A BIO-PHYSICAL MODEL OF TRIP GENERATION/TRIP DISTRIBUTION

By
Robert Johann Kölbl
Dipl.-Ing.

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Department of Civil and Environmental Engineering,
University of Southampton,
United Kingdom.

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ABSTRACT

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This thesis attempts to establish a bio-physical model for trip generation/trip distribution where an individual's energy usage is the main determinant for the *amount* of daily travel. Previous studies have used socio-economic variables (such as household size, income or car ownership) to assess trip making. An analysis of the data collected by the UK National Travel Survey (NTS) for the period 1972 - 1995 have been used to show that socio-economic variables have a variational rather than a determining effect on trip making. Trip generation and trip distribution can be combined, since daily travel time is linked to the number of trips per day (which is related to generation) and the single trip time (which is related to distribution). Two presuppositions are essential to the approach: firstly, the unit of reference is changed from the household to the individual, and secondly, modes of transport are considered separately. These enable a hypothesis to be formed which states that *the amount of daily travel of a person is determined by an individual's bio-physical energy budget, and the time spent in travelling is proportional to the mode of transport used for these travelling activities.* Empirically, this can be verified by combining ergonomic measurements of the internal energy expended in different travel activities, and the NTS data, which give the distribution of external, daily movement by different modes of transport. Theoretically, an analogy of statistical physics can be developed to ensure a methodological consistency with established principles of physics, and to gain a physically causal understanding of human travel behaviour. It was not possible to fully verify the approach mathematically, since not all functions of the internal energy expenditure are readily available. However, despite this limitation, a model can be developed which is valid for non-vehicular and vehicular modes of transport and which shows distance as a mode-dependent measure. Potential applications of the approach are discussed with guidelines, for example, to trip generation/trip distribution modelling.

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To those, who saw the light
but could not enjoy the sun.

Chapter 1

Introduction

1.1 Background

Traffic, or more generally, travelling seems to play an increasingly larger role of our life-style, society, culture and economy. The principal problems associated with the use of transport are congestion, delay, accidents and pollution. At the centre stands the simple notion of trips, i.e., movements from origins to destinations, as performed by people on a daily basis. An understanding of the underlying behaviour involved in trip making is essential if society is to make effective decisions in areas such as transport infrastructure, management and land use.

In general, modelling of trip making has been tackled traditionally from a socio-economic point of view. These approaches have used a variety of variables, such as household size, car-ownership, cost or income, as fundamental determinants to explain travel behaviour. Factors to represent non-tangible influences have included comfort and convenience. By-and-large, models using such variables have been based on limited empirical information. This approach limits their value to provide fundamental understanding and the extent to which their application remains valid, both temporally and spatially.

Despite technical, social and cultural differences, the value of these models by researchers and practioners alike, centres around the notion of understanding, i.e., the more fundamental the understanding the better the representation (of the pattern) of travel behaviour, and the notion of predictability, i.e., forecasting future performances as well as reproducing past and present behaviour performances accurately. Such rigorous assessment should then be the basis for a development of less equivocal guidelines for future transport policy and transport management.

1.2 Idea and Objectives

The idea of this thesis can be summed up in a simple example: a vehicle needs the power from fuel or the engine to move which determines its extent of movement. However, in the approach described in this thesis, the vehicle is exchanged for the human, the engine power is exchanged for the human's bio-physical energy and, instead of the vehicle's movement, the daily travel of an individual is considered.

The objectives can be described by determining the bio-physical boundary conditions of human daily travelling and by establishing an alternative model to the conventional trip generation/trip distribution ones. This will be attempted in the following stages:

- At the empirical level, model verification is based on a data analysis of the UK National Travel Survey (NTS) and ergonomics. The resulting model focuses on the *amount* of daily travelling, i.e., the travel time and the number of trips per person per day, and the human energy expenditure during a travel activity by different modes of transport. It considers only person trips and not those due to freight transport.
- At the methodological level, the approach based on statistical physics, attempts to establish a causal schema of travel behaviour in the classical physical sense. As such, the methodology should comprise an empirical data analysis agreeing with a theoretical approach, which is consistently embedded in the general concepts of established principles of physics.
- At the application level, some user guidelines are discussed which should make a practical realisation of the theoretical model possible. These guidelines suggest some methodical alterations to established models of trip generation/trip distribution and indicate some design tools for practical traffic development.

1.3 A Guide to the Thesis

1.3.1 The Concept for the Structure

The conceptual structure for this thesis is based on the schema of K. Popper, subsequently developed by E. Oeser as discussed below. Popper describes the schema of problem-solving with "the method of imaginative conjectures and criticism, or the method of conjecture and refutation" (Popper 1995).

The schema (in its simplest form) is:

$$P_1 \to TT \to EE \to P_2.$$

Here, P_1 is the problem from which we start, TT (the 'tentative theory') is the imaginative conjectural solution which we first reach, for example our first tentative interpretation. *EE* ('error-elimination') consists of severe critical examination of our conjecture, our tentative interpretation: it consists, for example, of the critical use of documentary evidence and, if we have at this early stage more than one conjecture at our disposal, it will also consist of a critical discussion and comparative evaluation of the competing conjectures. P_2 is the problem situation as it emerges from our first critical attempt to solve our problems. It leads up to our second attempt (and so on). A satisfactory understanding will be reached if the interpretation, the conjectural theory, finds support in the fact that it can throw new light on new problems - on more problems than we expected; or if it finds support in the fact that it explains many sub-problems, some of which were not seen to start with. Thus we may say that we can gauge the process we have made by comparing P_1 with some of our later problems (P_n, say) (Popper 1995).

Oeser developed this schema further and defined it as a systems-theoretical function model of scientific development (Figure 1.1) which provides the actual structure for this thesis: information (with situation & problem) - hypothesis - theory - prognosis (or application) (Oeser 1976).

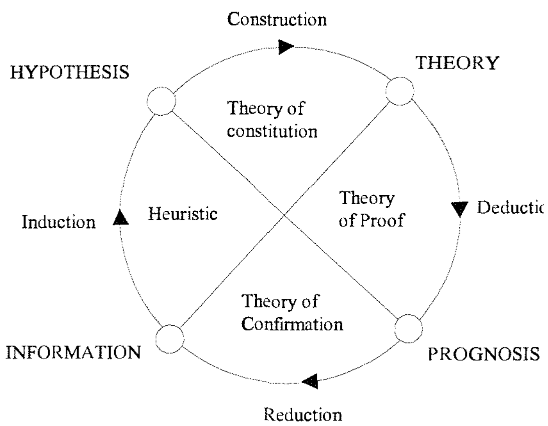


Figure 1.1: A Systems-Theoretical Function Model of Scientific Development (Oeser 1976)

Using 'information' Oeser describes the process of abstraction, where several pieces of information are chosen and connected in a coherent pattern. Presupposition for this first process of 'information condensation' are constant patterns where it is assumed that the perception depicts reality in an adequate way. "A simple sensual perception cannot be regarded as a cognition but only as a reason for a cognition" (Oeser 1976).

A hypothesis is based on observations or phenomena which is understood as a relationship between conditions and events and not between cause and effect. Induction is the process of formulating conclusions in relation to these phenomena, i.e., it is not a summation of events but a method which leads to another level of abstraction.

There is no absolute difference between information and hypothesis and in the same way there is only a gradual difference between hypothesis and theory. The methodological difference lies in, firstly, the constructive method, i.e., a synthetic method which connects the empirical analysis of induction with the formal analysis of deduction, and secondly, the deductive method, i.e., a systematic method which enables a logical and consistent systematisation without analytical leaps (which characterises the hypothesis). The axiomatic theory as a discrete, sequential systems of predications forms the highest degree of information condensation.

The 'prognosis' constitutes the empirical, reductive confirmation of the theoretical deduction. It is a mirror image of the inductive hypothesis and provides the decisive characteristics between competing hypothesis. The reduction describes the feedback and the comparison of theoretical assertions to the events of reality.

Together, the four stages describe a "step-by-step conquest of the unknown" (Oeser 1976). This process is repeated as there is no absolute start or finish, with no absolute verification or falsification, but only a tendency towards a higher level of cognition as indicated by the circle of Figure 1.1.

1.3.2 The Structure of the Study

Information, Situation and Problem

Many disciplines have contributed to transport modelling concepts. However, whilst probably the most significant influences has come from economics, the economic concepts involved are usually not explicitly described in the transport literature. Thus, a brief account of economic behaviour is therefore presented in Section 2.1 to highlight some of its concepts and assumptions and to draw some links to transport modelling.

The literature review of transport modelling introduced in Sections 2.2 and 2.3, begins with the identification of what characterises a trip. Because of the interdisciplinary nature of transport, a large number of diverse variables have to be identified as being important. The main problem lies in the selection of those which contribute most in relation to their magnitude of influence, whilst minimising the number of variables. The resulting variables can constrain the consequent modelling process and, therefore, limit the understanding of trip making.

Conventional models of trip generation and trip distribution are reviewed in Section 2.3.1 and 2.3.2 by concentrating only on their basic concepts. The activity-based approach is regarded as an alternative to the traditional four-stage models, hence the concepts of this approach are summarised in Section 2.3.3. Behavioural models which tackle the problem of daily travel travelling directly, are discussed in Section 2.3.4. In principle, two perspectives are used to attempt to explain daily travel time: the first one addresses it from an economic point of view and the other from an evolutionary point of view. This means that the original question of variables still remains.

Chapter 3 opens with a brief account of the data used in this thesis, i.e., the NTS and ergonomic data. The NTS data analysis of Section 3.2 shows the influence of the socio-economic variables in comparison to travel time and trip rate of the travel budget approaches. The degree of influence should provide an explanation for their significance since the socio-economic variables are used as explanatory trip variables in most transport models. In Section 3.3 the concept of ergonomics is introduced which provides an insight into the energy turnover and its fundamental role in the daily life cycle. Its application is crucial to the bio-physical approach.

Hypothesis

The limits of socio-economic variables to describe travel behaviour questions their conceptual basis as the primary factor governing such behaviour. An alternative concept is proposed, in which the bio-physical human energy is considered to determine the *amount* of daily travelling (Chapter 4). The basic assumptions are derived from both a systems-theoretical approach and a physical methodology. The systems-theoretical approach provides the framework for an alternative trip definition with the essential elements of a trip (Section 4.2.1), and the physical methodology provides the conceptual basis for the description and derivation of the energy variable (Section 4.2.2).

To describe travel behaviour from a perspective of human effort, the NTS data have to be sorted in such a way as to enable a connection to the ergonomic travel measures (Section 4.2.3). For the following postulation of the hypothesis an agreement should be found between the ergonomic measures, describing the internal human effort on the one hand, and the NTS data, describing the external travel behaviour on the other (Section 4.2.4). The data analysis should reflect, for example, that energy expenditure between the human body and its external movement is conserved. This condition should provide the basis that distance is not an *independent* unit (as it is in physics) but a *dependent* unit in relation to the mode of transport used and only time is the valid measure of human travel behaviour. This condition also forms a presupposition for the following physical derivation.

Theory

An analogy of statistical physics is used to integrate, calculate and test the relationship between travel behaviour and human energy. This should be verified firstly by juxtapositioning the assumptions and concepts of a physical system with those of a transport system (Section 4.3.2). One essential feature here is the understanding of a macroscopic system where physical properties emerge which cannot be observed from a microscopic perspective. Secondly, the actual derivation should validate the application of the Maxwell-Boltzmann distribution in transportation (Section 4.3.3 - 4.3.6). Thirdly, the calibration of the functional parameters should affirm the functional relationship in terms of its realistic shape and in terms of the parametrical values (Section 4.3.7). Finally, the mathematical result should conclusively substantiate the hypothesis of a constant travel energy budget (Section 4.3.8).

Application and Discussion

In Chapter 5 most of the issues raised in the previous chapters, especially of Sections 2.2 and 2.3 will be compared to the findings of the approach developed. In addition, some applications are given to illustrate the validity and the practicality of the approach. This is done in the following way: firstly, as mentioned under the hypothesis, some evidence is presented for the distance assumption which is fundamental to the approach and is mainly dependent on the mode of transport (Section 5.1). In the subsequent sections, trip rate is discussed in more detail to provide some evidence for the bio-physical model of trip generation. Afterwards the bio-physical approach is compared with current transport approaches, following the outline of the literature review of transport modelling (Section 5.3). In respect to trip generation and trip distribution, guidelines are presented to show the practical applicability of the proposed approach, a property which constitutes another facet of validity (Section 5.3.2). In the following section, economic behaviour is revisited to compare the results also in terms of economic rationality and its methodology (Section 5.3.3). Finally, some additional ideas are presented to show further implications of the bio-physical approach (Section 5.4).

The thesis concludes with Chapter 6 where the main findings are summarised.

Chapter 2

Context

Many methods used in traffic engineering are founded on an economic framework or are imported from the field of economics. It is therefore necessary to give a brief account of economic behaviour. In the following sections the preliminaries of transport modelling with trip variables, trip definitions and trip matrix are discussed where the economic influence should find its first repercussions. The next section on conventional modelling is separated into models of trip generation and trip distribution, activity-based approaches and travel budget approaches. In this section only the basic methods are described with their problems in terms of predictability and application.

2.1 Economic Behaviour

In economics the problem of behaviour is closely connected with the problem of rationality, since rationality is considered as the basic premise from which behaviour can be inferred (Arrow 1987), (Hargreaves-Heap & Hollis 1987), (Sen 1987), (Simon 1987). Moreover, "it seems to be asserted that a theory of the economy must be based on rationality, as a matter of principle. Otherwise, there can be no theory" (Arrow 1987). Behind this assumption of theory building lies the problem of quantification theory since mathematical methods are understood as the 'purest' form of rationality.

The theory of economic rationality can be considered to fall into one of two main groups: (i) on the individual level (or the level of the firm), i.e., a theory of reactions to stimuli, and (ii) on the social level, i.e., a theory of market interactions which will lead to theories of competition, general equilibrium and completeness of the market.

In transport modelling an equivalent distinction would be on the one hand related trip making by an individual or household like trip generation models or travel budget approaches and on the other hand, models related to transport systems and land-use like trip distribution models or transport management models.

2.1.1 The Individual Level or the Level of the Firm

Historically, rationality was interpreted as the principle for maximising profits by Smith and Ricardo; the marginalists (Walras, Jevons, and Menger) redefined rationality as maximisation of utility under budget constraints and developed a utility theory, where 'substantive' rationality is derived as the independently defined self-interest giving the ordinal effect of a utility function (Sen 1987). It is interesting to note that the first approach to optimisation of limited resources was developed in relation to traffic: Herman Heinrich Gossen, *Entwicklung der Gesetze des menschlichen Verkehrs*[1], 1854.

In contrast, neo-classical economic man is endowed with 'instrumental' rationality, i.e., he pursues his independently defined objectives expressed as a function of choice. To comprehend these properties of rationality, the *ideal* Homo Economicus is endowed with:

- perfect information and immaculate computing power,
- complete, fully ordered preferences with better means of choice than anyone else. He never pays more than he needs or gets less than he could for the price (Hargreaves-Heap & Hollis 1987).

These assumptions result in one general utility function for all individuals which varies marginally only in broad categories, such as family size. Practical applications of this type can be found in a Marxist profit-maximising capitalist or in institutions like banks or trade unions which can also be seen as unitary rational agents.

There are not only empirical doubts about the realistic context for this approach, but also methodological doubts. If all agents are absolutely the same and have the same *common knowledge* they will have the same interests, they will have the same taste and thus will make the same choices. In traffic engineering this means the same kind of people will use the same kind of means of transport with the same choice of route. In addition, to gain perfect knowledge one would need to invest infinite effort.

For more realistic approaches a number of adjustments have been proposed: the limits of knowledge can be estimated in the marginal costs of searching for information, but that makes it more difficult to assess the optimum of limited knowledge. The other consequence is that information is reflected in prices or, in the reverse order, prices show the scope of the information of the agents. Another refinement

[1] The Development of Laws of Human Traffic

resulted from Simon's 'satisficing' models or 'procedural' rationality (Sen 1987). In the satisficing model the agent does not maximise his achievements; he is satisfied with a certain level of achievement and beyond that level it becomes uncertain if he wants to improve his situation. Such a behaviour is described as a maximisation of incomplete information. It will lead to notions such as 'bounded rationality' where rationality is dependent on the order of alternatives and is reflected in a process of loosely integrated decision making. 'Procedural' rationality is of a similar kind where the agent follows a procedure and restrains the search once a good solution is found. The *absolute* Homo Economicus can be seen as "an Organisation Man rather than an abstract maximiser" (Hargreaves-Heap & Hollis 1987). (Here, 'absolute' is understood in a nominal rather than an idealistic sense.)

The actual motivation for a *relative* Homo Economicus is assumed not in an unconstrained form of a choice function but in a constrained form of a utility function (Sen 1987). This allows him to choose between alternatives in a consistent manner to gain greater utility. The choice process is characterised firstly by uncertainty and, secondly by the actual decision-making between various alternatives.

'Expected' uncertainty can be described as the likelihood of different outcomes and their consequences (Sen 1987). This characteristic has been embedded into different theories:

- The *theory of game:* Each player is driven by how they should act according to their interests (normative or prescriptive theory), and how they will act according to the game (positive or descriptive theory). In relation to this, cardinal utility functions are developed based on probabilities of different outcomes and ranked consistently over possible lotteries of different outcomes, and order the information in terms of the relevant characteristics.
- The *theory of risk*: Here, an action is assessed based on several possible consequences by discounting the utility of each consequence according to its probability distribution.
- *Holbrook Working's random walking theory of fluctuations*: Here, agents infer rationally from data and act on them.
- The *theory of rational expectations* describes an information-generation process which is based on the future expectations of actual properties of variables.

The rationally behaving agent then chooses the outcome with the highest overall utility. In deference to reality it is more plausible to search not for all alternatives but for all potential alternatives. Selecting such alternatives means searching for preferences and these can only be identified if the accuracy of the model is presupposed.

Substantiations from this individual level or level of the firm are mostly represented in transport modelling. 'Absolute' can be understood in certain aspects of time-invariant behaviour which do not change in magnitude. This premiss is generally assumed in transport modelling where, for example, different people show the same behaviour pattern in the same circumstances. Such patterns form the basis for cross-classification or category analysis of trip generation models.

It is interesting to note that, with the availability of information technology, the assumptions of the ideal Homo Economicus in terms of perfect information and computing power become potentially increasingly real since the observation of traffic and the decision of driving can be made by a computorial traffic management system. This means that the rationality of the driver is exchanged by the 'rationality of computer' (where the driver only follows the advice of the system).

For the relative Homo Economicus, the concept of a utility function could be inverted in such a way that a cost function can be envisaged as a 'dis-utility' function. Consequently, a rational agent would then minimise the costs, so eventually he or she should choose the means of transport with the minimal expenditure (in relation to revenues).

In contrast to the individual level, the social level described in the next section cannot obviously be detected in transport approaches, but is reflected in general terms of understanding how transport problems are tackled.

2.1.2 The Social Level or the Level of Market Interactions

"Rationality is not a property of the individual alone, although it is usually presented that way. Rather, it gathers not only its force but also its very meaning from the social context in which it is embedded" (Sen 1987). This interpretation could also be visualised in A. Smith's 'invisible hand' which appears in the background of the agents' economic system.

The most important theorem in welfare economics is Pareto's optimality of competitive equilibria or the 'Fundamental Theorem of Welfare Economics' which is reached when no further efficiency (or equity) can be gained without worsening someone elses. Another characteristic of Pareto's optimality is the self-interest maximisation of a group. These two criteria are again idealisations and presuppose perfect competition. For a more realistic approach, incomplete market and market power are introduced in the form of Marshall's rational expectations equilibrium, where the expectations are not completely arbitrary but converge without disturbance to the correct values. The individual then would need expectations of prices (expressed as probability distributions) which are in relation to the available information (i.e., the 'revealed preference theory' in the form of the 'Weak Axiom of Revealed Preference'). Thus, knowledge can be identified with market power. This incompleteness of the markets and information leads to models of rational market behaviour with not a single but a continuum of possible equilibria which is accompanied by a kind of instability due to competitive equilibria (Sen 1987).

The condition of equilibrium is also assumed in transport modelling, although in a different form and due more to analytical requirements. Generally, this condition seems difficult to justify because the transport system goes through perpetual changes. Thus, "the system ... may at best be in a continuous process of adjustment, searching for equilibrium but never reaching it, like the weather" (Goodwin 1990).

The second point to make is concerned with the maximisation of self-interest of a group. This can be recognised, for example, in consciously deciding to omit certain trips or groups of travellers and concentrating on one particular mode of transport. Such decisions may be made with the intention that they would not have any relevant influence on the approach and therefore do not merit further consideration. In the following review of transport modelling approaches more examples are provided to highlight the economic repercussions in traffic engineering.

2.2 Preliminaries of Transport Modelling

Generally speaking, qualitative approaches are concerned with the identification of 'explanatory variables' and quantitative approaches measure their impacts. From such a perspective, the variables and their consequences associated with a 'trip' will be reviewed since they raise the most fundamental questions in transport planning. Following this in the subsequent review of transport modelling, the limitations of existing modelling approaches will become apparent and the discussion will return to the starting point, i.e., the question of variables.

2.2.1 Trip Variables

The Unit of Reference

Variables can generally be inferred from the unit of reference. For travel modelling, two units are normally considered: the household and the individual. (Here, household and family are set as equal.) In the literature the household unit is preferred for various reasons: From a trip making point of view, the home is the basis where most trips start and end; from an economic point of view, income or car-ownership are usually shared by all member of the household; or from a social context, the family constitutes the 'cell of our society' where all basic needs are usually met. Alternatively, if the individual is considered to be the base unit then the problem of allocation of some of the above mentioned variables needs to be overcome, or different quantities have to be taken into consideration.

Lohse and Lätzsch distinguish three characteristic quantities for trip making: quantities of expenditure, criteria of location and isochrones (Lohse & Lätzsch 1997).

Quantities of Expenditure

The following set of variables V can be identified for the quantities of expenditure:

- the 'crow-fly' distance in metres,
- the travel distance in the traffic system in metres,
- the travel time distance in the traffic system in minutes, or
- the travel costs in the traffic system in monetary units.

An expenditure matrix $x_{ij}(V)$ can be developed for each of these variables or their combinations. The indices i and j stand for the cell of origin and destination respectively. Of particular interest is the travel time. Lohse and Lätzsch define complex travel time by:

$$t = \sum t_{inveh} + t_{acc} + t_{wo} + \sum t_{ch} + t_{sp} + t_{eg} = \sum t_{inveh} + t_{term} \qquad (2.1)$$

t	complex travel time
$\sum t_{inveh}$	sum of all in-vehicle times by all means of transport
t_{acc}	access time at the origin
t_{wo}	waiting time at the stop of origin
$\sum t_{ch}$	sum of all interchanging times including waiting time
t_{sp}	time for searching a parking space plus clearance time
t_{eg}	egress time from the stop of destination to the destination
t_{term}	terminal time (Lohse & Lätzsch 1997).

Ortúzar and Willumsen integrate cost-related factors into equation 2.1 by exchanging t for costs C and t_{sp} for terminal cost C_{sp} (e.g. parking costs) (Ortúzar & Willumsen 1994). In addition, the fare charged C_{fare}, and a modal penalty δ, (which includes generalised measures such as safety, comfort or convenience) are summed using the weighting factors $a_{1...6}$:

$$C = a_1 \sum t_{inveh} + a_2(t_{acc} + t_{eg}) + a_3 t_{wo} + a_4 \sum t_{ch} + a_5 C_{fare} + a_6 C_{sp} + \delta \qquad (2.2)$$

Again, indices ij could be used. If this is done, terminal costs are only destination related and the modal penalty is independent of origin and destination (Ortúzar & Willumsen 1994).

Criteria of Location

Lohse and Lätzsch present a list of what they define as *structural* variables S. In this list, variables are identified by:

- the geographical features, such as landscape, climate,
- features of dwelling areas, such as age structure, education and employment of inhabitants,
- the economy or economic production, such as type or value of companies or economy, and
- the social facilities, such as size of infrastructure, number of shops, cultural or leisure institutions (Lohse & Lätzsch 1997).

The quantification of these variables is generally given by their numerical magnitude. The disposition of location DL does not depend on size or significance of the district; it is assessed according the location of the district in the area:

$$DL = \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{SO_i}{SSO}\times\frac{SD_j}{SSD}\times x_{ij}(V) \qquad \text{where}$$

$$SSO = \sum_{i=1}^{m} SO_i \quad \text{and} \quad SSD = \sum_{j=1}^{n} SD_j$$

SO_i and SD_j represent for the specified structural variable of origin and destination respectively.

Isochrones

Isochrones are defined as lines of equivalent time distance. The difference between time zones exhibits the average expenditure in time for overcoming a distance in space. If a constant speed of travel is assumed, the isochrones are at an equal distance and their structure displays the advancements or catchment area of a transport system. The landscape of an area or other structural variables can play a considerable part in the layout of isochrones. For example, isochrones can reflect the differences in shopping opportunities between a middle-aged, white-collar worker with a car and a disabled pensioner relying on public transport. The importance of isochrones lies in the *practical* visualisation and estimation of the land-use of possible transport systems in relation to different structural variables. For further construction of isochrones see (Lohse & Lätzsch 1997).

