

MODELLING TRANSPORT

4th Edition

Juan de Dios Ortúzar | Luis G. Willumsen



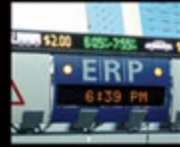
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Contents

[Cover](#)

[Title Page](#)

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[About the Authors](#)

[Preface](#)

[1: Introduction](#)

[1.1 Transport Planning and Modelling](#)

[1.2 Characteristics of Transport Problems](#)

[1.3 Modelling and Decision Making](#)

[1.4 Issues in Transport Modelling](#)

[1.5 The Structure of the Classic Transport Model](#)

[1.6 Continuous Transport Planning](#)

[1.7 Theoretical Basis Versus Expedience](#)

[2: Mathematical Prerequisites](#)

[2.1 Introduction](#)

[2.2 Algebra and Functions](#)

[2.3 Matrix Algebra](#)

[2.4 Elements of Calculus](#)

[2.5 Elementary Mathematical Statistics](#)

3: Data and Space

3.1 Basic Sampling Theory

3.2 Errors in Modelling and Forecasting

3.3 Basic Data-Collection Methods

3.4 Stated Preference Surveys

3.5 Network and Zoning Systems

4: Trip Generation Modelling

4.1 Introduction

4.2 Regression Analysis

4.3 Cross-Classification or Category Analysis

4.4 Trip Generation and Accessibility

4.6 Forecasting Variables in Trip Generation Analysis

4.7 Stability and Updating of Trip Generation Parameters

5: Trip Distribution Modelling

5.1 Definitions and Notation

5.2 Growth-Factor Methods

5.3 Synthetic or Gravity Models

5.4 The Entropy-Maximising Approach

5.5 Calibration of Gravity Models

5.6 The Tri-proportional Approach

5.7 Other Synthetic Models

5.8 Practical Considerations

6: Modal Split and Direct Demand Models

6.1 Introduction

6.2 Factors Influencing the Choice of Mode

6.3 Trip-end Modal-split Models

6.4 Trip Interchange Heuristics Modal-split Models

6.5 Synthetic Models

6.6 Direct Demand Models

7: Discrete Choice Models

7.1 General Considerations

7.2 Theoretical Framework

7.3 The Multinomial Logit Model (MNL)

7.4 The Nested Logit Model (NL)

7.5 The Multinomial Probit Model

7.6 The Mixed Logit Model

7.7 Other Choice Models and Paradigms

8: Specification and Estimation of Discrete Choice Models

8.1 Introduction

8.2 Choice-Set Determination

8.3 Specification and Functional Form

8.4 Statistical Estimation

8.5 Estimating the Multinomial Probit Model

8.6 Estimating the Mixed Logit Model

8.7 Modelling with Stated-Preference Data

9: Model Aggregation and Transferability

9.1 Introduction

9.2 Aggregation Bias and Forecasting

9.4 Aggregation Methods

9.5 Model Updating or Transference

10: Assignment

10.1 Basic Concepts

10.2 Traffic Assignment Methods

10.3 All-or-nothing Assignment

10.4 Stochastic Methods

10.5 Congested Assignment

10.6 Public-Transport Assignment

10.7 Limitations of the Classic Methods

10.8 Practical Considerations

11: Equilibrium and Dynamic Assignment

11.1 Introduction

11.2 Equilibrium

11.3 Transport System Equilibrium

11.4 Traffic Dynamics

11.5 Departure Time Choice and Assignment

12: Simplified Transport Demand Models

12.1 Introduction

12.2 Sketch Planning Methods

12.3 Incremental Demand Models

12.4 Model Estimation from Traffic Counts

12.5 Marginal and Corridor Models

12.6 Gaming Simulation

13: Freight Demand Models

13.1 Importance

13.2 Factors Affecting Goods Movements

13.3 Pricing Freight Services

13.4 Data Collection for Freight Studies

13.5 Aggregate Freight Demand Modelling

13.6 Disaggregate Approaches

13.7 Some Practical Issues

14: Activity Based Models

14.1 Introduction

14.2 Activities, Tours and Trips

14.3 Tours, Individuals and Representative Individuals

14.4 The ABM System

14.5 Population Synthesis

14.6 Monte Carlo and Probabilistic Processes

14.7 Structuring Activities and Tours

14.8 Solving ABM

14.9 Refining Activity or Tour Based Models

14.10 Extending Random Utility Approaches

15: Key Parameters, Planning Variables and Value Functions

15.1 Forecasting Planning Variables

15.2 Land-Use Transport Interaction Modelling

15.3 Car-Ownership Forecasting

15.4 The Value of Travel Time

15.5 Valuing External Effects of Transport

16: Pricing and Revenue

16.1 Pricing, Revenue and Forecasting

16.2 Private Sector Projects

16.3 Risk

16.4 Demand Modelling

16.5 Risk Analysis

16.6 Concluding Remarks

References

Index

MODELLING TRANSPORT

Fourth Edition

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About the Authors

Juan de Dios Ortúzar is Professor of Transport Engineering at Pontificia Universidad Católica de Chile, his alma mater and where he has worked since 1972. From this remote setting he has managed to form generations of young researchers in Latin America and Europe. Outside academia, he has been advisor to governments and international agencies, and has directed several transport studies involving the application of advanced demand modelling techniques and the collection of large-scale travel survey data. A keen golfer he also enjoys playing guitar and singing with friends.

