(ii) the type of structures built on the land (houses, factories, schools); and (iii) measures of the intensity of social and economic activities that take place on the land (population, employment, factory output, etc.).

(b) *Transport Supply*–forms the physical channels or links between land use. It includes (i) a variety of transport modes such as footpaths, roads, tramways, bus routes and railways; and (ii) the operational characteristics of these modes, such as travel times, costs or service frequencies.

(c) *Traffic*–is the joint consequence of land use *and* transport supply. Pedestrian and vehicular traffic represents the horizontal movement of people and goods over the transport network.

1.2 Understanding the System–a Description

Understanding how the system works is closely tied to the unravelling of the interactions between land use, traffic and transport supply. Five concepts are fundamental:

(a) accessibility;
(b) traffic generation;
(c) spatial pattern of traffic;
(d) selection of transport mode and route; and
(e) traffic on the transport network.

1.2.1 Accessibility

Accessibility is the concept which combines the geographical arrangement of land use and the transport that serves these land uses. Accessibility is a description of how conveniently land uses are located in relation to each other, and how easy or difficult it is to reach them via the transport network. Figure 1.2 presents a simple scheme for classifying accessibility. When many land-use activities are located close together and the transport connections are good, high accessibility is achieved. Conversely, when activities are located far apart and the transport connections are poor, low accessibility results.

Different geographical locations do not have the same accessibility because land-use activities are distributed unevenly and transport is neither of uniform coverage nor quality. Some land uses have a dispersed pattern (e.g. dwellings), others are more clustered (e.g. shops), and a

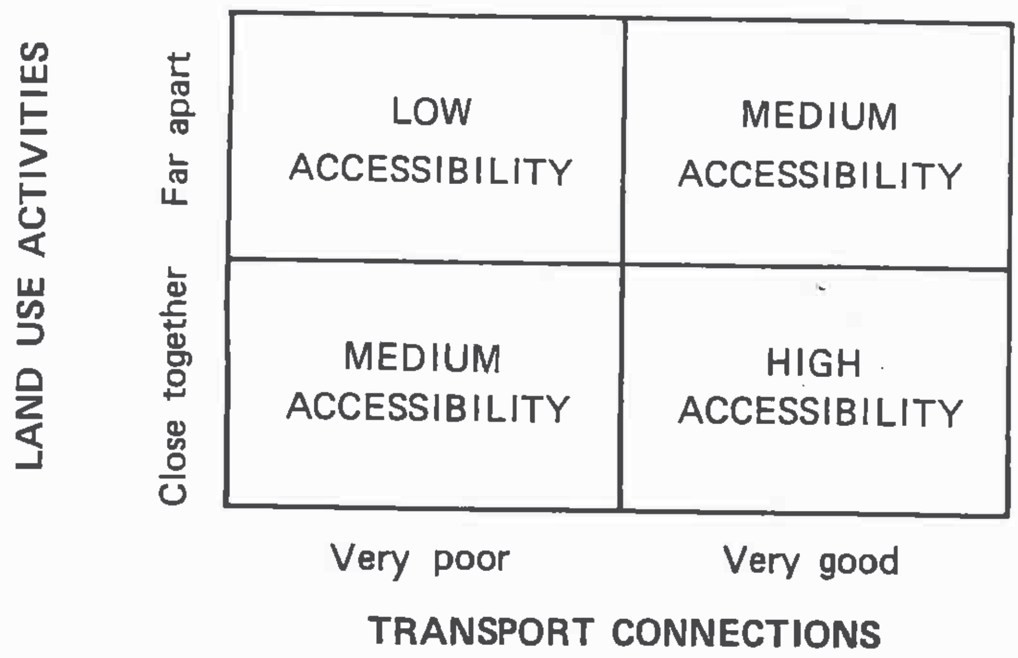

Figure 1.2: Classification of Accessibility Levels

few special activities have 'one-off' locations (e.g. airports). Inner-city public transport is usually better, especially when connecting the city centre.