2.2.2 Trip Definition

There are many different reasons why definitions are formulated: one is to clarify a notion for its scientific usage because in everyday language the term is too imprecise or is ambiguous. Another reason might be to highlight differences according to different approaches (Dasgupta, Raha & K. 1996). A third reason, which is probably the most common one, is to create a basis for an approach.

The following definitions of a trip or journey are typical of those found in transportation literature:

> *Trip*: a change of place (with a means of transport)[2] from origin to destination in respect to **one** purpose (Lohse & Lätzsch 1997).
>
> *Trip.* This is the fundamental unit of travel. It is defined as a journey between two locations (e.g., from home to work place).
> *Tour/Journey.* A tour is a sequence of trips that are 'chained' and begin and end at home. Therefore, a tour contains at least two trips (e.g., from home to the work place and back home) (Becker, Schneider & Schwartzmann 1991).
>
> "*Journey.* This is a one-way movement from a point of origin to a point of destination. Now, although the word 'trip' is literally defined as 'any outward and inward return journey, often for a specific purpose' (McLeod & Hanks 1986), in transport modelling both terms are used interchangeably. We are usually interested in all vehicular trips, but walking trips longer than a certain study-defined threshold (say 300 metres or three blocks) are often considered; finally, trips made by infants of less than five years of age will usually be ignored, ..." (Ortúzar & Willumsen 1994).

Another definition, for example, like Zahavi's definition of a traveller is given in Section 2.3.4 but the above definitions constitute the basic type of trip definitions found in the key literature. In addition to these examples, further definitions can be found which relate an *apposition* to specific applications. In terms of mode of transport a trip then becomes a 'Vehicular trip', if only mechanised modes of transport are taken into account, or a 'Vehicle trip', if any type of vehicle is under consideration (Dasgupta et al. 1996). Furthermore, definitions can be viewed in relation to the perspective of survey undertaken. An example is where the focus is on land use so the 'purpose' is transformed into origin and destination and replaced (in the wording of the definition) by "from and to a land use" (Dasgupta et al. 1996). A variation can be given in relation to trip chaining or tour. ITE distinguishes three types: 'Primary Trips', i.e., a trip without interruption for a specific purpose, 'Pass-by Trips' , i.e., an intermediate stop is made on the way to the primary destination but without a diversion from the route, and 'Diverted Linked Trips', i.e.,

[2] For the purpose of the description this part contained in parenthesis is inserted by the author from the equivalent definition.

a pass-by trip with a diversion because of the vicinity of an intermediate destination (ITE 1991).

From a technical perspective the difficulty with definitions lies in the assessment of the attribute. It is not only the problem of actual categorisation, i.e., defining clear boundaries, but even more the multiplication of scope and complexity of an approach, i.e., many categories require more observations to obtain representative samples.

From a conceptual perspective definitions do not necessarily have to be 'comprehensively and exhaustively derived' statements, at least in engineering terms. They should reflect a functional description of a phenomenon with its essential elements. An examination of the above mentioned definitions reveals that not all the essential components are included. For example, if an economic approach is adopted then 'cost' should be included, either in purchase and running of an individual means of transport or in fare for public transport. Another element is the distinction between the traveller and the means of transport; the traveller being discerned as unity or nucleus within the latter. Consequences can be found in units of efficiency which are usually in [vehicles/hour] and not in [person/hour]. However, it is essential to see the distinction between humans as the prime subject of travel and the modes as a secondary means. Such a distinction would enable the possibility of including individual or human related variables.

Another problem exists between 'quantification' and 'generalisation': the exclusion of short trips of less than 300 m would mean removing 30 - 70% of all walking trips (Peperna 1982). If such walking trips turn into vehicular trips they gradually become longer and are then accounted for. This gives rise to the often encountered conclusion that the 'car' has generated new trips, although this may not be the case, because trips by different means of travel are not equally evaluated. A similar problem can also be found in a linguistic sense: 'traffic' is usually used synonymously with individual vehicular traffic even when the latter accounted for only 55% of all trips in 1972/3, steadily increasing up to 72% in 1995 (DETR 1998b). And if this point of view is generalised, further problems will arise when such propositions are transferred to Developing Countries where a considerable number of trips are walking trips. In this way a lack of adherence to the initial constraints can lead to faulty conclusions if results are interpreted out of context.

2.2.3 The Trip Matrix

The *mathematical* description of travel flows is given by the trip matrix which is an essential part of nearly all computations of traffic flow. Every trip T_{ij} can be classified unequivocally in respect to its origin i and destination j. For this purpose a territory is divided into different zones or cells which are ranked according to their position in the schematic partition. Different kinds of travel flows can be identified, principally as inter-zonal flows T_{ij} and as intra-zonal flows T_{ii}. The following matrix presents the most important flows and their equations:

from i \ to j	$1 \quad \dots \quad j \quad \dots \quad n$	$\sum$	
1	T_{11}	O_1	
$\vdots$	$\ddots$	$\vdots$	
i	T_{ij}	O_i	$(= \sum_j T_{ij})$
$\vdots$	$\ddots$	$\vdots$	
m	T_{nm}	O_m	
$\sum$	$D_1 \quad \dots \quad D_j (= \sum_i T_{ij}) \quad \dots \quad D_n$	T	$(= \sum_i O_i = \sum_j D_j)$

O_i denotes the origin travel, D_j the destination travel, and T denotes the total trips in the territory. The external traffic flow, i.e., the traffic which comes into, through or goes out of the investigated area, can also be included in the analysis.

The partition of the trip matrix can be according to the structural variables. For example, Lohse and Lätzsch give some principles: topographical breaks, such as trunk roads or railway lines, or rivers should form the boundaries of the geographical partition. The cells should correspond to other socio-economic or demographic characteristics; they should also form a subsystem such as a focus of traffic generation or a local centre, and should be *homogeneous* in their features. The main determinant of the partition will depend on the purpose of the investigation and the available resources which will also restrict its scope. Lohse and Lätzsch additionally provided a diagram with a minimum and maximum number of cells according to the number of inhabitants. Further classification in terms of mode of transport, type of person or purpose of trips can be considered (Lohse & Lätzsch 1997).

Depending on the purpose of the investigation the matrix can be singly constrained, i.e., only one set of equation (either origin or destination) is satisfied $T = \sum_i O_i$ or $T = \sum_j D_j$, or doubly constrained, if both have to be simultaneously satisfied, i.e., $T = \sum_i O_i = \sum_j D_j$.

Additionally, 'weak' constraints can be introduced if the equal sign is replaced by an 'greater than or equal to' sign. These conditions are applied when limitations in capacity are assumed, either in the origin O_{max} or in the destination D_{max}. These specifications can then be tackled without constraints so that only

$$\sum_i O_{max} \gg T \qquad \text{and} \qquad \sum_j D_{max} \gg T \qquad \text{where} \qquad T = \sum_i \sum_j T_{ij}.$$

In terms of transport modelling, the origin travel O_i or destination travel D_i are determined by trip generation models and the T_{ij} are determined by trip distribution models which are discussed in the next sections.

2.3 Transport Modelling

In principle, all traffic models are designed as probabilistic models to represent traffic behaviour as mass phenomena, where the individual is regarded as a statistical element.

Although there are usually four stages involved in conventional transport modelling, attention in this review is paid only to the first two, namely trip generation and trip distribution, which form the basis for modal split and trip assignment models. To understand this better, modal split can also be envisaged as a form of trip generation, since the number of trips is related to a mode of transport, i.e., a *modal* trip generation. Lohse and Lätzsch take this fact into account by placing Trip-End Models, a variant of modal split models, between trip generation and trip distribution models whereas Trip-Interchange Models, another variant of modal split models, is positioned after trip distribution (Lohse & Lätzsch 1997). (In relation to Section 2.1, this can be seen as a problem of (dis-) aggregation or of rational preference.) However, this investigation attempts to determine how much people travel in the first instance, independent of the mode of transport. Hence, modal split and trip assignment are assumed to be constrained by trip generation and trip distribution and therefore they have not been reviewed. The activity-based approach is often presented as an alternative to the conventional four-stage modelling and is reviewed.

Despite the complexity of travel behaviour, there are a number of specific travel patterns which seem to be independent of transport systems, society or culture. One of those is the constancy of daily travel time, i.e., around one hour per person (Schafer 1998). Numerous travel time budget approaches (TTB) have been developed which attempt to explain this parameter. One branch provides an explanation in terms of 'generalised costs' which include some estimations of actual and perceived costs in respect to travel time. The other tackles the parameter from an evolutionary perspective which relates travel behaviour to physiological factors or instinct behaviour. This means that the question of variables continues to prevail.

2.3.1 Trip Generation

The principle aim of trip generation models is to determine the number of trips originating in, or attracted to, the zones of an investigated area. The basic classification is expressed in the terminology of economics with the notions of trip production and trip attraction. The home is generally considered as a source of production and work as one of attraction. These trips are also called 'home-based' trips and count for around 80% of all trips. If trips occur, for example, between work and shop, i.e., 'non-home-based' trips, then production and attraction change according to origin and destination respectively (Ortúzar & Willumsen 1994). Despite this ambiguity 'generation' is used as "trips are generated from their origins and attracted to their destinations" (Dasgupta et al. 1996). This mutual properties between generation and attraction also determines the variables of the model.

The following factors are regarded as the socio-economic variables for trip production: income, car ownership, household structure and family size, value of land, residential density, or accessibility (Ortúzar & Willumsen 1994). Lohse and Lätzsch usually consider the number of inhabitants, number of working places (differentiated according to industry and other sectors) and number of vehicles or degree of motorisation as variables for transport planning; and despite these components the constraints for trip generation stem from the transport system and its design in relation to society, economy and environment (Lohse & Lätzsch 1997). Dasgupta et al. used structural variables according to the land-use objectives and found a reasonable correlation between work trips and employment. They found it more difficult to establish similar relations for leisure and shopping activities where factors such as type of product, location or catchment area, should be considered (Dasgupta et al. 1996).

Most trip generation models deal only with motorised or specifically vehicular trips and few consider trips by non-vehicular mode of transport. A reason could be found in the need to reduce the complexity of the vehicular models and to avoid the development of measures for non-motorised transport. DKS suggest that possible variables for these modes of transport could be of a demographic nature; they should exhibit the fact that people are inclined to walk, if the desirable land-use is within walking distance, otherwise they will use the bicycle or a motorised means of transport (DKS 1994).

Generally, three computational models are used: Growth-Factor Analysis, Regression Analysis and Cross-Classification or Category Analysis.

Growth-Factor Analysis

This model characterises future trips by a factor of magnitude in relation to current trips. (The term 'growth' might come from the fact that the number of vehicular trips have increased continually over the last decades.) A growth factor G is determined by dividing the trip function of the design years $t(V^d)$ with the trip function of current years $t(V^c)$:

$$G = \frac{t(V^d)}{t(V^c)} \tag{2.3}$$

V denotes structural variables such as population P, income I or car ownership CO. If the origin variable is workers W and the destination variable is jobs J then equation 2.3 can be expressed in origin and destination trips for different zones i:

$$O_i = \frac{t(W_i^d)}{t(W_i^c)}, \quad D_i = \frac{t(J_i^d)}{t(J_i^c)}$$

This method is considered to be very crude, so a refinement can be made with a multiplicative formulation of growth factors:

$$G = G_P \times G_I \times G_C = \frac{t(P^d)}{t(P^c)} \times \frac{t(I^d)}{t(I^c)} \times \frac{t(CO^d)}{t(CO^c)}$$

This modification offers the possibility of including other variables. Additional adjustments can be made by a weighting for each factor.

The assumptions used in this model are that the future states are known and that the conditions of trip making remain stable. The growth-factor model is considered to be only a model for rough assessment.

Regression Analysis

The functions of trip making are calculated by regression analysis which can be either linear or non-linear; the latter is more difficult to handle but allows a greater flexibility. The application of regression analysis is only valid (i) if the circumstances remain stable, (ii) if the variables V_n have similar normal distributions and form a coherent correlation ellipse, and (iii) if the 'independent' variables are statistically independent (Lohse & Lätzsch 1997).

The computational procedure begins with the formulation of the variables of origin and destination:

$$O_i = a_0 + a_1 V_{1i} + a_2 V_{2i} + \ldots + a_n V_{ni} \tag{2.4}$$

$$D_j = b_0 + b_1 V_{1j} + b_2 V_{2j} + \ldots + b_m V_{mj} \tag{2.5}$$

For the linear case, the unknown regression co-efficients a, b are determined with the minimal condition:

$$\text{Min} \sum_i (O_i - a_0 - a_1 V_{1i} - a_2 V_{2i} - \ldots - a_n V_{ni})^2$$
$$\text{Min} \sum_j (D_j - b_0 - b_1 V_{1j} - b_2 V_{2j} - \ldots - b_m V_{mj})^2$$

With the partial differentiation of each coefficient, an equation system is obtained whose solution yields the regression co-efficients.

As an example, one of the specific equations can be found in DKS, a formula for a household model of home-based trips:

$$O_h = -1.42 + 1.46 HHS_h - 1.65 CH5_h + 1.69 AC_h + 0.75 W_h \quad \text{where} \quad R^2 = 0.38 \tag{2.6}$$

where:

O_h	the average number of person trips for a household in zone i
HHS_h	the size of the household h
$CH5_h$	the number of children under 5 in a household h
AC_h	the number of cars available to a household h
W_h	the number of workers in household h

DKS favour equation 2.6 because it relies on individual behaviour and does not depend on the zonal structure (DKS 1994).

The regression analysis is only applied to trip production O_i or trip attractions D_j, but not to the area as a whole (Lohse & Lätzsch 1997). It can only explain variations in travel behaviour between zones. When there is no zonal information available, these 'null zones' must be excluded from the analysis; and if the regression line does not pass through the origin naturally then the equation may be either rejected or forced to pass through the origin (Ortúzar & Willumsen 1994). Statistical tests are applied to check the accuracy and validity of the analysis.

Dasgupta et al. conclude that "much of the evidence from trip generation studies is anecdotal by nature and in many cases there are significant variations between similar studies ..." On another occasions they have stated more specifically that "the literature ... yields patchy evidence on trip length and, moreover, does not provide any longitudinal trends. Trying to establish coherent trends over time ... is fraught with the difficulties of the masking effects of outside factors ...". With regard to daily periods of time, many models are no longer used for peak-hour periods and operate on the basis of estimating 24 hours flows. Another stated problem is that variables do not satisfy the statistical requirements, for example, they can be internally correlated. Thus, regression analyses are more likely to introduce errors, especially in forecasting (Dasgupta et al. 1996).

Wootton and Pick draw attention to the methodological problem of the regression analysis: "A disadvantage of the method is that, being empirical in nature, it cannot provide a real insight into the mechanism of trip generation or establish causal relationships between the dependent and independent variables" (Wootton & Pick 1967). A methodological clarification can be found in Kendall:

> A statistical relationship, however strong and however suggestive, can never *establish* a causal connexion: our ideas on causation must come from outside statistics, ultimately from some theory or other. ... Even if rainfall and crop-yield were in perfect functional correspondence, we should not dream of reversing the 'obvious' causal connexion. We need not enter into a philosophical implications of this; for our purpose, we need only reiterate that statistical relationship, of whatever kind, cannot logically imply causation. ... Yet there are large fields of application (the social sciences and psychology, for example) where patterns of causation are not yet sufficiently well understood for correlation analysis to be replaced by more specifically structured statistical methods, and also large areas of multivariate analysis where the computation of what is in effect a matrix of correlation co-efficients is a necessary prelude to the detailed statistical analysis (Kendall & Stuart 1973).

This problem of regarding correlation as equivalent to causation is common place in the literature.

Cross-classification or Category Analysis

The determination of trips is attempted through a homogeneous classification. These categories can be related to person, household, workforce or space, time and purpose. "The 'art' of the method lies in choosing the categories ..." (Ortúzar & Willumsen 1994). It also depends on the orientation of the analysis: towards trip production, trip attraction or total traffic emergence. Lohse and Lätzsch offer solutions for all three categories including hard or weak marginal sums of the trip matrix (Lohse & Lätzsch 1997). The following three formulae, given in order of solution, show an origin determined trip generation (of a closed area)[3].

$$
\begin{aligned}
O_i &= \sum_g k_{ig} \times V_{ig} \\
T &= \sum_i O_i = \sum_j D_j \\
D_j &= F \times \sum_s k_{js} \times V_{js}
\end{aligned}
$$

The category value k is defined as the average trip rate in relation to the equivalent trip variable and is mainly determined by the socio-demographic characteristics of person group g, such as employment, position in the household, and age. Further subdivisions, for example, by purpose or means of transport are possible. Different trip variables are applied for trip production V_i, e.g. workers, and trip attraction V_j, e.g. employment. To ensure the marginal sum condition between (the fixed) trip production on the one hand and (the varying) trip attraction on the other, a correction process is applied with the balancing factor F which removes the variability in the zones and enhances the goodness of fit with the survey data.

DKS point out some drawbacks with this method:

- Since averages are used for the category values, internal cell variations are ignored or concealed throughout the calculation process. (According to the variance of the category value small changes in connection with the multiplication of, for example, large numbers of households can have a significant effect on the results.)
- Zonal dependent variables can vary with the size of zones.
- Increasing numbers of categories can lead to great variations of cell means or to empty cells. This can be counteracted by decreasing the number of cells either by minimising the variables or by aggregation of the values of variables (DKS 1994).

The process of selecting the variables is investigator-dependent and, therefore, is in some way arbitrary. Additionally, a study is only supported by the goodness of fit of the data and may be considered as descriptive or phenomenological, so the analysis only reinforces the initial assumptions. These arguments might be the reason why analogies with physical laws have been devised to achieve a causal relationship which can be found, for example, in the Gravity Model for trip distribution as discussed in the next section.

[3]By exchanging O for D and the index i for j, an attraction-orientated model can be obtained.

2.3.2 Trip Distribution

Trip distribution models determine trips made between different zones of an area and reflect trip making in terms of extent, i.e., trip length, trip time and direction in the network. Mathematically speaking, the elements of the trip matrix T_{ij} are to be calculated in relation to the trip cells of origin O_i and destination D_j (which have been assessed by the trip generation models). To solve the equation system of the trip matrix, $i \times j$ additional equations are required which are then supplemented by functions which include variables such as distance, time or cost. Thus, T_{ij} results in a function g of the marginal sums and of the supplementary condition.

$$T_{ij} = g(O_i, D_j, f_{ij}(V))$$

The supplementary condition $f_{ij}(V)$ attempts to explain trip distribution and therefore can be considered as the *structural* condition. In the literature it is referred to as the 'deterrence' function since it reflects the travel behaviour of decreasing trip making as travel expenditure increases and vice versa; Figure 2.1 depicts some exemplary functions of the subsequent models. The basic formulation of the equation system can be defined as

$$T_{ij} = f_{ij}(V) \times F_{Oi} \times F_{Dj} \tag{2.7}$$

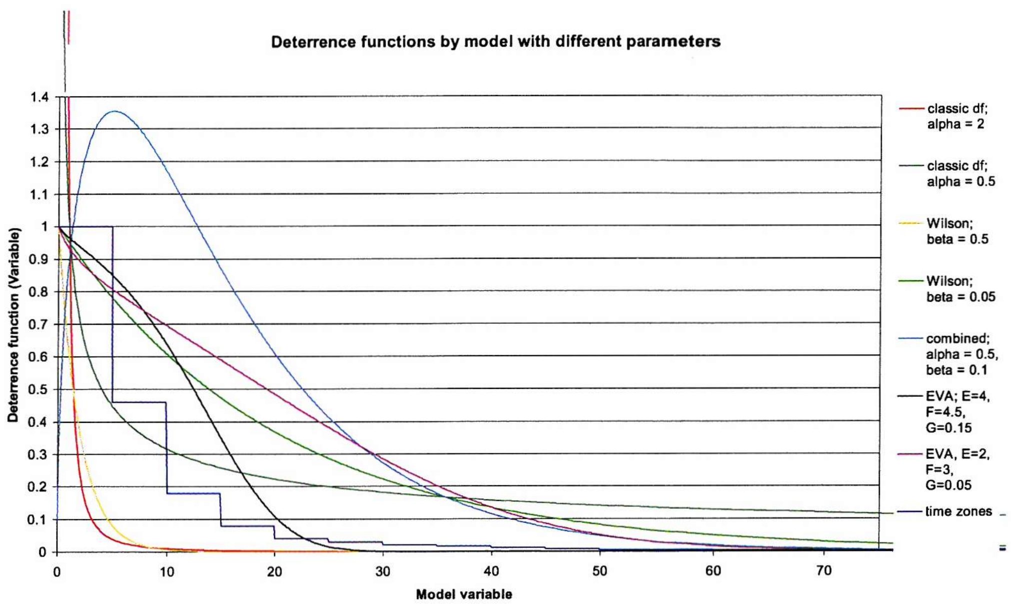


Figure 2.1: Deterrence Functions of Different Trip Distribution Models

The factors F_{Oi} and F_{Dj} are determined with the condition of the marginal sums of the trip matrix, including the supplementary condition. This yields a bilinear equation system which can only be solved iteratively. The following models are used in trip distribution: the Probability Model, the Growth-Factor Model, the Gravity Model and the Opportunity Model.

The Probability Model

This model can be seen as a special variant of the basic model where either

$$f_{ij} = 1 \qquad \text{or} \qquad f_{ij} = \text{constant}.$$

This is only valid for small or medium towns where the 'resistance' between different cells is assumed to be virtually nil.

The Growth-Factor Method

The trip function is equal to the current trips per cell:

$$f_{ij} = T_{ij}^c$$

Since trips of the designed year O_i^d and D_i^d are determined by the trip generation model, the model determines T_{ij}^d in the trip matrix. For double constrained models, several algorithms of iteration have been developed: the Detroit Model, the Furness Model or the Multi Model. For example, the algorithm for the Multi Model is formulated as (Lohse & Lätzsch 1997):

$$\begin{aligned} T_{ij}(n+1) &= T_{ij}(n) \times \frac{o_i(n)}{\bar{o}_i(n)} \times \frac{d_j(n)}{\bar{d}_j(n)} \times \frac{T}{T(n)} \\ \text{where} \quad o_i(n) &= \frac{O_i}{O_i(n)}, \qquad d_j(n) = \frac{D_j}{D_j(n)}, \\ \bar{o}_i(n) &= \frac{\sum_j T_{ij}(n) \times d_j(n)}{O_i(n)}, \qquad \bar{d}_j(n) = \frac{\sum_i T_{ij}(n) \times o_i(n)}{D_j(n)}. \end{aligned}$$

A special case here is the Uniform Growth-Factor Model where the origin and destination factors are replaced by a uniform factor F, where

$$T_{ij}^d = T_{ij}^c \times F.$$

All cells are multiplied with the same factor, which makes a further iteration unnecessary.

The application of the model is similar to the conditions in the trip generation model. It is only valid if the same data source is used; so if the data record contains faulty entries they remain undetected. The conditions for the traffic system have to be stable and hence, the model cannot cope with structural changes to the network. The model is therefore limited in time, in accuracy and, most of all, in understanding since it does not provide any further insight into the determination of trips in the design year.

The Gravity Model

In physics, the force of gravity P is defined as

$$P = \frac{m_1 \times m_2}{r^2} \gamma$$

with the masses m_1 and m_2, the distance r and the gravitation constant γ. An analogy to this law is where the structural condition is defined as

$$f_{ij} = \frac{O_i \times D_j}{l_{ij}^{\alpha}} \times k_i \times k_j \qquad (2.8)$$

Here, the force relates to the trip function, masses to the trips of origin and destination, the distance to the expenditure l_{ij} with a parameter α and the gravitation constant to the balancing constants k_i and k_j for the condition of the marginal sums of the trip matrix. Different adjustments have been made to this model:

- **The Classic Formulation**

  Combining equation 2.8 to the basic model equation 2.7, the deterrence function f_{ij} of the classical Gravity Model becomes

  $$f_{ij} = \frac{1}{h(W_{ij})} = \frac{1}{W_{ij}^{\alpha}}. \qquad (2.9)$$

  with W denoting the realisation of a trip under the consideration of structural variables, h denoting a function and α a parameter. This hyperbolic function agrees only roughly with reality since it overestimates short trips (as W_{ij}^{α} approaches 0, f_{ij} advances towards infinity - Figure 2.1).

