traveller can become better off by finding a route with travel times lower than those defined by an equilibrium, or an equal travel time, assignment (Wardrop, 1952). Equilibrium is an important concept, which is best clarified by studying the following simple example.

1.4 Land-use–Transport Interaction—an Example

Two zone centroids are connected by a main arterial road (route 1) and an alternative route along local streets (route 2). The focus for illustrative purposes is on one trip interchange only, between zones 1 and 2. Usually, of course, there will be many of these. Zone 1 is a residential area with 30,000 people and zone 2 is an employment centre with 10,000 jobs. In the following equations the measure of land-use intensity is $L_{o1} = 30{,}000$ and $L_{d2} = 10{,}000$. The equations and parameters below form the systems model of land-use–transport interaction. It is assumed that all travellers use one mode.

Accessibility

$$H_{12} = L_{d2}/T_{12} \tag{1.10}$$

where

H_{12} = the accessibility of zone 1 to the employment opportunities located in zone 2 in jobs reached per minute;

T_{12} = travel time in minutes from zone 1 to zone 2.

(More generally, later, it will be shown that T_{12} may be raised to some power.)

Traffic Generation

$$Q_{p1} = 0.4\,L_{o1} \tag{1.11}$$

$$Q_{a2} = 1.0\,L_{d2} \tag{1.12}$$

where

Q_{p1} = peak-hour number of vehicle trips produced by zone 1;

Q_{a2} = peak-hour number of vehicle trips attracted to zone 2;

L_{o1} = land-use activity of zone 1 (i.e. population);

L_{d2} = land-use activity of zone 2 (i.e. employment).

Spatial Pattern of Traffic

$$Q_{12} = 0.001\,Q_{p1}.Q_{a2}/T_{12} \tag{1.13}$$

where

Q_{12} = peak-hour number of vehicle trips from zone 1 to zone 2.

Flow-dependent Travel Times

$$T_{k(Q)} = T_{k(o)} \cdot \frac{1 - (1 - \lambda)\, Q_k / Q_{max(k)}}{1 - Q_k / Q_{max(k)}} \qquad (1.14)$$

where

$T_{k(Q)}$ = the travel time in minutes on route k at vehicular flow Q;
$T_{k(o)}$ = the travel time in minutes on route k at 'zero' traffic flow;
λ = level of service parameter associated with each route;
Q_k = traffic flow (vehicles per hour) on route k; and
$Q_{max(k)}$ = saturation flow (vehicles per hour), or transport capacity, of route k.

Table 1.1 gives the transport supply characteristics for the two roads.

Table 1.1: Transport Supply Characteristics for a Simple Network

Transport Supply Characteristics	Route	
	$k = 1$	$k = 2$
Length in kilometres	16	19
'Zero-flow' travel time in minutes, T_o	24	38
Level of service parameter, λ	0.3	1.0
Saturation flow, Q_{max} in veh/hour	3,000	2,000

1.4.1 The Problem and Solution

The problem is to find the equilibrium solution to the system of equations. This involves calculating: (a) the total peak-hour traffic flow from zone 1 to zone 2; (b) the amount of traffic using each route, assuming that traffic 'satisfies' Wardrop's principle of an equal travel time assignment; and (c) the inter-zonal travel time which will be identical on either route. The problem may be solved by a graphical analysis or by algebra.

The steps in the graphical approach are as follows. From equation (1.11) the zonal amount of traffic produced by zone 1 is:

$$Q_{p1} = 0.4 \times 30{,}000 = 12{,}000 \text{ vehicles per peak hour.}$$

From equation (1.12) the zonal amount of traffic attracted to zone 2 is:

$$Q_{a2} = 1 \times 10{,}000 = 10{,}000 \text{ vehicles per peak hour.}$$

Substituting these into equation (1.13) the inter-zonal pattern of traffic is:

$$Q_{12} = 120{,}000/T_{12} \text{ vehicles per peak hour.} \qquad (1.15)$$

The function for the traffic flow-dependent travel times on route 1 is obtained by substituting the appropriate values from Table 1.1 into equation (1.14). Simplifying the expression:

$$T_{1(Q)} = 24\,(3{,}000 - 0.7\,Q_1)/(3{,}000 - Q_1) \text{ minutes.} \qquad (1.16)$$