Luis (Pilo) Willumsen has some 40 years of experience as a consultant, transport planner and researcher with a distinguished academic career. He studied Engineering in Chile and has been based in Britain since 1975: he was a researcher and lecturer at Leeds University and then at University College London. He was a Board Director of Steer Davies Gleave having joined it full-time in 1989 with a special responsibility for technical and international development. He left that company in 2009 and is now Director of the Luis Willumsen Consultancy and Visiting Professor in the Department of Civil, Environmental and Geomatic Engineering at University College London.

Preface

This book is a result of nearly 40 years of collaboration, sometimes at a distance and sometimes working together in Britain and in Chile. Throughout these years we discussed many times what we thought were the strong and weak aspects of transport modelling and planning. We speculated, researched and tested in practice some new and some not so new ideas. We have agreed and disagreed on topics like the level of detail required for modelling or the value of disaggregate or activity based models in forecasting; we took advantage of a period when our views converged to put them in writing; here they are.

We wish to present the most important (in our view) transport modelling techniques in a form accessible to students and practitioners alike. We attempt this giving particular emphasis to key topics in contemporary modelling and planning:

- the practical importance of theoretical consistency in transport modelling;
- the issues of data and specification errors in modelling, their relative importance and methods to handle them;
- the key role played by the decision-making context in the choice of the most appropriate modelling tool;
- how uncertainty and risk influence the choice of the most appropriate modelling tool;
- the advantages of variable resolution modelling; a simplified background model coupled with a much more detailed one addressing the decision questions in hand;
- the need for a monitoring function relying on regular data collection and updating of forecasts and models

so that courses of action can be adapted to a changing environment.

We have approached the subject from the point of view of a modelling exercise, discussing the role of theory, data, model specification in its widest sense, model estimation, validation and forecasting. Our aim in writing this book was to create both a text for a diploma or Master's course in transport and a reference volume for practitioners; however, the material is presented in such a way as to be useful for undergraduate courses in civil engineering, geography and town planning. The book is based on our lecture notes prepared and improved over several years of teaching at undergraduate and graduate levels; we have also used them to teach practitioners both through in-house training programmes and short skills-updating courses. We have extended and enhanced our lecture notes to cover additional material and to help the reader tackling the book without the support of a supervisor.

Chapters 3 to 9, 12 and 15 provide all the elements necessary to run a good 30 sessions course on transport demand modelling; in fact, such a course - with different emphasis on certain subjects - has been taught by us at undergraduate level in Chile, and at postgraduate level in Australia, Britain, Colombia, Italy, Mexico, Portugal and Spain; the addition of material from Chapters 10 and 11 would make it a transport modelling course. Chapters 4 to 6 and 10 to 12 provide the basic core for a course on network modelling and equilibrium in transport; a course on transport supply modelling would require more material, particularly relating to important aspects of public transport supply which we do not discuss in enough detail. Chapters 13, 14 and 16 cover material which is getting more important as time goes by, in particular as the shift in interest in the profession is moving from passenger issues to freight and logistics, and to the role models play not only

in social evaluation but also in the analysis of private projects. Chapter 1 provides an introduction to transport planning issues and outlines our view on the relationship between planning and modelling. Chapter 2 is there mainly for the benefit of those wishing to brush up their analytical and statistical skills and to make the volume sufficiently self-contained.