  This method also corresponds to the travel law by Lill (Lill 1889). He found that the number of travellers N_{tr} in relation to the distance l is constant; and the constant reflects a value of travel:

  $$N_{tr} \times l = \text{constant} \qquad (2.10)$$

- **The Wilson Formulation**

  Wilson makes use of the combinatorial analysis for determining trips between cells:

$$f_{ij} = \frac{T!}{T_{11}!(T-T_{11})!} \times \frac{(T-T_{11})!}{T_{12}!(T-T_{11}-T_{12})!} \times \ldots = \frac{T!}{\prod_{ij} T_{ij}!} \tag{2.11}$$

The most probable state can be obtained by maximising the value of equation 2.11 with the use of Lagrangian methods and Stirling's approximation (Wilson 1970). The deterrence function can then be expressed as

$$f_{ij} = \exp(-\beta W_{ij}) \tag{2.12}$$

where β is a Lagrangian multiplicator (Figure 2.1). (Wilson points out that the same ansatz is used in statistical mechanics and will therefore be deployed again in Section 4.3.3, equation 4.17.) W_{ij} in equation 2.12 is interpreted in terms of (generalised) costs. Regarding statistical mechanics versus transportation, Leung and Yan point out that the scale of the system between particles ($2.7 \times 10^{19}\,\text{cm}^{-3}$) and spacial interaction (a city with 10^6 inhabitants) is enormous and the probability of occurrence of f_{ij} is actually very small, although the maximum of the probability curve is relatively sharp (Leung & Yan 1997).

- **The Combined Formulation**
  This function combines formally the classical and the Wilson model:

$$f_{ij} = W_{ij}^{-\alpha} \exp(-\beta W_{ij})$$

- **The EVA Formulation**
  This model is derived from the conditioned probability of the Bayesian formula (Lohse & Lätzsch 1997). The final formulae read as follows:

$$f_{ij} = \frac{1}{(1+W_{ij})^{\varphi(W_{ij})}}; \quad \varphi(W_{ij}) = \frac{E}{1+\exp(F - G \times W_{ij})}$$

  where E, F, G are parameters depending on the mode of travel. E determines the asymptotic behaviour, F the start of the curve and G the inclination of the curve (Figure 2.1). $\varphi(W_{ij})$ can be interpreted as the actual deterrence function. Similar to the probability model, if the generalised expenditure is small then $f_{ij} \approx 1$. Lohse and Lätzsch point out that the basic form is valid for pedestrians and to a high degree for cyclists. Since walking competes with short trips by car or public transport, the function for these modes of transport should not have a half-bell shape starting at 1 but a bell-shaped curve. Further difficulties arise if a complex travel expenditure (e.g. equation 2.1) is taken into account. In terms of understanding, the EVA-function is derived heuristically, i.e., as a conditional probability from the Bayesian formula, and therefore, is not based on external axioms or conditions (Lohse & Lätzsch 1997).

The Opportunity Model

Following the formulation by Tomazinis, the Opportunity Model is considered as an alternative to the Gravity Model (Tomazinis 1962). The trips of origin are distributed to cells of destination under the consideration of isochrones, i.e., equivalent time zones. From this perspective the model is origin-constrained but it can also be formulated in a double-constrained way, such that,

$$T_{ij} = \frac{DT_{i1(j)}}{DT_{ic(j)}} \times F_{Oi} \times F_{Dj}$$

$DT_{i1(j)}$ and $DT_{ic(j)}$ are the destination trips in relation to the isochrones $c = 1, \ldots, N$ where the destination cells lie within the time zone c. According to the structural condition, the Gravity Model and the Opportunity Model show similarities in the half-bell shape (Figure 2.1). The division of cells and time zones effect the shape of the time step function where an increasing number of times zones results in a steeper curve. However, if there is only one time zone then the probability model is automatically obtained. The determination of the time zone requires empirical observations. This constitutes a disadvantage since travel time cannot be explicitly built into the model. Additionally, the model does not provide any theoretical explanations for the shape of the function.

2.3.3 Activity-Based Approach

Activity-Based Approaches (ABA) are regarded as an alternative to the four-stage models. In such a respect RDC point out some shortcomings of conventional models: they do not recognise certain variables of travel behaviour, e.g. the influence of congestion in relation to trip generation; they do not recognise system changes; they recognise a trip as an independent entity; or they over-predict mode shift. Despite these criticisms RDC still acknowledge that "no single model system is suited for all study objectives" (RDC 1995).

Following Axhausen & Polak and Jones et al., the proposition of activity-based modelling states that travel behaviour cannot be fully understood from the 'trip-based paradigm' of the conventional approach and therefore travel activity should to be identified in combination with daily or multi-day activities, i.e., a more holistic framework of behavioural pattern (Axhausen & Polak 1991), (Jones, Koppelman & Orfeuil 1990). RDC summarise such a "paradigm shift:

- from trip-based analysis to activity-based analysis,
- from static, cross-sectional analysis to dynamic, longitudinal analysis,
- from deterministic demand equation to stochastic micro-simulation,
- from optimisation to satisficing, and
- from capacity- and level-of-service-based capital project evaluation to time-use-based assessment of travel demand management effectiveness as well as capital project evaluation" (RDC 1995).

The ABA attempts to tackle trip-making as a derived demand of a sequence of behaviour. An individual needs or desires to participate in various activities and travelling is therefore a means to satisfy these interdependent activities. (On the other hand, traditional methods might run the risk of mis-specifying discrete time-space trips for modal or destination choice.) From a cross-sectional analysis, the basic unit of reference is generally considered to be the household since the individual behaviour and decision-making is modified by the household role or the family cycle; or by the 'firm', in the terminology of economics or land-use.

Depending on the investigator's point of view, homogeneous classifications of travellers can be made from an *a priori* household- or individuum-grouped base with an after-comparison of their travel behaviour, or, vice versa, observing first the classified activity patterns and then comparing them with the socio-economic or other variables. 'Homogeneous' in this respect means that the groups are on average relatively homogeneous.

The variables of an activity pattern include among others: purpose, location, timing, duration, mode of transport, sequence of activity, numbers of other persons participating and the importance of the trip. Derived from these variables, the most common measures are the participation rates (activities/period), the activity time budgets (duration/period) and the sequence of activities (e.g. home - work - shop - home).

Depending on the emphasis, several disciplines are used as a framework for different ABA: geography and urban planning, economics and psychology which could be integrated into transportation.

Geography and Urban Planning

Ettema and Timmermans noted two branches of geography and urban planning (Ettema & H. 1997). The first is described by Hägerstrand who identified three classes of constraints: (i) capability constraints, due to physical and technological abilities, (ii) coupling constraints, due to time-space accessibility of the environment and people's interactions and (iii) authority constraints, due to juridical regulations of the legal system (Hägerstrand 1970). These constraints can be re-grouped with further refinements (RDC 1995). Under these constraints the '*prism*' concept determines on a probabilistic base all possible time-space paths which depend largely on the speed of movement.

The second branch is influenced by Chapin. Basic desires drive an individual to engage in particular activities which are 'energised' by status or career and are 'constrained' by work or gender (Chapin 1974). These activity patterns then determine the demand for land-use and form the basis for urban planning.

Several approaches have been developed to combine the spatio-temporal constraints with the role of personal characteristics and desires to generate possible activity sequences with the employment of combinatorial algorithms.

Economics

Following Ettema and Timmermans, activities are managed from the point of view of a decision maker who has to allocate money and time in relation to various activities during a day (Ettema & H. 1997). From this micro-economic perspective the needs and desires of an individual are defined by a bundle of consumption Q which includes several consumed quantities q_n:

$$Q = \{q_1, \dots, q_n\}$$

The budget constraints are given in relation to the fixed price p_n of a related quantity and an income I.

$$\sum_n p_n \times q_n \leq I$$

The presupposition for decision making is, as already mentioned in Section 2.1, rational behaviour. The actual question of decision making is approached on the basis of various assumptions: discrete choice (of none, or any one of a vector component), a more complex preference (if A is better than B, and B is better than C, then A is also better than C) and maximised utility (increasing demand of a commodity until a level of satisfaction is reached). The utility function U then consists of quantities of various goods which need to be maximised where U is a function of consumed quality values q_n,

$$U(q_1, \dots, q_n)$$

Ettema and Timmermans list several models, of which one is:

$$\max_{t_i, t_H, S_i} U(t_i, t_H, S_i, r_i)$$
$$s.t.$$
$$\sum_i t_i + \sum_i S_i + t_H = T$$

where,

S_i is the travel time associated with the activity i;

t_i is the time spent on an activity i;

t_H is the time spent at home (Ettema & H. 1997), (RDC 1994)[4].

Generally speaking, one problem is that the purpose of travel is not included in these models and therefore forecasting future travel demand in time and space does not seem possible. (Although one model has been presented which includes the travel purpose.)

Goodwin et al. develop a dynamic model based on the economic concept of equilibrium. Let $\mathbf{V}(t)$ be a vector of influential travel variables and $U(t)$ a continuous and differentiable measure of travel behaviour in $t \geq 0$, and let t_a and t_b be two different time instances, so that

$$\mathbf{V}(t_a) \neq \mathbf{V}(t_b) \quad \text{and} \quad \mathbf{V}(t) = \mathbf{V} \quad \text{for} \quad t \geq t_b > t_a > 0.$$

If there exists a time t_c ($\geq t_b$) then an equilibrium U^* can be obtained at t_c by

$$\mathrm{E}[U(t)] = U^* \quad \text{for any } t, \quad t \geq t_c > t_b \tag{2.13}$$

(where E is the expectation operator). In other words, when the contributing variables remain stable for 'not too long a period of time', an equilibrium of travel behaviour will be obtained and the behavioural activity will remain in equilibrium unless the contribution factors change their values (Goodwin 1990). However, in reality "travel varies from day-to-day, even in an 'equilibrium' situation" (Jones et al. 1990) so the behaviour will fluctuate around the equilibrium value. The speed of adjustment can therefore be assessed by the difference of the equilibrium and the actual value. For convenience, let $A(t) = \mathrm{E}[U(t)]$ so that equation 2.13 becomes:

$$\frac{\mathrm{d}A(t)}{\mathrm{d}t} = 0. \tag{2.14}$$

[4]Unfortunately, the term r_i is not explained.

The speed of a monotonic adjustment w can be expressed in a parametric form as:

$$\frac{\mathrm{d}A(t)}{\mathrm{d}t} = w[U^* - A(t)]. \tag{2.15}$$

The adjustment can have various forms, e.g. a partial adjustment, or depend on factors such as habits, inertia, thresholds, satisficing or information.

In addition, various approaches can be integrated into the schema: from an activity-choice perspective an (economic) utility-maximisation approach, or from a dynamic perspective a (geographic) time-space approach which combines variations of a traveller's behaviour from planning to executing with the necessary modification on a short- and long-term basis.

Other inferences can be made, for example, to draw links to trip generation models. Let G be a function with $\beta(t)$, a vector of model co-efficients, and $\varepsilon(t)$, a random error term then (for the contemporaneous case)

$$U(t) = G[\beta(t), \mathbf{V}(t), \varepsilon(t)]$$

The linear model can be formulated as

$$U(t) = \beta(t)'V(t) + \varepsilon(t)$$

which is similar to the equations 2.4 and 2.5.

Psychology

The main focus here is on the complex process of decision making. Two different premises form the basis: first, simple algebraic rules and second, heuristic or 'context-dependent' choice making, which is in contrast to 'optimal' choice making. Both, as seen above, presuppose rationality. Applications of the former can be found in Multinominal Logit Models and Stated Preference Models which do not distinguish between behaviour under experimental and real conditions, a criticism of the latter. These are based on strategic decision making within an imperfect and limited recognised environment. The process is analysed in terms of partial solutions and incoherences. The rules are computerised on an IF...THEN...ELSE basis which contains the scheduling behaviour of condition versus action (Ettema & H. 1997).

Transportation

There are various transport models, some being an extension of the four-stage approach and some partly containing the above approaches. Only one model will be shown to illustrate the combination of the different sections and the complexity of such ABA models: The Activity-Mobility-Simulator (AMOS) (RDC 1995).

The model incorporates several partial simulators:

1. the Socio-Demographic Simulator which simulates stochastically the life-cycle of an individual in socio-economic terms;
2. the Urban System Simulator which represents the household or firm in a dynamic, market-based urban environment;
3. the Vehicular Transactions Simulator which assesses the turnover of the vehicular fleet;
4. the Dynamic Network Simulator which calculates the traffic flows on a 24-hour basis which consists of:
   (a) the Activity-Mobility Simulator, i.e., the core of the model, a simulation of scheduling of the individual and household on a trial-and-error basis taking into consideration the 'satisficing' rule;
   (b) the Baseline Activity-Travel Synthesiser which assesses changes in the travel pattern and travel environment;
   (c) the Response Option Generator which provides the responses to different trip options by neural networks; and which feeds
   (d) the Activity Travel Adjuster, to simulate the daily travel experiences;
5. the Evaluation Module assesses the measures of different travel patterns. The program is supported by various screening procedures to exclude unfeasible options at different stages.

A description of each simulator's algorithm is not presented in the report.

A Brief Critique

The ABA has given rise to a broadening of the horizon of human travel behaviour and has developed further the methodology for data collection, for example 'before' and 'after' studies. There are many assumptions in conventional approaches which on re-examination have lead to criticisms.

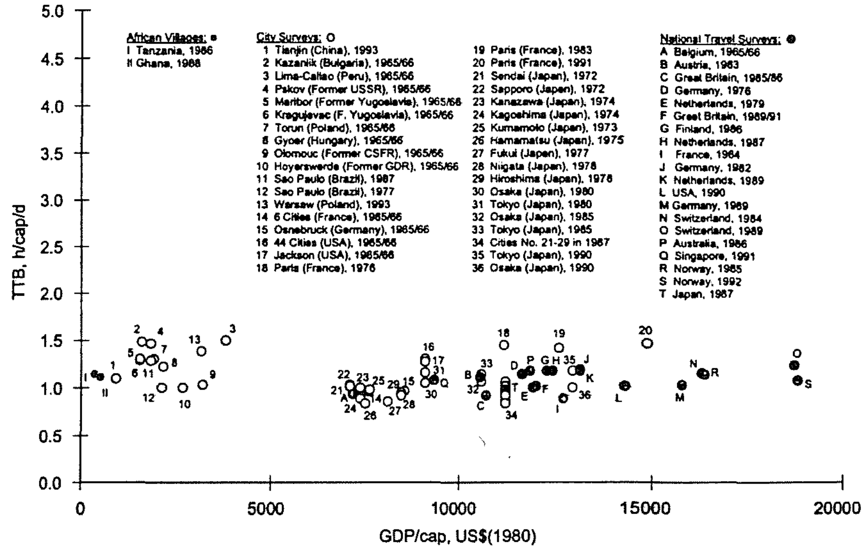
Ettema and Timmermans pointed out that "research in this area has been very fragmented and that a unifying framework is still missing" (Ettema & H. 1997). Borgers et al. stated that the "activity-based models are still in their infancy. ... At best, existing models are experimenting with particular notions that still need testing on a large scale basis, or address sub-problems that need to be linked to other submodels to derive a full-fledged operational transportation modelling framework" (Borgers, Hofman & Timmermans 1997). To specify the problems in question, Axhausen and Polak provided a list of unresolved issues (Axhausen & Polak 1991):

- ***Variables*** Activities and quantities have not been identified which should measured the variability of behavioural changes in respect to multiday or multiperiod data and hence the qualitative-quantitative problem still prevails.
- ***Complexity*** Due to the large number of variables, ABA constitutes more of an academic exercise rather than a user-orientated application. The practicality would be enhanced through a clarification of the concepts, a refinement of the methods and a simplification of the approach (Jones et al. 1990).
- ***Demand - Supply Interaction*** ABA has little sensitivity to short- and long-term changes in traveller preference, transport network, land-use and urban development.
- ***Inductiveness*** Most methods are inductive and lack behavioural principles. This hampers the transferability of the results and reduces their predictability.
- ***Interdisciplinarity*** The theoretical roots can be found in geography, planning theory, psychology and socio-economic theories. Despite this interdisciplinary base there is still a substantial need for theory developments since the ABA looks more like "a series of theories rather than an integrated, comprehensive and consistent framework" (Jones et al. 1990).
- ***Conventional Modelling*** Despite its general appeal, the ABA could not live up to the promises of replacing conventional transport modelling and could not provide firm guidelines for transport policies.

To conclude, the ABA still seems fragmented and without an integrating framework the contributions to transport planning practise are limited. Therefore an "agreement on an 'action' agenda among professionals working in the area is essential if activity approaches are to achieve the metamorphism from 'interesting but esoteric' to 'relevant and practical' " (Jones et al. 1990).

2.3.4 Travel Budget Approaches

Despite the general complexity of travel behaviour some particular patterns seem to exist which are unaffected by the development of a traffic system. One of these is the expenditure of daily travel time which is considered in the approaches of a 'travel time budget' (TTB). Daily travel time, as one of the fundamental variables of trip making, has been observed over decades and remains constant at around one hour per person. Schafer shows TTB relative to income per capita of different countries in Figure 2.2. TTB seems to be independent not only of changes in the transport system but also independent of societies, cultures, or geographies. "Residents of African villages spend an amount of travel time that is roughly comparable to



Travel time budget ($h\,cap^{-1}\,day^{-1}$) in numerous cities and countries throughout the world. Sources: Kloas *et al.*, (1993); GFV, (1987, 1992); Orfeuil and Salomon, (1993); UKDOT, (1994); DMT, (1993); Szalai *et al.*, (1972); Katiyar and Ohta, (1993); USDOT, (1992); Malasek, (1995); Vibe, (1993); Riverson and Carapetis, (1991); EIDF, (1994); FORS, (1988); Metrõ, (1989); Olszewski *et al.*, (1994); Xiaojiang and Li, (1995).

Figure 2.2: Daily Travel Time of Several Cities and Countries (Schafer 1998)

travel times in Latin American metropolitan areas, Singapore, Japan, Australia, Western Europe, and the USA" (Schafer 1998).

Several approaches have been developed to explain this characteristic which will have profound repercussions for all previous traffic models, for example, in terms of trip variables or methodology. Generally, two different perspectives have be adopted to tackle the problem of TTB: an economic and an evolutionary perspective.

From an Economic Angle

The economic point of view has to include monetary units, i.e., the travel money budget (TMB). The TMB also shows a certain stability of around 10% of the middle and higher income level and therefore it is assumed that both TTB and TMB are strongly related to the socio-economic characteristics of a household.

One of the main proponents of this concept has been Zahavi (Zahavi & Talvitie 1980), (Zahavi & Ryan 1980), (Roth & Zahavi 1981), (Supernak & Zahavi 1982). Zahavi outlines the basic idea of TTB as follows:

> A travel-time budget does not mean that each and every traveller must travel a fixed time per day each end every day - an interpretation that is quite absurd. Nor does it mean that travel-time expenditure will be regular, regardless of how they are stratified. ... The question, therefore, is not whether the daily travel times of travellers or persons are fixed - which, obviously, they are not - but whether regularities

that are transferable in both space and time exist as a useful level of disaggregation. Only when such regularities are fully transferable they can serve as the basis for transferable travel models (Supernak & Zahavi 1982).

The following definition of a traveller is used for this analysis: "A person above the age of five years who made at least one motorised trip during the survey day, although the daily travel times also include walking times as well as the access and egress times (door-to-door times)" (Zahavi & Ryan 1980), (Roth & Zahavi 1981). In addition, "travellers who travel extensively on their jobs ... should be excluded from the analyses" (Zahavi & Talvitie 1980). TTB per traveller is assessed using the speed of travel by

$$TTB = b + \frac{a}{\text{speed}} \tag{2.16}$$

where a and b are regression co-efficients. The regression co-efficients are calculated by the multiplication of equation 2.16 with the speed, so that the mean distance appears on the left side of the equation and the slope of the regression line represents the TTB:

$$\text{Distance} = b_0 + b_1 A + b_2 A(\text{speed}) + b_3(1 - A)\text{speed} \tag{2.17}$$

Car-ownership is included in the model with $A = 0$ for no-car and $A = 1$ for one or more cars per household. For two cities, Nuremberg and Munich, the actual values are given respectively as:

b_0	b_1	b_2	b_3
0.268	4.305	1.094	1.410
-6.359	7.511	1.083	1.667

Although the slope for all relationships was found to be acceptable, the intercept fluctuated widely and therefore "the statistical result could not be regarded as conclusive. ... [But] it suggests the possibility that the relationship ... is a transferable function between cities and therefore also over time" (Zahavi & Talvitie 1980).

TMB is assessed only by empirical data and counts for around 3 - 5% of income without a car and around 10 - 12% of income with cars. These figures are valid over a wide range of income groups (Schafer 1998). Zahavi et al. conclude that the concept of travel budgets shows (consistent) regularities, but they cannot be regarded as constant due to the wide variations between travellers and households and their functions which are composed of several variables. Nevertheless, the TTB- and TMB-approach may be as valid as conventional trip generation models although travel budgets are more difficult to obtain for the latter. They can both serve as a useful tool for predicting travel and for evaluating policies.

Tanner develops an approach of 'generalised costs' using money cost C per person-kilometre and time spent t in hours per person-kilometre (Tanner 1981). With an income I the travel time is valuated at αI per hour in [monetary units/h], and $\alpha It + C$ is the generalised cost per kilometre. Similarly, a generalised expenditure, in hours per year, is defined as (generalised time per person per year) = $((C/\alpha I) + t)\psi(I, C + \alpha It)$ where the kilometres travelled per person per year are denoted by x so $x = \psi(I, C + \alpha It)$. If constancy of TTB is assumed then the equations are only consistent with a constant generalised expenditure but not with a constant time budget or money budget. Broadly speaking, the approach is compatible with certain observed data, but some patterns of behaviour could not be explained by this model. For example, walking still plays a considerable role in travel, even with increasing income. Another problem is the relationship of costs per kilometre, since costs decrease with increasing distance travelled, and are also related to the speed of mode used. These considerations may have led Goodwin to conclude that "*budget* usually implies stability" (Goodwin 1981).

Fischer supposes that travel time budget t_d and TMB C_d are related according to the known, average travel speed of different modes of transport v_m (Fischer 1997). The constancies of the different budgets are presupposed, and have been shown by data, firstly, from Fiebinger (1992) where travel time to and from work accounted for 40 minutes per male per day between 1974 and 1990 and secondly, from the Statistischen Jahrbücher of East Germany where the relative expenditure of income on travel varied between 6% and 8% for a two-person household with low income, 11% and 12.6% for a four-person household with medium income and around 10% for a four-person household with a high income, between 1987 and 1995. The TTB is independent of mode of transport and the relativity of the cost budget is not strictly speaking constant, but can be considered as constant over a period of time. The specific travel expenditures are calculated according to equation 2.18 and can be applied as supplementary conditions for the distribution model:

$$t_d = \sum_{m=1}^{n} t_m = \text{const.} \qquad C_d = \sum_{m=1}^{n} C_m \times t_m = \text{const.}$$
$$TE = f(v_{m_n}) = \text{max.} \tag{2.18}$$

t_m represents travel time spent on a particular mode of transport m per period of time (e.g. month) and C_m represents travel costs of mode of transport per time unit. Travel effectivity TE is expressed in [km /time unit] and can be found by maximising the ratios of speeds of different modes of transport v_m under the boundary conditions of a constant travel time budget t_d and constant TMB C_d. If the number of modes of transport is larger than 2, TE has to be determined iteratively. An improvement in supply (either in time or in money) leads to an increase in TE, i.e., an increase in travel distance in respect to t_d, and vice versa. The maximisation of the travel distance reflects the hypothesis of a maximisation of the satisfaction of needs. The difference in increased length can be interpreted as *induced* traffic.

Goodwin attempts to define the *human effort* of mobility where generalised costs are composed of time, effort and money spent on a travel activity (Goodwin 1976). Measures of effort may be determined by energy expenditure, heart rate or galvanic skin response. An arbitrary points system, where travellers give 'scores' to different activities associated, was intended to combine monetary, physiological and time measures. In terms of physiological measures, Goodwin should also be listed in the following section.

From an Evolutionary Angle

Marchetti recognised man as a territorial animal with the basic instinct to expand his territory which can be measured by "the mean traveling time per day ... multiplied by a mean speed of moving ... which gives a distance, or a *range*, i.e., a territory" (Marchetti 1993). He also stated that this basic instinct drives "even people in prison for a life sentence, [who] having nothing to do and nowhere to go, walk around one hour a day in the open". (In this example, perhaps desire is modified by opportunity.)

Hupkes defines the constancy of trip rate and time budget as a *law* (Hupkes 1982). He attempts an explanation primarily on a bio-psychological basis initially identified by Michon (1978) who describes "man as a bio-psychological unit striving to maintain habitual patterns of behaviour ... because stress will result if [people] do not succeed, ... reinforced by past experiences of pleasure or displeasure, ... rather than by continuously rational weighting of all available options". Using the evolutionary argument Hupkes further describes man as a "descendent of the 'naked ape' who roamed the plains", and calls this quality of travel an *intrinsic utility*. His second explanation is based on a utility-optimising approach, rooted in economic thinking. His third, implied explanation may simply result from the statistical process of *averaging*. However, he states that the two former reasons cannot fully explain the constancy of the behaviour.