Accessibility also provides a measure of the performance of the land-use–transport system. Residents are primarily interested in accessibility to job opportunities, schools, shops, health services, leisure and recreation activities. Retailers are concerned about accessibility to customers. Industrialists rely on accessibility to labour markets and to suppliers of materials.

1.2.2 Traffic Generation

Traffic is a function of land use. The potential of a block of land to generate traffic is realised when activities take place on the land. Traffic generation of a block of land is a measure of the amount of traffic (number of people or vehicles, tonnes of freight) that visits during a specified time period (usually per day, or per hour). An example is the number of people going into and coming out of an office building each day.

The amount of traffic generated is related to: (a) the type of land use; and (b) the scale or intensity of the activity taking place in the land. Traffic generated by each land-use category is a reflection of its role in the social and economic functioning of the economy. For example, the average weekday number of vehicular trips generated by one hectare of commercial land is ten times higher than for one hectare of residential land with single-family detached houses; fast food restaurants generate ten times the number of vehicle trips per thousand gross square feet than quality restaurants (ITTE, 1976). As the scale or intensity of land-use activity increases, so too does the amount of traffic generated.

1.2.3 Spatial Pattern of Traffic

The spatial pattern or distribution of traffic is explained by two factors: (a) the disposition of land use; and (b) the restraints on movement–distance acts as a friction to movement. Interaction between two complementary but spatially separated land uses involves a movement of people, goods or information. The spatial separation represents a 'barrier' to interaction, and there is a general preference for short-distance movements rather than long-distance movements. The amount of traffic measured between any two places depends on the land-use intensity in both places and the frictional effect of distance. Figure 1.3 illustrates that the amount of traffic interaction is related positively to

DISTANCE	Small – Small	Small – Large	Large – Large
Long	NEGLIGIBLE INTERACTION	LOW INTERACTION	AVERAGE INTERACTION
Short	LOW INTERACTION	AVERAGE INTERACTION	VERY HIGH INTERACTION

LAND USE INTENSITY IN TWO ZONES

Figure 1.3: Classification of Traffic Interaction Levels

the intensity of land use and negatively (or inversely) to increasing distance between two places. Interaction is very high when two land uses with intensive development are close together. Conversely, interaction is negligible when two land uses with low activity levels are far apart. These are extreme situations and intermediate levels of traffic interaction are of course possible, and more likely.

1.2.4 Selection of Transport Mode and Route

When interaction between two land uses does take place, travellers, or shippers responsible for moving freight, must select which transport mode and what particular route to follow. The journey itself has unattractive aspects, including cost, time, discomfort, danger and uncertainty, and those modes or routes which are least unattractive will be preferred. A traveller will patronise the transport mode (or combination of modes) and route which takes the shortest travel time or costs the least from origin to destination. The choice is based on the desire to minimise the friction in overcoming distance. This assumes that the traveller or shipper has perfect information about the alternative modes and routes and then acts rationally in selecting the best way of getting about. It also assumes that people have a genuine choice: if not, they are said to be 'captive' to one transport mode or route.

1.2.5 Traffic on the Transport Network

As traffic increases on a mode or route the difficulty in getting about also increases, especially when traffic approaches the fixed capacity of the transport facility. Crowded buses mean waiting in queues; congested roads mean stop-start conditions for motorists; and crowded footpaths force pedestrians to shuffle along at a pace slower than normal walking speed.

Travel times are an indicative measure of the difficulty in getting around on transport. The travel times on transport networks vary with traffic flow. This relationship is non-linear: as traffic increases from zero travel times increase only slightly, but as traffic approaches capacity there are large increases in travel time with each increment of traffic.

1.3 Understanding the System–Systems Modelling

Most disciplines which are concerned with deeper levels of explanation of how things work progress from a descriptive to a quantitative approach, which in systems terms is called 'systems modelling'. The relationships between land use, traffic and transport described above can be expressed also as systems models.