During our professional life we have been fortunate to be able to combine teaching with research and consultancy practice. We have learnt from papers, research, experimentation and mistakes. We are happy to say the latter have not been too expensive in terms of inaccurate advice. This is not just luck; a conscientious analyst pays for mistakes by having to work harder and longer to sort out alternative ways of dealing with a difficult modelling task. We have learnt the importance of choosing appropriate techniques and technologies for each task in hand; the ability to tailor modelling approaches to decision problems is a key skill in our profession. Throughout the book we examine the practical constraints to transport modelling for planning and policy making in general, particularly in view of the limitations of current formal analytical techniques, and the nature and quality of the data likely to be available.

We have avoided the intricate mathematical detail of every model to concentrate instead on their basic principles, the identification of their strengths and limitations, and a discussion of their use. The level of theory supplied by this book is, we believe, sufficient to select and use the models in practice. We have tried to bridge the gap between the more theoretical publications and the too pragmatic 'recipe' books; we do not believe the profession would have been served well by a simplistic 'how to' book offering a blueprint to each modelling problem. In this latest edition we have also marked, with a shaded box, material which is more advanced and/or still under development but important

enough to be mentioned. There are no single solutions to transport modelling and planning. A recurring theme in the book is the dependence of modelling on context and theory. Our aim is to provide enough information and guidance so that readers can actually go and use each technique in the field; to this end we have striven to look into practical questions about the application of each methodology. Wherever the subject area is still under development we have striven to make extensive references to more theoretical papers and books which the interested reader can consult as necessary. In respect of other, more settled modelling approaches, we have kept the references to those essential for understanding the evolution of the topic or serving as entry points to further research.

We believe that nobody can aspire to become a qualified practitioner in any area without doing real work in a laboratory or in the field. Therefore, we have gone beyond the sole description of the techniques and have accompanied them with various application examples. These are there to illustrate some of the theoretical or practical issues related to particular models. We provide a few exercises at the end of key chapters; these can be solved with the help of a scientific pocket (or better still, a spreadsheet) calculator and should assist the understanding of the models discussed.

Although the book is ambitious, in the sense that it covers quite a number of themes, it must be made clear from the outset that we do not intend (nor believe it possible) to be up-to-the-minute in every topic. The book is a good reflection of the state of the art but for leading-edge research the reader should use the references provided as signposts for further investigation.

We wrote most of the first edition during a sabbatical visit by the first of us to University College London in 1988–89. This was possible thanks to support provided by the UK

Science and Engineering Research Council, The Royal Society, Fundación Andes (Chile), The British Council and The Chartered Institute of Transport. We thank them for their support as we acknowledge the funding provided for our research by many institutions and agencies over the past 30 years. The third and this fourth edition benefited greatly from further sabbatical stays at University College London in 1998–99 and 2009; these were possible thanks to the support provided by the UK Engineering and Physical Sciences Research Council. We also wish to acknowledge the support to our research provided by the Chilean Fund for Developing Scientific and Technical Research (FONDECYT) and the Millennium Institute on Complex Engineering Systems (ICM: P05-004F; FONDECYT: FBO16). Steer Davies Gleave also allowed the second author to spend time updating the second and third editions.

We have managed to maintain an equal intellectual contribution to the contents of this book but in writing and researching material for it we have benefited from numerous discussions with friends and colleagues. Richard Allsop taught us a good deal about methodology and rigour. Huw Williams's ideas are behind many of the theoretical contributions in Chapter 7; Andrew Daly and Hugh Gunn have helped to clarify many issues in Chapters 3, 7–9 and 15. Dirck Van Vliet's emphasis in explaining assignment and equilibrium in simple but rigorous terms inspired Chapters 10 and 11. Tony Fowkes made valuable comments on car ownership forecasting and stated-preference methods. Jim Steer provided a constant reference to practical issues and the need to develop improved approaches to address them.