Knoflacher and Spiegel refer explicitly to human energy expenditure as an underlying reason for human travel behaviour (Knoflacher 1981), (Knoflacher 1987), (Spiegel 1992). At the centre of their approaches lies the Sensation Law by Weber-Fechner which states that the sensation S and the intensity of a stimulation R are related as:

$$S = \ln R \tag{2.19}$$

For example, in walking: actual (physical) time is set into relation to peoples' expected time. The function of this 'value-of-time-factor' performs the above function. Spiegel also compares other types of similar equations, which found an even better fit at the extremities. Knoflacher relates equation 2.19 to the earlier stated Travel Law by Lill, equation 2.10 (Knoflacher 1995). Instead of taking the absolute numbers of travellers, he takes the relative frequency and by integration (to obtain the cumulative travel frequency H) a similar form to equation 2.19 is obtained where l is a (generalised) travel distance of stimulation:

$$H = \text{constant} \times \ln l \tag{2.20}$$

The constant can then be interpreted as travel budget. In this form, the constant depends on the generalised distance but with an additional minimum assumption a dimensionless form can be obtained. However, the full evolutionary dimension appears when he notes in reference to the work of Frisch that the same formula can be applied to bees' crawling versus flying and to humans' walking versus driving (Frisch 1977) (Knoflacher 1987).

Regarding effort and energy variable it is interesting to note that Zipf uses these variables in describing travel behaviour several decades earlier but he explains travel behaviour not in budget terms but in terms of least effort (Zipf 1949).

2.3.5 Recapitulation

The economic assumptions seem to encounter the same problems here as in the previous models. 'Money' influences travel behaviour to a certain extent but it cannot explain travel, especially non-vehicular travel. According to Tanner, the advantage of decreasing travel cost with longer distances seem to have the opposite effect. In comparison to Fischer, it does not encourage people to travel longer always according to the "maximum travel effectivity". On the other hand, the idea of people being driven by an instinctive or animalistic behaviour completely reverses the idea of the (ideal) rational Homo Economicus. This contrast shows that there should be some biological properties, which cannot be explained by economic rationality and which do not even fit into a 'rational' methodology (if compared with Section 2.1).

At a technical level, the use of speed of transport as one of the basic units would seem to demand a distinction between time spent on travelling and distance progressed since they are fueled from different sources, i.e., time by the human and distance by the speed of the method of transport. But again, this is a problem also encountered in the trip definition where the traveller and the means of transport are envisaged as one unit.

In the subsequent approach some of the ideas given above will be explored: the notion of budget, the focus on the individual and the energy variable as a basic requirement for travelling. A 'budget' and its constancy should explicitly be derived or verified, in contrast to the above approaches they are either presupposed or interpreted. Travel effort should be measured according to an objectively valuated unit and not in a subjective points system or as a relative measure of intensity. Furthermore, methodological connections should be made between TTB approaches on one hand, and trip generation/trip distribution models on the other; for example, Fischer relates his approach only to trip distribution models but not to trip generation models. This may mean that the number of trips are assumed to be independent of the time spent on travelling. But "the key question is whether travel expenditure can be forecast (and not so much whether [travel budgets] are stable)" (Kirby 1981).

Before an overall résumé of transport modelling can be given, trip generation models with the socio-economic variables are compared to the approach of travel time budget to gain some elucidation for the problems described above.

Chapter 3

The Data

Two data sets are used for the empirical analysis. The first data sets are those of the UK National Travel Survey (NTS) and are described according to the collection, sampling procedure, survey methods and their definitions (which can be compared with the definitions of Section 2.2.2).

In addition, some considerations are highlighted as background essential for the subsequent approach. The next step consists of a first application of the NTS data. They are used to depict the influence of the socio-economic variables in relation to daily travel time and the number of trips made per day. The objective of this analysis should be a comparison between the trip generation/trip distribution (with socio-economic variables) and TTB-approaches, and should therefore provide some verification of the assumptions and assertions embedded in these models. The methodological connection between these models will be made with the analysis of daily travel time, single trip time and trip rate, which will also form the basis for the hypothesis described in Chapter 4.

The second data set is related to ergonomics. This data is described in a similar way initial consideration of the original objectives of ergonomics and their definitions, methods and measurements. Although in the past, ergonomics has been primarily concerned with work-related issues, two examples will be presented to demonstrate the applicability to traffic engineering. (The direct connection to the NTS data will be made in the next chapter under Section 4.2.)

In regard to the verification of the global TTB, an attempt was made to obtain data from Japan and China but bureaucratic and other obstacles were insurmountable in the case of Japan, and in the case of China there is no such detailed data.

3.1 Travel Data Base

3.1.1 The Data Collector and Objectives

The NTS is carried out by the Social Survey Division of the Office of Population Census and Surveys (OPCS) which is responsible for questionnaire design, sample selection, the interviews, data collection and data editing. The principle investigator and the depositor is the Department of the Environment, Transport and Regions (DETR). The actual data files for the data analysis of this thesis have been provided by the Data Archive of the University of Essex, Colchester (1972-93) and the Transport Research Laboratory (1994-5) (DETR 1995).

The NTS is designed for the purpose of government of Great Britain and specifically to develop transport policies based on people's travel behaviour where their personal travel profile can be assessed and their future impact on social changes can be estimated. The NTS should therefore provide a national data base of personal travel information with the following objectives:

- "to estimate distribution of car ownership and the variation in car utilisation, and their dependence on demographic, socio-economic and other factors,
- to determine personal and household travel generation rates and the relationship between these rates and a wide range of demographic, socio-economic and other variables,
- to provide data affording an examination of the modal split for journeys of different types,
- to determine in what ways and what circumstances public transport is competitive with the private sector,
- to provide information to fill gaps in national transport data derived form other sources; for example, taxi and car hire usage, ownership and usage of two-wheeled vehicles, and distribution of expenditure between private and business travel" (DETR 1995).

3.1.2 Sampling Procedure

The Sampling Implementation Unit at the OPCS is responsible for managing the sampling process. The NTS is based on a random sample of (non-institutional) households from the 'smaller user' Postcode Address File provided by the Post Office. These files describe delivery points with less than 25 items of mail per day. A postal sector contains fewer than 500 such delivery points. These sectors form the basis for the Primary Sample Units (PSU) each containing around 2500 addresses. Great Britain has so been divided into 7953 PSUs. From each PSU a sample cluster size was drawn containing 21 addresses. For one year 240 PSUs were selected, i.e., 20 per month. Several additional procedures have been used to counterbalance houses with multi-occupations and to remove a bias in relation to region or population density. The final selection of addresses has been systematically randomised not only in terms of sample cluster or regions but also in terms of months of the year, i.e., around 8% of total data were collected each month so the recording of the data is equally distributed over a year.

Periodic surveys were carried out in the years 1972/3, 1975/6, 1978/9 and 1985/6. In 1988 there was a change of policy in data collection and since then a continuous survey has been performed. With this change of interval came also a change of sample size; the annual data sets are reduced to around one third of the periodical ones (Table 3.1).

The data editing was performed in the Primary Analysis Branch where an editing program from the Centre for Analysis and Modelling was used which produced through repeated re-editing clean data files. In this process the data were separated into batches according to household, vehicles, individual, day, journey and stage.

An overview of the data used in this study is given in Table 3.1 with the years and the absolute number of sample size per household, individuals and journeys. (The reason for division of journey data in 1-6 and 7 will be given in Section 3.1.4)

Year	Household	Individual	Journey (1-6)	Journeys (7)
1972/3	7113	20242	184611	48868
1975/6	15343	33867	320176	71953
1978/9	8429	22636	286331	69613
1985/6	10266	25785	317991	76060
1988	1754	4309	59192	13262
1989	3675	9001	123721	28247
1990	3535	8592	119039	26245
1991	3542	8692	118626	26223
1992	3453	8320	112072	24321
1993	3418	8161	105228	23718
1994	3407	8143	107988	24225
1995	3211	7723	103646	22442

Table 3.1: Number of NTS Observations by Survey Year (DETR 1998b)

3.1.3 Survey Methods

The household surveys are carried out where the participation is voluntary and the information obtained remains completely confidential. The 'face-to-face' interviews are carried out by professionals who have a special training and experience in survey methods. The interviewers were checked by the OPCS for completeness of documentation, i.e., in the field by field officers or routine recalls on selected addresses and by clerical staff before editing the data files.

Each household had to fill in a household questionnaire, an individual questionnaire, a travel record for each household member and a vehicle schedule for each household vehicle. The individual interviews of members under age of 11 were not done separately but in the presence of a parent. The vehicle schedule was completed with the main driver. Several assistance options (e.g. telephone calls) were provided where the subjects could get help for accurately recording their information.

The placement pattern for the NTS travel week has been set up fairly rigidly due to the high variability of travel behaviour. Individuals were scheduled to set rules to ensure an even spread of travel weeks throughout the month. The recording of travel spans over one week where the starting day of the record is randomly distributed and the travel data are collected in travel diaries.

The response rate was on average 80% which was higher than the target rate of 75% for all years. In areas where the response rate is low across all years, non-responding addresses are re-visited by a different, more experienced interviewer to persuade the subjects to participate. A selection of a replacement is not desirable since this would have disturbed the statistical placement pattern.

The editing of the data was carried out in three stages, firstly, the pre-editing where basic structural and range error were checked; secondly, the main editing where the data is hierarchically structured into household, vehicle, individual, day, journey and stage, and where the data is checked on continuity, consistency and plausibility; and thirdly, a half yearly check, where checks on missing or duplicated household serial numbers were performed.

3.1.4 Survey Definitions and Variables

The following definitions are used in the NTS which are relevant for this study (DETR 1995).

> "*Personal travel:* The survey is concerned with all travel - whether by land, water or air - which involves a person moving from one place to another in order for that person to reach a destination."

This definition makes it clear that NTS is concerned with personal travel and not with freight travel. In that respect, travelling to deliver goods or professional driving of public or commercial vehicles in the course of work is excluded.

> "*A Journey:* A journey is defined as a one-way course of travel having a single main purpose. ... Complex travel ... is broken into separate journeys as defined above so that the data can be analysed."

Regarding the definitions in Section 2.2.2 a journey is set equal to a trip and a trip chain is split up into single trips in relation to the different purposes fulfilled. For example, a round trip is divided into two trips, one to the destination and one back to the origin. Leisure pursuits like yachting and other water/air trips, which are not competitive to public transport are also excluded from the NTS data base.

> "*A stage:* A journey is subdivided into stages: a new stage is defined when a) there is a change of form of transport or b) there is a change of vehicle requiring a separate ticket."

These changes of mode of transport during the pursuit of one purpose are considered in the later stage of the thesis. In the data files of the years 1994 and 1995 the number of stages and travel time per stage are not given.

> "*Walking:* Travel by foot away from the public highway (footpaths, pedestrian precincts) is excluded unless both a) the surface is paved or tarred and b) there is unrestricted access (so a pedestrian precinct closed in the evening is excluded).
> Very short walks (of less than 50 yards) are always excluded. So too is playing in the road by young children.
> [*Regarding the travel week:*] On the first six days only walks of one mile or more are recorded but for the final day details of all walks of 50 yards or more are included."

In the questionnaire the following instruction is given: "On the first 6 days include walk as a method if it is a mile or more (20 minutes or more). On the final day include every walk you do." This qualitative difference in walking trips or in walking stages is indicated by 1-6 and 7 and will be considered in the data analysis. In Table 3.1 the number of journey observations is split up respectively (Columns 4 and 5). Travel times have been recorded only on the seventh day in the years 1972/3 and 1975/6. Walking trips in the course of work such as a postman are also excluded.

Regarding travel time, in the questionnaire travel time was described as: "Give time spent travelling on bus/train, in car or walking. Please do NOT include time spent waiting for buses/trains" (DETR 1995). In the final data base two entries could be found: overall travel time and overall journey time. This relates to the question of the complex travel time of equation 2.1. This two entries have been interpreted in the following way:

$$\text{Overall Journey Time} = \text{Overall Travel Time} + \text{Terminal Time}$$

The terminal time includes all different times except travel time. Since the terminal time can play an important part in time expenditure, the overall journey time of the journey data base will be used as the basic time measure. More disaggregated considerations with distinctions in time, i.e., season, weekday/weekend, or in location, i.e., region, county, town or city, are outside the scope of this thesis although the approach could also be applicable to these with further research.

3.1.5 Data Preliminaries

Several preconditions should be satisfied which could otherwise influence the data analysis, and consequently, the derived understanding of the approach. In addition, some considerations should be taken into account which, for example, have been mentioned in Section 2.2.2 (i.e., the exclusion of trips shorter than 300 m) and which could also be encountered in a similar form under walking in the above section. The importance of such simplifications lies in envisaging the human influence not only in the actual observations of certain events but also in the methodology of the survey. Hence, the following considerations are necessary:

- **The Rigour of the NTS**
  As pointed out in relation to the variability of travel behaviour, it is of the utmost importance that the data survey is performed in a rigorous and consistent way, so variations due to the data observations or the procedural influences are kept to a minimum. This condition is additionally significant since the hypothesis of this research is that certain constant patterns of behaviour should be verified by the data. As described above, the procedure of the NTS regarding data sampling, data surveying and data checks were carried out in such a meticulous way that it can be assumed that the data variations due to the data survey can be ignored. The variations due to the data size of different years will be shown in the analysis. This assumption can be supported also by the next point.
- **Definitions and Variables**
  Travel time definitions, instructions and procedure have not been changed over the years. The two most important variables for the following approach will be the trip or journey time and the number of trips per day. These rely on the trip definition which therefore remain unaltered. Also the procedure in terms of day 1-6 and 7 where additional short walks have been considered, has not been changed. On the other hand, for the data analysis this qualitative difference should be considered explicitly since there may be considerable differences in how walking may influence daily travelling.

However, travel time and the number of trips in the data base might be under-represented on the first six days in comparison to the seventh day or, in general, to real travel time and trip making. Nevertheless, door-to-door travel will be assumed, even though it is uncertain how well this is reflected in the data base. To come as close as possible to actual daily travelling, only data from the seventh day should be taken into account. With only one day of observations, the numerical size of the data set may fall to a non-representative sample size especially after further categorisations. Hence, for the subsequent analyses in this thesis it will always be indicated explicitly which day(s) of recording are taken into account.

The same problem may occur in relation to stages, i.e., the number of stages per trip. An assessment will be provided to show the relative dimension of this particular problem.

- **Data Size**

  According to the number of observations of Table 3.1, the substantial reduction in the continuous surveys might have some repercussions for the quality of measurements of these years, i.e., they might vary to a greater extent than the previous ones. As already mentioned in the previous point, this might not be the case at an overall level but may occur with an increasing degree of detail.

- **Measuring Time and Distance**

  The data sets of travel time are available unbanded, i.e., as absolute values, and banded, i.e., in predefined classes. In this study only the unbanded data sets are used. Inputs of travel time at five minute intervals are over-represented in the data base. This indicates that travellers read the times to the nearest 5 minutes for shorter journeys or assess the travel time up to nearest 15 minutes for longer journeys. To counteract this bias for some figures, a smoothing process is introduced using grouped data which averages the frequency over these intervals, keeping the number of counts constant. This should then reproduce the steady graph of real travel time distribution.

  Distance may be easy to measure in a car due to the availability of a mileage indicator. With other modes of transport, measuring may be more difficult. The distance data is only available in a banded form. (The actual classification will be given in the text below.)

It should be noted that the data analysis in this study has been derived from the *raw* or *source data*. This should enable a degree of accuracy which would otherwise be difficult to obtain. A first example of use of the NTS data, an evaluation of the socio-economic variables in comparison to travel time and number of trips per day is described below.

3.2 An Empirical Comparison

The objective of this section is to present some empirical evidence for the transport model variables discussed previously. Firstly, the unit of reference will be investigated which constitutes an essential basis for the following analysis. Secondly, as a measure of comparison, daily travel time and trip rate have been selected since they are probably the most important measures in transport modelling. Their properties with some implications of their choice will be discussed. Thirdly, these two measures are validated over the survey years which can be interpreted as an actual justification for the assumptions for the TTB approaches. In the following section the socio-economic variables are analysed in terms of these two measures.

3.2.1 The Unit of Reference

In the previous chapter the discussion was between the household, forming the unit of reference for most models of trip generation, trip distribution and ABA, and the individual, being the unit of reference for some of the TTB approaches. To quantify a particular measure, the number of trips per week, for example, it is essential that the unit of reference is stable or independent, so an unbiased comparison can be carried out, otherwise, the additional variation of the reference unit has to be taken into account.

This can be substantiated by the following consideration. If a matrix with several independent measures (or dimensions) is assumed for individuals and another matrix with the same number of independent measures (or dimensions) for households, then the 'household' matrix has always *one* dimension more than the 'individual' matrix, i.e., the number of household members. If one independent dimension is selected, then the household has additionally to consider the variability of the household members. Additionally, the household can be seen as the first level of averaging since specific differences can be outweighted through averaging. For example, for the independent measure of age the individual composition of two different households can be completely different, although both averages are the same.

Thus, the question is: has the household changed in relation to its members over the years? Figure 3.1 provides an impression where larger households ($n \geq 3$) decreased and smaller households ($n \leq 2$) increased between 1972 and 1995. In addition, if a test of equal means over the years is performed, i.e., an analysis of variance, then the hypothesis is to be rejected since $F = 73.55 > F_{.95} = 1.79$ (or

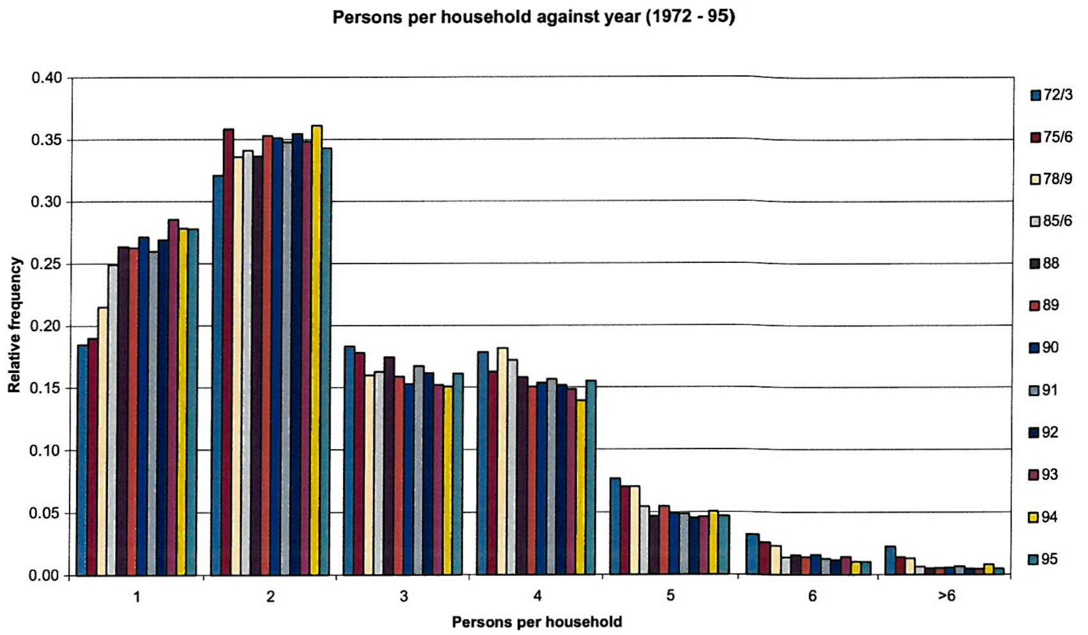


Figure 3.1: Household Sizes by Year (DETR 1998b, Source:)

$F_{.99} = 2.25$) so the average household size cannot be regarded as constant. This indicates that the individual should be the more stable unit of reference.

For the following analysis *the unit of reference will therefore always be a 'person' or a 'traveller'* since, for example, in the case of household the total number of trips per household can be obtained simply by multiplication of the number of household members.

3.2.2 Travel Time and Trip Rate

To reiterate, trip generation models determine the extent of travel in terms of the number of trips, trip distribution models determine the extent in terms of trip time or trip distance, and TTB approaches focus on daily travel time. The relationship between daily travel time or TTB, number of trips and single trip time can be defined as:

$$t_d = \sum_{s=1}^{r} t_s \tag{3.1}$$

where t_d is the travel time spent per day, i.e., the TTB, t_s is the time spent for a single trip and r is the total number of trips made by a person during one day, i.e., also expressed as the trip rate. These three measure will be used as the basic measures of travel throughout the thesis. Taking the travel times of different travellers in consideration then these times can vary substantially which can be expressed in form of probability distributions functions, equation 3.2, where P stands for different probability distributions of t_d and t_s:

$$P(t_d) = P(t_1 + \ldots + t_s + \ldots + t_r) \tag{3.2}$$

(The final result of this thesis will be the derivation of the probability distribution of daily travelling.) To obtain an empirical understanding from the NTS data, the probability distribution function of daily travel time $P(t_d)$ can be expressed in terms of the probability function of single trips $P(t_s)$ and of the trip rate $P(r)$ which are related by their expectations in form of

$$\begin{aligned} \mathrm{E}[P(t_d)] &= \mathrm{E}[P(r)] \times \mathrm{E}[P(t_s)] \qquad \text{or} \\ \langle t_d \rangle &= \langle r \rangle \times \langle t_s \rangle \end{aligned} \tag{3.3}$$

For the numbers in the tables, the three measures were always calculated separately, i.e., for the daily trip time the individual multiplication came before the averaging, so the multiplication of the averages of trip rate and single trip time can be used to check the average daily travel time and thus equation 3.3.

Concerning trip modelling, these equations show that the number of trips, i.e., the desired result of trip generation, is linked to trip duration (or trip length), i.e., a desired result of trip distribution. Combined they form the travel time spent per day, i.e., the desired result of the TTB approaches. Thus, the approaches are methodologically connected in equations 3.1 to 3.3.

The following sections consider the data verification of the different models from a view point of the basic measures of travel. Firstly, the travel times and trip rate are calculated on the most aggregate level to attest the TTB approaches. Secondly, daily travel time and trip rate are examined against the socio-economic variables (used in trip generation/trip distribution and ABA) to verify their effect on trip making.

3.2.3 Travel Budget Approaches

The data are split into the first six days and seventh day according to recording method of the NTS where short walks were excluded from the first six days and are only included on the seventh day. The figures in Table 3.2 and Figure 3.2 show the relative stability of travel times and trip rate. They present the averages over all years and the averages of differences are calculated for each section of days separately. Table 3.2 presents a summary of the detailed figures given in Table A.2 of Appendix A.

The most obvious characteristic is the sudden decrease of all three measures in 1975/6 (Figure 3.2). The peak in daily travel time occurs in 1989 whereas the peaks in single travel time have different years, 1985 for the first six days and 1990 for the seventh day. The daily travel time differs by about 7 min and the average single trip time is 2 min shorter on the seventh day than on the first six days.

Of all three measures, the trip rate seems to be the most stable. The difference in the two recording procedures accounts for 0.55 trips per day or 16.7% which have to be additionally recorded on the seventh day which passes from one mode used per day (1m/d) over to 2 and more modes used per day. The variations in stages are not as large as in modes (only $8 - 9\%$). Since 88.1% of all trips on average even on the seventh record day are made by one stage per trip (1st/j)[1] the inaccuracy of considering only the travel time of the journey data base is limited. However, this steady influence of the additional trip or stage means that the recording procedures is kept fairly stable over the years. The dispersion of each measure is shown by the various standard deviations σ.

R-day	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no]	σ_r	1m/d [%]	2m/d	≥3m/d	1st/j [%]	2st/j	≥3st/j
1-6	76.9	78.9	24.3	36.4	3.1	1.7	79.7	18.1	2.2	97.1	2.3	0.5
7	81.3	82.9	22.1	34.2	3.7	2.0	63.0	29.4	7.5	88.1	7.1	4.8
diff	6.7	6.1	-1.8	-1.2	0.5	0.3	-16.7	11.4	5.3	-9.0	4.7	4.3

R-day ... Recording Day, t_d ... Daily Travel Time, t_s ... Single Travel Time,
r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation
m/d ... Modes of Transport Used per Day, st/j ... Stage per Journey (Single Trip)
diff ... Difference between R-day 1-6 and R-day 7

Table 3.2: Average Trip Data by Record Day (DETR 1998b)

The hypothesis of TTB approaches is that the daily travel time is constant. Two statistical tests have been performed to examine this assertion; firstly, an analysis of variance and secondly, a test of confidence interval. The tests are applied to the data of the seventh day to exclude the influence of recording procedure as far as possible. In the analysis of variance, the calculated F-value equals 80.12 with $\nu_1 = 11$, $\nu_2 = 124302$, which is greater than $F_{.95} = 1.79$ and $F_{.99} = 2.25$. According to the second test the interval for 95% confidence are $76.9 < \mu < 85.7$; in this case the values of the years 1972 to 1978 and 1988 to 1990 lie outside the interval. For 99% confidence with $75.0 < \mu < 87.5$ the values of 1972/3, 1975/6 and 1989

[1]To avoid any confusion the index j is used for journey since t is used for time and the term 'trip' and 'journey' are used in the same sense.