The traffic flow-dependent travel times for route 2 are found in an identical way, and simplification gives:

$$T_{2(Q)} = 76{,}000/(2{,}000 - Q_2) \text{ minutes.} \qquad (1.17)$$

Equations (1.15), (1.16) and (1.17) are solved for a range of values of travel time and traffic flow substituted into the right-hand side and plotted graphically in Figure 1.5. The vertical axis of the graph is travel time in minutes and the horizontal axis is traffic flow in vehicles per hour. The upward-sloping flow-dependent curves plotted separately for the two routes indicate that travel times increase with additional traffic, whereas the downward-sloping curve (dashed line) for inter-zonal traffic demand decreases with an increase in travel time. The traffic flow-dependent travel times for the transport corridor are the sum of the curves for route 1 and route 2, as shown by the dotted and dashed line.

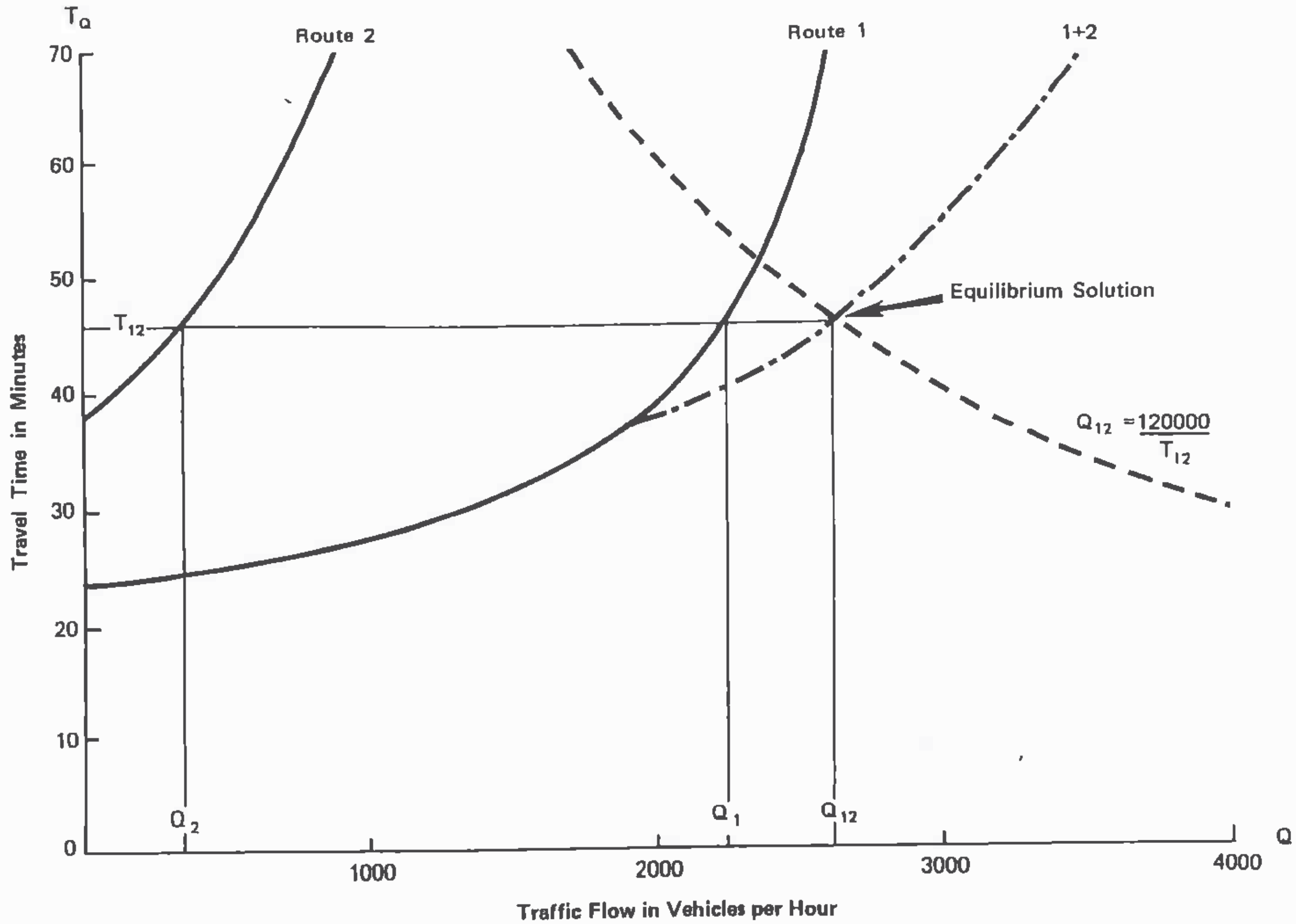
The point where the traffic flow-dependent travel time curve for the *transport corridor* intersects the inter-zonal traffic demand curve represents the equilibrium solution. From the graph the value obtained is a total flow of 2,610 vehicles per hour at a travel time of 46 minutes. A line drawn from the equilibrium point parallel with the horizontal axis intersects the curves for route 1 and for route 2 to give a traffic flow of 2,260 vehicles per hour on route 1 and 350 vehicles per hour on route 2.

