Lifestyles and values affect how people decide to use their resources for transportation. For example, a residential area consisting primarily of high-income workers will generate more trips by automobile per person than a residential area populated primarily by retirees.

The availability of transportation facilities and services, referred to as the *supply*, also affects the demand for travel. Travelers are sensitive to the level of service provided by alternative transportation modes. When deciding whether to travel at all or which mode to use, they consider attributes such as travel time, cost, convenience, comfort, and safety.

12.1.2 Sequential Steps for Travel Forecasting

Prior to the technical task of travel forecasting, the study area must be delineated into a set of traffic analysis zones (TAZ) (also called transportation analysis zones) that form the basis for analysis of travel movements within, into, and out of the urban area, as discussed in Chapter 11. The set of zones can be aggregated into larger units, called

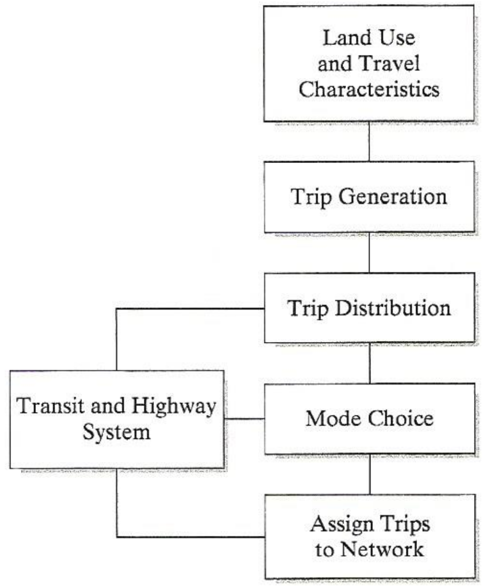


Figure 12.1 Travel Forecasting Process

districts, for certain analytical techniques or analyses that work at such levels. Land-use estimates are also developed.

Travel forecasting is solely within the domain of the transportation planner and is an integral part of site development and traffic engineering studies as well as area-wide transportation planning. Techniques that represent the state-of-the-practice of each task are described in this chapter to introduce the topic and to illustrate how demand forecasts are determined. Variations between forecasting techniques are also described in the literature.

The approach most commonly used to forecast travel demand is based on land-use and travel characteristics that provide the basis for the "four-step process" of trip generation, trip distribution, mode choice, and traffic assignment illustrated in Figure 12.1. Simultaneous model structures have also been used in practice, particularly to forecast intercity travel.

12.2 TRIP GENERATION

Trip generation is the process of determining the number of trips that will begin or end in each traffic analysis zone within a study area. Since the trips are determined without regard to destination, they are referred to as *trip ends.* Each trip has two ends, and these are described in terms of trip purpose, or whether the trips are either produced by a traffic zone or attracted to a traffic zone.

For example, a home-to-work trip would be considered to have a trip end produced in the home zone and attracted to the work zone. Trip generation analysis has two functions: (1) to develop a relationship between trip end production or attraction and land use, and (2) to use the relationship to estimate the number of trips generated at some future date under a new set of land-use conditions. To illustrate the process, two methods are considered: cross-classification and rates based on activity units.

Another commonly used method is regression analysis, which has been applied to estimate both productions and attractions. This method is used infrequently because it relies on zonal aggregated data. Trip generation methods that use a disaggregated analysis,

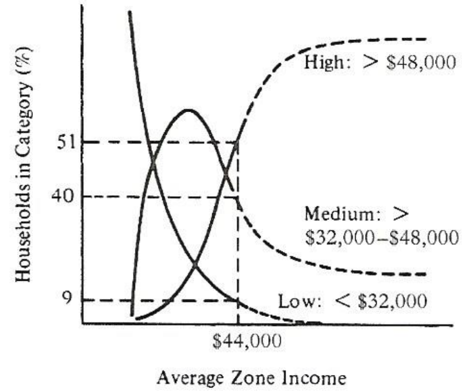


Figure 12.2 Average Zonal Income versus Households in Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977

based on individual sample units such as persons, households, income, and vehicle units, are preferred.

12.2.1 Cross-Classification

Cross-classification is a technique developed by the Federal Highway Administration (FHWA) to determine the number of trips that begin or end at the home. Home-based trip generation is useful because it can represent a significant proportion of all trips. A relationship between socioeconomic measures and trip production is developed. The variables most commonly used are average income and auto ownership. Figure 12.2 illustrates the variation in average income within a zone. Other variables that could be considered are household size and stage in the household life cycle. The relationships are developed based on income data and results of O-D surveys.

Example 12.1 Developing Trip Generation Curves from Household Data

A travel survey produced the data shown in Table 12.1. Twenty households were interviewed. The table shows the number of trips produced per day for each of the households (numbered 1 through 20), as well as the corresponding annual household income and the number of automobiles owned. Based on the data provided, develop a set of curves showing the number of trips per household versus income and auto ownership.

Solution:

Step 1. From the information in Table 12.1, produce a matrix that shows the number and percentage of households as a function of auto ownership and income grouping (see Table 12.2). The numerical values in each cell represent the number of households observed in each combination of income–auto ownership category. The value in parentheses is the percentage observed at each income level. In actual practice, the sample size would be at least 25 data points per cell to ensure statistical accuracy.

Table 12.1 Survey Data Showing Trips per Household, Income, and Auto Ownership

Household Number	*Trips Produced per Household*	*Household Income ($1000s)*	*Autos per Household*
1	2	16	0
2	4	24	0
3	10	68	2
4	5	44	0
5	5	18	1
6	15	68	3
7	7	38	1
8	4	36	0
9	6	28	1
10	13	76	3
11	8	72	1
12	6	32	1
13	9	28	2
14	11	44	2
15	10	44	2
16	11	52	2
17	12	60	2
18	8	44	1
19	8	52	1
20	6	28	1

Figure 12.3 illustrates how the data shown in Table 12.2 are used to develop relationships between the percent of households in each auto ownership category by household income.

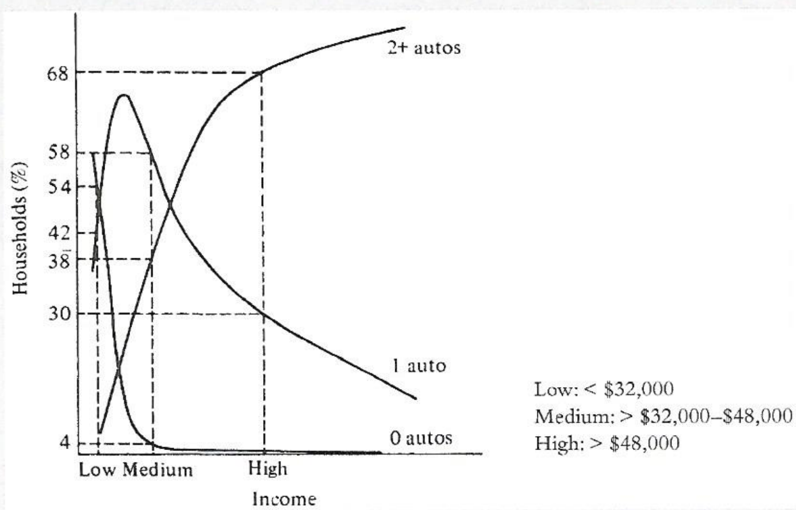


Figure 12.3 Households by Automobile Ownership and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977

Table 12.2 Number and Percent of Household in Each Income Category versus Car Ownership

Income ($1000s)	*Autos Owned* 0	1	2 +	*Total*
24	2(67)	1(33)	0(0)	3(100)
24–36	1(25)	3(50)	1(25)	5(100)
36–48	1(20)	2(40)	2(40)	5(100)
48–60	—	1(33)	2(67)	3(100)
>60	—	1(25)	3(75)	4(100)
Total	4	8	8	20

Note: Values in parentheses are percent of automobiles owned at each income range.

Step 2. A second table produced from the data in Table 12.1 shows the average number of trips per household versus income and cars owned. The results shown in Table 12.3 are illustrated in Figure 12.4, which depicts the relationship between trips per household per day by income and auto ownership. The table indicates that for a given income, trip generation increases with the number of cars owned. Similarly, for a given car ownership, trip generation increases with the rise in income.

Table 12.3 Average Trips per Household versus Income and Car Ownership

Income ($1000s)	*Autos Owned* 0	1	2+
≤24	3	5	—
24–36	4	6	9
36–48	5	7.5	10.5
48–60	—	8.5	11.5
>60	—	8.5	12.7

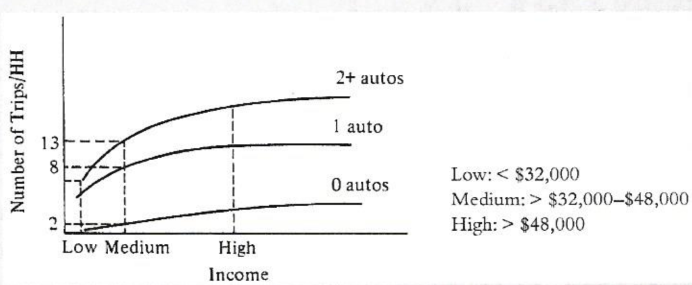


Figure 12.4 Trips per Household per Day by Auto Ownership and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning,* U.S. Department of Transportation, Washington, D.C., April 1977

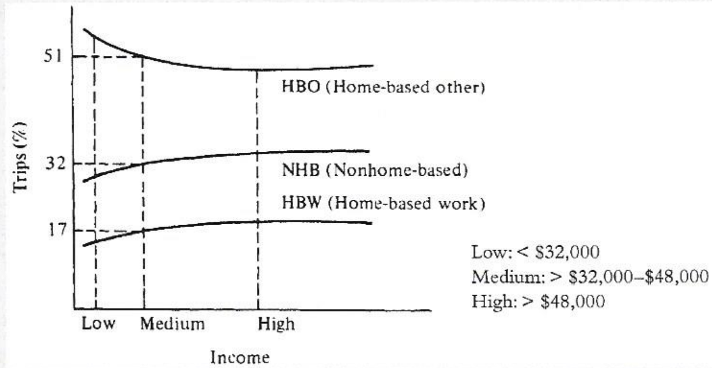


Figure 12.5 Trips by Purpose and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977

Step 3. As a further refinement, additional O-D data (not shown in Table 12.1) can be used to determine the percentage of trips by each trip purpose for each income category. These results are shown in Figure 12.5, wherein three trip purposes are used: home-based work (HBW), home-based other (HBO), and non-home-based (NHB). The terminology refers to the origination of a trip as either at the home or not at the home.

The trip generation model that has been developed based on survey data can now be used to estimate the number of home- and non-home-based trips for each trip purpose.

Example.12.2 Computing Trips Generated in a Suburban Zone

Consider a zone that is located in a suburban area of a city. The population and income data for the zone are as follows.

Number of dwelling units: 60

Average income per dwelling unit: $44,000

Determine the number of trips per day generated in this zone for each trip purpose, assuming that the characteristics depicted in Figures 12.2 through 12.5 apply in this situation. The problem is solved in four basic steps.

Solution:

Step 1. Determine the percentage of households in each economic category. These results can be obtained by analysis of census data for the area. A typical plot of average zonal income versus income distribution is shown in Figure 12.2. For an average zonal income of $44,000, the following distribution is observed.

Income ($)	*Households (%)*
Low (under 32,000)	9
Medium (32,000–48,000)	40
High (over 48,000)	51

Step 2. Determine the distribution of auto ownership per household for each income category. A typical curve showing percent of households, at each income level, that own 0, 1, or 2+ autos is shown in Figure 12.3, and the results are listed in Table 12.4.

Table 12.4 shows that 58 percent of medium-income families own one auto per household. Also, from the previous step, we know that a zone, with an average income of \$44,000, contains 40 pecent of households in the medium-income category. Thus, we can calculate that of the 60 households in that zone, there will be $60 \times 0.40 \times 0.58 = 14$ medium-income households that own one auto.

Step 3. Determine the number of trips per household per day for each income–auto ownership category. A typical curve showing the relationship between trips per household, household income, and auto ownership is shown in Figure 12.4. The results are listed in Table 12.5. The table shows that a medium-income household owning one auto will generate eight trips per day.

Table 12.4 Percentage of Households in Each Income Category versus Auto Ownership

	Autos/Household		
Income	*0*	*1*	*2+*
Low	54	42	4
Medium	4	58	38
High	2	30	68

Table 12.5 Number of Trips per Household per Day

	Autos/Household		
Income	*0*	*1*	*2+*
Low	1	6	7
Medium	2	8	13
High	3	11	15

Step 4. Calculate the total number of trips per day generated in the zone. This is done by computing the number of households in each income–auto ownership category, multiplying this result by the number of trips per household, as determined in Step 3, and summing the result. Thus,

$$P_{gh} = HH \times I_g \times A_{gh} \times (P_H)_{gh} \tag{12.1}$$

$$P_T = \sum_{g}^{3} \sum_{h}^{3} P_{gh} \tag{12.2}$$

where

HH = number of households in the zone

I_g = percentage of households (decimal) in zone with income level g (low, medium, or high)

A_{gh} = percentage of households (decimal) in income level g with h autos per household (h = 0, 1, or 2+)

P_{gh} = number of trips per day generated in the zone by households with income level g and auto ownership h

$(P_H)_{gh}$ = number of trips per day produced by a household at income level g and auto ownership h

P_T = total number of trips generated in the zone

The calculations are shown in Table 12.6. For a zone with 60 households and an average income of $44,000, the number of trips generated is 666 auto trips/day

Table 12.6 Number of Trips per Day Generated by Sixty Households

	Income, Auto Ownership	*Total Trips by Income Group*
$60 \times 0.09 \times 0.54 \times 1 =$ 3 trips	L, 0+	
$60 \times 0.09 \times 0.42 \times 6 =$ 14 trips	L, 1+	
$60 \times 0.09 \times 0.04 \times 7 =$ 2 trips	L, 2+	19
$60 \times 0.40 \times 0.04 \times 2 =$ 2 trips	M, 0+	
$60 \times 0.40 \times 0.58 \times 8 =$ 111 trips	M, 1+	
$60 \times 0.40 \times 0.38 \times 13 =$ 119 trips	M, 2+	232
$60 \times 0.51 \times 0.02 \times 3 =$ 2 trips	H, 0+	
$60 \times 0.51 \times 0.30 \times 11 =$ 101 trips	H, 1+	
$60 \times 0.51 \times 0.68 \times 15 =$ 312 trips	H, 2+	415
Total = 666 trips		666

Step 5. Determine the percentage of trips by trip purpose. As a final step, we can calculate the number of trips that are HBW, HBO, and NHB. If these percentages are 17, 51, and 32 respectively (see Figure 12.5) for the medium-income category, then the number of trips from the zone for the three trip purposes are $232 \times 0.17 = 40$ HBW, $232 \times 0.51 = 118$ HBO, and $232 \times 0.32 = 74$ NHB. (Similar calculations would be made for other income groups.) The final result, which is left for the reader to verify, is obtained by using the following percentages: low income at 15, 55, and 30, and high income at 18, 48, and 34. These yield 118 HBW, 327 HBO, and 221 NHB trips.