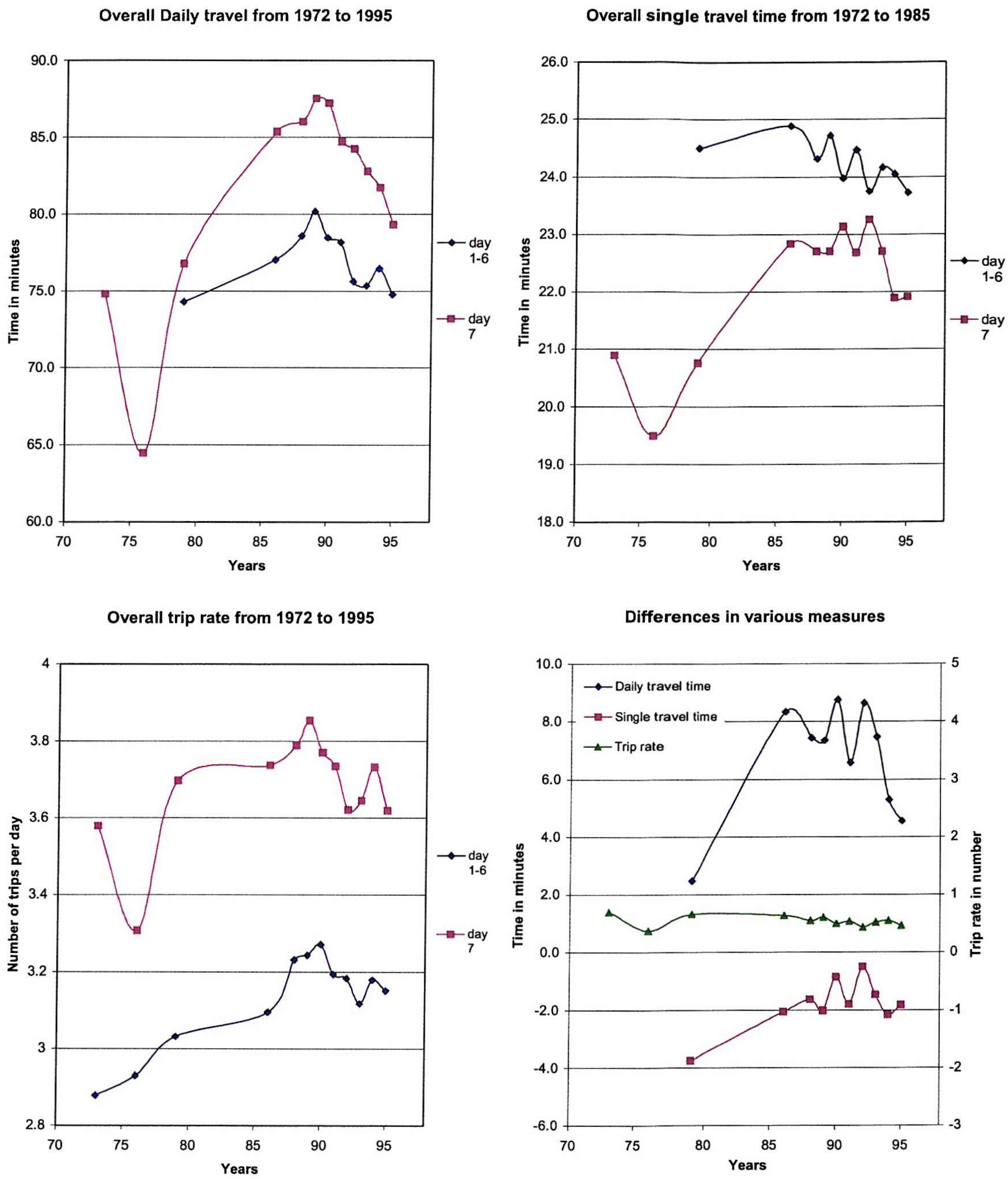


Figure 3.2: Overall Trip Measures Against Year (DETR 1998b)

would exceed the limits. The general conclusion is that the statistical hypothesis of constancy is to be rejected and the averages of daily travel time cannot be regarded as constant. However, it should be noted in respect of Kendall's statement about statistical relationships, that a statistical test gives a statement about the goodness of fit of the data and not about the matter itself. This means that the assertion can still be valid but the desired result has not been achieved because, for example, the variations in the modal mix might be too large.

Quantitative support can be given for equation 3.3 which still holds despite the large values of σ_{t_s} and σ_r which can be verified by multiplying the observed $\langle r \rangle$ and $\langle t_s \rangle$ to obtain $\langle t_d \rangle$.

3.2.4 The Socio-Economic Variables Versus TTB

The most important variables of the trip generation models and ABAs are income, car ownership, household structure and family size, value of land, residential density, or accessibility (Ortúzar & Willumsen 1994). In this section only the first four will be considered since their definitions are directly related to household as the basic unit of reference. Residential density, value of land and accessibility are not generally associated with the household and in the case of accessibility, there is no standard definition in the transport literature, so an examination would not provide the specific predication required for this analysis.

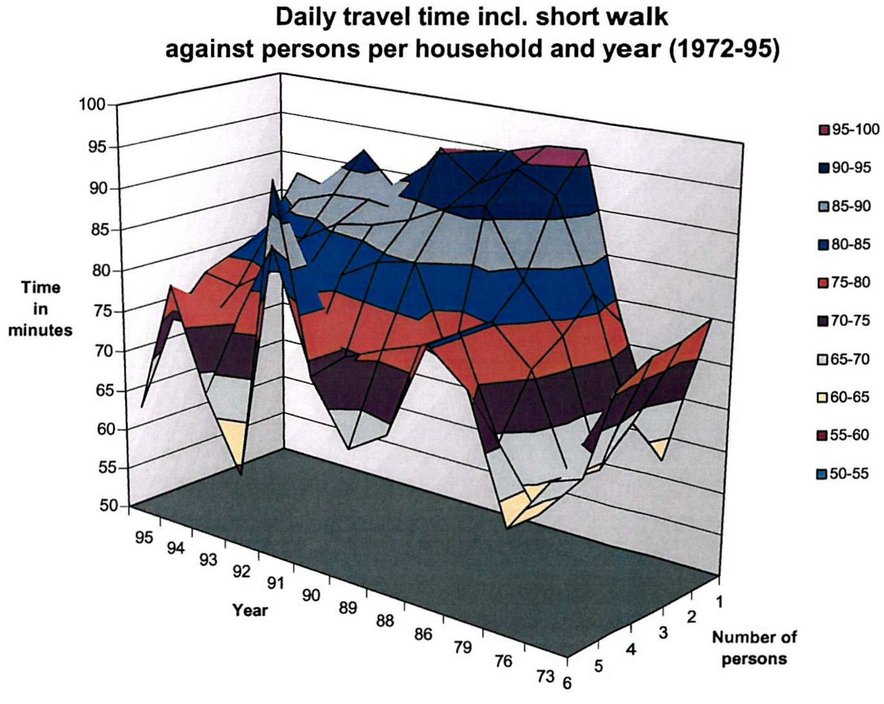


Figure 3.3: Distibution Surface of Travel Time per Person (DETR 1998b)

Each of the variables considered will be treated as statistically independent according to the requirements of these models. As a common base, Zahavi's definition of a traveller (Section 2.3.4) can be used since it coincides well with those of trip generation and it offers the possibility of combining trip generation and ABA on the one hand with TTB-approaches on the other.

The depiction of one variable forms a surface with the category units on the x-axis, the years on the y-axis and the actual values of daily travel time or trip rate on the z-axis, as in Figure 3.3. The trajectories of the surface are formed according to the category units in one direction and to the years in the others. The changes over the years should show the dynamic behaviour of the variables. However, the function can be better identified from two dimensional diagrams, i.e., by looking at only one set of trajectories, and so all the diagrams in this section will be depicted in this way.

Although, for example, the number of persons are discrete units, the curves are treated in a continuous way to preserve the idea of a surface and to allow a clearer understanding of the changes. In addition, the diagrams allow a comparison with the TTB-approaches (of Figure 3.2) which can be found in the figures under the notation 'overall'. The 'averages', on the other hand, were calculated without any weighting function for all years. Since the data quality of the seventh day is nearly equivalent to the first six days, only the seventh day data are used in this section (with the advantage of time data in 1972/3 and 1975/6). The data tables for the figures below are given in Appendix A.

Household Size

In this analysis, the household size is equated with the family size. (Figure 3.1 has already depicted the changes of household size over the years.) As the data for large households becomes more variable as the number of observations diminishes (Table A.3), the maximum household size in Figure 3.4 has been set to 6. The daily travel time-functions against number of persons decline increasingly up to 4 persons per household and then tend to level out. The trip rate-function against number of persons shows the equivalent pattern, but in a convex curve. The TTB- and the trip rate-graphs of different household sizes against year follows the overall trend (Figure 3.4).

Household Structure

The household structure is given in 13 categories (DETR 1995):

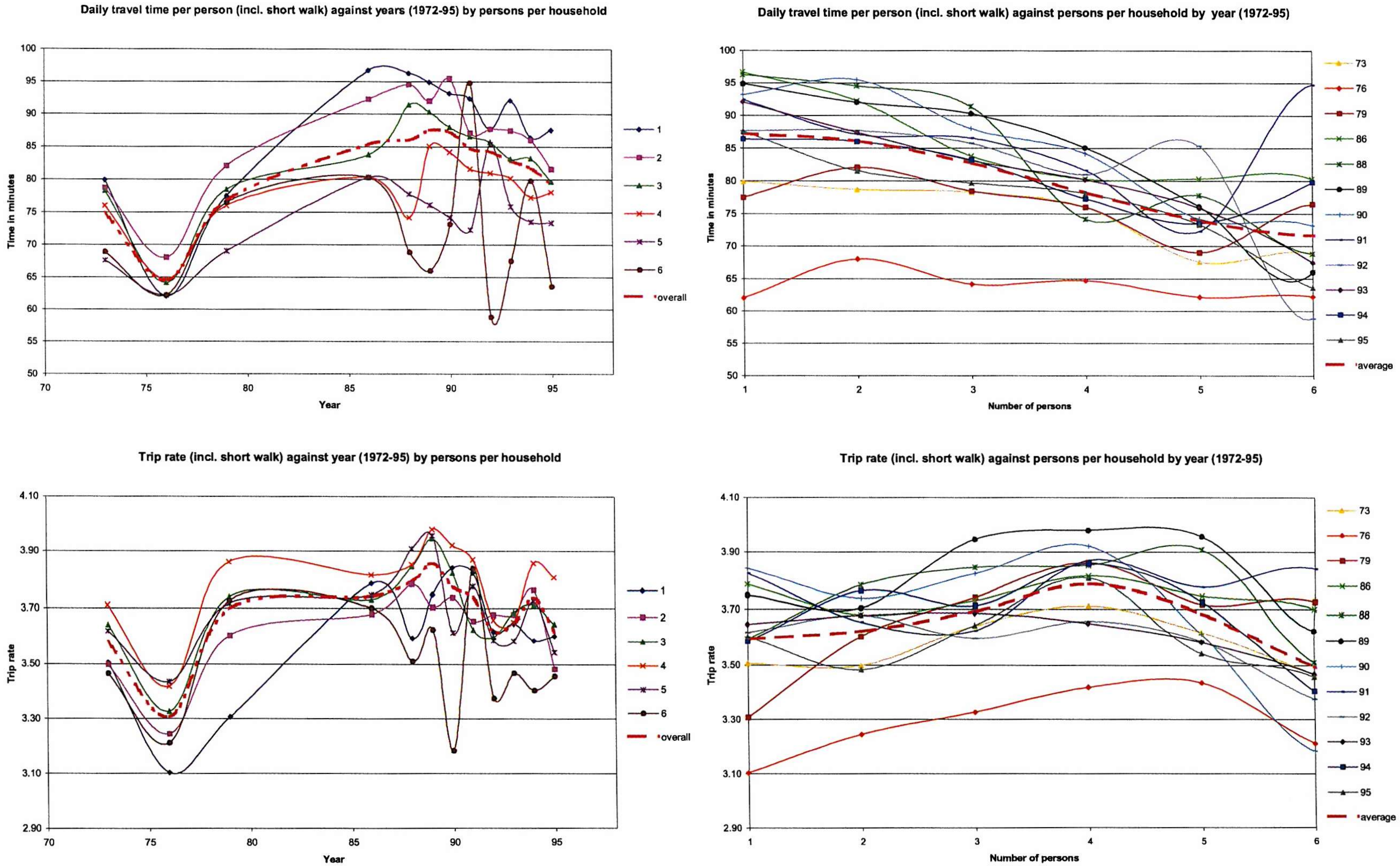


Figure 3.4: TTB and TR against Household Size and Year (DETR 1998b)

Category	Description
1	Single person < 65
2	Single person ≥ 65
3	Two persons, household < 30
4	Two persons, household $30 - 64$
5	Two persons, household ≥ 65
6	Three persons $(1 - 2$ children)
7	Three adults
8	Four persons $(2 - 3$ children)
9	Four persons (1 child)
10	Four adults
11	Five or more persons (≥ 3 children)
12	Five or more persons $(1 - 2$ children)
13	Five or more adults

The categories are related to the number of persons per household but with an additional degree of detail. Generally speaking, households of older people and household with children spend less time travelling (Figure 3.5 and Table A.4). As above, the trend of the increasing number of persons per household spending less travel time can also be found here. The trip rate is on average relatively stable over the groups as well as over the years with an average value of around 3.64 trips per person per day for all groups.

Car-Ownership

Car-ownership categories have changed over the years. In 1972/3 the highest category was '3 or more cars per household'; in 1975/6 and 78/9 it increased to '4 or more' and since 1985/6 it has been extended to '5 or more'. In relation to this categorisation, the observations of higher levels of ownership are relatively small and therefore vary, but remain stable up to 3 cars per household.

The daily travel 'time-line' over car-ownership is a bell-shaped distribution which has a peak for a car-ownership level of 3 and demonstrates an overall positive slope (Figure 3.6 and Table A.5). The trip rate also has a convex distribution with a peak at 3 cars per household. The overall trend is that households with two or more cars spend around 10 minutes per day more on travelling than those with no or one car. Similar increases also occur according to the number of trips per day. The curves over the years, especially the trip rates, run fairly parallel up 1985, but afterwards exhibit increasing variability. (This might be due to the lower number of recordings after 1985.)

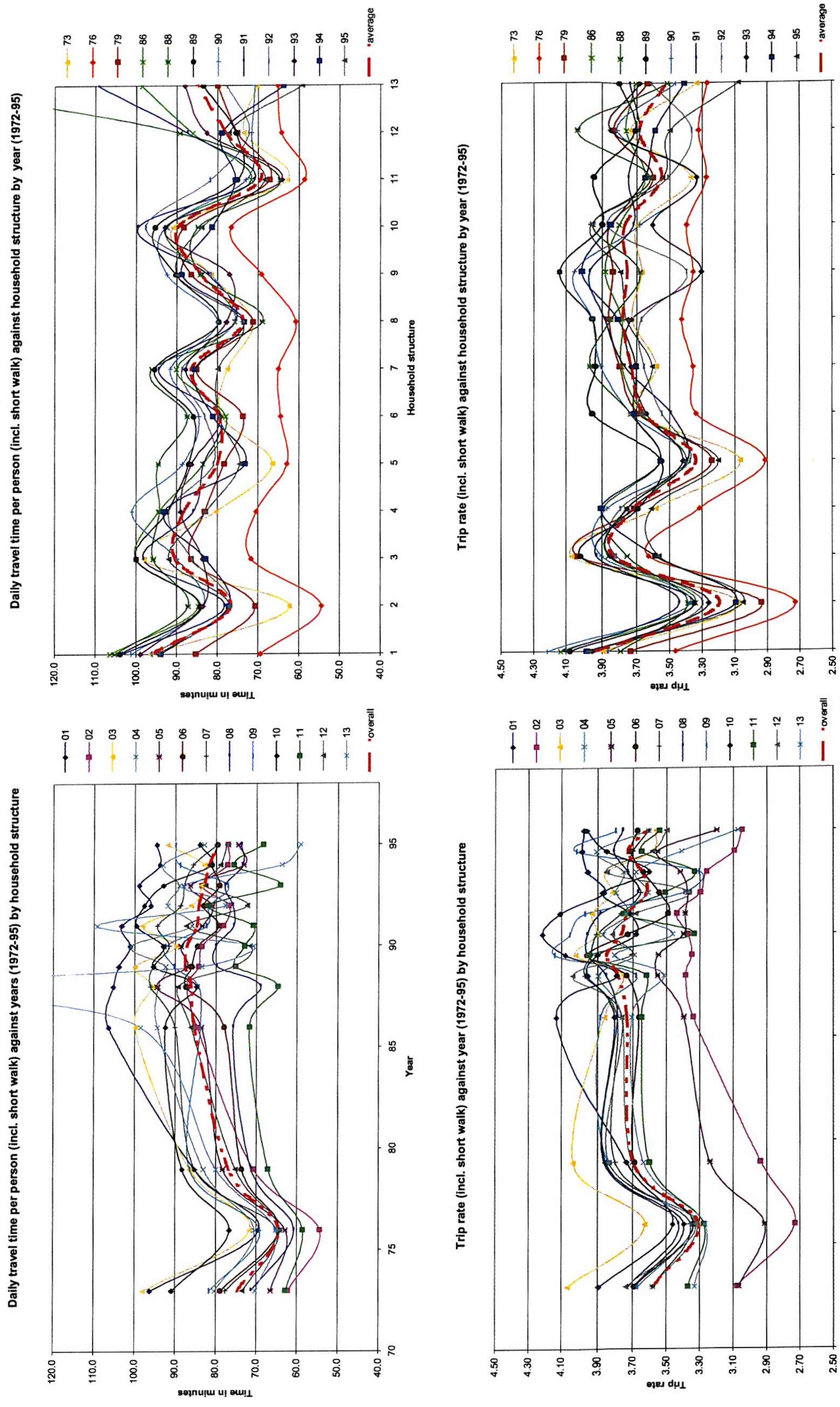


Figure 3.5: TTB and TR against Household Structure and Year (DETR 1998b)

Although car-ownership is considered as a socio-economic variable in trip generation, owning a car does not give any evidence of whether or not a trip is actually made by car. If a household owns more cars it seems to be more likely that trips are also made by car and so car-ownership may be taken as an indicator for a classification of mode of transport. If this is assumed, then the figures suggest that car-travellers spend more time on daily travelling than non-car travellers.

Income

Basically, incomes are grouped according to their numerical value. Over the years classes with higher numerical values have been added so that the number of classes have risen from 13 in 1972/3 to 21 in 1995. Within these changes there have also been changes in the inflation rate. To account for all these changes, a regrouping has been performed to obtain comparable categories. Such ordinal groups start with no or very low income corresponding to 1 up the highest income group corresponding to 9. The number of observations in the lowest group is low, but they seem to be in line with the overall trend. The higher income data are represented with sufficient data. The daily travel time demonstrates a concave line with the lowest level between income group 2 and 4 (Figure 3.7 and Table A.6). The average trip rate decreases from 1 to bottom at 2 and then goes straight up to 9 within the same slope, i.e., a nearly linear correlation between income and trip rate. The curves over the years follow up in a parallel manner but, again become less stable in the 1990's.

3.2.5 Two Inferences of the Comparison

The most important inference can be made in ranking and organisation of the variables. The variables with an ordinal nature such as number of persons, car-ownership and income show a functional relationship between their categorical unit and daily travel time or trip rate. Their non-linear graphs are usually assessed through regression analysis. A comparison of the different trend lines seems to show no definite tendency, neither against the variable units nor against the years. But the curves lie within certain boundaries and generally preserve their shape over the years, i.e., they seem to be time-independent. A superpositioning of the graphs over the years shows that the trajectories run nearly parallel to the overall trend. This raises the question as to why daily travel time and trip rate occur in the first place? This is of most importance to this research. The socio-economic variables appear only to influence daily travel time and trip rate but not to determine them. Alternatively, even the socio-economic variables seem to be dependent on them.

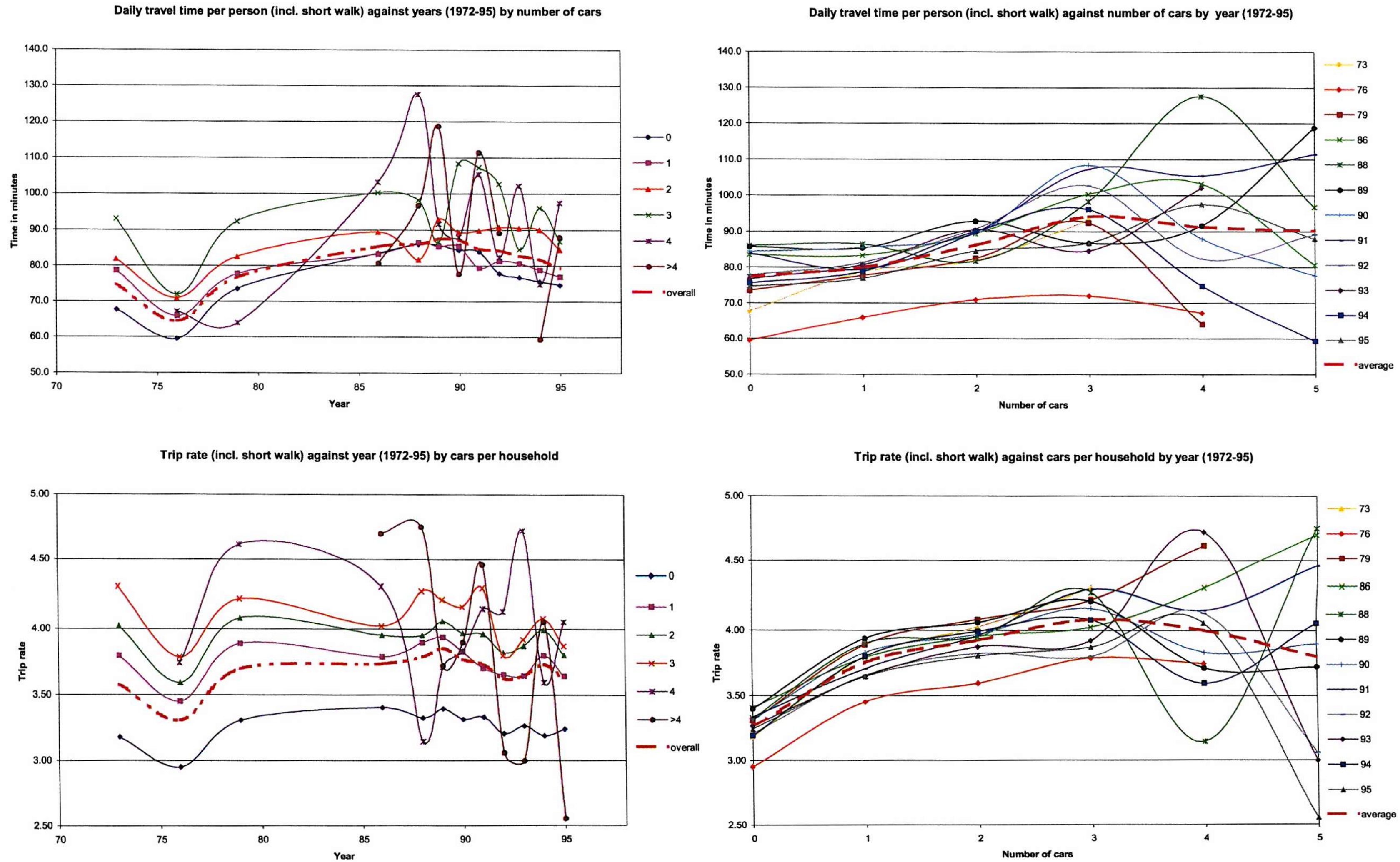


Figure 3.6: TTB and TR against Car-Ownership and Year (DETR 1998b)

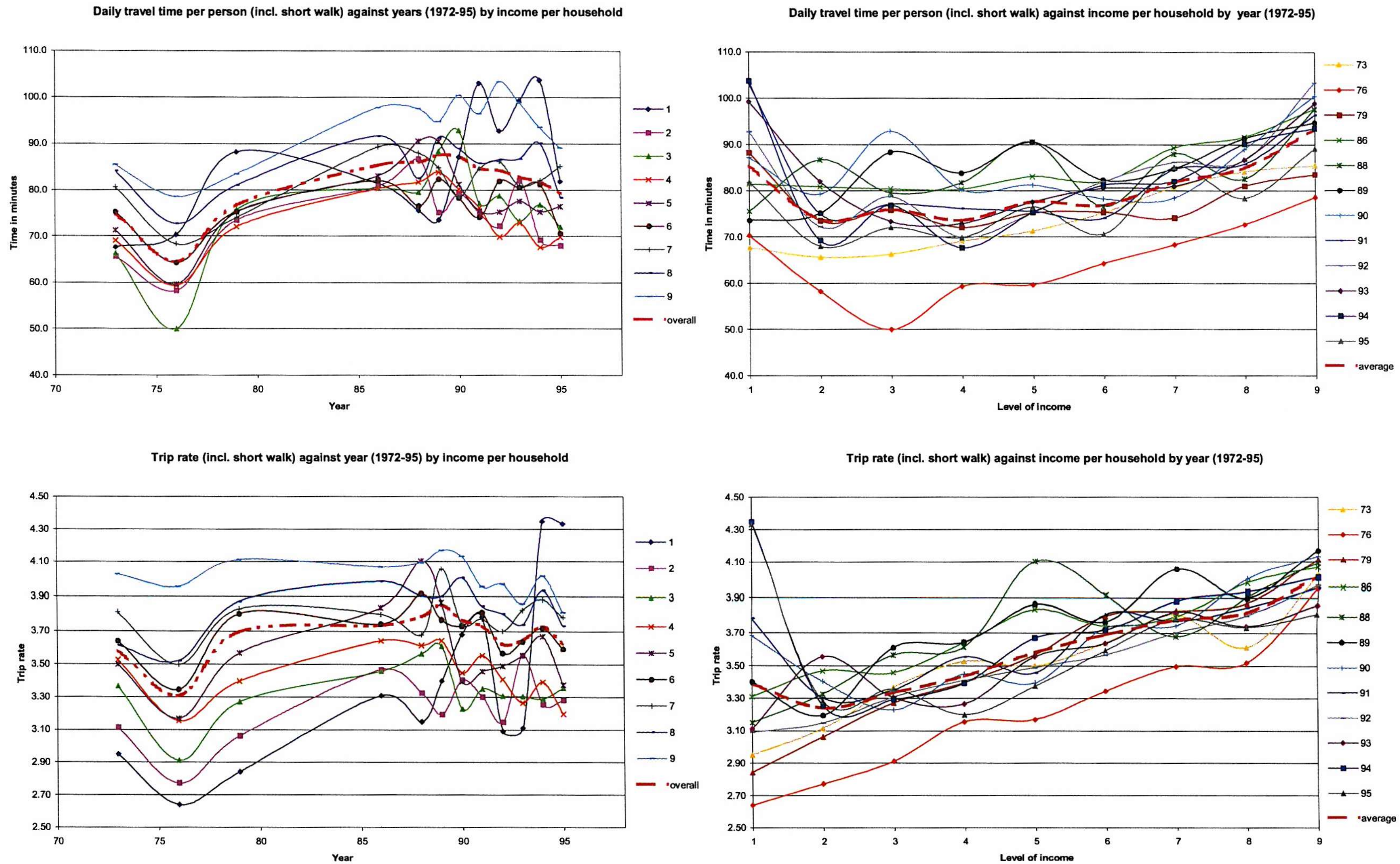


Figure 3.7: TTB and TR against Household Income and Year (DETR 1998b)

This result suggests that there should be an underlying dynamic behaviour which is independent of the socio-economic variables.