The steps leading to an algebraic solution follow. In order to simplify the equations traffic flows and saturation flows (transport capacity) are expressed in units of 1,000. Thus, equation (1.15) now becomes:

$$Q_{12} = 120/T_{12} \text{ vehicles per peak hour in 1,000s} \qquad (1.18)$$

equation (1.16) now becomes:

Figure 1.5: Graphical Solution to Land-use–Transport Interaction Problem–the Existing Situation



$$T_{1(Q)} = 24\,(3 - 0.7\,Q_1)/(3 - Q_1) \text{ minutes} \qquad (1.19)$$

and equation (1.17) now becomes:

$$T_{2(Q)} = 76/(2 - Q_2) \text{ minutes.} \qquad (1.20)$$

The overall objective with the algebraic method is to obtain from equations (1.18) to (1.20) a function which isolates one of the unknown variables (i.e. Q_1 or Q_2 or $T_{1(Q)}$ or $T_{2(Q)}$). Equation (1.18) can also be expressed as:

$$Q_1 + Q_2 = 120/T_{1(Q)} \qquad (1.21)$$

or as

$$Q_1 + Q_2 = 120/T_{2(Q)}. \qquad (1.22)$$

There is a choice of proceeding with either equation because for an equal travel time assignment:

$$T_{1(Q)} = T_{2(Q)}.$$

Equation (1.22) is chosen because the algebra is simpler. Substituting equation (1.20) into equation (1.22) and simplifying:

$$Q_1 = 3.158 - 2.579\,Q_2 \qquad (1.23)$$

$$Q_2 = 1.224 - 0.388\,Q_1 \qquad (1.24)$$

For an equal travel time assignment, equations (1.19) and (1.20) are equal. Substituting the value of Q_2 from equation (1.24) into equations (1.19) and (1.20):

$$\frac{24\,(3 - 0.7\,Q_1)}{3 - Q_1} = \frac{76}{2 - (1.224 - 0.388\,Q_1)}$$

Multiplying out the brackets, and collecting the terms together

$$-6.516\,Q_1^2 + 90.892\,Q_1 - 176.16 = 0 \qquad (1.25)$$

which is a quadratic equation of the general form:

$$a\,Q_1^2 + b\,Q_1 + c = 0$$

whose roots are solved in the standard way from:

$$Q_1 = \frac{-b \pm (b^2 - 4ac)^{1/2}}{2a}$$

either $Q_1 = 2.261$ or $Q_1 = 11.69$. The practical solution is $Q_1 = 2.261$ because the other solution gives a negative flow on route 2 which is mathematically outside the relevant boundary conditions of the problem.

From equation (1.24), $Q_2 = 0.348$; from equation (1.21) $T_1 = 46.0$; and from equation (1.22) $T_2 = 46.0$. The total amount of traffic from zone 1 to zone 2 is 2,609 vehicles per hour, with 2,261 vehicles per hour on route 1 and 348 vehicles per hour on route 2. Inter-zonal travel time is 46 minutes.