Trip generation values as determined in the preceding examples are used to calculate the number of trips in each zone. Values for each income or auto ownership category can be developed using survey data or published statistics compiled for other cities. Figure 12.6 illustrates the trip generation rate per household for single-family detached housing. The average rate is 9.57, and the range of rates is 4.31 to 21.85. This table is one of over 1000 included in the Institute of Transportation Engineers publication, *Trip*

Single-Family Detached Housing

Average Vehicle Trip Ends vs: Dwelling Units
On a: Weekday

Number of Studies: 350
Avg. Number of Dwelling Units: 197
Directional Distribution: 50% entering, 50% exiting

Trip Generation per Dwelling Unit

Average Rate	Range of Rates	Standard Deviation
9.57	4.31–21.85	3.69

Data Plot and Equation

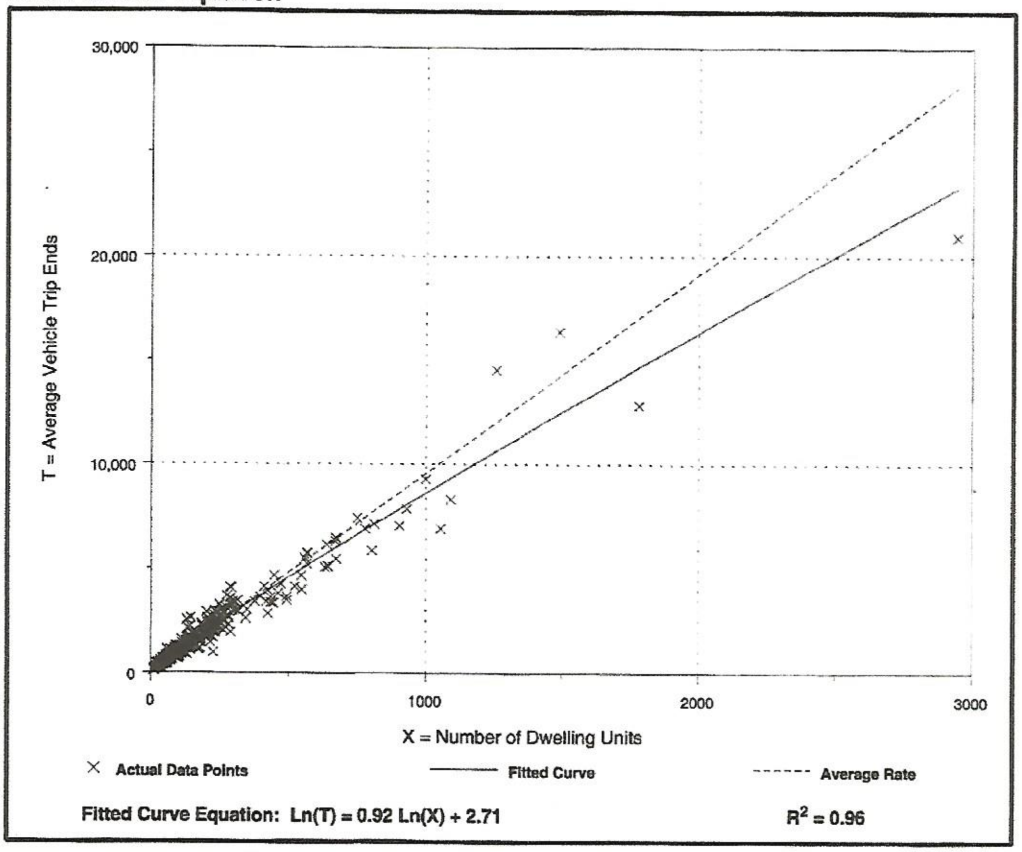


Figure 12.6 Trip Generation Characteristics

SOURCE: *Trip Generation*, 7th ed., Institute of Transportation Engineers, Washington, D.C., 2003. www.ite.org. Used by permission

Generation for 10 Different Land Uses, including port and terminal, industrial, agricultural, residential, lodging, institutional, medical, office, retail, and services. An extensive amount of useful trip generation data are also available in *Quick Response Urban Travel Estimation Techniques and Transferable Parameters.* The ITE *Transportation Planning Handbook* also provides trip generation rates.

12.2.2 Rates Based on Activity Units

The preceding section illustrated how trip generation is determined for residential zones where the basic unit is the household. Trips generated at the household end are referred to as *productions,* and they are *attracted* to zones for purposes such as work, shopping, visiting friends, and medical trips. Thus, an activity unit can be described by measures such as square feet of floor space or number of employees. Trip generation rates for attraction zones can be determined from survey data or are tabulated in some of the reference sources listed at the end of this chapter. Trip attraction rates are illustrated in Table 12.7.

Table 12.7 Trip Generation Rates by Trip Purpose and Employee Category

	Attractions per Household	*Attractions per Nonretail Employee*	*Attractions per Downtown Retail Employee*	*Attractions per Other Retail Employee*
HBW	—	1.7	1.7	1.7
HBO	1.0	2.0	5.0	10.0
NHB	1.0	1.0	3.0	5.0

Example 12.3 Computing Trips Generated in an Activity Zone

A commercial center in the downtown contains several retail establishments and light industries. Employed at the center are 220 retail and 650 nonretail workers. Determine the number of trips per day attracted to this zone.

Solution: Use the trip generation rates listed in Table 12.7.

$$\text{HBW: } (220 \times 1.7) + (650 \times 1.7) = 1479$$

$$\text{HBO: } (220 \times 5.0) + (650 \times 2.0) = 2400$$

$$\text{NHB: } (220 \times 3.0) + (650 \times 1.0) = 1310$$

$$\text{Total} = 5189 \text{ trips/day}$$

Note that three trip purposes are given in Table 12.7: home-based work (HBW), home-based other (HBO), and non-home-based (NHB). For example, for HBO trips, there are 5.0 attractions per downtown retail employee (in trips/day) and 2.0 attractions per nonretail employee.

12.2.3 Balancing Trip Productions and Attractions

A likely result of the trip generation process is that the number of trip productions may not be equal to the number of trip attractions. Trip productions, which are based on census data, are considered to be more accurate than trip attractions. Accordingly, trip attractions are usually modified so that they are equal to trip productions.

Table 12.8a illustrates how adjustments are made. The trip generation process has produced 600 home-based work productions for zones 1 through 3. However, the same process has produced 800 home-based work attractions. To rectify this imbalance, each attraction value for zones 1 through 3 is reduced by a factor equal to 600/800, or 0.75. The result is shown in Table 12.8a in the column "Balanced HBW Trips." Now both productions and attractions are equal. A similar procedure is used for HBO trips.

An extra step is required for balancing NHB trips. This extra step is that after total productions and total attractions are equal, the productions for each zone are set equal to the attractions for each zone. For example, in Table 12.8b, since there are 180 NHB attractions for zone 1 after balancing productions and attractions, the number of NHB productions for zone 1 is also changed from 100 to 180. The rationale behind this extra step is that the true origin of non-home-based trips is not provided by survey or census data, and thus the best estimate of the number of NHB trips produced in each zone is the number of NHB trips attracted to each zone.

Table 12.8a Balancing Home-Based Work Trips

	Unbalanced HBW Trips		*Balanced HBW Trips*	
Zone	*Productions*	*Attractions*	*Productions*	*Attractions*
1	100	240	100	180
2	200	400	200	300
3	300	160	300	120
Total	600	800	600	600

Table 12.8b Balancing Non-Home-Based Trips

	Unbalanced NHB Trips		*Balanced NHB Trips*	
Zone	*NHB Productions*	*NHB Attractions*	*NHB Productions*	*NHB Attractions*
1	100	240	180	180
2	200	400	300	300
3	300	160	120	120
Total	600	800	600	600

12.3 TRIP DISTRIBUTION

Trip distribution is a process by which the trips generated in one zone are allocated to other zones in the study area. These trips may be within the study area (internal-internal) or between the study area and areas outside the study area (internal-external).

For example, if the trip generation analysis results in an estimate of 200 HBW trips in zone 10, then the trip distribution analysis would determine how many of these trips would be made between zone 10 and each of the other internal zones.

In addition, the trip distribution process considers internal-external trips (or vice versa) where one end of the trip is within the study area and the other end is outside the study area. Figure 11.11 illustrates external stations for a study area boundary. If a trip begins somewhere south of the study area and ends in the center of the study area using Route 29, then an external-internal trip is defined that begins at external station 103 and ends in a zone located in the center of the study area.

Several basic methods are used for trip distribution. Among these are the gravity model, growth factor models, and intervening opportunities. The gravity model is preferred because it uses the attributes of the transportation system and land-use characteristics and has been calibrated extensively for many urban areas. The gravity model has achieved virtually universal use because of its simplicity, its accuracy, and its support from the U.S. Department of Transportation. Growth factor models, which were used more widely in the 1950s and 1960s, require that the origin-destination matrix be known for the base (or current) year, as well as an estimate of the number of future trip ends in each zone. The intervening opportunities model and other models are available but not widely used in practice.

12.3.1 The Gravity Model

The most widely used and documented trip distribution model is the *gravity model,* which states that the number of trips between two zones is directly proportional to the number of trip attractions generated by the zone of destination and inversely proportional to a function of travel time between the two zones. Mathematically, the gravity model is expressed as

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_j A_j F_{ij} K_{ij}} \right] \tag{12.3}$$

where

T_{ij} = number of trips that are produced in zone i and attracted to zone j
P_i = total number of trips produced in zone i
A_j = number of trips attracted to zone j
F_{ij} = a value which is an inverse function of travel time
K_{ij} = socioeconomic adjustment factor for interchange ij

The values of P_i and A_j have been determined in the trip generation process. The sum of P_i for all zones must equal the sum of A_j for all zones. K_{ij} values are used when the estimated trip interchange must be adjusted to ensure that it agrees with the observed trip interchange.

A calibrating process in which trip generation values as measured in the O-D survey are distributed using the gravity model determines the values for F_{ij}. After each distribution process is completed, the percentage of trips in each trip length category produced by the gravity model is compared with the percentage of trips recorded in the O-D survey. If the percentages do not agree, then the F_{ij} factors that were used in the distribution process are adjusted and another gravity model trip distribution is performed.

Figure 12.7 illustrates F values for calibrations of a gravity model. (Normally this curve is a semilog plot.) F values can also be determined using travel time values and an inverse relationship between F and t. For example, the relationship for F might be in the form t^{-1}, t^{-2}, e^{-t}, and so forth, since F values decrease as travel time increases. The friction factor can be expressed as $F = ab^t e^{-ct}$, where parameters a, b, and c are based

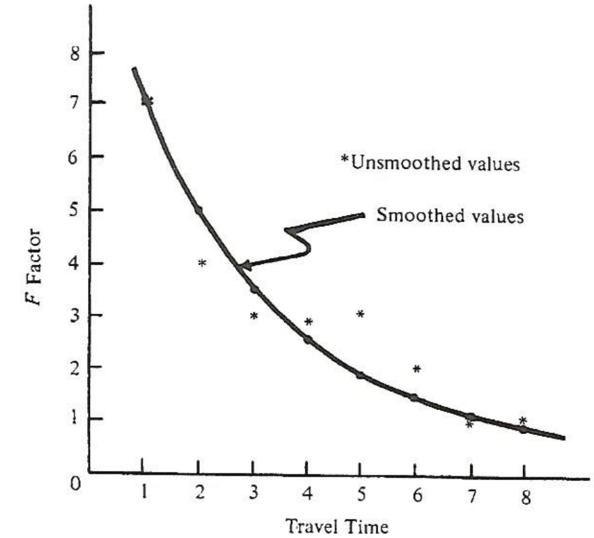


Figure 12.7 Calibration of F Factors

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977

on national data sources, such as NCHRP Report 365, or the formula may be calibrated using local data.

The socioeconomic factor is used to make adjustments of trip distribution T_{ij} values between zones where differences between estimated and actual values are significant. The K value is referred to as the "socioeconomic factor" since it accounts for variables other than travel time. The values for K are determined in the calibration process, but it is used judiciously when a zone is considered to possess unique characteristics.

Example 12.4 Use of Calibrated F Values and Iteration

To illustrate the application of the gravity model, consider a study area consisting of three zones. The data have been determined as follows: the number of productions and attractions has been computed for each zone by methods described in the section on trip generation, and the average travel times between each zone have been determined. Both are shown in Tables 12.9 and 12.10. Assume K_{ij} is the same unit value for all zones. Finally, the F values have been calibrated as previously described and are shown in Table 12.11 for each travel time increment. Note that the intra-zonal travel time for zone 1 is larger than those of most other inter-zone times because of the geographical

Table 12.9 Trip Productions and Attractions for a Three-Zone Study Area

Zone	*1*	*2*	*3*	*Total*
Trip productions	140	330	280	750
Trip attractions	300	270	180	750

Table 12.10 Travel Time between Zones (min)

Zone	*1*	*2*	*3*
1	5	2	3
2	2	6	6
3	3	6	5

Table 12.11 Travel Time versus Friction Factor

Time (min)	*F*
1	82
2	52
3	50
4	41
5	39
6	26
7	20
8	13

Note: F values were obtained from the calibration process.

characteristics of the zone and lack of access within the area. This zone could represent conditions in a congested downtown area.

Determine the number of zone-to-zone trips through two iterations.

Solution: The number of trips between each zone is computed using the gravity model and the given data. (*Note:* F_{ij} is obtained by using the travel times in Table 12.10 and selecting the correct F value from Table 12.11. For example, travel time is 2 min between zones 1 and 2. The corresponding F value is 52.)

Use Eq. 12.3.

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_{j=1}^{n} A_j F_{ij} K_{ij}} \right] \qquad K_{ij} = 1 \text{ for all zones}$$

$$T_{1-1} = 140 \times \frac{300 \times 39}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 47$$

$$T_{1-2} = 140 \times \frac{270 \times 52}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 57$$

$$T_{1-3} = 140 \times \frac{180 \times 50}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 36$$

$$P_1 = 140$$

Make similar calculations for zones 2 and 3.

$$T_{2-1} = 188 \quad T_{2-2} = 85 \quad T_{2-3} = 57 \quad P_2 = 330$$

$$T_{3-1} = 144 \quad T_{3-2} = 68 \quad T_{3-3} = 68 \quad P_3 = 280$$

Table 12.12 Zone-to-Zone Trips: First Iteration, Singly Constrained

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	47	57	36	140	140
2	188	85	57	330	330
3	144	68	68	280	280
Computed *A*	379	210	161	750	750
Given *A*	300	270	180	750	

The results summarized in Table 12.12 represent a *singly constrained* gravity model. This constraint is that the sum of the productions in each zone is equal to the number of productions given in the problem statement. However, the number of attractions estimated in the trip distribution phase differs from the number of attractions given. For zone 1, the correct number is 300, whereas the computed value is 379. Values for zone 2 are 270 versus 210, and for zone 3 they are 180 versus 161.

To create a doubly constrained gravity model where the computed attractions equal the given attractions, calculate the adjusted attraction factors according to the formula

$$A_{jk} = \frac{A_j}{C_{j(k-1)}} A_{j(k-1)} \tag{12.4}$$

where

A_{jk} = adjusted attraction factor for attraction zone (column) j, iteration k
A_{jk} = A_j when $k = 1$
C_{jk} = actual attraction (column) total for zone j, iteration k
A_j = desired attraction total for attraction zone (column) j
j = attraction zone number, $j = 1, 2, \ldots, n$
n = number of zones
k = iteration number, $k = 1, 2, \ldots, m$
m = number of iterations

Repeat the trip distribution computations using modified attraction values so that the numbers attracted will be increased or reduced as required. For zone 1, for example, the estimated attractions were too great. Therefore, the new attraction factors are adjusted downward by multiplying the original attraction value by the ratio of the original to estimated attraction values.

$$\text{Zone 1: } A_{12} = 300 \times \frac{300}{379} = 237$$

$$\text{Zone 2: } A_{22} = 270 \times \frac{270}{210} = 347$$

$$\text{Zone 3: } A_{32} = 180 \times \frac{180}{161} = 201$$

Apply the gravity model (Eq. 12.3) for all iterations to calculate zonal trip interchanges using the adjusted attraction factors obtained from the preceding iteration. In practice, the gravity model becomes

Table 12.13 Zone-to-Zone Trips: Second Iteration, Doubly Constrained

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	34	68	38	140	140
2	153	112	65	330	330
3	116	88	76	280	280
Computed *A*	303	268	179	750	750
Given *A*	300	270	180	750	

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_j A_j F_{ij} K_{ij}} \right]$$

where T_{ijk} is the trip interchange between i and j for iteration k, and $A_{jk} = A_j$, when $k = 1$. Subscript j goes through one complete cycle every time k changes, and i goes through one complete cycle every time j changes. This formula is enclosed in parentheses and subscripted to indicate that the complete process is performed for each trip purpose.

Perform a second iteration using the adjusted attraction values.

$$T_{1-1} = 140 \times \frac{237 \times 39}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 34$$

$$T_{1-2} = 140 \times \frac{347 \times 52}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 68$$

$$T_{1-3} = 140 \times \frac{201 \times 50}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 37$$

$$P_1 = 140$$

Make similar calculations for zones 2 and 3.

$$T_{2-1} = 153 \quad T_{2-2} = 112 \quad T_{2-3} = 65 \quad P_2 = 330$$

$$T_{3-1} = 116 \quad T_{3-2} = 88 \quad T_{3-3} = 76 \quad P_3 = 280$$

The results are summarized in Table 12.13. Note that, in each case, the sum of the attractions is now much closer to the given value. The process will be continued until there is a reasonable agreement (within 5 percent) between the A that is estimated using the gravity model and the values that are furnished in the trip generation phase.