1.3.1 Model Definition

A 'model' is a representation of something else and is designed for a specific purpose. When the purpose is to remind ourselves what that 'something else' looks like, the representation might take the form of a scale model, a photograph or a map. When the purpose is explanation of something that is quite complex, the model need not necessarily 'look like' whatever it represents; instead it may take the form of mathematical equations. All models share one common characteristic irrespective of their intended purpose: the mapping or transformation of the real world into a 'model'. When every feature is retained the model becomes a replica but usually abstractions, simplifications or generalisations are made from the real world. The mathematical model is highly abstract because our perception of the real world is simplified and translated into the 'language' of mathematics.

> Mathematical notation is a more precise language than English. Because it is less ambiguous, a mathematical model is a description which has greater clarity than most verbal models . . . There is nothing inherent in the symbols of mathematics which guarantees accuracy. However, the precision required to translate words into symbols can often reveal inadequacies in the verbal description, and may thus lead to a sharpening-up or clarification of our mental image of the way in which we think the real-world system operates (Lee,,1973, p. 8).

1.3.2 Glossary–Systems Modelling

The following glossary may be helpful because technical terms commonly used in systems modelling occur in this book.

Notation: the most elementary algebra consists of forming expressions with letters, which stand for numbers or a range of numbers, and with the basic operations of ordinary arithmetic–addition, subtraction, multiplication and division. Standard symbols represent arithmetic operations but the choice of notation is somewhat arbitrary. Consistency is important so in this book, *variables* are indicated by upper-case Roman letters, and *parameters* or *coefficients* by lower-case Greek letters.

Function: a mathematical concept used whenever the value of some quantity (dependent *variable*) is regarded as dependent on, or determined by, another quantity or quantities (independent *variables*).

Argument: denotes what a *function* is a function of, i.e. the independent variables. Particular values of the function can be calculated by assigning values to the variables which occur in its expression, or argument.

Variable: a quantity that is able to assume different numerical values. If a letter is used to denote the value of the *function* it is called the dependent variable. If letters are used for the *argument* of the *function*, they are called independent variables.

Parameter: a quantity which is constant in each case under consideration, but which may vary from case to case. The *functions* for the different cases may all have the same general *argument* of *variables* and parameters, but the value of the parameters is unique to each particular case.

Coefficient: in mathematics and its applications, a term synonymous with *parameter*.

Calibration: the process of estimating the *parameters* or *coefficients* to get the best correspondence between the model predictions and data representing the real world.

Algorithm: a procedure for performing a complicated arithmetic operation by carrying out a precisely determined sequence of simpler ones. These procedures form suitable subjects for computer programmes.

Those readers in need of a short refresher in mathematics are referred to Lee (1973, pp. 28–40) or to Wilson and Kirkby (1975, pp. 3–103), where the necessary mathematical preliminaries essential to an understanding of urban models are explained. A check-list of factors to consider when designing any type of model is given by Wilson (1974, p. 31).

In transport analysis, the *purpose* behind a systems model that represents land use, traffic and transport is twofold: to gain a better understanding of how the system works; and to predict the traffic consequences of planned changes to land use and transport.

1.3.3 Land-use–Transport Systems Model

The land-use–transport systems model contains three quantifiable variables: land use (number of people, number of jobs, income, car ownership characteristics of the population), traffic (number of passengers, number of vehicles) and transport (travel times, costs). Traffic is the dependent variable except in the calculation of transport travel times when it becomes an independent variable. Land use is a variable because its intensity varies in different parts of an urban area and because it changes over historical time. Transport is a variable because its quality and quantity vary geographically and because it too changes over time—the building of new roads, the extension or contraction of public transport services. Each variable in the model is identified by the notation: L = land use; T = transport supply; Q = traffic.

As the ultimate aim is to represent the amount of traffic in the urban area, the variables require identification in a location-specific way. The urban area is partitioned into a set of discrete geographical zones with the amount of zonal land-use activity assumed to be located in one place called the centroid. The number of zones chosen by the analyst is a question of aggregation, but obviously greater precision is obtained with a large number of small zones. The major transport facilities are represented by networks connecting the zone centroids.