1.4.2 Transport Planning

The system equations are used to forecast the traffic implications of changes to the characteristics of transport supply. Consider, for example, two different plans: (a) close route 2 to through traffic, or (b) traffic engineering measures to improve the level of service on route 1. Students are encouraged to solve these problems by graphical and algebraic methods.

(1) Street closure of route 2: the closure of route 2 to through traffic reduces the capacity of the transport corridor and the plot of the flow-dependent travel times for route 1 is now the flow-dependent travel times for the transport corridor. Plotting the original inter-zonal traffic demand, the new equilibrium is a traffic flow of 2,370 vehicles per hour and a travel time of 51 minutes. The algebraic solution is simplified considerably because route 2 is eliminated from the analysis.

(2) Traffic engineering measures: plans to co-ordinate traffic signals along route 1 improve traffic flow, which is modelled by changing the level of service parameter from $\lambda = 0.3$ to $\lambda = 0.1$. The traffic flow-dependent travel times for route 1 are now calculated from:

$$T_{1(Q)} = 24\,(3{,}000 - 0.9\,Q_1)/(3{,}000 - Q_1) \text{ minutes.}$$

The traffic flow-dependent travel times on route 2 remain unchanged. The new equilibrium solution is a total traffic of 2,850 vehicles per hour, with 2,650 vehicles per hour on route 1 and 200 vehicles per hour on route 2. Travel time is 42 minutes. The algebraic approach is identical to the problem solved in section 1.4.1 except for a different equal travel time assignment.

1.4.3 Land-use–Transport Planning

A typical problem in long-term planning is when the city is expected to grow larger. Two situations are examined: land-use growth in zones 1 and 2, but with the characteristics of the transport network remaining unchanged; the same land-use growth, but with an urban motorway planned to link the zone centroids. Zone 1 is expected to accommodate a total of 40,000 people, and zone 2 is expected to provide a total of 12,000 job opportunities. An increase in land-use activity means that traffic generation increases. From equation (1.11) future trip production of zone 1 is:

$$Q_{p1} = 0.4 \times 40{,}000 = 16{,}000 \text{ vehicles per hour.}$$

From equation (1.12) future trip attraction of zone 2 is:

$$Q_{a2} = \quad 1 \times 12{,}000 = 12{,}000 \text{ vehicles per hour.}$$

From equation (1.13), the future inter-zonal traffic pattern is:

$$Q_{12} = 192{,}000/T_{12} \text{ vehicles per hour.}$$

This illustrative example shows a weakness of the very simple model used. Q_{12} obviously increases by a factor $\frac{40{,}000}{30{,}000} \times \frac{12{,}000}{10{,}000}$. If production had doubled and attraction had doubled, Q_{12} would have quadrupled. This contradicts common sense, but is resolved in a more refined version of the model to be presented in Chapter 3. This function is evaluated for a range of travel times and the results are plotted as in Figure 1.5 (the transport supply characteristics remain unchanged). The new equilibrium solution is 3,225 vehicles per hour, with 2,500 vehicles per hour on route 1 and 725 vehicles per hour on route 2. Travel times are 60 minutes. The algebraic approach is similar to section 1.4.1 except that equation (1.22) is replaced by:

$$Q_1 + Q_2 = 192/T_{2(Q)}.$$

Assuming the same growth in land-use activity, the introduction of a proposed motorway is likely to lower travel times and induce more trips to be made. The transport characteristics of the proposed motorway (which is not very direct between the two zones) are: a saturation flow of 4,000 vehicles per hour; a level of service parameter 0.05; a zero-flow travel time of 18 minutes; and a length of 24 kilometres.

Figure 1.6 plots separately the traffic flow-dependent travel times for the three routes, and combines them into an equivalent traffic flow-dependent travel time function for the transport corridor. The equilibrium solution is 5,570 vehicles per hour from zone 1 to zone 2. Travel time is 34.5 minutes. The assignment of traffic is 1,780 vehicles per hour on route 1, zero on route 2, and 3,790 vehicles per hour on route 3–the motorway.

An algebraic approach is not recommended here because it involves solving a cubic equation in terms of Q_3. The roots of a cubic equation may be solved by Cardan's method (Tranter, 1957, pp. 131-3), but the calculations are tedious.