A singly constrained gravity model requires that computed and actual productions must be equal, whereas a doubly constrained gravity model requires that computed and actual productions and attractions must be equal. The singly constrained gravity model may be preferred if the friction factors are more reliable than the attraction values. The doubly constrained gravity model is appropriate if the attraction values are more reliable than friction factors. To illustrate either choice, consider the following example.

Example 12.5 Selecting Singly or Doubly Constrained Gravity Model Results

A three-zone system with 900 home-based shopping productions is shown in Table 12.14. Zones 1 and 2 each generate 400 productions, while zone 3 generates 100 productions. Each zone contains a shopping mall with 300 attractions. The shopping mall in zone 1 can be easily reached due to the parking availability and transit service. Thus, F_{11}, F_{21}, and $F_{31} = 1.0$. Parking costs at the shopping mall in zone 2 are moderate with some transit service. Thus, F_{12}, F_{22}, and $F_{32} = 0.5$. Parking costs at the mall in zone 3 are high and transit service is unavailable. Thus, F_{13}, F_{23}, and $F_{33} = 0.2$.

Application of the singly constrained gravity model yields the results shown in Table 12.15 and application of the doubly constrained gravity model yields the results shown in Table 12.16.

Which of the results shown for the singly constrained gravity model and for the doubly constrained gravity model are more likely to be the most accurate?

Solution: Table 12.15 is more likely to be accurate if engineering judgment suggests the occurrence of travel impedances and thus the friction factors are more accurate than trip attractions. Table 12.16 is more likely to be accurate if the attractions are more accurate than the friction factors.

In practice, these judgments must be made based on the quality of the data set. For example, if local land-use data had been recently used to develop trip attraction rates whereas friction factors had been borrowed from another area, then the selection of the doubly constrained gravity model results in Table 12.16 is recommended.

Table 12.14 Home-Based Shopping Productions and Attractions

Zone	*Productions*	*Attractions*
1	400	300
2	400	300
3	100	300
Total	900	900

Table 12.15 Zone-to-Zone Trips: Singly Constrained Gravity Model

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	235	118	47	400	400
2	235	118	47	400	400
3	59	29	12	100	100
Computed *A*	529	265	106	900	900
Given *A*	300	300	300	900	

Table 12.16 Zone-to-Zone Trips: Doubly Constrained Gravity Model

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	133	133	133	400	400
2	133	133	133	400	400
3	33	33	33	100	100
Computed *A*	300	300	300	900	900
Given *A*	300	300	300	900	

12.3.2 Growth Factor Models

Trip distribution can also be computed when the only data available are the origins and destinations between each zone for the current or base year and the trip generation values for each zone for the future year. This method was widely used when O-D data were available but the gravity model and calibrations for F factors had not yet become operational. Growth factor models are used primarily to distribute trips between zones in the study area and zones in cities external to the study area. Since they rely upon an existing O-D matrix, they cannot be used to forecast traffic between zones where no traffic currently exists. Further, the only measure of travel friction is the amount of current travel. Thus, the growth factor method cannot reflect changes in travel time between zones, much like the gravity model.

The most popular growth factor model is the *Fratar method* (named for Thomas J. Fratar, who developed the method), which is a mathematical formula that proportions future trip generation estimates to each zone as a function of the product of the current trips between the two zones T_{ij} and the growth factor of the attracting zone G_j. Thus,

$$T_{ij} = (t_i G_i) \frac{t_{ij} G_j}{\sum_x t_{ix} G_x} \tag{12.5}$$

where

T_{ij} = number of trips estimated from zone i to zone j
t_i = present trip generation in zone i
G_x = growth factor of zone x
$T_i = t_i G_i$ = future trip generation in zone i
t_{ix} = number of trips between zone i and other zones x
t_{ij} = present trips between zone i and zone j
G_j = growth factor of zone j

The following example illustrates the application of the growth factor model.

Example 12.6 Forecasting Trips Using the Fratar Model

A study area consists of four zones (A, B, C, and D). An O-D survey indicates that the number of trips between each zone is as shown in Table 12.17. Planning estimates for

Table 12.17 Present Trips between Zones

Zone	*A*	*B*	*C*	*D*
A	—	400	100	100
B	400	—	300	—
C	100	300	—	300
D	100	—	300	—
Total	600	700	700	400

the area indicate that in five years the number of trips in each zone will increase by the growth factor shown in Table 12.18 and that trip generation will be increased to the amounts shown in the last column of the table.

Table 12.18 Present Trip Generation and Growth Factors

Zone	*Present Trip Generation (trips/day)*	*Growth Factor*	*Trip Generation in Five Years*
A	600	1.2	720
B	700	1.1	770
C	700	1.4	980
D	400	1.3	520

Determine the number of trips between each zone for future conditions.

Solution: Using the Fratar formula (Eq. 12.5), calculate the number of trips between zones A and B, A and C, A and D, and so forth. Note that two values are obtained for each zone pair, (that is, T_{AB} and T_{BA}). These values are averaged, yielding a value for $T_{AB} = (T_{AB} + T_{BA})/2$.

The calculations are as follows.

$$T_{ij} = (t_i G_i) \frac{t_{ij} G_j}{\sum_x t_{ix} G_x}$$

$$T_{AB} = 600 \times 1.2 \frac{400 \times 1.1}{(400 \times 1.1) + (100 \times 1.4) + (100 \times 1.3)} = 446$$

$$T_{BA} = 700 \times 1.1 \frac{400 \times 1.2}{(400 \times 1.2) + (300 \times 1.4)} = 411$$

$$\overline{T}_{AB} = \frac{T_{AB} + T_{BA}}{2} = \frac{446 + 411}{2} = 428$$

Similar calculations yield

$$\overline{T}_{AC} = 141 \quad \overline{T}_{AD} = 124 \quad \overline{T}_{BC} = 372 \quad \overline{T}_{CD} = 430$$

The results of the preceding calculations have produced the first estimate (or iteration) of future trip distribution and are shown in Table 12.19. The totals for each zone do not equal the values of future trip generation. For example, the trip generation in zone A is estimated as 693 trips, whereas the actual value is 720 trips. Similarly, the estimate for zone B is 800 trips, whereas the actual value is 770 trips.

Proceed with a second iteration in which the input data are the numbers of trips between zones as previously calculated. Also, new growth factors are computed as the ratio of the trip generation expected to occur in five years and the

Table 12.19 First Estimate of Trips between Zones

Zone	*A*	*B*	*C*	*D*	*Estimated Total Trip Generation*	*Actual Trip Generation*
A	—	428	141	124	693	720
B	428	—	372	—	800	770
C	141	372	—	430	943	980
D	124	—	430	—	554	520
Totals	693	800	943	554		

trip generation estimated in the preceding calculation. The values are given in Table 12.20.

Table 12.20 Growth Factors for Second Iteration

Zone	*Estimated Trip Generation*	*Actual Trip Generation*	*Growth Factor*
A	693	720	1.04
B	800	770	0.96
C	943	980	1.04
D	554	520	0.94

The calculations for the second iteration are left to the reader to complete and the process can be repeated as many times as needed until the estimate and actual trip generation values are close in agreement.

A more general form of the growth factor model is the *average growth factor model.* Rather than weighting the growth of trips between zones *i* and *j* by the growth across all zones, as is done in the Fratar method, the growth rate of trips between any zones *i* and *j* is simply the average of the growth rates of these zones.

$$T'_{ij} = T_{ij}\left(\frac{G_i + G_j}{2}\right) \tag{12.5a}$$

Application of the average growth factor method proceeds similarly to that of the Fratar method. As iterations continue, the growth factors converge toward unity. Iterations can cease when an acceptable degree of convergence in the values is reached; one such practice is to continue until all growth factors are within 5 percent of unity (i.e., between 0.95 and 1.05).

Example 12.7 Accounting for Trips

Consider a simple region comprised of two zones. One hundred individuals live in zone 1, walk to work in zone 2 in the morning, and then walk home to zone 1 in the evening. Prepare

(a) A production-attraction matrix
(b) An origin-destination trip matrix

Which of these is similar to Table 12.12? Which is similar to Table 12.17?

Solution:

(a) A production-attraction matrix is similar to Table 12.12.

In the morning the 100 individuals generate 100 productions at the home end in zone 1 and 100 attractions at the work end in zone 2. Then, in the evening, these individuals generate another 100 attractions at the home end in zone 1 and 100 productions at the work end in zone 2. Thus, for a 24-hour period, there are 200 productions in zone 1 and 200 attractions in zone 2. The production attraction matrix is as follows:

Production-Attraction Trip Matrix (Zone-to-Zone Trips)

	Zone 1	*Zone 2*	*Total Productions*
Zone 1	0	200	200
Zone 2	200	0	200
Total attractions	200	200	

(b) The origin–destination trip matrix is similar to Table 12.17.

Origin–Destination Trip Matrix (Trips between Zones)

	Zone 1	*Zone 2*	*Total Origins*
Zone 1	0	100	100
Zone 2	100	0	100
Total destinations	100	100	

12.4 MODE CHOICE

Mode choice is the aspect of the demand analysis process that determines the number (or percentage) of trips between zones that are made by automobile and by transit. The selection of one mode or another is a complex process that depends on factors such as the traveler's income, the availability of transit service or auto ownership, and the relative advantages of each mode in terms of travel time, cost, comfort, convenience, and safety. Mode choice models attempt to replicate the relevant characteristics of the traveler, the transportation system, and the trip itself, such that a realistic estimate of the number of trips by each mode for each zonal pair is obtained. A discussion of the many mode choice models is beyond the scope of this chapter, and the interested reader should refer to sources cited.

12.4.1 Types of Mode Choice Models

Since public transportation is a vital transportation component in urban areas, mode choice calculations typically involve distinguishing trip interchanges as either auto or transit. Depending on the level of detail required, three types of transit estimating procedures are used: (1) direct generation of transit trips, (2) use of trip end models, and (3) trip interchange modal split models.

Direct Generation Models

Transit trips can be generated directly by estimating either total person trips or auto driver trips. Figure 12.8 is a graph that illustrates the relationship between number of

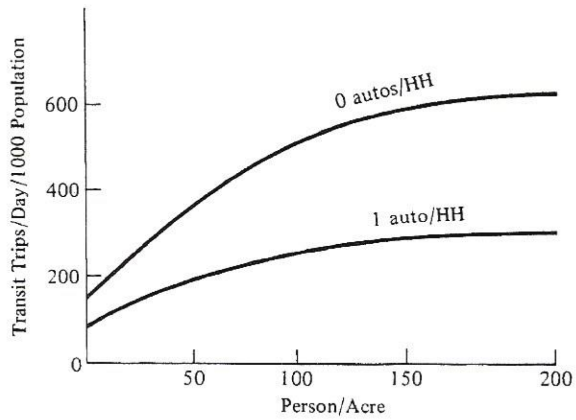


Figure 12.8 Number of Transit Trips by Population Density and Automobile Ownership per Household

Example 12.8 Estimating Mode Choice by Direct Trip Generation

Determine the number of transit trips per day in a zone, which has 5000 people living on 50 acres. The auto ownership is 40 percent zero autos per household and 60 percent one auto per household.

Solution: Calculate the number of persons per acre: 5000/50 = 100. Then determine the number of transit trips per day per 1000 persons (from Figure 12.8) to calculate the total of all transit trips per day for the zone.

Zero autos/HH: 510 trips/day/1000 population

One auto/HH: 250 trips/day/1000 population

Total Transit Trips: $(0.40)(510)(5) + (0.60)(250)(5) =$

$1020 + 750 = 1770$ transit trips per day transit trips per 1000 population and persons per acre versus automobile ownership. As population density increases, it can be expected that transit ridership will also increase for a given level of auto ownership.

This method assumes that the attributes of the system are not relevant. Factors such as travel time, cost, and convenience are not considered. These so-called "pre-trip" distribution models apply when transit service is poor and riders are "captive," or when transit service is excellent and "choice" clearly favors transit. When highway and transit modes "compete" for auto riders, then system factors are considered.

Trip End Models

To determine the percentage of total person or auto trips that will use transit, estimates are made prior to the trip distribution phase based on land-use or socioeconomic characteristics of the zone. This method does not incorporate the quality of service. The procedure follows:

- Generate total person trip productions and attractions by trip purpose.
- Compute the urban travel factor.
- Determine the percentage of these trips by transit using a mode choice curve.
- Apply auto occupancy factors.
- Distribute transit and auto trips separately.

The mode choice model shown in Figure 12.9 is based on two factors: households per auto and persons per square mile. The product of these variables is called the urban travel factor (UTF). Percentage of travel by transit will increase in an "*S*" curve fashion as the UTF increases.

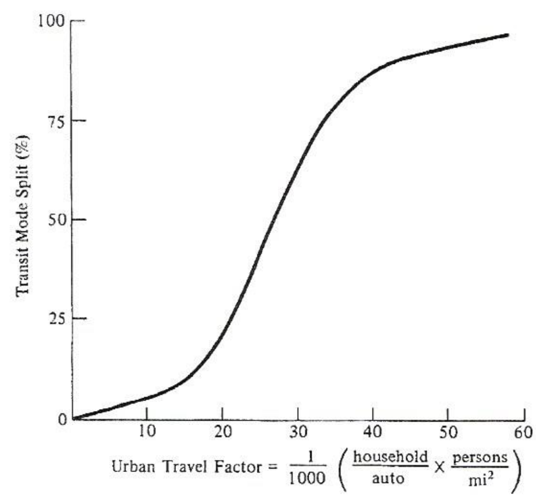


Figure 12.9 Transit Mode Split versus Urban Travel Factor

Example 12.9 Estimating Trip Productions by Transit

The total number of productions in a zone is 10,000 trips/day. The number of households per auto is 1.80, and residential density is 15,000 persons/square mile. Determine the percent of residents who can be expected to use transit.

Solution: Compute the urban travel factor.

$$\text{UTF} = \frac{1}{1000}\left(\frac{\text{household}}{\text{auto}}\right)\left(\frac{\text{persons}}{\text{mi}^2}\right)$$

$$= \frac{1}{1000} \times 1.80 \times 15{,}000 = 27.0$$

Use Figure 12.9. Transit mode split = 45%.

Trip Interchange Models

In this method, system level-of-service variables are considered, including relative travel time, relative travel cost, economic status of the trip maker, and relative travel service. An example of this procedure takes account of service parameters in estimating mode choice using the following relationship:

$$MS_a = \frac{I_{ijt}^{-b}}{I_{ija}^{-b} + I_{ija}^{-b}} \times 100 \text{ or } \frac{I_{ija}^{b}}{I_{ijt}^{b} + I_{ija}^{b}} \times 100 \tag{12.6}$$

$$MS_t = (1 - MS_a) \times 100 \tag{12.7}$$

where

MS_t = proportion of trips between zones i and j using transit
MS_a = proportion of trips between zones i and j using auto
I_{ijm} = a value referred to as the *impedance* of travel of mode m, between i and j, which is a measure of the total cost of the trip
Impedance = (in-vehicle time, min) + [(2.5)(excess time, min) + {(3)(trip cost) $ ÷(income earned min)]
b = an exponent, which depends on trip purpose
m = t for transit mode; a for auto mode

In-vehicle time is time spent traveling in the vehicle, and excess time is time spent traveling while not in the vehicle, including waiting for the train or bus and walking to the station. The impedance value is determined for each zone pair and represents a measure of the expenditure required to make the trip by either auto or transit. The data required for estimating mode choice include (1) distance between zones by auto and transit, (2) transit fare, (3) out-of-pocket auto cost, (4) parking cost, (5) highway and transit speed, (6) exponent values, b, (7) median income, and (8) excess time, which includes the time required to walk to a transit vehicle and time waiting or transferring. Assume that the time worked per year is 120,000 min.

Example 12.10 Computing Mode Choice Using the QRS Model

To illustrate the application of the QRS method, assume that the data shown in Table 12.21 have been developed for travel between a suburban zone *S* and a downtown zone *D*. Determine the percent of work trips by auto and transit. An exponent value of 2.0 is used for work travel. Median income is $24,000 per year.