Representing land use and transport in this way has analytical advantages because the system can be specified in numerical terms.

(a) A map reference (grid co-ordinate) defines the exact position of each zone centroid.
(b) A numerical code is used instead of a place-name to identify the geographical location of a zone.
(c) Different measures of zonal land use can be tabulated and cross-referenced with the zone numbering scheme.
(d) The operational characteristics of transport—travel times or costs—are attached to each link of the transport network. Inter-zonal travel time is obtained by adding times on the sequence of links from an origin zone centroid to a destination zone centroid.
(e) The amount of traffic produced by or attracted to each zone centroid is measured. Traffic flow over the network is also measured.
(f) A numerical code is used to identify the position of the transport facilities. Separate coding schemes may be developed for each transport mode.

The conventional notation is to refer to any origin zone as zone i and any destination zone as zone j. Variables associated with any zone are labelled with the subscripts i or j, or both. A journey has an origin *and* a destination, so two subscripts are necessary for some variables:

L_{oi} = land use in the origin zone i;
L_{dj} = land use in the destination zone j;
T_{ij} = transport travel time or cost from zone i to zone j;
Q_{pi} = total traffic produced by zone i;

Q_{aj} = total traffic attracted to zone j;
Q_{ij} = traffic from zone i to zone j;
Q_k = traffic flow on route k.

This notation is used to indicate how the descriptive interactions between land use, traffic and transport are translated into a conceptual model of the system. Additional notation is introduced when necessary.

The *accessibility* of an origin zone is an indication of how convenient land-use activities are located in relation to that zone, and how easy or difficult it is to reach them via the transport network. The total accessibility of zone i to any nominated activity in all destination zones j, including those activities located in the origin zone, is a function (f) of land-use intensity and transport supply:

$$H_i = f(L_{dj}, T_{ij}) \tag{1.1}$$

where

H_i = accessibility of zone i to a nominated land-use activity.

Traffic generation is a function of land use. The amount of traffic produced by an origin zone i is proportional to the type and to the intensity of land use in zone i:

$$Q_{pi} = f(L_{oi}) \tag{1.2}$$

Some recent hypotheses on traffic generation include accessibility as an independent variable. The amount of traffic attracted by a destination zone j is proportional to the type and intensity of land use in zone j:

$$Q_{aj} = f(L_{dj}) \tag{1.3}$$

Different measures of land use are appropriate for all origin zones and for all destination zones. Zonal traffic generation is the sum of traffic production and traffic attraction.

The *spatial pattern of traffic* amongst zones is a function of the land-use intensity in zone i, which produces traffic, the land-use intensity in zone j, which attracts traffic (different measures of land use are appropriate for all origin zones and for all destination zones), and transport difficulty of getting from one zone to another:

$$Q_{ij} = f(L_{oi}, L_{dj}, T_{ij}) \tag{1.4}$$

The *selection of transport mode and route*, for those origin-destination journeys where there is an element of choice, is based on a comparison of the operational characteristics of the competing transport modes and routes. Mode selection, in the simplest case of a choice between public transport (m=1) and private transport (m=2), is:

$$Q_{ij(m)} = f\,(T_{ij(1)}, T_{ij(2)}) \tag{1.5}$$

where the traffic carried on the alternative modes is identified by the additional subscript m. Similarly, mode-specific route selection–the sequence of network links followed from an origin zone centroid– is based on a comparison of the operational characteristics of alternative transport routes for each mode:

$$Q_{ij(k)} = f\,(T_{ij(1)}, T_{ij(2)}, \ldots T_{ij(k)}) \tag{1.6}$$

where the traffic carried on each alternative route is identified by the subscript k. Here, the implicit (m)-label has been dropped for simplicity. Thus, $T_{ij(1)}$ in this equation should be carefully distinguished from $T_{ij(1)}$ in equation (1.5). If necessary, the notation $T_{ij(m)(k)}$, for the travel time of the kth route in mode m, could be used.