Secondly, since the socio-economic variables are household-related variables and daily travel time and trip rate are individual-related variables, a change of the unit of reference should also be made from household to individual. This has also other advantages; for example, the grouping of household removes the individual differences which should influence travel behaviour and therefore each individual will be equally accounted for. This change will be specified in more detail in Section 4.2.1.

To clarify some of these issues, another set of data will be required, i.e., those of ergonomics. The following section introduces this type of data and will provide the necessary background for an understanding and application to travel behaviour.

3.3 The Ergonomic Data

3.3.1 Ergonomics

Ergonomics is in general concerned with the evaluation of stress at work on the basis of scientific methods. It attempts to capture subjective sensations of humans in an objective way. Such assessment should give evidence about the purposeful and optimal distribution of work, the rational design of work and related devices, the best use of the working gadgets and provide some insight into the signs of fatigue. As an evaluation measure of working activities in the Anglo-American literature the oxygen expenditure is used, whereas in the German literature the energy expenditure is common (Hettinger 1989). Since the aim of this research is to relate human activity expenditure in a physical way to travel behaviour the latter is actually necessary.

The following definitions are used in following approach:

Stress is defined as the parameter which is exerted onto the individual and which triggers a human reaction.

Basic turnover is the energy expenditure which is required for sustaining a human body in a lying position at 20°C after 12 hours of a nutrition-free period.

Working turnover is the energy expenditure which is necessary for carrying out a type of work.

Permanent performance limit is defined as limit of an activity which can be performed in an 8 hour shift work without relaxation periods and without any apparent signs of fatigue.

Resting pulse is the pulse per minute measured without an activity. The resting pulse is determined at different body positions, i.e., standing, sitting or lying.

Working pulse is the pulse per minute required for work in addition to the resting pulse (Hettinger, Kaminsky & Schmale 1980).

3.3.2 The Energy Turnover

Energy Related Quantities

"The turnover of energy is a hallmark of every living cell" (Rohmert & Ulmer 1983), and therefore should be a hallmark for the whole organism. All living processes are ones of respiration and, since oxygen cannot be stored in the body, there has to be a continuous exchange of air (Hettinger 1989). This means that the oxygen consumed in each breath is a direct measure for a human's turnover of energy. The amount of energy is calculated through the relationship where 1 litre of oxygen corresponds to 20.36 kJ.

Another parameter which can be used for determining the energy turnover is the pulse rate. The ratio of working joule to working pulse is between 1:2 and 1:2.5, i.e., 1 kJ is equivalent to 2 to 2.5 pulse beats. Under certain circumstances such as static work or different climate the deviation can amount up to 1:3 or 1:4. This means that for such activities the work of the heart circulation is bigger than the energy turnover (Spitzer et al. 1982).

Daily Energy Turnovers

Hettinger et al. divide the daily turnover of energy into a basic turnover (BT) or turnover at rest, a turnover of leisure (LT), and a turnover of work (WT) (Figure 3.8). The basic turnover represents the turnover of sustainability. It is dependent on age, gender, body height and body weight and is about 7100 kJ / d for a man of average age, height and weight; (where d denotes day). The turnover of leisure activities is between around 2500 and 3500 kJ / d and the turnover for work stretches from 4200 kJ / d for light work to over 8400 kJ / d for the heaviest work.

If the human is viewed as a machine then two criteria for its characterisation are firstly, the output power in kW (= kJ / s) and secondly, the (degree of) efficiency, i.e., the ratio between the energy input and working output. The power will be discussed in the following sections where it will be described mainly as energy turnover. The efficiency of the human body can be assessed where the chemical nutrition as the input energy is transformed into mechanical work as output (Rohmert & Ulmer 1983). With the following formula it is possible to assess the daily energy need from nutrition (DN) in kJ:

$$DN = \frac{BT + LT + WT}{0.88}$$

The division by 0.88 is necessary due to the effects of digestion (Spitzer et al. 1982). The effective efficiency varies between a maximum of 30% to a minimum of 1%. The reason for this difference can be found, for example, in the additional movement of the body as a whole or parts of it for certain types of work. However, it should be noted that the purpose of the work does not lie in the generation of mechanical energy but in the production of work (Rohmert & Ulmer 1983).

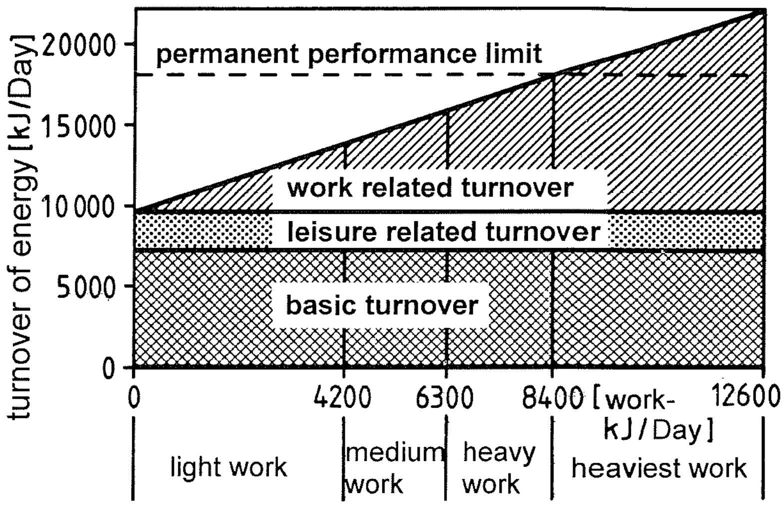


Figure 3.8: Classification of Energy Turnovers (Hettinger 1989)

The Measuring System

Two systems can be used for measuring the amount of energy. The first one is described as the *closed* system where the air breathed comes from a container with a known mixture of gases. This method is only used in clinics.

The second system is described as the *open* one where regular air is used. With a mask over the mouth and nose, breathing is regulated by a valve. The exhaled air is collected in a container either as a whole (e.g. Douglas-bag-method) or as a certain percentage of each breath (e.g. the respiration-gas meter by Müller and Franz). Since the open air has a nearly constant amount of oxygen (21%) the exhaled gas is then analysed in terms of its oxygen content. For hard work it is advantageous to also analyse the amount of carbon dioxide. The absolute amount of oxygen and thus the energy turnover is calculated in relation to the total exhaled air and the percentage of used oxygen (Hettinger 1989).

The Measuring Method

There are two measuring methods, the partial or steady state method and the integral method. The partial or steady state method is used for light and medium work. The measuring begins after 3 to 5 minutes of the start of the working activity since the breathing has to increase from the oxygen level at rest to the oxygen level at work. Afterwards, a steady state develops where the breathing of oxygen corresponds to the equivalent energy turnover. As a rule of thumb the respiration experiment should not exceed 30 minutes because of reasons of inconvenience to the operator, as for example, the pressure of the mask may become irritating. The energy turnover of the overall working stress must therefore be evaluated additively, i.e., several measurement are added up in relation to the time spent on different work activities.

The integral method is used with hard work. Here, the measuring process starts simultaneously with the beginning of the work since the need of oxygen is greater than breathing can provide; the maximum intake of oxygen is around 3 litres/ min for a man. This means that a steady state cannot be achieved and also that heavy work can only be performed over a period of some minutes. However, to balance the oxygen deficit in relation to the activity, the measuring continues until the breathing of rest has been reached again. In relation to the power value, the energy turnover for the working activity is assessed only according to the duration of work but not to the duration of the measuring (Hettinger 1989).

3.3.3 Travel Activity Measures

Spitzer, et al. present tables with power values for various activities and a short selection is presented in Table 3.3 (Spitzer et al. 1982). The measurements were carried out by the Max-Plank Institute for work physiology in Dortmund, Germany. The values only give the turnover of work which can be calculated by:

$$\text{Turnover of Work} = \text{Total Turnover} - \text{Basic Turnover}$$

They correspond directly to persons with average body weight (a man of about 75 kg body weight, a woman of about 65 kg body weight). Under similar circumstances the energy value between different persons can deviate by up to ±10%. With the same person in a laboratory experiment the value varies by around ±5%. In a practical experiment the deviation can increase to ±20%. The values also vary with the speed of the movement which can be seen for activities such as walking, jogging and cycling in Table 3.3. This also shows the non-linear relationship between power and speed. The interpolation of values is allowed whereas the extrapolation should be avoided (Spitzer et al. 1982).

The influence of the body weight is important during the movement of the whole body such as walking. Under equal circumstances and a walking speed of 4.8 km / h, the energy value increases from 8.1 kJ / min of person of 35 kg weight to 16.9 kJ / min of person of 95 kg weight, i.e., an increase of 110%. However, dividing the body weight and the distance the former consumes 2.89 J /(m kg) whereas the latter consumes only 2.22 J /(m kg), i.e., a decrease of 30%. From a body weight around 60 kg onwards the deviation consolidates itself at around 10% which is therefore called the 'DURIG constant of length'. (Table A.1 presents the full detail of these measurements.)

For light work ($< 8 - 10$ kJ / min) the energy value can be overpowered by other components such as psychological or circumstantial factor. This influence is shown Table 3.3 with 'standing restless' compared to 'standing relaxed' and with 'car in a city during rush hours' compared to 'roads'. This problem occurs in a similar way with static activities. For such activities comparative measurements have been made with the pulse rate.

Another factor of influence is the climate. The measures above have been obtained between 10 and 30°C and within this range the temperature does not need to be considered. If a base temperature of 12°C is assumed than the increase at 30°C is 5% and at 39°C it is 14%. Considering 'cold' temperatures, an increase in energy turnover can be noticed at −30 °C by around 10%. Consequently, the energy turnover remains fairly stable under different climate changes.

The permanent performance limit is estimated to lie for a man between 16.5 and 18.0 kJ / min and for a woman between 11.0 and 12.0 kJ / min. These values are only valid if the involved muscle mass is over around $\frac{1}{7}$ of the total body mass (e.g. this less than two arms but more than two legs) and if the work is mainly dynamic and the climatic influence is under normal conditions. The short time performance limit on the other hand, can reach up to 85 kJ / min but this has to be followed by periods of relaxation. In high-performance sports the value can even go above 250 kJ / min (Spitzer et al. 1982).

To summerise, the values of different energy turnover may vary with the location of activities and with different psychological and sociological circumstances; they have therefore the quality of index values. Nevertheless, for practical applications the values possess the required accuracy to interpret realistically the activity-related stress (Hettinger et al. 1980).

Activity	Speed	kJ/dist.	kJ/min
Body position			
at rest and lying down			0.2
at rest on the chair			0.4
sitting on a chair			1.5
standing, relaxed			2.6
standing, restless			6.7
Walking, on an even path	km / h	kJ / m	
	3	0.22	10.8
	4	0.21	14.1
	5	0.22	18
	6	0.24	23.9
	8	0.32	43.2
Walking uphill, on an even path			
5°	3	0.35	17.6
5°	4	0.38	25.6
10°	3	0.58	27.1
10°	4	0.65	42.9
15°	3	0.80	40.1
Walking downward, on an even path			
5°	5	0.12	9.9
10°	5	0.10	8.1
15°	5	0.10	8.6
Carrying weight, on an even path			
10 kg	4	0.23	15.1
20 kg	4	0.34	23.0
30 kg	4	0.35	23.4
40 kg	4	0.42	28.1
Jogging, on an even path			
	10	0.25	42.2
	12	0.22	44.9
	15	0.22	55.6
Cycling, on even path, without headwind		kJ / km	
	10	70.8	11.8
	12	73.5	14.7
	14	77.6	18.1
	16	81.8	21.8
	18	88.3	26.5
	20	98.4	32.8
	40	156	104
Motor bike			9.5
Car			
roads			4.2
test drive			8.0 (5.9-12.6)
in a city during rush hours			13.4
Van, roads			5.5
Lorry, roads			6.3

Table 3.3: Ergonometric Measurements (Spitzer et al. 1982)

3.3.4 Two Examples

The following examples provide a practical impression of the energy values. The first example consists of walking on an even path at 5 km / h for 40 min, going uphill at 10° inclination at 3 km / h for 8 min, and then walking downhill at 15° inclination at 5 km / h for 12 min:

Activity	kJ / min	Time	Energy Turnover in kJ
Walking	18.0	40	720
Walking Upwards	27.1	8	217
Walking Downwards	8.6	12	103
$\sum$	-	60	1040

The division of 1040 : 60 = 17.3 kJ / min gives the average turnover of energy over the whole activity.

The second example consists of carrying a load of 10 kg on an even path over 100 m with a speed of 4 km / h. The values are for 0.23 kJ / m for carrying a load on the back and for carrying in the hands the value increases by 10%, i.e., 0.253 kJ / m. The total energy used is therefore

$$100\,\text{m} \times 0.253\,\text{kJ}\,/\,\text{m} = 25.3\,\text{kJ}$$

Using 4 km / h $\triangleq$ 66.66 m / min, the average amount of energy per minute can be calculated by:

$$0.253\,\text{kJ}\,/\,\text{m} \times 66.66\,\text{m}\,/\,\text{min} = 16.7\,\text{kJ}\,/\,\text{min}$$

If the two results are compared with the permanent performance figures then in both cases the values would be within the performance range for men but would exceed that for women. This means that this activity may not be carried out in a continuous way and appropriate breaks are required.

Spitzer et al. conclude in their analysis:

> The energy turnover is one, but not the only evaluation criterion for physical work. However, according to our opinion its consideration as a part aspect must not be omitted in any evaluation of a work place (Spitzer et al. 1982).

In exactly the same manner the following approach of this thesis should be understood in terms of daily travelling.

3.3.5 Ergonomic Preliminaries

The following concepts are essential for the consecutive approach:

- **The Human Energy Concept**
  As the human energy turnover is used above to assess the working stress in the same way, it will be used to calculate the energy expenditure for daily travelling. In doing so it should be noted that it describes *one* aspect of travelling in relation to the human travel effort. The ideas above are mainly expressed in relation to work but if the meaning of 'work' is also used in a physical sense then it coincides with the 'work' of travel activities. In theory, there should be no difference between work physiology and travel physiology.
- **A Macroscopic Point of View**
  The values given in Table 3.3 are not meant to represent a particular person, i.e., a microscopic viewpoint, but provide an index for the average person of a group or a population. The concept of assessing a population as a whole will be discussed later because distributional properties will emerge which cannot be obtained from the microscopic perspective due to individual variations.
- **The Steady State**
  This notion requires clarification since it will be used in the consecutive approach but in a different context. Here, it describes an equilibrium within an individual person between the oxygen input through breathing and the energy output through the physical activity. In the following approach it will be used not in a microscopic but in a macroscopic perspective where it is applied to the population as a whole. There, the internal bio-physical effort of the population is assumed to be in balance with its external travel behaviour. In principle, there is no basic difference since both describe a system where the input equalises the output.
- **The Measurements**
  The different values have actually been obtained by two methods, firstly by measuring breathing and secondly by measuring the pulse rate. The values should therefore remain stable which could also be demonstrated with the deviations. Since measurements of travel activities vary even more than those of ergonomics (e.g. Table 3.2), the comparison between ergonomics and travel behaviour should be justified.
- **Travel Activities**
  Walking and cycling are fairly well documented in Table 3.3 and their values lie well above the area of medium work. Vehicular travel such as driving a car or using public transport are assumed to be in the range of light or medium

work where, for example, the psychological influence can play a major role. Additionally, no explicit values for public transport are present in the original tables. For the following approach it is important that the obtained energy values lie within a sensible range of the ergonomic values to provide some quantitative evidence.

3.3.6 Beyond Ergonomics

Following the concept of different energy turnovers, the energy turnover for daily mobility can be assumed to be in the leisure turnover. However, for the purpose of this analysis this classification should be taken less strictly, i.e., the energies of the leisure and work turnovers may be combined in one group, so their values may change relative to their consumed magnitude. For example, under the assumption that white collar workers use less physical working energy than blue collar workers, some evidence in the NTS data suggests that white collar workers travel more than blue collar workers. Since these categories are not given over the whole period, the analysis was therefore not included in this study.

There seems to be a biological reason for mobility, or physical or motor activity as it is defined in the medical disciplines, since there exists "an inherent control centre within the central nervous system that regulates one's daily energy expenditure through motor activity" (Rowland 1998). A Finnish study carried out on 15,902 twins between 1977 and 1995 supports the fact that a physical activity is essential to maintain and sustain the human body. Kujala et al. showed this by the relationship between physical activity and mortality, i.e., physically active people live longer, "even after genetic and other familial factors are taken into account" (Kujala, Kaprio & M. 1998). In terms of energy budget this means that a certain amount of energy on average has to be consumed every day to keep the (human) body in a healthy state and one aim will be to assess this energy budget of mobility.

Some qualitative deductions can be drawn:

- *In terms of variables,* it can be seen that bio-physical energy may be regarded as a causal variable since the sustainability of a body itself and so the whole (daily) life cycle with the working or mobility activities depends on it. Alternatively, age, body height, body weight, gender or work can be understood as influential variables since they would only alter the amount of behaviour.
- *In terms of the energy turnover,* there seems to be an interrelationship between work and leisure or mobility since in regard to energy both are just different activities of expenditure. This means that the energy which is not used during work should be consumed for mobility, i.e., longer journeys, or other leisure

activities, i.e., sports, so the complexity of the life style may become more apparent.

- *In terms of the daily energy turnover or the permanent performance,* there is a biological intention to keep the activity level fairly stable and not to exceed the performance limits. This may result in establishing of a daily routine which makes it quite reasonable to adopt not a more detailed classification of time (such as week days, weeks or seasons) for a first estimate of an index value of a mobility energy turnover.
- *In terms of travel,* the purpose of mobility can be envisaged in a complementary way, on an unconscious bio-physical level, where the body is to be retained in healthy state and, on a conscious economic level, where the purpose of a trip, e.g. work or leisure, is to be fulfilled. Such a distinction may resolve a supposed conflict of interest between the rationalistic point of view and the mechanistic point of view, since both describe the 'opposite sides of the same coin'.

The ergonomic concept will be applied in Section 4.2 for the first time. But before, a summary will be given to recapitulate the context and problems raised up to now.

3.4 In Retrospect

So far, the problem of transport modelling has been described according to the aspects of the framework, the variables and definitions, and their consequences in various trip models.

The economic framework gives modelling a quite idealistic layout. It can be amended with various more-realistic characteristics on the one hand, but which would dilute some of the stringency and consistency on the other hand. The analysis of the trip variables and trip definition showed that even monetary quality, the most essential element of an economic approach, does not appear in all transport approaches in a consistent manner.

Another basic problem, raised in the sections of the trip definition and the trip models, was that nearly all approaches are oriented towards vehicular traffic; this means that approaches concerning walking, cycling or public transport are under-represented and therefore undervalued. Additionally, the vehicular preference entails numerous consequences as exemplified by the recording method of walking trips. If this is taken into account a separation of traveller and means of travel becomes essential.

Trip models, especially trip generation models, rely mainly on regression analysis and averaging. They show difficulties not only from a technical interpretation, e.g. the interpretation of the co-efficients for regression analysis or the Lagrangian multiplicator in the case of the Gravity Model, but provide so only a phenomenological explanation in terms of understanding . The ABA attempts to combine many features so in the end it is difficult to develop a conclusive and definitive understanding. Both modelling approaches are unable to supply an explanation for phenomena as pointed out by the approaches of travel behaviour. The economic models of TTB approaches face similar problems as the former models. Although the evolutionary models take completely different variables into consideration, they remain descriptive since their measures may not be objectively verifiable. The empirical comparison shows that trip models actually tackle trip making in a different dimension than the travel behaviour models and therefore both should be viewed in a synthesised way.

It is interesting to note that the trip purpose, although included in the trip definition, does not seem to play an explicit role in trip generation/trip distributions models and in the TTB approaches; only the ABAs use it as an explanatory variable. One reason may lie in the categorisation measure which is the 'day', and the trip purpose would exhibit the next level of detail which is, for example, the specific amount of time spent on different activities during a day. In addition, the aim of these approaches - and in particular of this thesis - is to determine only the *amount* of daily travel and this is characterised by the trip rate and the travel times. Regarding the trip rate, a journey (or a trip) in the NTS data "is defined as a one-way course of travel having a single main purpose". Hence, the number of trips equals the number of main purposes and is indirectly represented in this measure. Therefore, the trip purpose may play a minor role in such models and so it will not be of any further consideration in the subsequent approach. It most definitely plays a major role in land-use planning or trip assignment models but these are not tackled in this thesis.

A starting point for the analysis in the next chapter may be found in the question of variables and their constraints, which can be located in all models. It can be distinguished as a problem of influence on the one hand, and a problem of cause, on the other. Variables of influence can be assumed to vary behaviour to a limited extent whereas variables of cause can control behaviour to the full extent. As illustrated above, the socio-economic trip variables influence travel behaviour but they do not generate or control it. In addition, money may control economic behaviour but income only influences travel behaviour.

As an alternative concept, ergonomics has been introduced where the key measure is the energy expenditure. With the turnover of energy it could be demonstrated that energy expenditure controls the human body as well as its activities. On the other hand, age, gender, body height or body weight can be classified as variables of influence. In addition, travel behaviour can be described as an activity which is embedded in the daily life cycle. This perspective makes it possible to view travel behaviour not in isolation but in context to other activities, an aim of the ABA. However, the difference is that the ergonomic concept is simple and is restricted to one basic level of explanation whereas the ABA is perhaps too complex and attempts to explain travel on several levels simultaneously. Nevertheless, so far, only qualitative evidence could be given by ergonomics in relation to these problems. In the following chapter the quantitative support will be developed.

Chapter 4

A Bio-Physical Travel Model

4.1 Introduction

The objective of this chapter is to develop a bio-physical approach for daily travel. The internal structure of the approach will have a similar layout as the analysis on the previous chapters: firstly, a hypothesis, starting with the question of framework which should clarify some of the issues of the trip definition with its variables, and secondly, the Maxwell-Boltzmann distribution, where a probability distribution of travelling will be derived based on statistical physics.

Instead of an economic framework, a systems-theoretical framework is used which will allow interdisciplinary interactions. From the theoretical system definition an applied trip definition will be deduced. This will raise the energy component as one essential part of trip making and will enable a connection with ergonomics. The empirical verification will consist of an agreement between the NTS data representing the 'external' movement, and the ergonomic data representing the 'internally' provided energy.

The theoretical verification will be based on an analogy of statistical physics to ensure primarily consistency with established principles. The energy exchange is the driving source for all movements and so the notion of causality will be understood only in this physical sense. The physical analysis should also underline the fact that whilst a human's bio-physical energy may not seem to be an obvious key determinant of trip making from a perceptive-inductive point of view, it will become one from a methodological-deductive point of view. Such an analysis may transform a descriptive hypothesis to a physically causal theory. A main feature for the travel model should be that the same principles can be applied to all modes of transport. Thus, a mode-independent model can eventually be established.