Table 12.21 Travel Data between Two Zones, *S* and *D*

	Auto	*Transit*
Distance	10 mi	8 mi
Cost per mile	$0.15	$0.10
Excess time	5 min	8 min
Parking cost	$1.50 (or 0.75/trip)	—
Speed	30 mi/h	20 mi/h

Solution: Use Eq. 12.6.

$$MS_a = \frac{I^b_{ija}}{I^b_{ijt} + I^b_{ija}}$$

$$I_{SDa} = \left(\frac{10}{30} \times 60\right) + (2.5 \times 5) + \left\{\frac{3 \times [(1.50/2) + 0.15 \times 10]}{24{,}000/120{,}000}\right\}$$

$$= 20 + 12.5 + 33.75$$

$$= 66.25 \text{ equivalent min}$$

$$I_{SDt} = \left(\frac{8}{20} \times 60\right) + (2.5 \times 8) + \left[\frac{3 \times (8 \times 0.10)}{24{,}000/120{,}000}\right] = 24 + 20 + 12$$

$$= 56 \text{ equivalent min}$$

$$MS_a = \frac{(56)^2}{(56)^2 + (66.25)^2} \times 100 = 41.6\%$$

$$MS_t = (1 - 0.416) \times 100 = 58.4\%$$

Thus, the mode choice of travel by transit between zones *S* and *D* is 68.4 percent, and by highway the value is 41.6 percent. These percentages are applied to the estimated trip distribution values to determine the number of trips by each mode. If, for example, the number of work trips between zones *S* and *D* was computed to be 500, then the number by auto would be 500 × 0.416 = 208, and by transit, the number of trips would be 500 × 0.584 = 292.

12.4.2 Logit Models

An alternative approach used in transportation demand analysis is to consider the relative utility of each mode as a summation of each modal attribute. Then the choice of a mode is expressed as a probability distribution. For example, assume that the utility of each mode is

$$U_x = \sum_{i=1}^{n} a_i X_i \tag{12.8}$$

where

U_x = utility of mode x
n = number of attributes
X_i = attribute value (time, cost, and so forth)
a_i = coefficient value for attributes i (negative, since the values are disutilities)

If two modes, auto (A) and transit (T), are being considered, the probability of selecting the auto mode A can be written as

$$P(A) = \frac{e^{U_A}}{e^{U_A} + e^{U_T}} \tag{12.9}$$

This form is called the *logit model,* as illustrated in Figure 12.10, and provides a convenient way to compute mode choice. Choice models are utilized within the urban transportation planning process and in transit marketing studies.

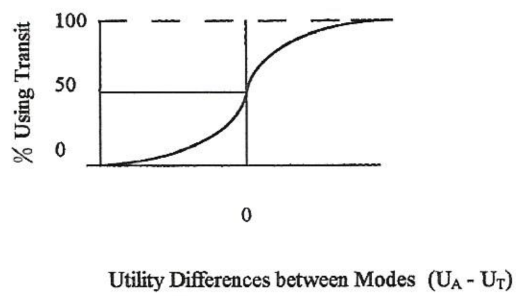


Figure 12.10 Modal Choice for Transit versus Automobile

Example 12.11 Use of Logit Model to Compute Mode Choice

The utility functions for auto and transit are as follows.

$$\text{Auto: } U_A = -0.46 - 0.35T_1 - 0.08T_2 - 0.005C$$

$$\text{Transit: } U_T = -0.07 - 0.05T_1 - 0.15T_2 - 0.005C$$

where

T_1 = total travel time (minutes)
T_2 = waiting time (minutes)
C = cost (cents)

The travel characteristics between two zones are as follows:

	Auto	*Transit*
T_1	20	30
T_2	8	6
C	320	100

Solution: Use the logit model to determine the percent of travel in the zone by auto and transit.

$$U_x = \sum_{i=1}^{n} a_i X_i$$

$$U_A = -0.46 - (0.35 \times 20) - (0.08 \times 8) - (0.005 \times 320) = -9.70$$

$$U_B = -0.07 - (0.35 \times 30) - (0.08 \times 6) - (0.005 \times 100) = -11.55$$

Using Eq. 12.9 yields

$$P_A = \frac{e^{U_A}}{e^{U_A} + e^{U_T}} = \frac{e^{-9.70}}{e^{-9.7} + e^{-11.55}} = 0.86$$

$$P_T = \frac{e^{U_T}}{e^{U_A} + e^{U_T}} = \frac{e^{-11.55}}{e^{-9.7} + e^{-11.55}} = 0.14$$

Example 12.12 Role of the Difference in Utilities in the Logit Model

Referring to Example 12.11, suppose rising fuel prices lead to an increase of \$1.00 for each mode. How will mode shares be affected?

Solution: An increase of 100 cents will lead to new utilities but not new mode shares.

$$U_A = -9.70 - 0.005(100) = -10.2$$

$$U_T = -11.55 - 0.005(100) = -12.05$$

$$P_A = \frac{e^{U_A}}{e^{U_A} + e^{U_T}} = \frac{e^{-10.2}}{e^{-10.2} + e^{-12.05}} = 0.864$$

$$P_T = \frac{e^{U_T}}{e^{U_A} + e^{U_T}} = \frac{e^{-12.05}}{e^{-10.2} + e^{-12.05}} = 0.136$$

The answer does not change, because the difference between U_A and U_T did not change, and it is this difference, not the utilities themselves, that determines P_A and P_T. This concept is shown in the logit curve of Figure 12.10, where the proportion of individuals using transit is governed by the difference $U_A - U_T$. A change would result only if the increase in fuel price did not have the same impact on costs for transit and auto.

Borrowing Utility Functions from Other Sources

If a utility function such as that shown in Eq. 12.9 is not available, then the coefficients for the function either may be borrowed from another source or derived from survey data. To the extent that the selection of a mode is governed by its in-vehicle travel time, out-of-vehicle travel time, and cost, a utility function may be written as:

$$\text{Utility}_i = b(IVTT) + c(OVTT) + d(COST) \tag{12.10}$$

where

$Utility_i$ = utility function for mode i
$IVTT$ = in-vehicle travel time (min)
$OVTT$ = out-of-vehicle travel time (min)
$COST$ = out-of-pocket cost (cents)

The following approach for calibrating the coefficients b, c, and d in Eq. 12.10 are based on methods published in NCHRP Report 365.

- In-vehicle travel time ($IVTT$) has a coefficient of $b = -0.025$.
- Out-of-vehicle travel time has a coefficient of $c = -0.050$, which reflects the observation that time waiting for a vehicle is perceived to be twice as great as time spent inside a moving vehicle.
- Cost coefficient d is computed as follows:

$$d = \frac{(b)(1248)}{(TVP)(AI)}$$

where

TVP = the ratio of (value of one hour travel time) ÷ (hourly employment rate). In the absence of other data, $TVP = 0.30$
AI = the average annual regional household income, ($). The number in the numerator is a factor that converts $/yr to cents/min, which is 1248.

Example 12.13 Borrowing Utility Coefficients from Other Sources

A transit authority wishes to determine the number of total travelers in a corridor that will shift from auto to a proposed new bus line. Since local data are unavailable, use of borrowed utility values is the only option. It is believed that the key factors in the decision to use transit will be time and cost. Average annual household income (AI) is $60,000, $TVP = 0.30$, and waiting time is perceived to be twice as long as riding time. System times and cost values are as follows.

Variable	*Bus*	*Auto*
IVIT (min)	30	20
OVIT (min)	6	8
Cost (cents)	100	320

Determine the proportion of persons who will use the new bus line.

$$b = -0.025$$

$$c = -0.050$$

$$d = \frac{(b)(1248)}{(TVP)(AI)} = \frac{(-0.025)(1248)}{(0.30)(\$60{,}000)} = -0.00173$$

$a_t = 0$ since the problem stated *IVTT*, *OVTT*, and *COST* sufficiently explain mode choice.

The utility functions are:

$$U_{auto} = b(IVTT) + c(OVTT) + d(COST)$$
$$= -0.025(20) + -0.050(8) + -0.00173(320) = -1.454$$
$$U_{bus} = b(IVTT) + c(OVTT) + d(COST)$$
$$= -0.025(30) + -0.050(6) + -0.00173(100) = -1.223$$

The proportion of travelers using the bus is computed using Eq. 12.9.

$$P_{bus} = \frac{e^{U_{bus}}}{e^{U_{bus}} + e^{U_{auto}}} = \frac{e^{-1.223}}{e^{-1.223} + e^{-1.454}} = 0.557$$

Thus, this model predicts that 56 percent of travelers will use the new bus line.

Example 12.14 Using Local Data to Improve Utility Coefficients

In Example 12.13, suppose ten residents at the local Department of Motor Vehicles are given a survey where they are asked the following two questions:

- What is your hourly salary?
- What would you be willing to pay to shorten your travel time by one hour?

Data from residents are shown below.

Resident	*Hourly Salary*	*Amount Resident is Willing to Pay to Shorten Travel Time by 1 Hour*
1	\$8	\$3
2	\$9	\$5
3	\$10	\$5
4	\$15	\$8
5	\$20	\$9
6	\$20	\$11
7	\$24	\$12
8	\$25	\$13
9	\$30	\$12
10	\$40	\$24

(a) Use the local data to re-estimate the proportion of travelers using the new bus line.
(b) Interpret the reason for the change in proportion.
(c) Indicate whether the sample of 10 residents likely represents the region as a whole.

Solution:

(a) Use local data to re-estimate the proportion of travelers using the new bus line.

The sample data may be used to compute a local TVP. For example, for person 1, the TVP is \$3/\$8 = 0.375. For person 2, the TVP is \$5/\$9 = 0.56. The average TVP for all 10 residents is 0.50 rather than the assumed value of 0.30 in the original problem. Accordingly, the cost coefficient d may be recomputed as

$$d = \frac{(b)(1248)}{(TVP)(AI)} = \frac{(-0.025)(1248)}{(0.50)(\$60{,}000)} = -0.00104$$

Thus the utility functions U_{auto} and U_{bus} and the bus proportion P_{bus} are

$$U_{auto} = b(IVTT) + c(OVTT) + d(COST)$$

$$U_{auto} = -0.025(20) - 0.05(8) - 0.00104(320) = -1.233$$

$$U_{bus} = b(IVTT) + c(OVTT) + d(COST)$$

$$U_{bus} = -0.025(30) - 0.05(6) - 0.00104(320) = -1.154$$

$$P_{bus} = \frac{e^{U_{bus}}}{e^{U_{auto}} + e^{U_{bus}}} = \frac{e^{-1.154}}{e^{-1.233} + e^{-1.154}} = 0.520$$

Thus the proportion using the bus changes from 55.7 percent to 52.0 percent.

(b) Interpret the reason for the change in proportion.

In the original assumption, TVP was assumed to be 30 percent, whereas in part (a), local data was used to calculate a TVP of 50 percent. The higher value of TVP in part (a) means that additional cost has a lesser disutility than what was originally assumed. This change is evident in the new value of the cost coefficient d, which had an original value of -0.00173 and a new value in part (a) of -0.00104. The new value signifies that increased costs will have less of an impact on the utility than was the case in the original problem.

Examination of in-vehicle travel time and cost for each mode shows that the bus generally offers lower cost whereas the auto offers lower travel time. Because the cost parameter d has less of an impact on utility in part (a) than the original problem, the relative importance of lower costs is diminished in part (a). Accordingly, it is not surprising that the mode share of the bus drops in part (a) relative to the original problem.

(c) Indicate whether the sample of 10 residents likely represents the region as a whole.

It is unlikely that these 10 residents represent the region as a whole. The average hourly salary of the 10 residents is \$10.20, which, assuming 2080 hours per year, yields an average salary of \$41,808, which is considerably smaller than the regional salary of \$60,000. A survey with a greater sample size, conducted at multiple locations rather than only the DMV, should attract a more representative population. Such data would need to be examined to determine whether the calculated value of TVP should be modified.

Example 12.15 Adding a Mode-Specific Constant to the Utility Function

Referring to Example 12.13, upon inaugurating the bus service, the percentage of travelers that use the new bus service is actually 65 percent. Follow-up surveys confirm that the coefficients *b*, *c*, and *d*, which were used to estimate potential bus service, appear to have been correct. However, the surveys suggest that a further incentive (beyond time and cost) for using the bus is influenced by the availability of laptop outlets at each seat and a complimentary beverage service.

Given this added information, explain how to modify the utility function to reflect the influence of added amenities.

Solution: Because the coefficients *b*, *c*, and *d* do not include the additional features that favor bus usage, a mode-specific coefficient (a_i) should be included in one of the utility functions. This term may either be a positive coefficient that is added to the bus utility function or a negative coefficient that is subtracted from the auto utility function. Using the former approach, simply add a constant value (which in this example is 0.3885) to the bus utility function in order to yield the required 65 percent of travelers using the bus.

$$P_{\text{bus}} = \frac{e^{(U_{\text{bus}}+0.3885)}}{e^{(U_{\text{bus}}+0.3885)} + e^{U_{\text{auto}}}} = \frac{e^{(-1.223+0.3885)}}{e^{(-1.223+0.3885)} + e^{-1.454}} = 0.650$$

Thus, the bus utility function is rewritten and the auto utility function is unchanged, as follows.

$$U_{\text{bus}} = a_{\text{bus}} + b(IVTT) + c(OVTT) + d(COST)$$

$$U_{\text{bus}} = 0.3885 + -0.025(\text{IVTT}) + -0.050(\text{OVTT}) + -0.00173(\text{COST})$$

Modifying a Logit Model for Changes in Service Parameters

If the value of the *IVTT*, *OVTT*, or *COST* parameters has changed, then the new mode share P_i' can be calculated from the original mode share P_i and the change in the utility function value as shown in Eq. 12.11. This property is useful because determination of P_i' does not require knowledge of the mode-specific constant *a*. Since the *a* values cancel when calculating Δu_b, the difference between utility function values $U_{i\text{-}new}$ and $U_{i\text{-}old}$ in Eq. 12.11 is the incremental logit model and can be applied if the mode is already in service. The incremental logit model cannot be used for new modes where prior data to compute P_t are unavailable.

$$P_i' = \frac{P_i e^{\Delta u_b}}{\sum_i P_i e^{\Delta u_b}} \qquad (12.11)$$

where

P_i' = proportion using mode *i* after system changes
P_i = proportion using mode *i* before system changes
Δu_b = difference in utility functions values $U_{i\text{-new}} - U_{i\text{-old}}$

Example 12.16 Applying the Incremental Logit Model

The regional transportation agency in Example 12.15 is considering an investment in signal preemption for transit vehicles, which would reduce the in-vehicle travel time for bus service from 30 to 25 min. All other service amenities will remain. Determine the percentage of travelers who will use bus service if this investment is made.

Solution: Equation 12.11 may be applied as follows.

$$P_{\text{bus}} = 65\%$$

$$P_{\text{auto}} = 35\%$$

$$\Delta U_{\text{bus}} = U_{\text{busnew}} - U_{\text{busold}}$$

$$\Delta U_{\text{bus}} = [0.3855 + -0.025(IVTT_{\text{new}}) + -0.050(OVTT_{\text{new}}) + -0.00173(COST_{\text{new}})] - [0.3855 + -0.025(IVTT_{\text{old}}) + -0.050(OVTT_{\text{old}}) + -0.00173(COST_{\text{old}})]$$

Since bus travel time is the only variable that has been changed, from 30 to 25 min:

$$\Delta U_{\text{bus}} = -0.025\,(25 - 30)$$

$$\Delta U_{\text{bus}} = 0.125$$

$$\Delta U_{\text{bus}} = 0 \text{ (assuming no change in auto travel time or cost)}$$

Using Eq. 12.11:

$$P'_{\text{bus}} = \frac{P_{\text{bus}} e^{\Delta U_{\text{bus}}}}{P_{\text{auto}} e^{\Delta U_{\text{bus}}} + P_{\text{bus}} e^{\Delta U_{\text{bus}}}}$$

$$P'_{\text{bus}} = \frac{0.65e^{0.125}}{0.35e^{0} + 0.65e^{0.125}} = 0.68$$

This answer to Example 12.16 can also be obtained if the logit model was used with all system parameters and the amenity value a, as shown in Example 12.15. The advantage of the incremental logit model applied in Example 12.16 is that knowledge of the mode specific constant a_i is not required.

Calibrating Utility Functions with Survey Data

A second approach to determine utility function coefficients is to calibrate the coefficients based on survey data using the method of maximum likelihood estimation. Software packages such as SAS and ALOGIT are available that support maximum likelihood estimation and replace manual procedures presented here. The utility functions that are best supported by data are determined through a variety of statistical tests that represent a fundamental component of this calibration process. To illustrate this process, a simple calibration of a utility function using survey data is shown in Example 12.17 . For discussion of more complex cases, refer to references at the end of the chapter.