1.4.4 A Summary

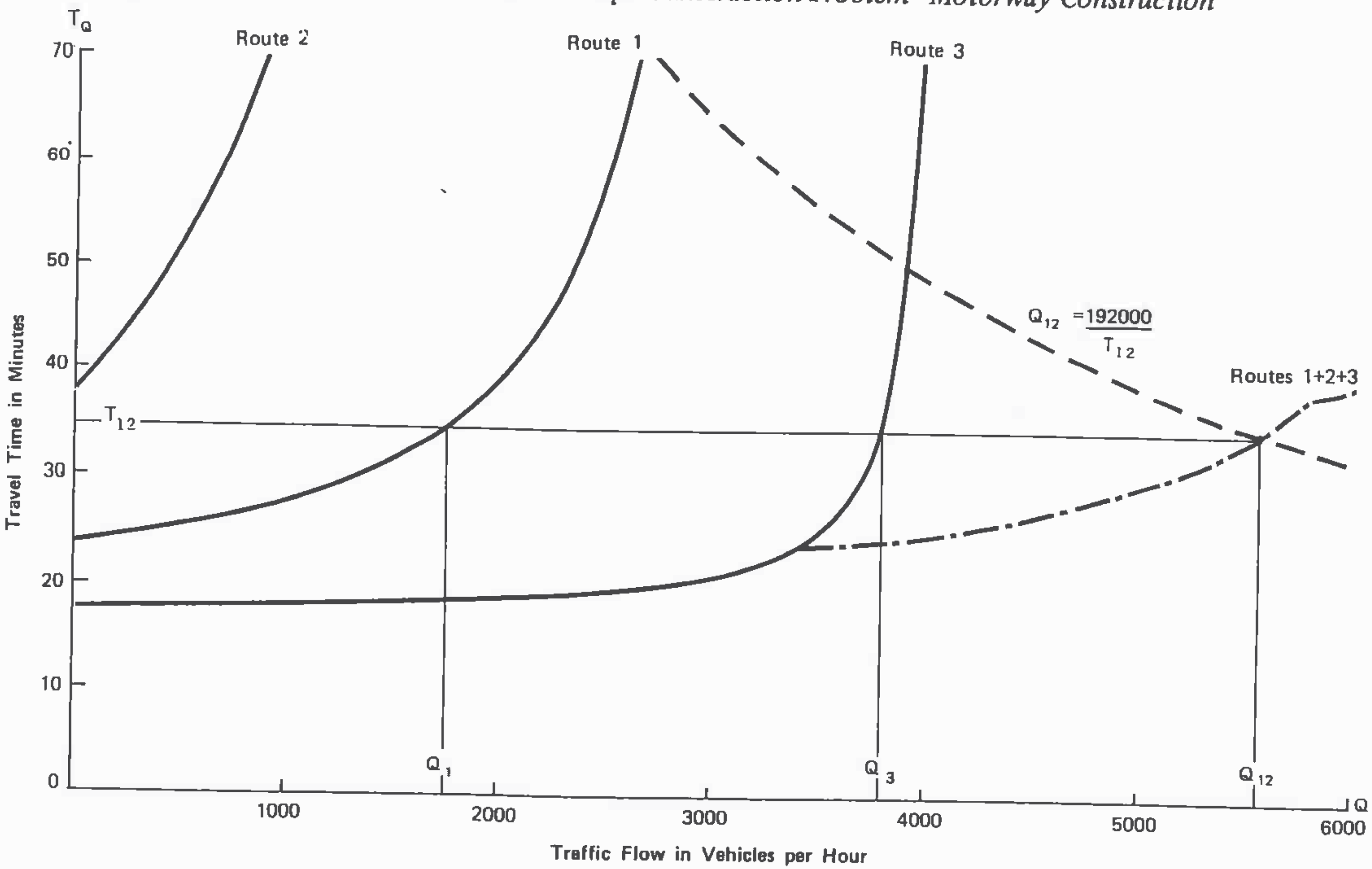
Changes to land use and transport alter the amount of traffic and the allocation of this traffic to the various parts of the transport network.