Many parts of the first edition of the book also benefited from a free, and sometimes very enthusiastic, exchange of ideas with our colleagues J. Enrique Fernández and Joaquin de Cea at the Pontificia Universidad Católica de Chile, Sergio Jara-Díaz and Jaime Gibson at the Universidad de Chile, Marc

Gaudry at the Université de Montréal, Roger Mackett at University College London, Dennis Gilbert and Mike Bell at Imperial College. Many others also contributed, without knowing, to our thoughts.

Subsequent editions of the book have benefited from comments from a number of friends and readers, apart from those above, who have helped to identify errors and areas for improvement. Among them we should mention Michel Bierlaire from the Ecole Polytechnique Fédérale de Lausanne, Patrick Bonnel from the French Laboratoire d'Economie des Transports, David Boyce at the University of Illinois, Victor Cantillo from Universidad del Norte, Barranquilla, Elisabetta Cherchi from University of Cagliari, Michael Florian from Université de Montréal, Rodrigo Garrido, Luis I. Rizzi and Francisca Yañez from Pontificia Universidad Católica de Chile, Cristián Guevara now at Universidad de Los Andes in Chile, Stephane Hess at Leeds University, Ben Heydecker from University College London, Frank Koppelman from Northwestern University, Mariëtte Kraan at the University of Twente, Francisco J. Martínez and Marcela Munizaga at the Universidad de Chile, Piotr Olszewski from Warsaw University of Technology, Joan L. Walker from University of California at Berkeley, and Sofia Athanassiou, Gloria Hutt, Neil Chadwick, John Swanson, Yaron Hollander and Serbjeet Kohli at Steer Davies Gleave. Special thanks are due to John M. Rose at ITLS, University of Sydney, for his contributions to Chapter 3.

Our final thanks go to our graduate and undergraduate students in Australia, Britain, Chile, Colombia, México, Italy, Portugal and Spain; they are always sharp critics and provided the challenge to put our money (time) where our mouth was. We have not taken on board all suggestions as we felt some required changing the approach and style of the text; we are satisfied future books will continue to clarify issues and provide greater rigour to many of the topics

discussed here; transport is indeed a very dynamic subject. Despite this generous assistance, we are, as before, solely responsible for the errors remaining in this latest edition. We genuinely value the opportunity to learn from our mistakes.

Juan de Dios Ortúzar and Luis G. Willumsen

1

Introduction

1.1 Transport Planning and Modelling

1.1.1 Background

The world, including transport, is changing fast. We still encounter many of the same transport problems of the past: congestion, pollution, accidents, financial deficits and pockets of poor access. We are increasingly becoming money rich and time poor. However, we have learnt a good deal from long periods of weak transport planning, limited investment, emphasis on the short term and mistrust in strategic transport modelling and decision making. We have learnt, for example, that old problems do not fade away under the pressure of attempts to reduce them through better traffic management; old problems reappear in new guises with even greater vigour, pervading wider areas, and in their new forms they seem more complex and difficult to handle.

We now have greater confidence in technical solutions than in the previous century. This is not the earlier confidence in technology as the magic solution to economic and social problems; we have also learnt that this is a mirage. However, Information Technology has advanced enough to make possible new conceptions of transport infrastructure (e.g. road transport informatics), movement systems (e.g. automated driverless trains) and electronic

payment (e.g. smartcards, video tolling). Mobile phones and GPS services are changing the way to deliver useful traveller information, facilitating payment and charging for the use of transport facilities. Of particular interest to the subject of this book is the advent of low-cost and high-speed computing; this has practically eliminated computing power as a bottleneck in transport modelling. The main limitations are now human and technical: contemporary transport planning requires skilled and experienced professionals plus, as we will argue below, theoretically sound modelling techniques with competent implementations in software.