Example 12.17 Calibrating Utility Functions

A regional transportation agency wishes to calibrate a utility function that can be used with the logit model to predict modal choice between bus, auto, and rail. Survey data were obtained by interviewing seven people identified as persons *A* through *G* who reported the travel time for three modes they considered (car, bus, and rail) and the mode that was selected. The results of the survey are shown in the following table. The agency has proposed to select a utility function of the form $U = b$ (time).

Use the method of maximum likelihood estimation to calibrate this utility function for the parameter, *b*.

Sample Interview Survey Data:

Respondent	*Auto Time (min)*	*Bus Time (min)*	*Rail Time (min)*	*Mode*
A	10	13	15	Auto
B	12	9	8	Auto
C	35	32	20	Rail
D	45	15	44	Bus
E	60	58	64	Bus
F	70	65	60	Auto
G	25	20	15	Rail

Solution: The utility function is

$$U = b(\text{IVTT})$$

where

b = a constant to be determined from the calibration process
IVTT = in-vehicle travel time (in minutes)

A maximum likelihood function may be used to derive model coefficients that replicate the observed data. For these data, a "perfect" function would predict that respondents *A*, *B*, and *F* would select auto; *C* and *G* would select rail; and *D* and *E* would select bus. For respondent *A*, the utility function is as shown, since *A* selected auto and not the bus or rail. Thus,

$$L_A = (P_{A-\text{auto}})$$

The probability that *A* will select a mode is computed using Eqs. 12.8 and 12.9. The probability that respondent *A* will select auto, rail, or bus is:

$$P_{A,\text{auto}} = \frac{e^{U_{1\text{auto}}}}{e^{U_{1\text{auto}}} + e^{U_{1\text{bus}}} + e^{U_{1\text{rail}}}} = \frac{e^{b10}}{e^{b10} + e^{b13} + e^{b15}}$$

$$P_{A,\text{bus}} = \frac{e^{U_{1\text{bus}}}}{e^{U_{1\text{auto}}} + e^{U_{1\text{bus}}} + e^{U_{1\text{rail}}}} = \frac{e^{b13}}{e^{b10} + e^{b13} + e^{b15}}$$

$$P_{A,\text{rail}} = \frac{e^{U_{1\text{rail}}}}{e^{U_{1\text{auto}}} + e^{U_{1\text{bus}}} + e^{U_{1\text{rail}}}} = \frac{e^{b15}}{e^{b10} + e^{b13} + e^{b15}}$$

Substitution of the appropriate equation into the expression for L_A yields the maximum likelihood function for respondent *A*.

$$L_A = \left(\frac{e^{b10}}{e^{b10} + e^{b13} + e^{b15}}\right)$$

For the entire data set, therefore, the maximum likelihood function may be computed as

$$L = (L_A)(L_B)(L_C)(L_D)(L_E)(L_F)(L_G)$$

Since b cannot be determined such that L is exactly equal to 1.0, the best possible result is to select a value of b such that L is as close to 1.0 as possible. Theoretically, L could be differentiated with respect to b and equated to zero. However, the nonlinear equations that result usually necessitate the use of specialized software to solve. Plot L versus b is as shown in Figure 12.11. The value of $b = (-0.1504)$ maximizes L. Thus, the utility expression based on the data collected about user behavior is

$$U = (-0.1504)(\text{IVTT})$$

Several tests may be used in logit model calibration to determine which parameters are statistically significant. One example is the likelihood ratio test, defined in Eq. A as

$$-2|L(\mathbf{0}) - L(\mathbf{B})|$$

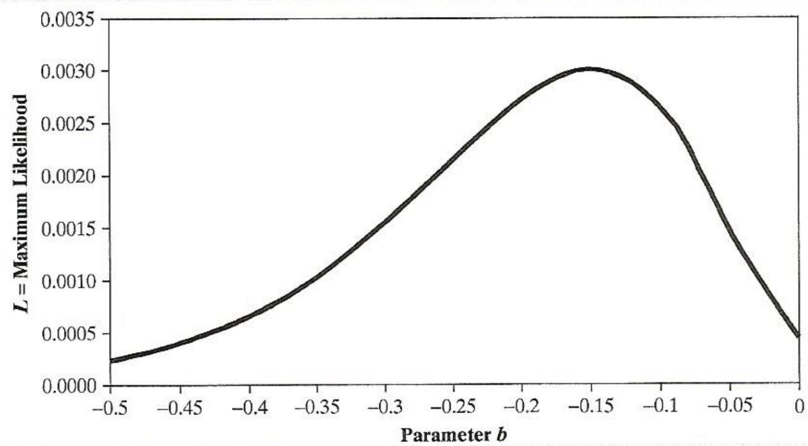


Figure 12.11 Plot of Maximum Likelihood Function versus b.

where

$L(\mathbf{0})$ is the log-likelihood value when all model parameters are zero
$L(\mathbf{B})$ is the log-likelihood value of the calibrated model

The quantity is compared to the Chi-square statistic with K degrees of freedom. For this example:

$K = 1$ since the model has one nonzero parameter.
$L(\mathbf{0}) = -7.69$, since with no parameters the probability of choosing each mode is 1/3 and, with seven respondents, $7 \ln(1/3) = -7.69$
$L(\mathbf{B}) = -5.81$ since $\ln(0.003) = -5.81$ (see Figure 12.11)

Thus the likelihood ratio test is:

$$-2|L(\mathbf{0}) - L(\mathbf{B})|$$
$$-2|-7.69 - -5.81 = 3.76$$

Because 3.76 is less than $\chi_{.025,1} = 5.03$, which can be found from the Excel function CHI-INV (.025,1), the parameter b is not statistically significant. In practice, either more data would be collected or another utility function would be devised.

12.5 TRAFFIC ASSIGNMENT

The final step in the travel demand forecasting process is to determine the street and highway routes that are likely to be used and to estimate the number of automobiles and buses that can be expected on each roadway segment. The procedure used is known as *traffic assignment.* Since the number of trips by transit and auto that will travel between zones are known from the previous steps in the process, each trip O-D can be assigned to a highway or transit route. The sum of the results for each segment of the system is a forecast of the average daily or peak hour traffic volumes that will occur on the urban transportation system that serves the study area.

To carry out a trip assignment, the following data are required: (1) number of trips that will be made from one zone to another (this information was determined in the trip distribution phase), (2) a description of the highway or transit routes between zones, (3) travel time on each route segment, and (4) external trips that were not considered in the previous trip generation and distribution steps. Finally, a decision rule is required (or algorithm) that explains how motorists or transit users select a route.

12.5.1 Basic Approaches

Three basic approaches can be used for traffic assignment purposes: (1) diversion curves, (2) minimum time path (all-or-nothing) assignment, and (3) minimum time path with capacity restraint.

Diversion Curves

This method is similar in approach to a mode choice curve. The traffic between two routes is determined as a function of relative travel time or cost. Figure 12.12 illustrates a diversion curve based on travel time ratio.

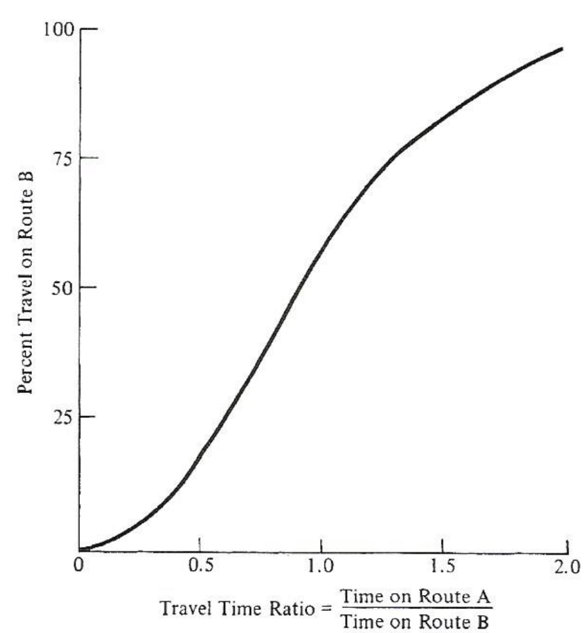


Figure 12.12 Travel Time Ratio versus Percentage of Travel on Route *B*

Minimum Path Algorithm

The traffic assignment process is illustrated using the minimum path algorithm. This method is selected because it is commonly used, generally produces accurate results, and adequately demonstrates the basic principles involved. The *minimum time path* method assigns all trips to those links that comprise the shortest time path between the two zones.

The minimum path assignment is based on the theory that a motorist or transit user will select the quickest route between any O-D pair. In other words, the traveler will always select the route that represents minimum travel time. Thus, to determine which route that will be, it is necessary to find the shortest route from the zone of origin to all other destination zones. The results can be depicted as a tree, referred to as a *skim tree.* All trips from that zone are assigned to links on the skim tree. A node in the area-wide network represents each zone. To determine the minimum path, a procedure is used that finds the shortest path without having to test all possible combinations.

The algorithm that will be used in the next example is to connect all nodes from the home (originating) node and keep all paths as contenders until one path to the same node is a faster route than others, at which juncture those links on the slower path are eliminated.

The general mathematical algorithm that describes the process is to select paths that minimize the expression

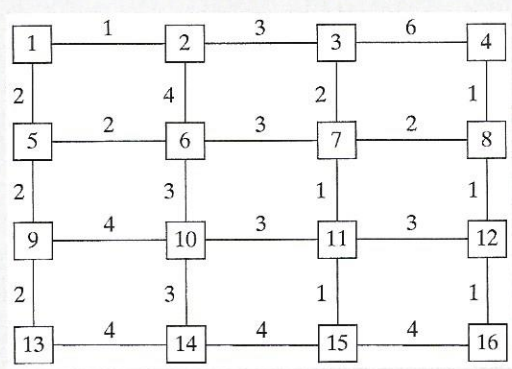
$$\sum_{\text{all}ij} V_{ij} T_{ij} \tag{12.12}$$

where

V_{ij} = volume on link i,j
T_{ij} = travel on link i,j
i,j = adjacent nodes

Example 12.18 Finding Minimum Paths in a Network

To illustrate the process of path building, consider the following 16-node network with travel times on each link shown for each node (zone) pair.

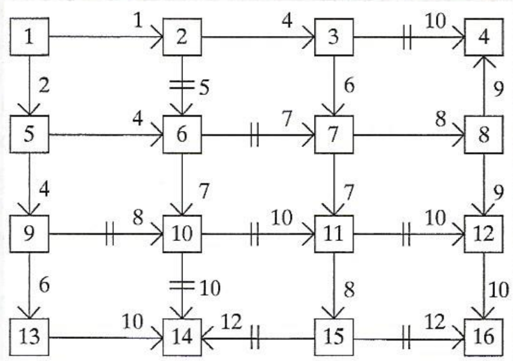


The link and node network is representative of the road and street system. Determine the shortest travel path from node 1 (home node) to all other zones.

Solution: To determine minimum time paths from node 1 to all other nodes, proceed as follows.

Step 1. Determine the time to nodes connected to node 1. Time to node 2 is 1 min. Time to node 5 is 2 min. Times are noted near nodes in diagram.

Step 2. From the node closest to the home node (node 2 is the closest to home node 1), make connections to nearest nodes. These are nodes 3 and 6. Write the cumulative travel times at each node.



Step 3. From the node that is now closest to the home node (node 5), make connections to the nearest nodes (node 6 and 9). Write the cumulative travel times at each node.

Step 4. Time to node 6 via node 5 is shorter than that via zone 2. Therefore, link 2 to 6 is deleted.

Step 5. Three nodes are equally close to the home node (nodes 3, 6, and 9). Select the lowest-numbered node (3); add corresponding links to nodes 4 and 7.

Step 6. Of the three equally close nodes, node 6 is the next lowest numbered node. Connect to zones 7 and 10. Eliminate link 6 to 7.

Step 7. Building proceeds from node 9 to nodes 10 and 13. Eliminate link 9 to 10.

Step 8. Build from node 7.

Step 9. Build from node 13.

Step 10. Build from node 10, and eliminate link 10 to 11.

Step 11. Build from node 11, and eliminate link 11 to 12.

Step 12. Build from node 8, and eliminate link 3 to 4.

Step 13. Build from node 15, and eliminate link 14 to 15.

Step 14. Build from node 12, and eliminate link 15 to 16.

To find the minimum path from any node to node 1, follow the path backward. Thus, for example, the links on the minimum path from zone 1 to zone 11 are 7 to 11, 3 to 7, 2 to 3, and 1 to 2. This process is then repeated for the other 15 zones to produce the skim trees for each of the zones in the study area. Figure 12.13 illustrates the skim tree produced for zone 1.

Note that link 10 to 14 has been eliminated in the skim tree, although it was not explicitly eliminated in the above analysis. The reason for the elimination of link 10 to 14 is that there was a "tie" between link 10 to 14 and link 13 to 14, where the use of

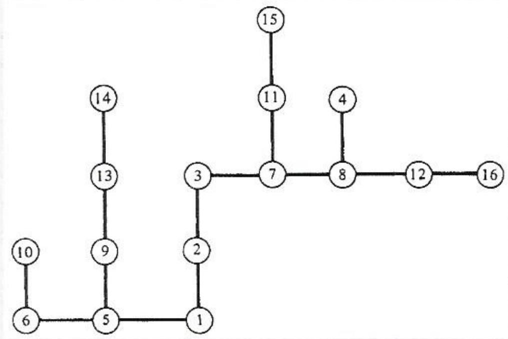


Figure 12.13 Minimum Path Tree for Zone 1

Table 12.22 Dealing with Link Elimination when Travel Times Are Equal

Link 13 to 14 option	*Link 10 to 14 option*
Link 1–5 (2 units)	Link 1–5 (2 units)
Link 5–9 (2 units)	Link 5–6 (2 units)
Link 9–13 (2 units)	Link 6–10 (3 units)
Link 13–14 (4 units)	Link 10–14 (3 units)
Total to reach node 14 (10 units)	Total to reach node 14 (10 units)
Total to reach the node preceding node 14 (6 units)	Total to reach the node preceding node 14 (7 units)

either link will still result in the same number of minutes (10) to reach node 14. The link is selected by considering how many minutes are required to reach the preceding node (e.g., node 10 for link 10 to 14 or node 13 for link 13 to 14). Table 12.22 shows that link 10 to 14 was eliminated, since 7 min are required to reach node 10 but only six units were required to reach node 13.

Example 12.19 Network Loading Using Minimum Path Method

The links that are on the minimum path for each of the nodes connecting node 1 are shown in Table 12.23. Also shown is the number of auto trips between zone 1 and all other zones. From these results, the number of trips on each link is determined.

To illustrate, link 1 to 2 is used by trips from node 1 to nodes 2, 3, 4, 7, 8, 11, 12, 15, and 16. Thus, the trips between these node pairs are assigned to link 1 to 2 as illustrated in Table 12.23. The volumes are 50, 75, 80, 60, 30, 80, 25, 20, and 85 for a total of 505 trips on link 1 to 2 from node 1.

Solution: Calculate the number of trips that should be assigned to each link of those that have been generated in node 1 and distributed to nodes 2 through 16 (Table 12.24). A similar process of network loading would be completed for all other zone pairs. Calculations for traffic assignment, as well as for other steps in the forecasting model system, can be performed using computer programs for transportation modeling.

Table 12.23 Links on Minimum Path for Trips from Node 1

From	*To*	*Trips*	*Links on the Minimum Path*
1	2	50	1–2
	3	75	1–2, 2–3
	4	80	1–2, 2–3, 3–7, 7–8, 4–8
	5	100	1–5
	6	125	1–5, 5–6
	7	60	1–2, 2–3, 3–7
	8	30	1–2, 2–3, 3–7, 7–8
	9	90	1–5, 5–9
	10	40	1–5, 5–6, 6–10
	11	80	1–2, 2–3, 3–7, 7–11
	12	25	1–2, 2–3, 3–7, 7–8, 8–12
	13	70	1–5, 5–9, 9–13
	14	60	1–5, 5–9, 9–13, 13–14
	15	20	1–2, 2–3, 3–7, 7–11, 11–15
	16	85	1–2, 2–3, 3–7, 7–8, 8–12, 12–16

Table 12.24 Assignment of Trips from Node 1 to Links on Highway Network

Link	*Trips on Link*
1–2	50, 75, 80, 60, 30, 80, 25, 20, 85 = 505
2–3	75, 80, 60, 30, 80, 25, 20, 85 = 455
3–7	80, 60, 30, 80, 25, 20, 85 = 380
1–5	100, 125, 90, 40, 70, 60 = 485
5–6	125, 40 = 165
7–8	80, 30, 25, 85 = 220
4–8	80 = 80
5–9	90, 70, 60 = 220
6–10	40 = 40
7–11	80, 20 = 100
8–12	25, 85 = 110
9–13	70, 60 = 130
11–15	20 = 20
12–16	85 = 85
13–14	60 = 60

12.5.2 Capacity Restraint

A modification of the process just described is known as *capacity restraint.* The number of trips assigned to each link is compared with the capacity of the link to determine the extent to which link travel times have been increased by the additional volume placed on the formerly empty link. Using relationships between volume and travel time (or speed) similar to those derived in Chapter 6, it is possible to recalculate the new link travel time. A reassignment is then made based on these new values. The iteration process continues until a balance is achieved, such that the link travel time based on the loaded volume does not change with successive assignments.