Table 1.2: Land-use–Transport Performance Measures

Alternative Situation	Accessibility (Jobs/Minute)	Travel Time (Minutes)	Transport Output (Vehicle Hours)
Existing situation	217	46	2,000
Street closure	196	51	2,015
Traffic engineering	238	42	1,995
Land-use growth	200	60	3,225
Growth plus motorway	348	34.5	3,203

Table 1.2 summarises some land-use–transport performance measures of each situation, such as accessibility to employment (calculated from equation (1.10)), inter-zonal travel time and transport output (total system travel time). The average rate at which jobs are reached in the existing situation is 217 jobs per minute. Street closures increase travel time so accessibility to employment is lower at 196 jobs per minute, whereas the traffic engineering measures reduce travel time, thereby increasing accessibility to 238 jobs per minute. Although the growth in job opportunities in zone 2 from 10,000 to 12,000 normally would improve accessibility to employment, the extra traffic and increased

Figure 1.6: Graphical Solution to Land-use–Transport Interaction Problem–Motorway Construction



travel times result in a low level of accessibility of 200 jobs per minute. However, the construction of a motorway dramatically increases accessibility to 348 jobs per minute.

In this example, insufficient information on the relevant costs and benefits is available to allow any assessment to be made of the alternative plans. Generally, plans are beneficial if there are travel time savings to road-users, and to those people induced to travel. One measure of road-user benefit is the change in consumer surplus, as explained in section 4.6.1. The traffic engineering scheme gives a total benefit to users of 182 hours of travel saved, whereas the street closure alternative produces user disbenefits of 208 hours of extra travel. Total user benefits of 1,869 hours saved are calculated for the motorway, compared with the situation of growth in land-use activity *without* any transport improvements.

1.5 Planning the Land-use–Transport System

For planning to be effective, there is a necessity to *understand* how an urban area 'works' in terms of land use, traffic and transport *before attempting to devise solutions.* The preparation of alternative land-use and transport plans must be based therefore on a sound understanding of the way that the urban area functions, how it might evolve over time, if left to develop alone, or most importantly, how it might react to different policies.

An important aspect of the systems planning approach is to predict what would happen if there was no forward planning—sometimes referred to as the 'do-nothing' solution. The consequences of doing nothing are well worth investigating because what is likely to happen in the ordinary course of events provides a yardstick against which to assess the advantages or otherwise of any deliberate planned intervention involving changes to land use and transport.

Following the systems approach, the way to proceed with such investigations is to use equations or quantitative relationships which govern the present behaviour of the system to predict the future behaviour of the system. The traffic implications of *alternative* land-use and transport plans are calculated with the aid of the systems equation by substituting the future, anticipated values of the land-use and transport variables, which are assumed to be under some degree of control by the planner.

When alternative plans are proposed, there is the difficult problem of determining which is the best course of action to follow. The systems approach suggests that plans must be evaluated with the original goals and objectives of the study in mind, but this is controversial because plans can be judged from different, and often competing, standpoints. In principle, it is a matter of measuring and weighing up the relevant costs and benefits to all sections of the community likely to be affected. The direct costs are related to constructing new roads or railways, widening old roads, installing traffic control devices, or providing public transport services; the indirect, or more intangible costs, are related to the adverse social and environmental effects of transport. The benefits accrue mainly to transport users in the form of lower travel times and costs, and improved accessibility.

1.6 Summary

This chapter has introduced the methodology of land-use–transport planning, and has argued that the systems approach provides a convenient framework to organise the component activities of the planning process. The main steps in this planning process are the formulation of goals and objectives, data collection, systems modelling, forecasting and the evaluation of alternative plans.

Emphasis has been given in this chapter to definitions of land use, traffic and transport and to rudimentary explanations of the way that the land-use–transport system works. This system is conceptualised as a transport network connecting land-use zones, with the theoretical interactions being accessibility, traffic generation, the spatial pattern of traffic, the choice of transport mode and route and traffic on the transport network. Each concept was described and represented by a systems model. The worked example was designed to show how system models can be used to calculate the traffic implication of planned changes to land use or to transport.

The practical applications of the systems approach to urban transport planning are described in detail in Part Two of this book. The next three chapters build upon the fundamentals: Chapter 2 elaborates on data collection and the analysis of transport supply; Chapter 3 expands on the analysis of urban travel demand; and Chapter 4 explains forecasting procedures and plan evaluation methods.