Emerging countries are becoming more significant in the world stage but they suffer serious transport problems as well. These are no longer just the lack of roads to connect distant rural areas with markets. Indeed, the new transport problems bear some similarities with those prevalent in the post-industrialised world: congestion, pollution, and so on. However, they have a number of very distinctive features deserving a specific treatment: relatively low incomes, fast urbanisation and change, high demand for public transport, scarcity of resources including capital, sound data and skilled personnel.

The birth of the twenty-first century was dominated by two powerful trends affecting most aspects of life and economic progress. The stronger trend is *globalisation*, supported and encouraged by the other trend, cheap and high-capacity *telecommunications*. The combination of the two is changing the way we perceive and tackle many modern issues; their influence in transport planning is starting to be felt. Some of these influences are the role of good transport infrastructure in enhancing the economic competitiveness of modern economies; a wider acceptance of the advantages of involving the private sector more closely in transport supply and operations; the possible role of telecommunications in reducing the need to travel.

Important technical developments in transport modelling have taken place since the mid-1970s, in particular at major research centres; these developments have been improved and implemented by a small group of resourceful consultants. However, many of these innovations and applications have received limited attention outside the more academic journals. After these years of experimentation there is now a better recognition of the role of modelling in supporting transport planning. This book attempts a review of the best of current practice in transport modelling; in most areas it covers the 'state of the art' but we have selected those aspects which have already been implemented successfully in practice. The book does not represent the leading edge of research into modelling. It tries, rather, to provide a survival tool-kit for those interested in improving transport modelling and planning, a kind of bridge or entry-point to the more theoretical papers that will form the basis of transport modelling in the future.

Transport modelling is not transport planning; it can only support planning, and in a few cases it may have the most important role in the process. We have known many good professionals who have developed sophisticated transport models but are frustrated because their work has apparently been ignored in many key planning decisions. In truth, planning and implementation have the power to change the world and transport modelling can only assist in this if adopted as an effective aid to decision making. This requires wise planners and, above all, better modellers.

1.1.2 Models and their Role

A *model* is a simplified representation of a part of the real world—the system of interest—which focuses on certain elements considered important from a particular point of view. Models are, therefore, problem and viewpoint specific. Such a broad definition allows us to incorporate both

physical and abstract models. In the first category we find, for example, those used in architecture or in fluid mechanics which are basically aimed at design. In the latter, the range spans from the mental models all of us use in our daily interactions with the world, to formal and abstract (typically analytical) representations of some theory about the system of interest and how it works. Mental models play an important role in understanding and interpreting the real world and our analytical models. They are enhanced through discussions, training and, above all, experience. Mental models are, however, difficult to communicate and to discuss.

In this book we are concerned mainly with an important class of abstract models: mathematical models. These models attempt to replicate the system of interest and its behaviour by means of mathematical equations based on certain theoretical statements about it. Although they are still simplified representations, these models may be very complex and often require large amounts of data to be used. However, they are invaluable in offering a 'common ground' for discussing policy and examining the inevitable compromises required in practice with a level of objectivity. Another important advantage of mathematical models is that during their formulation, calibration and use the planner can learn much, through experimentation, about the behaviour and internal workings of the system under scrutiny. In this way, we also enrich our mental models thus permitting more intelligent management of the transport system.

A model is only realistic from a particular perspective or point of view. It may be reasonable to use a knife and fork on a table to model the position of cars before a collision but not to represent their mechanical features, or their route choice patterns. The same is true of analytical models: their value is limited to a range of problems under specific

conditions. The appropriateness of a model is, as discussed in the rest of this chapter, dependent on the context where it will be used. The ability to choose and adapt models for particular contexts is one of the most important elements in the complete planner's tool-kit.

This book is concerned with the contribution transport modelling can make to improved decision making and planning in the transport field. It is argued that the use of models is inevitable and that of formal models highly desirable. However, transport modelling is only one element in transport planning: administrative practices, an institutional framework, skilled professionals and good levels of communication with decision makers, the media and the public are some of the other requisites for an effective planning system. Moreover, transport modelling and decision making can be combined in different ways depending on local experience, traditions and expertise. However, before we discuss how to choose a modelling and planning approach it is worth outlining some of the main characteristics of transport systems and their associated problems. We will also discuss some very important modelling issues which will find application in other chapters of this book.