The speed-volume relationship most commonly used in computer programs was developed by the U.S. Department of Transportation and is depicted in Figure 12.14. It is called a link performance function and is expressed in the following formula.

$$t = t_0\left[1 + 0.15\left(\frac{V}{C}\right)^4\right] \tag{12.13}$$

where

t = travel time on the link
t_0 = free-flow travel time
V = volume on the link
C = capacity of the link

The capacity restraint relationship given in Eq. 12.13 can be generalized by allowing the coefficients to be adjusted to corridor-specific or roadway-type, as follows.

$$t = t_0\left[1 + \alpha\left(\frac{V}{C}\right)^\beta\right] \tag{12.13a}$$

where

t = travel time on the link
t_0 = free-flow travel time
V = volume on the link
C = capacity of the link

α and β are link or roadway-type specific parameters.

One study of freeways and multilane highways found the parameters (as a function of free-flow speed) shown in Table 12.25. Alternatively, a traffic engineering study can be conducted for a specific corridor and the model fitted to the collected speed and volume data to determine appropriate values for α and β.

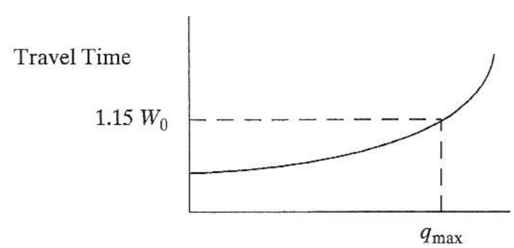


Figure 12.14 Travel Time versus Vehicle Volume

Table 12.25 Roadway-Type Specific Parameters for Capacity Restraint

	Freeways			*Multilane Highways*		
Coefficient	*70 mi/h*	*60 mi/h*	*50 mi/h*	*70 mi/h*	*60 mi/h*	*50 mi/h*
α	0.88	0.83	0.56	1.00	0.83	0.71
β	9.8	5.5	3.6	5.4	2.7	2.1

Example 12.20 Computing Capacity-Restrained Travel Times

In Example 12.19, the volume on link 1 to 5 was 485, and the travel time was 2 minutes. If the capacity of the link is 500, determine the link travel time that should be used for the next traffic assignment iteration.

Solution:

$$t_1 = t_0\left[1 + 0.15\left(\frac{V}{C}\right)^4\right]$$

$$t_{1-5} = 2\left[1 + 0.15\left(\frac{485}{500}\right)^4\right]$$

$$= 2.27 \text{ min}$$

Total System Cost Assignment

Application of Eq. 12.12 in conjunction with the equation for capacity restraint, Eq. 12.13, will result in an equilibrium assignment where no single user may reduce their individual travel time by changing travel paths. However, user-equilibrium assignment is not necessarily the method that results in the lowest total travel time for all travelers. Rather, a total system cost assignment may be an option if the lowest total cost (as compared with lowest individual cost) is preferred. If a system cost assignment is used, route selection decisions are no longer made by the motorist but are the responsibility of the transportation agency.

To illustrate the potential benefits of a system cost assignment, consider a simple highway network shown in Figure 12.15. In this situation, there are two origin zones (1 and 2) and one destination zone (3). If 400 travelers desire to travel from zone 2 to zone 3, they have only one option: use Link_{23}. If 300 travelers desire to travel from zone 1 to zone 3, they have two options: (1) Link_{12} and Link_{23} in succession, or (2) Link_{13} separately.

The travel times for each link can be given by the following relationships:

$$\text{Travel time}_{12} = \frac{3}{1 - \text{volume}_{12}/10{,}000}$$

$$\text{Travel time}_{23} = \frac{3}{1 - \text{volume}_{23}/800}$$

$$\text{Travel time}_{13} = \frac{12}{1 - \text{volume}_{13}/100{,}000}$$

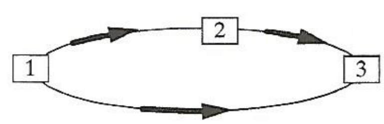


Figure 12.15 Three-Zone Highway System

An equilibrium assignment where each of the travelers from zone 1 to zone 3 individually chooses the fastest route will result in a total system cost of about 7198 min, as shown next. Only those traveling between zone 1 and zone 3 can reduce driving time by changing routes.

Results of an Equilibrium Assignment for a Three-Zone Highway Network

Link	*Link Volume*	*Link Travel Time*	*Travel Time between Zone 1 and Zone 2*
$Link_{12}$	132.73	3.04	12.02
$Link_{23}$	532.73	8.98	
$Link_{13}$	167.27	12.02	12.02
Total system cost			7198

Consider the situation where drivers must use a prescribed route. For example, all 300 motorists traveling from zone 1 to zone 3 could be told to use $Link_{13}$. Under this scenario, the travel time for these motorists will increase slightly—from 12.02 to 12.04 min—and the motorists who must travel between zone 2 and zone 3 will experience dramatically lowered travel times. The net result will be a lower system cost, as shown in the following table, where the total travel time has been reduced from 7198 to 6011 minutes.

Lowest System Cost Assignment

Link	*Link Volume*	*Link Travel Time*	*Travel Time between Zone 1 and Zone 2 (min)*
$Link_{12}$	0	3.00	9.00
$Link_{23}$	400	6.00	
$Link_{13}$	300	12.04	12.02
Total system cost			6011

In general, the assumption of user-equilibrium assignment is a more realistic basis for depicting individual decision making, since travelers act on what they consider to be their own best interest. The lowest system cost assignment may be of use for evaluating potential benefits of public interventions, such as traffic management strategies or improvements to infrastructure. For example, a public entity might choose to subsidize rail freight capacity if it found that total system costs for the rail and the adjacent interstate facility could be reduced, or variable message signs may direct motorists away from congested areas.

The process of calculating the travel demand for an urban transportation system is now completed. The results of this work will be used to determine where improvements are needed in the system, to make economic evaluations of project priority, as well as to assist in the geometric and pavement design phases. In actual practice, computers carry out the calculations because the process becomes computationally more intensive as the number of zones increases.

Example 12.21 Capacity Restraint for a More Complex Network

A sample network is shown in Figure 12.16. In this network, there is just one origin zone (zone 1), one destination zone (zone 2), two intersections (shown as 3 and 4), and five unidirectional links designated as L13, L14, L32, L34, and L42.

For the network shown in Figure 12.16,

(a) Write the general capacity restraint relationship if $\alpha = 1$ and $\beta = 2$.
(b) Compute the "cost" of travel for link L13 if $V_{13} = 30$.
(c) Identify all possible travel paths from zone 1 to zone 2.
(d) Perform an equilibrium assignment.
(e) Remove the appropriate constraints to perform a system optimal assignment.

Solution:

(a) A general capacity restraint relationship was given in Eq. 12.13a as

$$\text{Link congested time} = \text{link free-flow time}\left[1 + \alpha\left(\frac{\text{link volume}}{\text{link capacity}}\right)^{\beta}\right] \quad (12.13a)$$

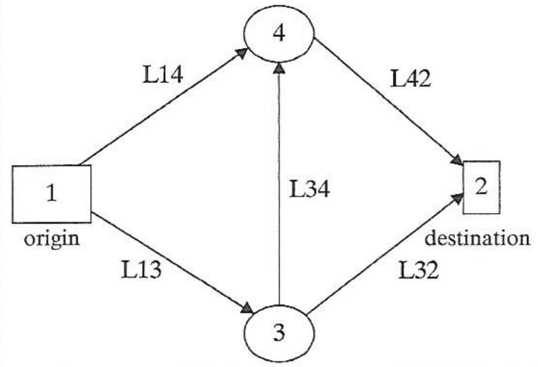
Setting $\alpha = 1$ and $\beta = 2$ yields

$$\text{Link congested time} = \text{link free-flow time}\left[1 + \left(\frac{\text{link volume}}{\text{link capacity}}\right)^{2}\right]$$

(b) Compute the "cost" of travel for link L13 if $V_{13} = 30$.
The cost may be defined as the link travel time multiplied by the link volume, as shown in Eq. 12.12.

$$\text{Link cost} = V_{\text{link}} T_{\text{link}} \quad (12.12)$$

The free-flow times and capacities for each link are shown in Figure 12.16. For example, consider link L13, with a free-flow time of 5 and a capacity of 20.



Link Free Flows and Capacities

Link	Link Free-Flow Time	Link Capacity
L13	5	20
L14	20	200
L34	3	50
L42	4	20
L32	5	20

Figure 12.16 Sample Network.

SOURCE: From Yin, Y., and H. Idea. Optimal Improvement Scheme for Network Reliability. In *Transportation Research Record*: Journal of the Transportation Research Board, No. 1783, Figure 4, p. 5. Copyright, National Academy of Sciences, Washington, D.C., 2002. Reproduced with permission of the Transportation Research Board

With zero volume, the link congested time is simply 5. With a volume of 30, the congested time for L13 is

$$\text{Link L13 congested time} = 5\left[1 + \left(\frac{30}{20}\right)^2\right] = 5[1 + 1.5^2] = 16.25$$

For Link L13, Eq. 12.12 shows that the link cost is thus

$$(30 \text{ vehicles})(16.25 \text{ minutes}) = 487.5 \text{ veh-min}$$

(c) There are three possible paths from zone 1 to zone 2:
- Path 1: Links L14 and L42
- Path 2: Links L13, L34, and L42
- Path 3: Links L13 and L32

(d) An equilibrium assignment may be performed using spreadsheet software, such as Microsoft Excel. Letting *i* and *j* be origin and destination zones, respectively, with *k* travel paths between these zones, deterministic user equilibrium assignment seeks to minimize Eq. 12.12, rewritten as Eq. 12.14, where V_{ijk} denotes volume between zones *i* and *j* using path *k* and T_{ijk} denotes travel time between zones *i* and *j* using path *k*.

$$\sum_{i=1}^{\text{origins}} \sum_{j=1}^{\text{destinations}} \sum_{k=1}^{\text{paths}} (V_{ijk}\, T_{ijk}) \tag{12.14}$$

subject to the constraint that

$$T_{ij1} = T_{ij2} = \cdots = T_{ijk} \text{ for all trips between zone } i \text{ and zone } j \tag{12.15}$$

Since there is only one origin zone ($i = 1$), one destination zone ($j = 2$), and three paths between these zones ($k = 1, 2$, or 3), we seek to minimize the system cost, which is

$$\sum_{k=1}^{3} (V_{12k}\, T_{12k})$$

subject to the constraint that

$$T_{121} = T_{122} = T_{123}$$

Thus all three paths (L14–L42, L13–L34–L42, and L13–L32) must have the same travel time. Note that the system cost is the same whether one multiplies the *path* volumes by the *path* travel times or the *link* volumes by the *link* travel times. That is, the minimization function could have been written following the exact formulation of Eq. 12.12 but tailored to this example.

$$\sum_{\text{link}=1}^{5} (V_{\text{link}}\, T_{\text{link}})$$

To obtain an equilibrium assignment such that no traveler can reduce their travel time by changing routes, Excel Solver may be used as shown in Figure 12.17a.

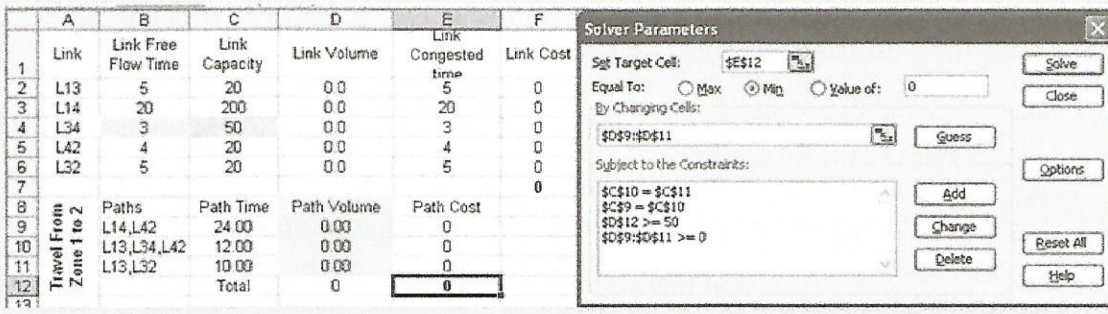


Figure 12.17a Deterministic User Equilibrium Assignment in Excel (Starting Point)

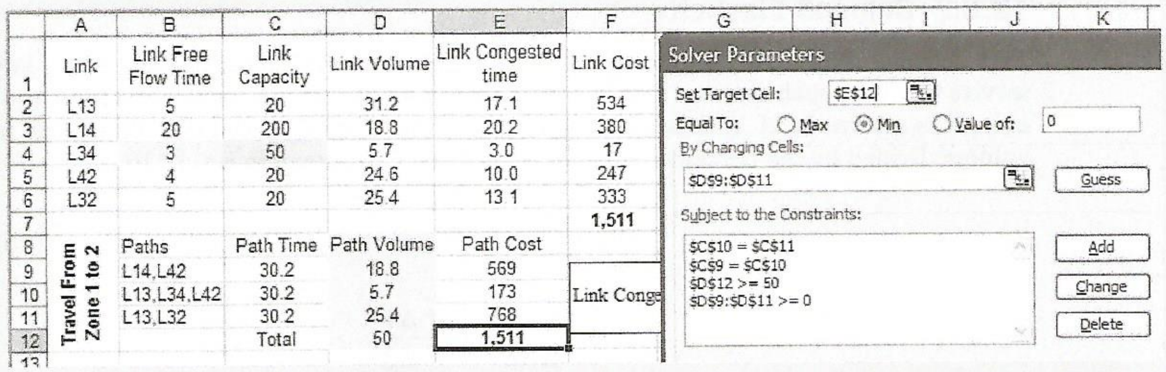
SOURCE: Created using Microsoft Office

To implement the solution shown in Figure 12.17a, notice the following:

Link free-flow times (cells B2–B6) are values.	Example: Cell B2 has "5"
Link capacities (cells C2–C6) are values.	Example: Cell C2 has "20"
Link congested times (cells E2–E6) are formulas.	Example: Cell E2 has "=B2*(1+(D2/C2)^2)"
Link costs (cells F2–F6) are formulas.	Example: Cell F2 has "=D2*E2"
Path times (cells C9–C11) are formulas summing link times.	Example: Cell C9 has "=E3+E5"
Path costs (cells E9–E11) are formulas.	Example: Cell E9 has "=C9*D9"
Path volumes (cells D9–D11) will be computed by Excel.	Example: Cell D9 will be found to have 18.8
Total path volume (cell D12) is the sum of all three paths.	Example: Cell D12 has "=SUM(D9:D11)"
Link volumes (cells D2–D6) reflect volumes from each path.	Example: Cell D2 has "=D10+D11"

The right side of Figure 12.17a shows that we seek to minimize Eq. 12.14 (in Cell E12) by changing the volumes using each of the three paths (in cells D9-D11). The constraints are that travel times on each path must be equal (hence path travel times in cells C9, C10, and C11 must be equal), 50 vehicles must be assigned to the network (cell D12), and finally Excel Solver must only assign positive values (hence the constraint that cells D9, D10, and D11 must be greater than or equal to zero). The result of applying Excel Solver is shown in Figure 12.17b. Note that the individual path travel times are all 30.22 min and that the total system cost is 1511 veh-min.

(e) Note that the travel time for each path is the same as 30.2 such that $T_{ij1} = T_{ij2} = \cdots = T_{ijk}$. Removal of this constraint from the problem (e.g., eliminating the requirement that cells C9, C10, and C11 have the same value) reduces the system cost to 1388 veh-min. Notice that the paths have unequal travel times but that the total system cost is lower than in part (d).