4.2 The Hypotheses

4.2.1 An Alternative Trip Definition

One of the basic questions concerns the appropriate framework from which the essential trip making features can be derived. In the 70's, systems theory received much attention in urban planning with, for example, Forrester in (Forrester 1975), but since then has diminished. In this thesis, an approach of General Systems Theory (GST) is used which is based on works of Aristotle, v. Bertalanffy, Lorenz and Riedl (Smith & Ross 1908), (Bertalanffy 1968), (Lorenz 1976), (Riedl 1985). The concept itself is described here only as far as necessary to support this approach.

The aim of GST is to discover and describe principles or axioms irrespective of the actual kind or nature of the subject matter. For example, the term 'system' is usually used only in connection with an application, i.e., the computer system, the living system or the transport system. According to the above idea, questions are asked which define a system without such application. The definition of a system can so be viewed as a description which conceptualises things in an abstract form. As a consequence different subject matters can then be related on the authority of such abstract principles. For the framework, this means in turn that this conception allows firstly to be generally applicable with a neutral evaluation and secondly, to enable consistent, interdisciplinary connections.

Paraphrasing Aristotle, a system can be defined as follows:

> *A system consists of four causes - the material, the formal, the energy and the informational one - and creates out of their relations an existential whole.*

This definition is different to those usually used in Systems Science where "a 'system' stands, in general, for a set of some things and a relation among the things" (Klir 1991). The two definitions are basically identical with the first definition giving a specific indication which variables should be taken into account.

If the former definition is applied to a 'trip' then an individual (a traveller), a means of transport and a path can be regarded as the material elements. The formal cause assembles and combines these elements and shows their structural relationship. Since a definition has to be found for all kind of trips, i.e., vehicular and non-vehicular, a means of transport can be taken as optional. From such a point of view the separation of the traveller (as the prime subject) and the means of transport (as the secondary means) becomes a necessity.

The energy cause can be separated into two main groups: firstly, in the energy which is necessary for establishing and maintaining the material elements and secondly, in the energy for acting upon the material parts. According to the different nature of the elements, energy can have different forms, such as nutrition or fuel. If these items of energy are assumed to be on a 'primary' level then monetary currency can be envisaged as an energy entity on a 'secondary' level, since money can be exchanged, for example, for fuel. Similarly, the monetary value of a ticket for public transport can be considered as an energy value as well. One difference in the energy value is that the primary value of fuel is determined by its content of physical energy and the secondary value of its monetary unit is regulated by the principles of the market. Because these are just some examples of the variety of energies involved in trip making, the energy cause will be summarised as a single 'energy' in the trip definition below. The definition of the specific energy discussed in this research will be presented in the following section.

The informational cause is originally described by Aristotle as "the *purpose* and the *good* ... and for that, for the sake of which other things are" (Smith & Ross 1908). In terms of trips, this means that the purpose yields the information as to why a trip is made, for example, to work, to a shop or to a leisure activity. This characterisation provides the separation of different types of activities: the activity of actual trip making and the 'end-activity' for which a trip is made. (Further refinements in terms of stages are possible.) Therefore, the purpose of a trip can be equated with the activity at the end of a trip and the activity of actual trip making can be regarded as a means to achieve this purpose.

To conclude, the trip definition can finally be stated as following:

> "*A trip can be defined as a locomotion of a person, who goes with or without the use of one or several means of transport m, from an origin i over a route u to a destination j, with an energy ϵ and according to a purpose p*" (Kölbl 1995).

As stated above, the individual is always the basic unit of reference in this study so a symbol or an index is not necessary; it might be required if a distinction in types of person is considered. Apart from the traveller him/herself, the means of transport and the energy will be discussed in the following analysis. The trip purpose, as noted above, is assumed not to be significant for the objective of this research. The same can be assumed for the route with origin and destination which have a positional and directional dependency. These will become significant in trip assignment or land-use planning. Since this kind of models is not within the aim of this thesis, these variables are not considered any further.

4.2.2 The Energy Variable

In physics, energy exchange is the driving source for all movement. The physical energy ϵ can be defined as

$$\epsilon = P \times t \qquad \text{in} \qquad [\mathrm{J} = \mathrm{W} \times \mathrm{s}] \tag{4.1}$$

with the power P and time t. There exists a great variety of different energies (as mentioned in the previous section). For this analysis the focal point will be the bio-physical energy expenditure of an individual traveller, which might be taken too much for granted in the consideration of transport planning. Equation 4.1 will be used to calculate and assess the traveller's internal energy ϵ_{int}.

An external movement, on the other hand, can be calculated by the kinetic energy ϵ_{kin}

$$\epsilon_{kin} = \frac{1}{2}mv^2 \qquad \text{in} \qquad [\mathrm{J} = \mathrm{kg} \times (\mathrm{m}\,/\,\mathrm{s})^2] \tag{4.2}$$

with m as the mass of the object and v as its speed. Since the speed (as an instant measure) might vary during the movement, v can also be interpreted as the average speed (i.e., the distance travelled divided by the trip time). As a first example, the walking of a pedestrian is assumed where m would equal the mass of the human body and v would be the walking speed. For the second example, a driver with his car is assumed then m would equal the mass of the car plus the mass of the human body and v would be the speed of the car.

Under the assumption of a horizontal movement (where the potential energy can be ignored) the conservation of energy can be written as

$$\epsilon = \epsilon_{int} + \epsilon_{kin} = \text{constant} \tag{4.3}$$

Consideration of the boundary conditions of trip making give the following (where time $t \geq 0$). At the start of trip with $t = 0$ the internal energy $\epsilon_{int} \neq 0$, i.e., the total energy budget is available, and the kinetic energy $\epsilon_{kin} = 0$, i.e., no movement has yet been made, so equation 4.3 would be expressed as $\epsilon = \epsilon_{int}$. At the end of daily travelling where $t = t_d$, the internal energy $\epsilon_{int} = 0$ (i.e., all the energy budget has been consumed) and the kinetic energy $\epsilon_{kin} \neq 0$ (i.e., all the energy budget has been transformed into the kinetic energy) so $\epsilon = \epsilon_{kin}$. Therefore, equation 4.3 can be written by substituting the detailed formulae as

$$|P \times t| = \left| -\frac{1}{2}mv^2 \right| \tag{4.4}$$

i.e., the amount of the personal energy ϵ_{int} should equal the amount of the energy of motion ϵ_{kin}. For the two examples above, equation 4.4 would be satisfied for the pedestrian, since the bio-physical energy provides the only source for the kinetic energy of the walking movement. In the second case of the driver, equation 4.4 would *not* be satisfied since the bio-physical of the driver is used to control the movement of the car, whilst the driving speed is provided by the car which comes from the motor or the fuel. Thus, the question is how to satisfy equation 4.4, not only in the case of the car driver but also for other modes of transport, such as bus or railway?

An answer can be given by re-formulating the problem, by finding a measure which is the same for the internal personal energy as well as the external movement. Thus, although the movement of the driver derives from the car, it is the driver who controls the car's movements and the travel time, i.e. when he/she starts and finishes the trip. The same applies to other modes of transport such as bus or train, where passengers choose the appropriate use of the mode by getting on and off, i.e. the duration of travel.

Therefore, the travel time is the key measure, from which the external movement (of the NTS data) can be *directly* compared with the internal energy expenditure (of ergonomics). The same result becomes apparent from the units in equations 4.1 and 4.2 in which the only common unit is time, apart from the energy itself. This implies that *distance is not an independent basic unit in relation to the human influence (as it is in physics) but is dependent on the mode of transport.* In other words, distance can be understood as a measure of consequence or output and time as a measure of prerequisite or input. So the main attention of the approach will primarily be on travel time and not on travel distance.

The human energy expenditure with the corresponding power value has already been discussed in Section 3.3. In the following section the NTS data have to be analysed in terms of travel time in such a way that they can be related consistently to the ergonomic data.

4.2.3 Pure Modes of Transport

The ergonomic values in Table 3.3 reflect 'pure' activities and they can only be taken as indicative of real travel behaviour. To achieve comparable measurements with external travelling, the NTS databases have to be sorted into 'pure' modes. This would be possible with the stage data. But the objective of this comparison is to find the effort of daily travelling and in this respect *'pure' mode* means that *only one (main) transport mode is used throughout the day.* The determination of the main mode relies upon the categorisation already given in the data base. Nevertheless, a 'main-mode' distinction represents more realistically the effort of modal travelling since, for example, the usage of a bus or railway also involves walking to the bus stop or railway station.

The focus in the modal choice is on the most common modes of travel, which are walking, cycling, car-driver, car-passenger, bus and railway. Together these count for more than 90% of all modes. In view of the source classification of the data base, two combinations have been made: firstly, London stage bus and other stage bus are combined and secondly, short walks, which are accounted for only on the seventh day, are summed with long walks on the same day.

As already pointed out in Section 3.1.5, a problem in the empirical verification is the actual number of observations due to increasing detail of categorisation. From these trips the numbers of days where only one mode is used throughout the day are given in Table 4.1. (A multiplication of the observations per day with the average trip rates yields the number of observations of single trips per day.)

R-day	Peri. of Obs.	walk	bike	car-dr	car-pas	bus	rail
				[no of obs.]			
1-6	pre 85	8481	2400	25818	20689	12661	1313
	post 88	1756	592	10969	7909	2742	430
7	pre 85	4242	315	3063	2207	1245	126
	post 88	1347	89	1640	1076	321	62
R-day ... Recording Day, peri ... Period, Obs ... Observations.							

Table 4.1: Average Number of Observations per Year and Recording Period (DETR 1998b)

The modal split of the different mode of transport is given in Figure 4.1 and Tables B.1 - B.6, and is calculated in relation to the number of trips. By concentrating on the seventh day, the modal split of walking declined continuously from 40.4% in 1972/3 to 23.7% in 1995. In contrast, that of car-driver rose from 22.1% in 1972 to 36.7% in 1995. The gain of car-passengers of 7% was lost by bus from 12.5% to 7%. This means that walking and bus lost nearly half of their agents whereas car (with car-driver and car-passenger) gained one half of their share. The number of cyclists declined by one third, from 2.8% to 1.8% and rail travel remained constant at around 1.3%.

The influence of walking, according to the methodical distinction between the first six and seventh day, can be accounted for in the percentage of stage numbers per journey (Table 4.2). Around 99% of all walking or bicycle journeys are performed in one stage; the one percent left may be due to faulty data entries. The difference between days 1-6 and 7 is also statistically insignificant. Although car trips are

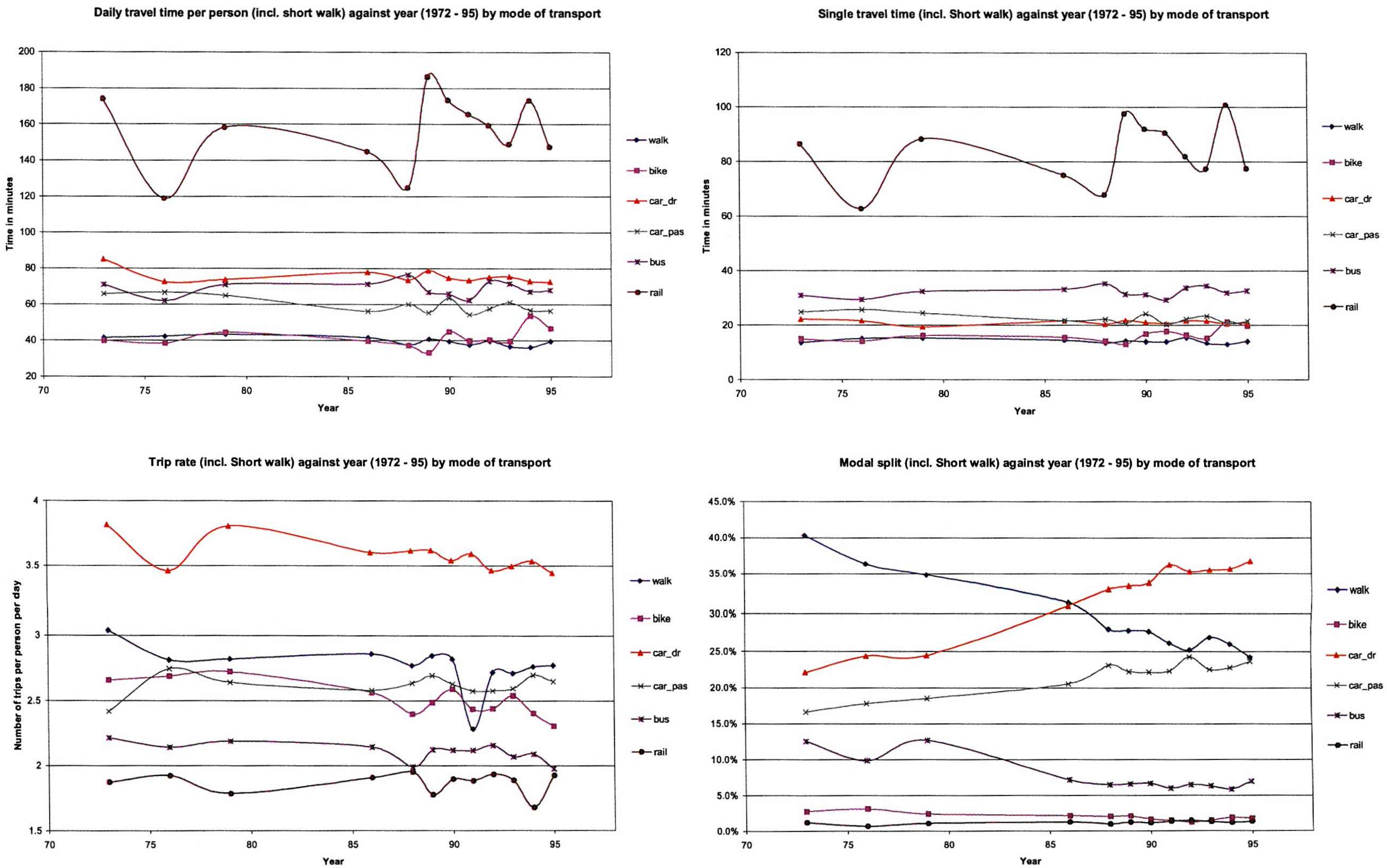


Figure 4.1: TTB and TR by Mode of Transport (DETR 1998b)

R-day	Mode	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [min]	σ_r	1st/j [%]	2st/j	3st/j	≥4st/j	P_m [kJ/min]
1-6	walk	67	69	30	31	2.2	2.3	99.7	0.2	0.0	0.0	9.1
7	walk	40	41	14	15	2.8	2.9	99.8	0.1	0.0	0.0	15.4
diff	walk	-28	-28	-16	-16	0.5	0.6	0.1	-0.1	0.0	0.0	6.3
1-6	bike	42	44	16	18	2.5	2.7	99.8	0.1	0.1	0.0	14.7*
7	bike	42	45	16	18	2.5	2.6	99.0	0.9	0.1	0.0	14.9*
diff	bike	0	1	0	0	0.0	-0.1	-0.8	0.8	0.0	0.0	0.2
1-6	car-dr	75	76	21	21	3.6	3.7	99.6	0.4	0.1	0.0	8.3
7	car-dr	76	78	21	22	3.6	3.7	93.5	5.8	0.5	0.1	8.1
diff	car-dr	1	2	1	1	0.0	0.0	-6.0	5.5	0.5	0.1	-0.2
1-6	car-p	56	58	22	23	2.6	2.7	98.9	0.9	0.2	0.0	11
7	car-p	60	63	23	24	2.6	2.7	91.8	7.2	0.8	0.3	10.2
diff	car-p	4	5	1	1	0.1	0.0	-7.1	6.2	0.7	0.3	-0.7
1-6	bus	64	66	30	31	2.1	2.2	93.9	5.7	0.3	0.0	9.6
7	bus	69	72	32	33	2.1	2.2	31.2	29.9	36.3	2.5	8.9
diff	bus	5	6	2	3	0.0	0.0	-62.7	24.2	36.0	2.5	-0.7
1-6	rail	149	157	79	83	1.9	1.9	33.5	41.6	21.7	3.1	4.1
7	rail	156	170	83	91	1.9	1.9	3.1	14.7	51.0	31.2	4
diff	rail	7	12	4	8	0.0	0.0	-30.4	-26.9	29.3	28.0	-0.2

R-day ... Recording Day, Mode ... Modes of Transport, t_d ... Daily Travel Time, t_s ... Single Travel Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation, st/j ... Stages per Journey (Single Trip), P_m ... Calculated Power by Transport Mode, diff ... Difference between R-day 1-6 and R-day 7, * ... Assumed Value.

Table 4.2: Average Trip Data per Recording Period and Mode of Transport (DETR 1998b)

generally made in one stage, around 6% of car-driver and 7% of car-passenger have to walk more than 50 yards to or from their car park. However, as expected, the biggest influence can be seen in bus and train. The stage shift of bus accounts for around 60% from one to two and three stages. Over 90% of one-stage bus trips on the first six days show that the distance to a bus stop is generally less than one mile. Trips by train are generally characterised by more modes, around 30% walk to the train station within one mile. The stage shift to three and four stages on the seventh day indicates that bicycle, bus or car are additionally required (which are counted in the two or three stages on the first six days). A more detailed analysis of this stage-mode-mix, i.e., the relative proportion of different modes in relation to the main mode, is left to further studies.

Generally it should be noted that the quality of the data points is dependent on the amount of data and perhaps there are generally too few observations. Additionally, substantial distributional variations occur within each mode; Figure 4.2 gives an example of the different modal distributions and an estimate for these variations, i.e., the standard deviation σ, is provided in Table 4.2 for both travel times and trip rate.

The difference between travel time of the first six days and the seventh day has a variable effect on the mode of transport. The average difference of walking amounts to around 28 minutes for daily travel time t_d, 16 min for single trip time t_s and 0.5 trips/day. The other noticeable difference can be observed with bus and 5.4 min for t_d and 2.3 min for t_s, and with rail and 8.9 min for t_d and 6 min for t_s. But these two variations lie within the margins of recording accuracy (as pointed out in the NTS data sets where people's assessment of the travel time causes over-proportional high '5-minute' entries). There is little statistical difference for the other main modes either in travel times or in trip rate. This implies that the influence of walking in terms of time is not as apparent as with the stage numbers.

The travel times and trip rates vary in absolute terms with different modes of transport. The quickest mode of transport can be defined as that which takes up the minimum amount of time spent on daily travel, as is usually performed in the field of economics. (The average speed, which is the usual perceptive measure, would again be a measurement of mode, as illustrated above.) According to this definition, walking and cycling lead the list with an average (taken over all years) of 40 and 42 min respectively (Tables 4.2 and Table B.1 to B.6). Car-passenger comes next with around 58 min followed by the bus with around 66 min. Car-driver

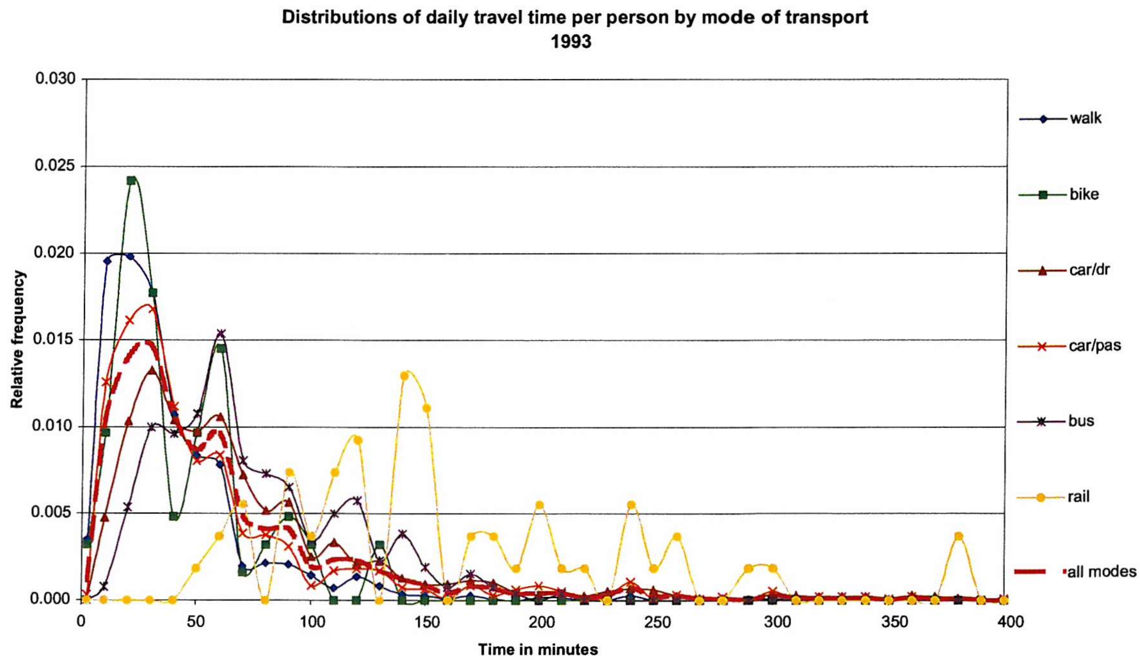


Figure 4.2: TTB Distribution by Modes of Transport (DETR 1998b)

amounts for around 72 min and the mode of transport with the most time spent on daily travelling is railway with 150 min.

If these results are compared with the hypothesis of constant TTB then with differences between 16, 30 or 110 min it becomes difficult to support the assertion of constant daily travel time without a modal distinction. In addition, the overall hypothesis relies on averaging. Averaging can conceal large variations of the next level of detail. If the modal distinction is adopted then the question of constancy can be again asked and the same statistical tests, i.e., an analysis of variance and a confidence interval estimates for means, can be applied.

As before, taking the data from the R-day 7, the statistical tests lead to the following results:

Mode	F	ν_1	ν_2	$F_{.95}$	$F_{.99}$	95%	99%
walk	4.18	11	25302	1.79	2.25	$38.2 < \mu < 41.2$	$37.6 < \mu < 41.9$
bike	2.27	11	1786	1.79	2.25	$38.1 < \mu < 45.1$	$36.6 < \mu < 46.5$
car-dr	4.61	11	23419	1.79	2.25	$73.2 < \mu < 78.0$	$72.2 < \mu < 79.0$
car-p	6.10	11	16020	1.79	2.25	$57.1 < \mu < 62.9$	$55.9 < \mu < 64.1$
bus	5.67	11	6930	1.79	2.25	$66.1 < \mu < 71.9$	$64.9 < \mu < 73.1$
rail	2.58	11	897	1.79	2.25	$142.8 < \mu < 169.8$	$137.2 < \mu < 175.3$

In the case of the confidence interval estimates, the general results are similar to those on the overall level. On the 99% confidence level, one or two values in each mode category always lie outside the interval. But a different impression can be obtained from the analysis of variance. Although none of the modes satisfies the criterion, the F-value of the overall case (80.12) is reduced by 15 or 30 times to the modal F-values $(2.27 - 6.10)$, a result indicates that there is a strong tendency towards a hypothesis of a constant *modal* TTB. However, more sophisticated statistical tests which are not available in standard statistical packages, are required to verify such a hypothesis.

Another attempt has been undertaken to show the relative difference between the mode of transport. This method is based on the whole distribution, i.e., to include all the variations (and not only the averages) and to test if the different shapes of distributions incorporate the same distributional characteristics. This has been done by keeping one modal distribution fixed and multiplying all other distributions with a 'stretching' factor. Although the curves match up to the full extent, i.e., the relative difference approached zero, the stretching factor still varies too widely so that no conclusive value could be obtained. This may mean that the number of observations for such a test is too small, so each distribution would need to be more steadfast. In statistical terms this shows that the average value is a robust measure of representation whereas the 'stretching' factor is sensitive and not-representative. But the matching up of the distributions may indicate that there is an underlying common property.

To sum up, it can be asserted that the modal travel times and trip rates remain fairly stable despite the changes in modal split over the 23 years of surveys. The hypothesis of a constant modal TTB has not been fully established (according to the statistical test), but it provides an explanation to a fairly high degree. In this sense, the analysis will be continued since an explanation 'outside the statistical methods' (Kendall & Stuart 1973) has to be found.

4.2.4 Travel Energy Budget

In this section the travel data can now be related to the ergonomic data to develop the final version of the hypothesis. The internal energy expenditure appears is the power value P_m of the mode of transport used m and the extent of the external movement is related to the modal daily travel time, so equation 4.1 can be given as:

$$\epsilon_d = P_m \times t_{dm} \tag{4.5}$$

On the basis of equation 4.5 the final hypothesis can be formulated as:

> *A human spends on average the same amount of physical energy for daily travel. Thus,*

$$\langle \epsilon_d \rangle = \text{constant.} \tag{4.6}$$

Or, on average, the same quantity of bio-physical energy per person per day is used for different qualities of mode of transport. Thus, the final form can be described as the *hypothesis of a constant travel energy budget* (TEB).