1.2 Characteristics of Transport Problems

Transport problems have become more widespread and severe than ever in both industrialised and developing countries alike. Fuel shortages are (temporarily) not a problem but the general increase in road traffic and transport demand has resulted in congestion, delays, accidents and environmental problems well beyond what has been considered acceptable so far. These problems

have not been restricted to roads and car traffic alone. Economic growth seems to have generated levels of demand exceeding the capacity of most transport facilities. Long periods of under-investment in some modes and regions have resulted in fragile supply systems which seem to break down whenever something differs slightly from average conditions.

These problems are not likely to disappear in the near future. Sufficient time has passed with poor or no transportation planning to ensure that a major effort in improving most forms of transport, in urban and inter-urban contexts, is necessary. Given that resources are not unlimited, this effort will benefit from careful and considered decisions oriented towards maximising the advantages of new transport provision while minimising their money costs and undesirable side-effects.

1.2.1 Characteristics of Transport Demand

The demand for transport is *derived*, it is not an end in itself. With the possible exception of sight-seeing, people travel in order to satisfy a need (work, leisure, health) undertaking an *activity* at particular locations. This is equally significant for goods movements. In order to understand the demand for transport, we must understand the way in which these activities are distributed over space, in both urban and regional contexts. A good transport system widens the opportunities to satisfy these needs; a heavily congested or poorly connected system restricts options and *limits* economic and social development.

The demand for transport services is highly *qualitative* and *differentiated*. There is a whole range of specific demands for transport which are differentiated by time of day, day of week, journey purpose, type of cargo, importance of speed

and frequency, and so on. A transport service without the attributes matching this differentiated demand may well be useless. This characteristic makes it more difficult to analyse and forecast the demand for transport services: tonne and passenger kilometres are extremely coarse units of performance hiding an immense range of requirements and services.

Transport demand takes place over *space*. This seems a trivial statement but it is the distribution of activities over space which makes for transport demand. There are a few transport problems that may be treated, albeit at a very aggregate level, without explicitly considering space. However, in the vast majority of cases, the explicit treatment of space is unavoidable and highly desirable. The most common approach to treat space is to divide study areas into zones and to code them, together with transport networks, in a form suitable for processing with the aid of computer programs. In some cases, study areas can be simplified assuming that the zones of interest form a corridor which can be collapsed into a linear form. However, different methods for treating distance and for allocating origins and destinations (and their attributes) over space are an essential element in transport analysis.

The spatiality of demand often leads to problems of lack of coordination which may strongly affect the equilibrium between transport supply and demand. For example, a taxi service may be demanded unsuccessfully in a part of a city while in other areas various taxis may be plying for passengers. On the other hand, the concentration of population and economic activity on well-defined corridors may lead to the economic justification of a high-quality mass transit system which would not be viable in a sparser area.

Finally, transport demand and supply have very strong *dynamic* elements. A good deal of the demand for transport

is concentrated on a few hours of a day, in particular in urban areas where most of the congestion takes place during specific peak periods. This time-variable character of transport demand makes it more difficult-and interesting-to analyse and forecast. It may well be that a transport system could cope well with the *average* demand for travel in an area but that it breaks down during peak periods. A number of techniques exist to try to spread the peak and average the load on the system: flexible working hours, staggering working times, premium pricing, and so on. However, peak and off-peak variations in demand remain a central, and fascinating, problem in transport modelling and planning.

1.2.2 Characteristics of Transport Supply

The first distinctive characteristic of transport supply is that it is a *service* and not a good. Therefore, it is not possible to stock it, for example, to use it in times of higher demand. A transport service must be consumed when and where it is produced, otherwise its benefit is lost. For this reason it is very important to estimate demand with as much accuracy as possible in order to save resources by tailoring the supply of transport services to it.

Many of the characteristics of transport systems derive from their nature as a service. In very broad terms a transport system requires a number of fixed assets, the *infrastructure*, and a number of mobile units, the *vehicles*. It is the combination of these, together with a set of rules for their operation, that makes possible the movement of people and goods.