The amount of *traffic on each transport route* determines the transport travel times (and user costs), especially on roads. Thus,

$$T_k = f\,(Q_k) \tag{1.7}$$

where the subscript k identifies the transport network route followed by the tráveller.

The non-linear relationship between traffic flow-dependent travel times on transport facilities has been studied extensively, and one of the possible algebraic functions with the required theoretical properties (Blunden, 1971, pp. 80–4) is:

$$y = (1 - \alpha x)/(1 - x) \tag{1.8}$$

This is plotted graphically for three selected values of the parameter α (Figure 1.4). The y-axis can be interpreted as the ratio of the travel time for a range of traffic loads to the minimum travel time with no traffic load; and the x-axis as the ratio of traffic flow to saturation flow (transport capacity), which is a measure of the traffic load. The gradient of the function is determined by the parameter.

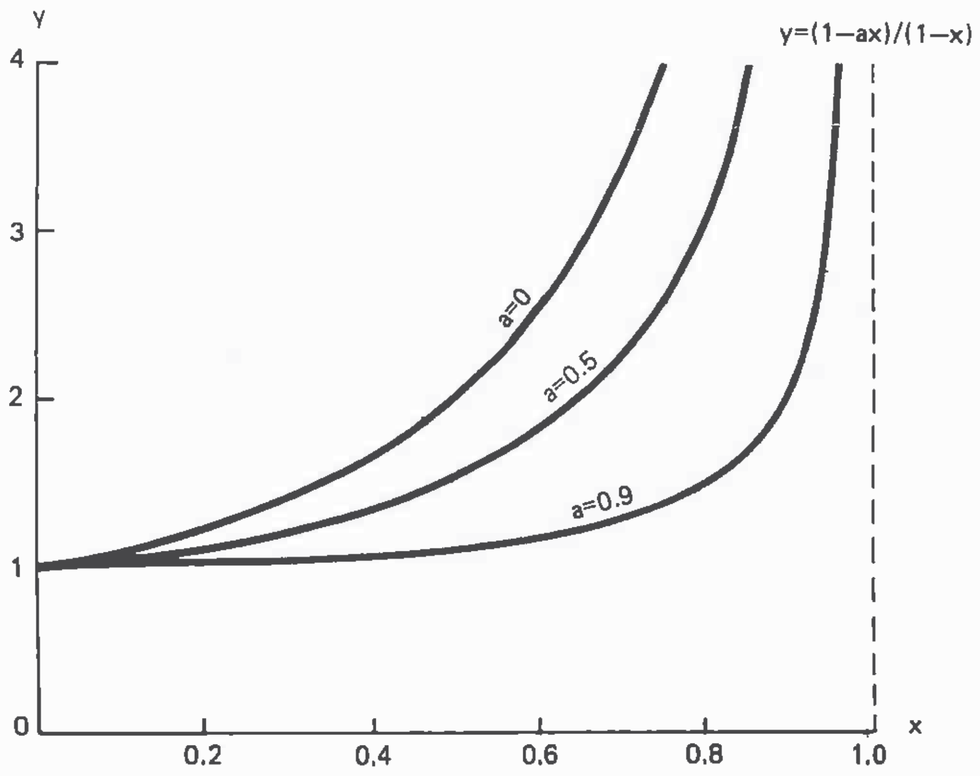

Figure 1.4: Properties of a Traffic Flow–Transport Impedance Function

Conceptually, the equations of the system are the travel demand and transport supply. Equations (1.2) to (1.6) are the amount of travel by location, by geographical pattern and by transport mode and route, whereas equation (1.7) is the mode-specific supply function. The solution to any set of equations with specified parameters is not straightforward because both traffic and transport supply variables are found on the left- and on the right-hand sides of the model. Continuous adjustments in traffic and transport supply are required to reach a solution that balances in all equations. Such a solution is called the *equilibrium solution* to the problem.

Under heavy traffic conditions there is a spread, or diversion of vehicles, over alternative transport routes, such that travel times become equal:

$$T_1 = T_2 = \ldots = T_k \tag{1.9}$$

This is based on the traffic flow principle which holds that no individual 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

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