	A	B	C	D	E	F
1	Link	Link Free Flow Time	Link Capacity	Link Volume	Link Congested time	Link Cost
2	L13	5	20	31.2	17.1	534
3	L14	20	200	18.8	20.2	380
4	L34	3	50	5.7	3.0	17
5	L42	4	20	24.6	10.0	247
6	L32	5	20	25.4	13.1	333
7						1,511
8	Travel From Zone 1 to 2	Paths	Path Time	Path Volume	Path Cost	
9		L14,L42	30.2	18.8	569	
10		L13,L34,L42	30.2	5.7	173	Link Conge
11		L13,L32	30.2	25.4	768	
12			Total	50	1,511	

Figure 12.17b Deterministic User Equilibrium Assignment in Excel (Solution)

SOURCE: Created using Microsoft Office

Results of Deterministic User Equilibrium Assignment

Link	*Link Free Flow Time*	*Link Capacity*	*Link Volume*	*Link Congested Time*	*Link Cost*
L13	5	20	31.2	17.1	534
L14	20	200	18.8	20.2	380
L34	3	50	5.7	3.0	17
L42	4	20	24.6	10.0	247
L32	5	20	25.4	13.1	333
Total system cost					**1511**

12.6 OTHER METHODS FOR FORECASTING DEMAND

This chapter has described how travel demand is forecast by using the four-step procedure of trip generation, distribution, mode choice, and traffic assignment. There are many variations within each of these steps, and the interested reader should refer to the references cited for additional details. Furthermore, there are other methods that can be used to forecast demand. Some of these are described in the following section.

12.6.1 Trend Analysis

This approach to demand estimation is based on the extrapolation of past trends. For example, to forecast the amount of traffic on a rural road, traffic count data from previous years are plotted versus time. Then, to compute the volume of traffic at some future date, the *trend line* is extrapolated forward, or else the average growth rate is used. Often a mathematical expression is developed using statistical techniques, and quite often a semi-log relationship is used. Although simple in application, trend line analysis has the disadvantage that future demand estimates are based on extrapolations of the past, and thus no allowance is made for changes that may be time-dependent. For example, rather than presuming that trip generation rate trends will continue to increase as they have in the past, understanding the underlying causes of increased trip generation (e.g., wealth, employment changes, and land-use patterns) may be more productive.

12.6.2 Demand Elasticity

Travel demand can also be determined if the relationship between demand and a key service variable (such as travel cost or travel time) is known. If V is the volume (demand) at a given service level X, then the elasticity of demand, $E(V)$, is the percent change in volume divided by the percent change in service level, as shown in Eq. 12.16.

$$E(V) = \frac{\%\Delta \text{ in } V}{\%\Delta \text{ in } X} \tag{12.16}$$

$$E(V) = \frac{\Delta V/V}{\Delta X/X} = \frac{X}{V}\frac{\Delta V}{\Delta X}$$

Example 12.22 Forecasting Transit Ridership Reduction Due to Increase in Fares

To illustrate the use of demand elasticity, a rule of thumb in the transit industry states that for each 1 percent increase in fares, there will be one-third of 1 percent reduction in ridership. If current ridership is 2000/day at a fare of 30¢, what will the ridership be if the fare is increased to 40¢?

Solution:

In this case, $E(V) = 1/3$ and, substituting into Eq. 12.16,

$$\frac{1}{3} = \frac{X}{V}\frac{\Delta V}{\Delta X} = \frac{30}{2000} \times \frac{\Delta V}{10} \quad \text{or} \quad \frac{30\Delta V}{(2000)(10)}$$

$$\Delta V = 222.2 \text{ passengers/day}$$

Thus, the ridership will decline to 2000 − 222 = 1778 passengers/day.

Using Midpoint Arc and Linear Arc Elasticities

The principal advantage of using elasticity methods for demand estimation is that elasticity constants are often available in published sources. There are several methods that can be used to determine the elasticity constant. In addition to the linear formulation illustrated in Example 12.22, two additional methods have been used: (1) *midpoint (for linear) arc elasticity* and (2) *log arc elasticity*. Midpoint arc elasticity is computed as shown in Eq. 12.17. Log arc elasticity is computed as shown in Eq. 12.18.

$$\text{Midpoint arc elasticity, } e_M = \frac{\Delta D/D_{avg}}{\Delta X/X_{avg}} \tag{12.17}$$

$$\text{Log arc elasticity, } e_L = \frac{\log D_o - \log D_n}{\log X_o - \log X_n} \tag{12.18}$$

where

D_o = the original demand level
D_n = the new demand level
X_o = the original service level

X_n = the new service level
$AD = D_o - D_n$
$D_{avg} = (D_o + D_n)/2$
$AX = X - X_n$
$X_{avg} = (X_o + X_n)/2$

Example 12.23 Computing the Midpoint Arc and Log Arc Elasticity

A transit system has increased its service route mileage by 110 percent. Following this increase in service miles, demand increased by 28 percent.

(a) Find the midpoint arc elasticity and the log arc elasticity.
(b) What might be the explanation for the elasticity values obtained?

Solution:

(a) Find the midpoint arc elasticity and the log arc elasticity.

$$D_o = 1.00$$
$$D_n = 1.28$$
$$X_o = 1.00$$
$$X_n = 2.10$$
$$\Delta D = D_o - D_n = 1.0 - 1.28 = -0.28$$
$$\Delta X = X_o - X_n = 1.0 - 2.10 = -1.10$$
$$X_{avg} = (X_o + X_n)/2 = (1.00 + 2.10)/2 = 1.55$$

Midpoint arc elasticity is obtained from Eq. 12.17.

$$\frac{\Delta D / D_{avg}}{\Delta X / X_{avg}} = \frac{-0.28/1.14}{-1.10/1.55} = 0.35$$

Log arc elasticity is obtained from Eq. 12.18.

$$\frac{\log D_o - \log D_n}{\log X_o - \log X_n} = \frac{\log(1.0) - \log(1.28)}{\log(1.0) - \log(2.1)} = 0.33$$

(b) What might be the explanation for the elasticity values obtained?

There are several possible reasons for the relatively low change in demand given a significant increase in system mileage. Among these are:

- Most of the transit patrons had no other modal options available such that the market for transit was fixed.
- In the process of more than doubling system mileage, the transit routes were restructured, although the original routes had greater ridership.
- The buses were unreliable, ranging in age from 6 to 21 years, thus limiting the effect of expanded mileage.

Geographic Variations in Midpoint Arc Elasticities

Midpoint arc elasticities that show the responsiveness of travelers to fare increases are shown in Table 12.26. The values in the table demonstrate that there is variation in elasticities by geographical area. For example, a fare increase of 10 percent will reduce the ridership by 32 percent in Spokane, Washington; but only by 14 percent in San Francisco, California. Table 12.26 also shows that peak hour travel is less sensitive to fare changes than nonpeak travel, which is due to a larger proportion of work trips in the peak hour.

Table 12.26 Bus Fare Midpoint Arc Elasticities for Urban Areas

Urban Area	*Peak Bus Fare Elasticity*	*Off-Peak Bus Fare Elasticity*
Spokane, Washington	−0.32	−0.73
Grand Rapids, Michigan	−0.29	−0.49
Portland, Oregon	−0.20	−0.58
San Francisco, California	−0.14	−0.31
Los Angeles, California	−0.21	−0.29

SOURCE: Linsalata, J., and Pham, L. H., *Fare Elasticity and Its Application to Forecasting Transit Demand.* American Public Transit Association, Washington, D.C., 1991.

Example 12.24 Using Midpoint Arc Elasticity Data to Forecast Demand

The current peak ridership for urban area X is 1000, the current fare is \$1, and a proposed new fare is \$2.

Estimate the future peak ridership of this community using published elasticity values for Portland, OR.

Solution: Use Eq. 12.17 to compute the midpoint arc elasticity.

$$e_M = \frac{\Delta D / D_{avg}}{\Delta X / X_{avg}}$$

$$e_M = \frac{(D_o - D_n)/[(D_o + D_n)/2]}{(X_o - X_n)/[(X_o + X_n)/2]}$$

Rearrange the expression for e_M to solve for D_n.

$$D_n = \frac{(e_M - 1)(X_o D_o) - (e_M + 1)(X_n D_o)}{(e_M - 1)(X_n) - (e_M + 1)(X_o)}$$

The data for city X are

$$e_M = -0.20 \text{ (from Table 12.26)}$$
$$X_o = \$1$$
$$X_2 = \$2$$
$$D_o = 1000$$

Use Eq. 12.17.

$$D_n = \frac{(-0.20-1)(\$1(1000)) - (-0.20+1)(\$2(1000))}{(-0.20-1)(\$2) - (-0.20+1)(\$1)}$$

$$D_n = \frac{-1200-1600}{-2.4-0.8} = 875$$

Thus 875 riders (a decrease of 125) are estimated if the fare is increased from \$1 to \$2. If the value (−0.20) was a log arc rather than midpoint arc elasticity, the forecasted demand would have been 871 passenger trips. Either result is within estimated accuracy, which was also the case for the results in Example 12.23. Thus, both methods are similar with regard to results obtained. Computations for the log arc method are left for the reader to verify using the expression $D_n = D_o(X_n/X_o)^{-0.20}$.

12.7 ESTIMATING FREIGHT DEMAND

This section discusses procedures available for estimating freight traffic. The first approach is based on observation of vehicle flows. The second method is based on the use of commodity flow data.

12.7.1 Using Trend Analysis of Freight Vehicle Travel

The forecasting methods presented in this chapter for passenger travel are equally suitable for freight travel forecasting. At the state level, freight flows may be computed using

Example 12.25 Estimating Truck Travel Demand Based on Trend Data

It has been observed that interstate truck traffic has been growing at an average rate of 3 percent annually for the past 20 years. Currently, truck ADT volumes are 4000 veh/day.

(a) Provide an estimate of truck traffic 5 years hence if the past 20 years of growth is expected to continue.

(b) Comment on the usefulness of this method of forecasting freight flows.

Solution:

(a) Use the following equation:

$$V_5 = V_o(1+i)^n$$

where

V_o = current truck volume
V_5 = truck volume in 5 years
i = growth rate
n = number of years

$$V_5 = 4000\,(1+0.03)^5 = 4637 \text{ trucks/day}$$

(b) Comment on the usefulness of this method.

This estimate may be useful for preliminary sketch planning purposes, especially when little or no other information is available.

Table 12.27 Sketch Methods for Estimating Commodity Flows

Method	*Use When*	*Advantages*	*Disadvantages*
Fratar method	An older zone-to-zone commodity flow table is available and simply needs to be updated	Does not require information about impedances between travel zones	Requires a prior commodity flow table Cannot address changes in travel impedance
Gravity model	A new commodity flow table is generated and impedances between zones are available	Does not require an existing commodity flow table	Requires a well-calibrated impedance measure based on time and cost for various commodities
Logit model	Shippers' choices for O–D flows can be represented as a utility function	May allow for representation of specific policy choices within the model	Requires a calibrated utility function that is rare in freight forecasting

the trend analysis of traffic flow that forecasts freight movements by truck and rail or may be determined directly from observations of prior goods movement activity.

12.7.2 Using Commodity Flow Data to Forecast Freight Vehicle Travel

A more productive approach for estimating freight travel is to base forecasts on commodity travel. Once commodity flows are estimated, they can be converted to vehicle flows. This conversion must be based on the payload for each mode (which will vary by commodity), the extent to which there are empty (return) trips, and the number of days per year that the mode will be operable. Table 12.27 compares the advantages and disadvantages of the principal forecasting methods described earlier in this chapter and suggests when their use is appropriate.

To illustrate, one state study found that for lumber, pulp, and paper categories, 5 percent of the goods were moved by light truck (less than 64,000 pounds gross vehicle weight [GVW]), 47 percent by medium truck (64,000 to 80,000 pounds GVW), and 48 percent by heavy truck (over 80,000 pounds GVW). For all three types, it was found that 83 percent of the trucks were loaded. Data for these conversions may be obtained from the literature (e.g., one study suggested a rail car may be assumed to have a 130,000-pound shipment) or from freight-related data sources such as the U.S. Census Bureau's *Vehicle Inventory and Use Survey* (VIUS) (for trucks) and the *Rail Carload Waybill Sample* (for rail).

12.8 TRAFFIC IMPACT STUDIES

The purpose of a *traffic impact study* or a *transportation impact analysis* is to determine the impact on traffic and the need for transportation services in the immediate vicinity of a proposed development or as the result of a change in zoning designation. Impact studies are conducted for a variety of reasons. These include: (1) to determine whether a landowner should be granted permission to develop a given parcel of land that may require rezoning from its current designated use to the use proposed by the developer (e.g., from agricultural to commercial), (2) to permit a landowner to subdivide the property into two or more parcels such that a portion of the subdivision may be used for additional high-density development, (3) to obtain a building permit, (4) to grant direct access from a development to the transportation network, (5) to evaluate the effects of a county-initiated rezoning plan, or (6) to create a special-use tax district.

A traffic impact study provides quantitative information regarding how the construction of a new development will change transportation demand. Consider a proposed 100-dwelling unit subdivision from which each household generates 10 vehicle trips/day. An impact estimate of trip generation from this proposed subdivision is computed as (10)(100) = 1000 veh/day that will be added to the current highway network. The study can also quantify the change in demand for other modes of transportation, and it can compute the increase in traffic delay and estimate the cost of necessary improvements to mitigate these effects. This type of data is found in the Institute of Transportation Engineers publication, *Trip Generation.*

The primary difference between a traffic impact study and a regional travel demand forecast is the geographic scope involved. A regional travel demand forecast is suitable for large metropolitan areas containing hundreds or thousands of zones. A traffic impact study is intended to forecast the demand created by a specified neighborhood that may encompass an area smaller than a single traffic analysis zone.

Accordingly, traffic impact studies differentiate trips made solely for the purposes of reaching the new development *(primary trips)* and trips where travel to or through the development is part of an existing trip (either *pass-by trips* or *diverted linked trips).* For example, if a new restaurant is built adjacent to an arterial highway, restaurant patrons who otherwise would not make the trip to this parcel of land (e.g., a family leaves home, visits the restaurant, and returns home) are now making primary trips to the site. Patrons who already use the arterial and choose to stop at the new restaurant, such as a person traveling home from work, are making a pass-by trip. Patrons who make a change in their route, such as a person traveling home from work but who otherwise would use the adjacent interstate, are making a diverted linked trip.

Example 12.26 Impact of Rezoning on Intersection Delay

A county wishes to consider rezoning several land parcels adjacent to a reconstructed interchange. The county is interested in knowing how the change in zoning from residential to commercial would increase development and cause increased vehicle delay at a nearby signalized intersection. Figure 12.18 depicts the study area and shows the land parcels A, B, C, D, and E, as well as the critical intersections, I_1, I_2, I_3, I_4, and I_5 that could be affected by developing these parcels. The traffic impact study consists of the following steps:

1. Collect existing traffic counts at each intersection.
2. Determine the development permitted under commercial zoning.
3. Determine the number of trips generated by each type of development.
4. Add new trips generated by the development to existing trips.
5. Determine the vehicle delay at each intersection.