It is often the case that infrastructure and vehicles are not owned nor operated by the same group or company. This is certainly the case of most transport modes, with the notable exception of many rail systems. This separation between

supplier of infrastructure and provider of the final transport service generates a rather complex set of interactions between government authorities (central or local), construction companies, developers, transport operators, travellers and shippers, and the general public. The latter plays several roles in the supply of transport services: it represents the residents affected by a new scheme, or the unemployed in an area seeking improved accessibility to foster economic growth; it may even be car owners wishing to travel unhindered through somebody else's residential area.

The provision of transport infrastructure is particularly important from a supply point of view. Transport infrastructure is 'lumpy', one cannot provide half a runway or one-third of a railway station. In certain cases, there may be scope for providing a gradual build-up of infrastructure to match growing demand. For example, one can start providing an unpaved road, upgrade it later to one or two lanes with surface treatment; at a later stage a well-constructed single and dual carriageway road can be built, to culminate perhaps with motorway standards. In this way, the provision of infrastructure can be adjusted to demand and avoid unnecessary early investment in expensive facilities. This is more difficult in other areas such as airports, metro lines, and so on.

Investments in transport infrastructure are not only lumpy but also take a long time to be carried out. These are usually large projects. The construction of a major facility may take from 5 to 15 years from planning to full implementation. This is even more critical in urban areas where a good deal of disruption is also required to build them. This disruption involves additional costs to users and non-users alike.

Moreover, transport investment has an important political role. For example, politicians in developing countries often

consider a road project a safe bet: it shows they care and is difficult to prove wrong or uneconomic by the popular press. In industrialised nations, transport projects usually carry the risk of alienating large numbers of residents affected by them or travellers suffering from congestion and delay in overcrowded facilities. Political judgement is essential in choices of this kind but when not supported by planning, analysis and research, these decisions result in responses to major problems and crises only; in the case of transport this is, inevitably, too late. Forethought and planning are essential.

The separation of providers of infrastructure and suppliers of services introduces economic complexities too. For a start, it is not always clear that all travellers and shippers actually perceive the total costs incurred in providing the services they use. The charging for road space, for example, is seldom carried out directly and when it happens the price does not include congestion costs or other external effects, perhaps the nearest approximation to this being toll roads and modern road-pricing schemes. The use of taxes on vehicles and fuels is only a rough approximation to charging for the provision of infrastructure.

But, why should this matter? Is it not the case that other goods and services like public parks, libraries and the police are often provided without a direct charge for them? What is wrong with providing free road space? According to elementary economic theory it does matter. In a perfect market a good allocation of resources to satisfy human needs is only achieved when the marginal costs of the goods equal their marginal utility. This is why it is often advocated that the price of goods and services, i.e. their perceived cost, should be set at their marginal cost. Of course real markets are not perfect and ability to pay is not a good indication of need; however, this general framework

provides the basis for contrasting other ways of arranging pricing systems and their impact on resource allocation.

Transport is a very important element in the welfare of nations and the well-being of urban and rural dwellers. If those who make use of transport facilities do not perceive the resource implications of their choices, they are likely to generate a balance between supply and demand that is inherently inefficient. Underpriced scarce resources will be squandered whilst other abundant but priced resources may not be used. The fact that overall some sectors of the economy (typically car owners) more than pay for the cost of the road space provided, is not a guarantee of more rational allocation of resources. Car owners probably see these annual taxes as fixed, *sunk*, costs which at most affect the decision of buying a car but not that of using it.

An additional element of distortion is provided by the number of concomitant- or *side-effects* associated with the production of transport services: accidents, pollution and environmental degradation in general. These effects are seldom *internalised*; the user of the transport service rarely perceives nor pays for the costs of cleaning the environment or looking after the injured in transport related accidents. Internalising these costs could also help to make better decisions and to improve the allocation of demand to alternative modes.

One of the most important features of transport supply is *congestion*. This is a term which is difficult to define as we all believe we know exactly what it means. However, most practitioners do know that what is considered congestion in Leeds or Lampang is often accepted as normal in London or Lagos. Congestion arises when demand levels approach the capacity of a facility and the time required to use it (travel through it) increases well above the average under low demand conditions. In the case of transport infrastructure the inclusion of an additional vehicle generates