It is expected that an electronics superstore that is 44,000 ft^2 in area will be constructed within area E, near intersection I_1 shown in Figure 12.18. A peak hour trip generation rate of 4.5 vehicle trips/1000 ft^2 gross floor area is used for this type of development. The calculation below forecasts a total of 198 veh/peak hr, of which 51 percent

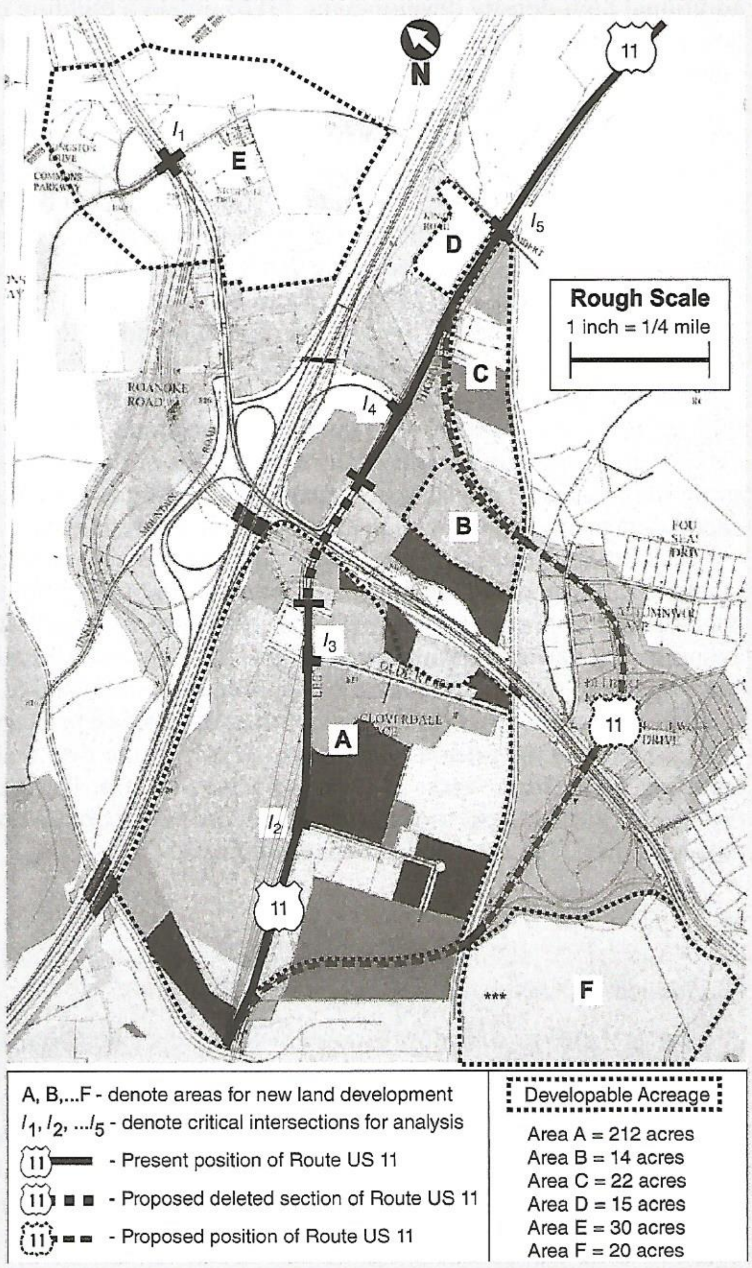


Figure 12.18 Sample Study Area: Land Parcels and Critical Intersections

Note: All alignments, zoning, and acreage estimates are tentative and subject to change. Colors denote different zoning at present; however, in the future, all areas will be rezoned B2. The "deleted" section of U.S. 11 refers to the fact that existing U.S. 11 will be split into two dead-end sections terminating on either side of Interstate 81.

SOURCE: J.S. Miller and A.K. Goswami, *Providing Technical Assistance in an Environment of Uncertainty: A Case Study in Coordinating Transportation and Land Use*, Virginia Transportation Research Council, Charlottesville, VA, February 2005

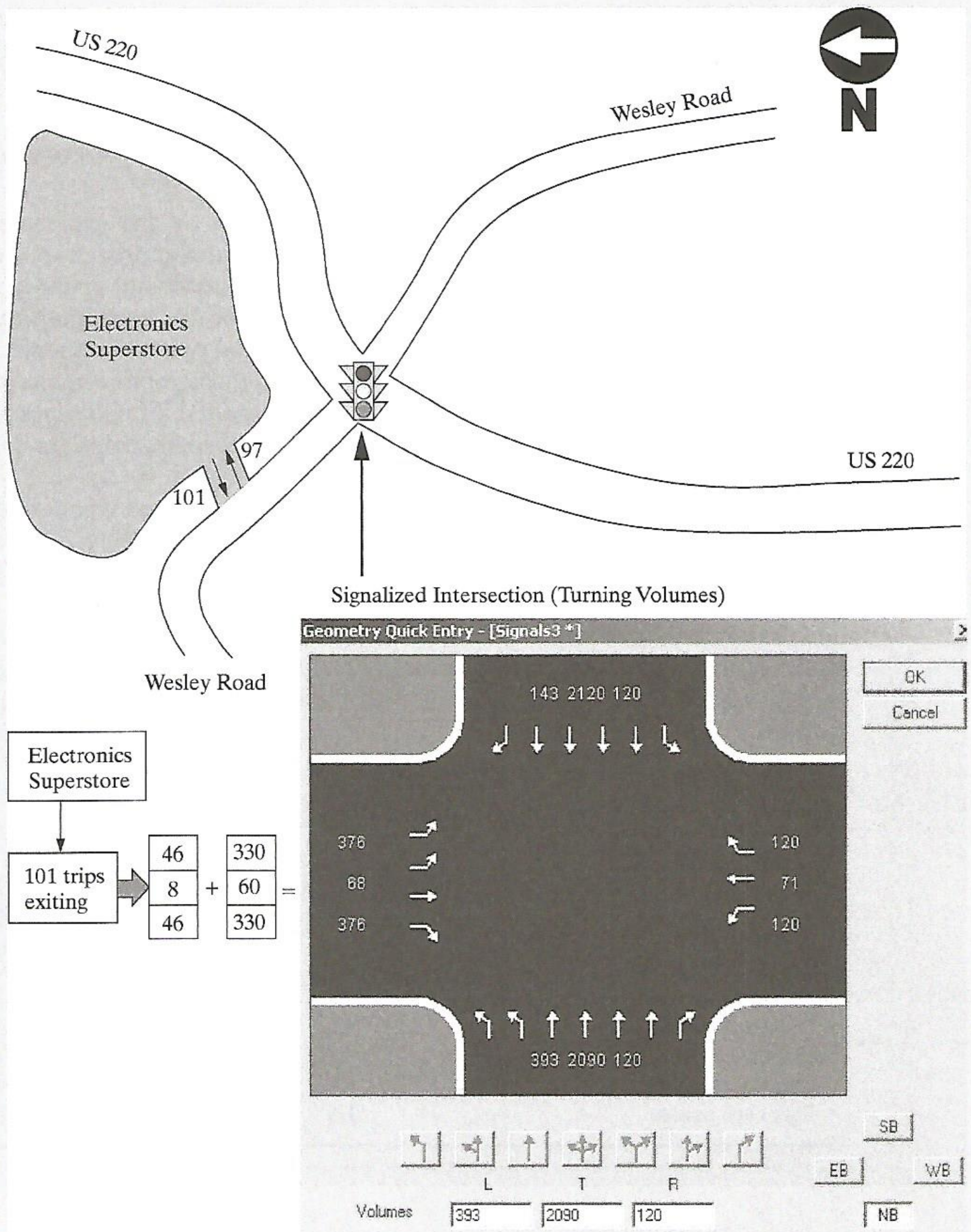


Figure 12.19 Area E, Intersection I_1

SOURCE: J.S. Miller and A.K. Goswami. *Providing Technical Assistance in an Environment of Uncertainty: A Case Study in Coordinating Transportation and Land Use.* Virginia Transportation Research Council, Charlottesville, VA, February 2005 will exit the store and 49 percent will enter during the evening peak hour (based on ITE recommended values). Accordingly, (0.51)(198) or 101 vehicles exit from the store parking lot during the evening peak hour.

$$\text{Trips generated} = 44{,}000 \text{ square feet}\left(\frac{4.5 \text{ trips}}{1000 \text{ square feet}}\right) = 198 \text{ vehicle trips}$$

The addition of primary vehicle trips generated by the superstore to existing vehicles on the network is illustrated with the eastbound approach of the intersection in Figure 12.19. For the 101 exiting vehicles and the eastbound approach for intersection I_1, observations suggest that 8 percent would use the eastbound through movement and 46 percent would use the eastbound left and right movements. Accordingly, (0.08)(101) or 8 vehicles are added to the existing through movement of 60 vehicles, and (0.46)(101) or 46 vehicles are added to the eastbound left and right movements of 330 vehicles. In this analysis, assume that no pass-by or linked trips are destined for the superstore.

Highway Capacity Software (HCS), the computerized version of the *Highway Capacity Manual 2010,* is used to estimate the vehicle delay at the traffic signal. Table 12.28 shows that the delay for the superstore is about 34 sec/veh. Because other land uses will be permitted, and the parcel is configured so the superstore can be developed east or west of the intersection, Table 12.28 also shows the delay values for several additional uses of area E and demonstrates that (even with the same type of zoning) there is variability in delay due to the wide variety of land-use types that are permitted within a given zoning category.

Table 12.28 Intersection Delay as a Result of Single-Parcel Development

	Results for Area E	
Land Development	*Intersection Delay at I_1 If Parcel is West of I_1 (sec/veh)*	*Intersection Delay at I_1 If Parcel is East of I_1 (sec/veh)*
No development	29.7	29.7
Electronics superstore	34.5	33.2
Nursing home	30.2	29.7
Quality restaurant	38.4	37.4
Day care center	51.5	67.3

12.8.1 Data Requirements for a Traffic Impact Study

Tables 12.29 and 12.30 summarize the data elements needed for a traffic impact study. Table 12.29 identifies those data elements that will come from the governmental units that have authority over land development. Examples are the county planning commission and the local land development office. Table 12.30 identifies those elements that are available from the administrative unit responsible for the transportation system; such units may be the city, county, or state traffic engineering department and/or a consultant hired to obtain this information as part of a special study.

Not all data elements will be available, and thus assumptions may be necessary to complete a traffic impact study. Some data are easily obtained, while acquiring other

Table 12.29 Data Available from Governmental Units with Authority over Land Development

Data Element	*Example*	*Effort Level*
Zoning according to county ordinance	Commercial, which allows community shopping and service businesses	Low
Maximum floor area ratio (FAR)[a]	0.40	Low
Maximum allowable density	17,500 ft^2/acre	Low
Net acreage land encompassed by parcel	30 acres	Medium
Developable acreage as opposed to net acreage	12 acres	Medium
Specific land uses to be built on parcel, such that they are compatible with ITE land use codes	Office building, furniture store, and electronic superstore	High
Size of development to be constructed on parcel	30,000 ft^2 of office space, 30,000 ft^2 for furniture store, and 20,000 ft^2 for electronic superstore	High

[a]The FAR is the ratio of square footage of development to square footage of open land. For example, a FAR of 0.40 means that 1 acre of land (43,560 ft^2) may have no more than 17,424 ft^2 of development since $0.40 \times 43,560 = 17,424$.

Table 12.30 Data Available from Sources Responsible for the Transportation System

Data Element	*Example*	*Effort Level*
List of affected walkways and bikeways	There is an Appalachian Trail crossing in what is now an urban area	Low
Number of through lanes and posted speed limits	4 total (two in each direction) Speed limit of 45 mi/h	Low
24-hour volumes (Average Daily Traffic or ADT)	U.S. 220 has 21,897 vehicles per day between I-81 and Route 779 North of Daleville (both directions)	Low
Traveler characteristics (basic)	*Walking:* Visual observation suggests that most persons in the area are currently drivers, although there is some pedestrian activity *Biking:* None observed *Transit:* No fixed-route public transportation currently serves area	Low
Peak hour directional volumes	U.S. 220 p.m. peak = 1264 veh/h NB and 995 veh/h SB	Medium
Truck volumes	US 220 p.m. peak NB: 2.3% US 220 p.m. peak SB: 4.8%	Medium
Traveler characteristics (advanced)	*Walking:* Pedestrian counts of 20/h on U.S. 220 *Biking:* 5 crossings/h at intersection of U.S. 220 and Wesley Road *Transit:* No fixed route public transportation, but potential for future service exists as result of *x* industries	High
Peak hour turning movements and cycle lengths of new signals	For Wesley Road (Route 653) and U.S. 220, turning movements are not directly available. However, it is known that only 653 veh/day used Wesley Road between U.S. 220 and Route 1071 (Cedar Ridge Road)	High

data may involve considerable effort in both time and cost. Tables 12.29 and 12.30 show three levels of data collection effort: low, medium, and high, defined as follows.

- *Low-effort level* data are those that can be obtained with a minimal time investment and that yield order of magnitude comparisons only.
- *Medium-effort level* data require more time to obtain but can give more precise predictions.
- *High-effort level* data are quite time-consuming to obtain and are often only available when specific development proposals are being considered.

Table 12.31 illustrates how specific data may increase the precision of the results for a traffic impact study using Figure 12.17 as an illustration. For example, suppose that the county desires to know how a proposed development will increase vehicle delay during the evening peak hour. Table 12.31 shows that with low-effort data, such as knowledge of the type of zoning for the parcel, a delay of between 29 and 128 sec/veh is obtained. The reason for this large range in delay is that commercial zoning permits a wide variety of land developments, all exhibiting different trip generation rates. However, if the county knows the exact size and type of development that will be proposed, this data narrows the range to between 51 and 53 seconds.

In practice, other factors besides those discussed here, such as variation in signal timing and fluctuations in existing traffic, will increase the range of the estimates.

Although Table 12.31 illustrates the general principle that better data improves estimates, it is not always necessary to obtain such data. In any traffic impact study, the level of effort made to obtain data should be consistent with the level of precision needed for a study.

Table 12.31 Impacts of Better Land-Use Data for Peak Hour Intersection Delay Estimates

Data Extent	*Low Effort*	*High Effort*
Data elements	Commercial zoning; building size 1 to 3 acres	There will be 216,000 ft^2 of office space, 9000 ft^2 for quality restaurant, and 37,000 ft^2 electronic superstore
Reason for uncertainty	Commercial zoning permits wide range of land uses (e.g., motel, bank, restaurant, office building, school), mean trip generation rates range from 0.5 to 55 trips per 1000 ft^2 and size unknown	Exact sizes of buildings known
Range of values for trips generated	The site could have a 5000 ft^2 furniture store that generates 2.25 trips or a 13,000 ft^2 drive-in bank that generates 700 trips	This combination of office, restaurant, and retail uses will generate 518 to 556 trips
Range of delay estimates at intersection	Accordingly, mean delay varies from 29.5 to 128.2 sec/vehicle	Accordingly, mean delay varies from 51.9 to 53.1 sec/vehicle

12.9 SUMMARY

The process of forecasting travel demand is necessary to determine the number of persons or vehicles that will use a new transportation system or component. The methods used to forecast demand include extrapolation of past trends, elasticity of demand, and relating travel demand to socioeconomic variables.

Urban travel demand forecasting is a complex process, because demand for urban travel is influenced by the location and intensity of land use; the socioeconomic characteristics of the population; and the extent, cost, and quality of transportation services.

Forecasting urban travel demand involves a series of tasks. These include population and economic analysis, land-use forecasts, trip generation, trip distribution, mode choice, and traffic assignment. The development of computer programs to calculate the elements within each task has greatly simplified implementation of the demand forecasting process. The inability to foresee unexpected changes in travel trends, of course, remains a part of demand forecasting. Travel demand forecasts are also required for completing an economic evaluation of various system alternatives. This topic is described in the next chapter.

PROBLEMS

12-1 Identify and briefly describe the two basic demand forecasting situations in transportation planning.

12-2 Identify the three factors that affect demand for urban travel.

12-3 Define the following terms:

- **(a)** home-based work (HBW) trips
- **(b)** home-based other (HBO) trips
- **(c)** non-home-based (NHB) trips
- **(d)** production
- **(e)** attraction
- **(f)** origin
- **(g)** destination

12-4 Given cross-classification data for the Jeffersonville Transportation Study Area, develop the family of cross-classification curves.
Determine the number of trips produced (by purpose) for a traffic zone containing 500 houses with an average household income of $35,000. (Use high = $55,000; medium = $25,000; low = $15,000.)

	HH (%)			*Autos/HH (%)*				*Trip Rate/Auto*				*Trips (%)*		
($) Income	*High*	*Med*	*Low*	*0*	*1*	*2*	*3*	*0*	*1*	*2*	*3+*	*HBW*	*HBO*	*NHB*
10,000	0	30	70	48	48	4	0	2.0	6.0	11.5	17.0	38	34	28
20,000	0	50	50	4	72	24	0	2.5	7.5	12.5	17.5	38	34	28
30,000	10	70	20	2	53	40	5	4.0	9.0	14.0	19.0	35	34	31
40,000	20	75	5	1	32	52	15	5.5	10.5	15.5	20.5	27	35	38
50,000	50	50	0	0	19	56	25	7.5	12.0	17.0	22.0	20	37	43
60,000	70	30	0	0	10	60	30	8.0	13.5	18.0	23.0	16	40	44

12-5 Given: A person travels to work in the morning and returns home in the evening. Determine productions and attractions generated in the work and residence zones.