The qualitative evidence given so far is:

1. The energy is a causal variable required for all physical movements.
2. The human energy expenditure is based on continuing daily turnover.
3. The physical activity is necessary to keep the body in a healthy state.
4. The control of the urge for physical activity is controlled by the biological process of a human body.

The quantitative evidence is based on the following preliminaries:

1. Since average values are provided, a macroscopic approach is adopted and not a microscopic one.
2. The power values are index values according to their absolute amount.

3. The daily travel times are fairly constant.

Since there is no *absolute* measure of the energy expenditure for daily travel, the verification has to be based on the *relative* measures, i.e., the power values must be in the correct ratios to the daily travel times. If bicycle is chosen as a reference mode then according to equation 4.5, the total amount of daily travel energy (around 615 kJ) is calculated by multiplying the daily time (42 min) with the ergonomic value of 14.7 kJ / min (Table 3.3) which is in accordance with the average cycling speed of the NTS data. Then, by dividing the energy total by the time spent on each mode, the average energy expenditure per min is obtained and a first assessment for the hypothesis is given in column P_m (Tables 4.2 and Table B.1 to B.6).

The values for car-driver (8.3 kJ / min in Table 4.2) agree when compared to P_m-values in Table 3.3 (8.0, 5.9 – 12.6 kJ / min). Walking (on the seventh day) with 15.4 kJ / min also fits the right range (4 km / h $\triangleq$ 14.1 kJ / min, 5 km / h $\triangleq$ 18.1 kJ / min) since the actual walking speed fluctuates around 5 km / h. Car-passengers with 10 – 11 kJ / min have to walk more than car-drivers; from this perspective the values coincide too. Although no ergonomic data for public transport (bus and railway) are available, a fairly good agreement can be obtained with the body position data of Table 3.3. The energy values must be higher than the body position data since using public transport involves, for example, walking to the bus stop or railway station. On the train one can anticipate 1.5 kJ / min when sitting, with the access and egress effort increasing the value to an average 4 kJ / min. The 9 kJ / min for bus travel may fit the data if walking plus standing with the more abrupt motion of bus, as compared to standing restless (6.7 kJ / min), is taken into consideration. From the perspective of car-passenger the hypothesis remains consistent if car-passengers walk more than bus passengers although sitting in the car is more comfortable than riding on a bus. (This could be answered with the above question of stage-mix and also with the more detailed consideration of the terminal time.) Another unknown quantity can be the level of stress involved, as indicated by the values standing relaxed versus standing restless and driving on the road versus driving in the city during rush hours.

Taking all the above into consideration, a fairly good agreement of the power values could be obtained in spite of the fact that the travel data comes from the UK and the power values come from Germany, i.e., two different data sets. So far, the verification has been based on averages of quantitative-statistical methods but without a qualitative-analytical explanation for the distributions, which have to be assumed. The next section describes the theoretical approach which supports these general findings.

4.3 A Principle of Travel Distribution

4.3.1 Introduction

In this section, an attempt is made firstly, to develop a distribution function which describes travel behaviour and its variations (because until now the functional form of the distribution has been unknown) and secondly, to provide the theoretical explanation for the hypothesis of human travel energy.

The Maxwell-Boltzmann distribution is used in physics for the following reason: "The thermal velocity is a certain average property of the thermal motion of particles. In reality, different molecules move with different velocities and we may ask what is the velocity distribution of the molecules, that is, how many (on average) of the molecules in the body have a particular velocity?" (Landau, Akhiezer & Lifshitz 1967) In the following derivations, particles are exchanged with travellers but the main idea remains exactly the same.

The approach starts with conceptual *parallels* between statistical physics and transportation to show the feasibility of the assumption which forms methodological preconditions. Afterwards, the actual mathematical derivation is formulated which determines the physical boundary conditions of daily trip making and which should eventually yield a *distribution function* valid for the overall travel as well as for mode-specific travel, where the consistencies with the established principles of physics are preserved. The section finishes with theoretical verification of the *mean energy* but many open questions remain.

The terminology used in this section attempts to add the connotation of transport to that of statistical physics. In doing so the direct connection with physics will be preserved so the analogy can be pursued. This falls also into line with the approaches of A. Wilson who has previously used this methodology in transportation (Wilson 1967), (Wilson 1970).

Regarding the statistical calculus of Kendall's statement in Section 2.3.1 (that "causation must come from outside"), a clear distinction can be made between probability calculus on one hand, and subject-related methodology on the other. The notion of 'causation' can be understood where the 'outside' methodological mechanism can provide an explanatory schema of the subject which would be unobtainable only by probabilistic calculus. And thirdly, 'causality' is here understood only in relation to energy, i.e., it is used only as *one* descriptive component of travel behaviour, and it should not be taken in a sense of total or sole explanation of trip making.

As a guideline, the work by Lifshitz et al. is used for the analogical parallels and the work by Tolman for the derivation of the probability distribution function (Lifshitz & Pitaevskii 1980), (Tolman 1938).

4.3.2 Parallels

The following concepts form a preconditional basis for the subsequent analysis.

Incompleteness

Statistical physics and travel behaviour are concerned with incomplete specifications of precise states due to the high degree of complexity in terms of numbers or degrees of freedom involved, where neither the exact states of particles nor travellers can be determined. Therefore, both require a substantiation where certain simplifications are necessary to limit the number of variables involved.

Macroscopic Versus Microscopic

Both disciplines are concerned with macroscopic systems, i.e., systems consisting of a large number of individual agents. As is often the case, as the number of agents increases the collective system exposes a discernible behaviour which eventually leads to statistical principles. Therefore, both employ statistical methods where the individual behaviour cannot be defined precisely, but where the macroscopic behaviour can be described in terms of distribution functions.

The Concept of Aggregate States

In physics, the concept of aggregate states of matter is described in the following way: "Owing to the low density of matter in the gaseous state, its molecules are relatively far apart, being at distance large compared with the size of the molecules themselves. The interaction between the molecules of a gas is therefore of subordinate importance, and for the greater part of the time the molecules move freely, undergoing collisions with one another only quite rarely" (Landau et al. 1967).

In traffic engineering, the size of travellers compared to their distance apart usually satisfies the low density measure although, for example, during rush hours the flow-concentration can increase to a high density level. However, it can be assumed that the occurrence of such instances is generally low in comparison to the whole trip. In terms of collision, such instances happen relative rarely indeed and the act of preventing collisions requires energy for correction. Nevertheless, it can again be assumed that the correcting energy is relatively low in comparison to the energy expenditure for the whole trip and so the concept of aggregated states is also applicable in transportation.

The Concept of Phase Space

In statistical physics "every distribution function must be expressed entirely in terms of combinations of the so-called general co-ordinate q and momentum p." The density of this distribution function ρ remains "constant at any given point and is proportional to the corresponding value of ρ ... and must obviously satisfy the normalisation condition, ... [i.e.,] the sum of the probabilities of all possible states must be unity".

$$\int \rho \mathrm{d}p\mathrm{d}q = 1 \tag{4.7}$$

This concept of phase space is "a purely mathematical concept" and serves as an invariant operator, which can be transformed to suitable units without losing the stringency of the approach in question (Lifshitz & Pitaevskii 1980).

In a physical system the particles are singular agents without any further energy input and therefore the general co-ordinates are 'true' representative units. In a human system co-ordinate and momentum may not be 'true' representative units because, due to the possibility of additional means of transport, the movement of the traveller receives an additional energy input. As already outlined in Section 4.2.2, the only 'true' input units would be time, or energy, which reflect human effort as the prime controller of travel behaviour. Thus, the condition of a conservative phase space can be satisfied if the human bio-physical input of energy can equal the amount of the external movement in terms of time. This phase space can then be described as a generalised human-energy phase space.

Closed Versus Open System

Most problems in physics are tackled from the viewpoint that the system is closed. Whilst it is clearly not the case that a traffic region can be regarded as closed, it is a reasonable approximation since 95% of all travel occurs within a radius of about 25 miles of a settlement and 99% within about 100 miles (Figure D.1).

But a closed system is not only understood in territorial terms, it is foremost understood in energy terms, which means that no additional energy enters or leaves the system. In such a respect there is only an energy exchange between travellers and their movements, i.e., the bio-physical energy is transformed into the energy of motion (in relation to time) within the traffic system. This condition then corresponds to the condition of a conservative phase space, i.e., the energy does not leave the system and is therefore conserved. Thus, taking both conditions, the system can be viewed as subsystems which are "quasi-closed over not too long intervals of time" (Lifshitz & Pitaevskii 1980) and this, therefore, agrees well with the conditions of a transport system.

Classification of Subsystems

In physics, this division is according to the different types of particles in question. In the transport approach, the classification is according to different modes of transport (within the context of this thesis). Further distinctions are possible, for example, in terms of person types.

Equilibrium Versus Steady State

Thermodynamic or thermal equilibrium can be assessed with a statistical equilibrium where a subsystem, after passing through every possible state over a sufficiently long period of time, will approach a limit of a quantity w, i.e., its probability:

$$w = \lim_{T \to \infty} \Delta t / T \tag{4.8}$$

This means that a (microscopic) subsystem does not depend on its initial state, since over a sufficiently long period of time the effect of this initial state will be entirely outbalanced by the effect of the (macroscopic) system and time. Averaging in that respect forms a special case:

> The averaging with respect to the distribution function (called statistical averaging) frees us from the necessity of following the variation with time of the actual value of the physical quantity ... in order to determine its mean value. It is also obvious that, by the definition of the probability, [equation 4.8], the statistical averaging is exactly equivalent to a time averaging. The latter would involve the variation of the quantity with time, establishing the function $f = f(t)$, and determining the required mean value as
>
> $$\bar{f} = \lim_{T \to \infty} \frac{1}{T} \int_0^T f(t) \mathrm{d}t. \tag{4.9}$$
>
> Thus ... statistical physics enables us to make predictions which are valid to a very high accuracy for by far the greater part of any time interval which is long enough for the effect of their initial state of the body to be entirely eliminated. In this sense the predictions of statistical physics become practically determinate and not probabilistic (Lifshitz & Pitaevskii 1980).

Human systems operate in a steady state or 'Fließgleichgewicht' (Bertalanffy 1968). Even after a perturbation, both will subsequently return to their equilibrium and steady state respectively, which can be demonstrated, for example, by the expectations of daily travel time. Such performance values of steady state can be described by mean values and the statistical averaging stabilises the variations over the years. The mean values of a steady state should therefore be as predictable as the equilibrium value of particles. The independence of initial states together with the macroscopic property of distribution functions enable a probabilistic prediction which makes the approach nearly deterministic.

Significance of Energy

There are three crucial properties of energy: firstly it is mechanically invariant, which is due to the fulfillment of the principles of thermodynamics, secondly it is independent of the matter involved, and thirdly it is an additive quantity, by which different motions of energy can be summed. These properties make it possible to measure, compare and evaluate modes of travel through different usages of energy.

The following methodology has also been partly adopted by Wilson as mentioned in Section 2.3.2 but here the energy units are exchanged for monetary units (Wilson 1967). In this thesis the original units are retained and the ergonomic measurements are integrated.

4.3.3 The Maxwell-Boltzmann Distribution

The Case of a Singular Mode

In this subsection the derivation is described for one group of travellers. The extension to different groups of travellers, i.e., for a multi-modal system, will be made in the following subsection.

Three basic assumptions are made for the following derivation: firstly, an area contains N_{tot} inhabitants which are described as travellers or agents. The term 'agent' will be used since the notion can be understood in a physical as well as in a transport sense. Secondly, according to the ergonomic classification, each agent spends an energy budget E for daily travelling. And thirdly, the agents move around randomly in a closed area in relation to their energy budgets. The result will be the Maxwell-Boltzmann distribution which describes the frequency distribution in terms of their energy budgets.

Let N_{tot} agents be classified in I groups according to their equivalent energy levels E_M thus

$$N_{tot} = N_1 + N_2 + \ldots + N_I = \text{constant} \tag{4.10}$$

and assume N_{tot} number of inhabitants in the area remains constant over 'a not too long interval of time'.

$$dN_{tot} = \sum_{M=1}^{I} dN_M = 0 \tag{4.11}$$

According to ergonomics, the agents provide a total energy E_{tot} of daily travelling in an area:

$$E_{tot} = \sum_{M=1}^{I} E_M N_M \tag{4.12}$$

and the total energy of the system remains constant which can be given as

$$dE_{tot} = \sum_{M=1}^{I} E_M dN_M = 0 \tag{4.13}$$

whilst the energy amount of a single person of N_{tot} travellers can vary.

The probability P of different configurations of the system can be given by

$$P = \frac{N_{tot}!}{N_1!N_2! \ \ldots \ N_I!} \tag{4.14}$$

Taking the logarithm and using Stirling's approximation for factorials of large numbers, equation 4.14 can be given as:

$$\log P = N_{tot} \log N_{tot} - \sum_{M=1}^{I} N_M \log N_M \tag{4.15}$$

Combining with definition 4.10, equation 4.15 can be written for the most probable or steady state as

$$d \log P = - \sum_{M=1}^{I} (\log N_M + 1) dN_M = 0 \tag{4.16}$$

In order to secure the most probable state, equations 4.11, 4.13 and 4.16 have to be satisfied simultaneously. With the application of Lagrangian's method of undetermined multipliers, i.e., multiplying each equation with a parameter and summing them, the following equation can be obtained:

$$\sum_{M=1}^{I} (\log N_M + \alpha + \beta E_M) dN_M = 0 \tag{4.17}$$

where α and β are the so called Lagrangian multipliers. Using equation 4.11 once again the Maxwell-Boltzmann distribution principle is obtained

$$N_M = e^{-\alpha-\beta E_M} \tag{4.18}$$

which describes the most probable distribution of travellers according to their energy levels for a system in a macroscopic condition of a steady state. The Wilson model described in its basic form in equation 4.18, differs only in terms of units. In this model, the energy term (from equation 4.12 onwards) is exchanged for a (generalised) cost expenditure to work (Wilson 1967), (Wilson 1970).

The Case of Multiple Modes

If the system is composed of (non interacting) elements of different types, the same derivation is valid also for an ensemble of different types of agents. Equation 4.14 can be grouped according to the modal type and after the transformations can be expressed as:

$$\begin{aligned} \mathrm{d}\log P = &-\sum_{M=1}^{I}(\log N_M + 1)\mathrm{d}N_M \\ &-\sum_{K=1}^{I'}(\log N'_K + 1)\mathrm{d}N'_K - \sum_{L=1}^{I''}(\log N''_L + 1)\mathrm{d}N''_L - \ldots = 0 \end{aligned}$$

where N, N', N'', ... are the different types of agents.

$$\begin{aligned} \mathrm{d}N &= \sum_{M=1}^{I} \mathrm{d}N_M = 0 \\ \mathrm{d}N' &= \sum_{K=1}^{I'} \mathrm{d}N'_K = 0 \\ \mathrm{d}N'' &= \sum_{L=1}^{I''} \mathrm{d}N''_L = 0 \\ &\ldots \end{aligned} \tag{4.19}$$

The total energy is again constant and with the consideration of different energy levels gives

$$\mathrm{d}E_{tot} = \sum_{M=1}^{I} E_M \mathrm{d}N_M + \sum_{K=1}^{I'} E'_K \mathrm{d}N'_K + \sum_{L=1}^{I''} E''_L \mathrm{d}N''_L + \ldots = 0. \tag{4.20}$$

Applying once again the Lagrangian method, this results in

$$\sum_{M=1}^{I}(\log N_M + \alpha + \beta E_M)\mathrm{d}N_M + \sum_{K=1}^{I'}(\log N'_K + \alpha' + \beta E'_K)\mathrm{d}N'_K + \\ + \sum_{L=1}^{I''}(\log N''_L + \alpha'' + \beta E''_L)\mathrm{d}N''_L + \ldots = 0$$

where α, α', α'', ... and β are multipliers. The variations can now be treated independently and can be transformed into:

$$\begin{aligned} N_M &= e^{-\alpha-\beta E_M}, \\ N'_K &= e^{-\alpha'-\beta E'_K}, \\ N''_L &= e^{-\alpha''-\beta E''_L}, \\ &\ldots \end{aligned} \tag{4.21}$$

These are the distributions for different transport modes where α', α'', α''', ... and E', E'', E''', ... are mode specific and β is mode independent. The result is similar to the equation 4.18 which means that the different modes can be treated independently. Since the case of multiple modes is similar to that of the single mode, only the latter is subsequently considered.

4.3.4 The Energy Variable Revisited

The total energy of the system can be expressed in terms of energy categories as in equation 4.12 as well as in terms of the energy of a single agent ϵ_i. ϵ_{ij} stands for the energy between two single agents, described as the *system's* internal energy.

$$E_{tot} = \sum_{i=1}^{N_{tot}} \epsilon_i + \sum_{i,j=1}^{N_{tot}} \epsilon_{ij} \tag{4.22}$$

Three reasons can be given why the second term can be ignored. Firstly, in physics, where the concept of aggregated states is assumed as defined in the section above. Although the effects are shown to be minor it could be possible to take 'collisions' into consideration whilst preserving the Maxwell-Boltzmann distribution. However, the problem becomes increasingly complex with the question of types of interaction, i.e., inelastic or elastic interactions or deflections (Lifshitz & Pitaevskii 1980).

Secondly, in traffic engineering, the equivalent to the concept of aggregate states would be a free flow in the flow-concentration relationship of the fundamental diagram (i.e., a level of service of A or B) and $\sum_{ij} \epsilon_{ij}$ would stand for the energy used for higher concentrations. However, a free flow can still be assumed since people do not bump into each other and the energy expenditure for prevention such collisions is relatively small in comparison to the total energy expenditure.

And thirdly, in terms of concept. The concept of aggregated states is an ideal one and collisions would mean a deviation from this ideal state. So collisions would have an influence on the velocity distribution, but depending on the type of interaction the shape of the distribution function would be similar.

As a result for this thesis, the concept of aggregated states of matter is assumed so the second term of equation 4.22 can be ignored and for further research this term might be taken into consideration.

The total energy of a single agent can then be expressed in the general co-ordinates as

$$\epsilon_i = \pi_i(q_1 \dots q_s) + \kappa_i(p_1 \dots p_s) + \iota_i \tag{4.23}$$

where π_i is its potential energy, κ_i its kinetic energy and ι_i its internal energy or, for reasons of clarity, heat source of the agent or intra-personal energy which is independent of general co-ordinates.

Substituting equation 4.23 into equation 4.12 leads to

$$E_{tot} = \sum_{M=1}^{I} (P_M(q_1 \dots q_s) + K_M(p_1 \dots p_s) + I_M)N_M \tag{4.24}$$

where P_M is the potential energy, K_M the kinetic energy and I_M the intra-personal energy attached to the energy level M.

According to the dependencies of the general co-ordinates, the different energies can be treated separately. For the potential energy the system surface can be regarded as the relative base and is assumed to be 'rigid' within itself. All the agents act within the partially closed system plane and the majority of agents are assumed to move on the surface area. Changes in altitude which would make the consideration of P_M necessary, are therefore assumed to have negligible effects on the overall energy of the system. In addition, the energy of an individual agent is independent of its position of the surface area. This means that the total potential energy of all agents is only a constant and thus, P_M in equation 4.24 can be ignored. (Note that this differs from *physical* gravity models which would be studied within this framework by including such a P-term.)

4.3.5 The Energy Distribution

Equation 4.18 describes a distribution function of N_M which depends only on the energy and therefore can be expressed as

$$N_M = N(E_M) \tag{4.25}$$

A change from discrete to continuous variables enables the change of the probability function over a volume of phase space to be written as

$$\mathrm{d}n = n(E)\mathrm{d}q_1 \ldots \mathrm{d}p_s = N_{tot}Ce^{-\beta E_M}\mathrm{d}q_1 \ldots \mathrm{d}q_s\mathrm{d}p_1 \ldots \mathrm{d}p_s \tag{4.26}$$

where $e^{-\alpha}$ is replaced by $N_{tot}C$ with C as a constant and $\mathrm{d}q_1 \ldots \mathrm{d}q_s\mathrm{d}p_1 \ldots \mathrm{d}p_s$ are the extensions of the phase space to s-dimensions. s refers to the number of degrees of freedom present in the system. Substituting the kinetic energy in the equation 4.26 and using the generalised form, where $\dot{\mathbf{x}}$ is an s-dimensional vector with $\dot{\mathbf{x}}^2 = \dot{x}_1^2 + \dot{x}_2^2 + \ldots + \dot{x}_s^2$ and $\mathrm{d}\dot{\mathbf{x}} = \mathrm{d}\dot{x}_1\mathrm{d}\dot{x}_2 \ldots \mathrm{d}\dot{x}_s$ the following expression is obtained.

$$\mathrm{d}n = N_{tot}Ce^{-\beta\frac{1}{2}m\dot{\mathbf{x}}^2}\mathrm{d}\dot{\mathbf{x}} \tag{4.27}$$

C can then be expressed as

$$C = \frac{1}{\int\limits_{-\infty}^{+\infty} e^{-\beta\frac{1}{2}m\dot{\mathbf{x}}^2}\mathrm{d}\dot{\mathbf{x}}} = \left(\frac{m\beta}{2\pi}\right)^{\frac{s}{2}}$$

Substituting C into equation 4.27 the Maxwell-Boltzmann distribution can be written as

$$\mathrm{d}n = N_{tot}\left(\frac{m\beta}{2\pi}\right)^{\frac{s}{2}} e^{-\beta\frac{1}{2}m\dot{\mathbf{x}}^2}\mathrm{d}\dot{\mathbf{x}} \tag{4.28}$$

As described above, the generalised co-ordinates do not represent the 'true' units of travel, and equation 4.28 has to be transformed into an expression of energy.

The intermediate step consists of a transformation from orthogonal co-ordinates into polar co-ordinates (Landau et al. 1967, p.163/4). Considering the independence of direction, the transformation is performed by integrating the directional information as the surface area of an $(s-1)$-dimensional sphere. The differential in equation 4.28 is replaced by

$$\begin{aligned} \mathrm{d}\dot{\mathbf{x}} &= \mathrm{d}(Area_{(s-1)})\mathrm{d}v \\ &= \mathrm{d}\left(2\frac{\pi^{\frac{s}{2}}v^{s-1}}{\Gamma(\frac{s}{2})}\right)\mathrm{d}v \end{aligned}$$

where v is the length of the radius vector (Sommerville 1929) and, with the integration of the $(s-1)$-area, equation 4.28 becomes

$$\frac{\mathrm{d}N}{N_{tot}} = 2^{1-\frac{s}{2}}\frac{(m\beta)^{\frac{s}{2}}}{\Gamma(\frac{s}{2})}e^{-\beta\frac{1}{2}mv^2}v^{s-1}\mathrm{d}v. \tag{4.29}$$

From the kinetic energy $v^2 = 2K/m$, we obtain $\mathrm{d}v = \frac{\mathrm{d}K}{mv} = \sqrt{\frac{1}{2mK}}\mathrm{d}K$, so that equation 4.29 can be re-expressed as

$$\frac{\mathrm{d}N}{N_{tot}} = \frac{\beta^{\frac{s}{2}}}{\Gamma(\frac{s}{2})}e^{-\beta K}K^{\frac{s}{2}-1}\mathrm{d}K \tag{4.30}$$

Equation 4.30 describes the distribution function only in terms of energy. It can now be used to derive a distribution function of travelling for a comparison with human energy expenditure.

4.3.6 The Maxwell-Boltzmann Distribution of Travelling

As described in Section 3.3.1 the energy turnover of an activity depends only on time, although individual performances are influenced by factors such as work, age, gender, etc. But in Section 3.3.1, no energy function with such factors was given. Here, an attempt is made to construct a model by specifying a 'power' function which varies with the amount of time spent performing an activity. As a first approximation, a power function is chosen of the simplest form

$$P = a \times t^{c-1} \tag{4.31}$$

where a and c are parameters determining the behaviour for the overall performance or for a given mode of transport. Recalling equation 4.1 or 4.5, the bio-physical energy I_M can thus be written as

$$I_M = a \times t^c \tag{4.32}$$

The incorporation of such an energy function into the model, with appropriate choice of parameters, should yield a probability distribution of travel times. This energy can be defined in different ways, such as bio-physical energy or the heat from the human body or effort.

According to conservation of energy, i.e., equation 4.3, the increase in kinetic energy must then be equal to the decrease in effort, i.e., equation 4.4. Substituting equation 4.32 into equation 4.30 with $\mathrm{d}I_M = act^{c-1}\mathrm{d}t$,

$$\frac{\mathrm{d}N}{N_{tot}} = \frac{\beta^{\frac{s}{2}}}{\Gamma(\frac{s}{2})} ca^{\frac{s}{2}} e^{-\beta a t^c} t^{(\frac{sc}{2}-1)} \mathrm{d}t \tag{4.33}$$

The Maxwell-Boltzmann distribution of travelling is thus obtained which describes the most probable distribution of travellers in relation to their time expenditure for a partially closed transport system in a steady state.

Equation 4.33 depends only on the radius vector or time and is rotationally symmetrical. This is in accordance to real travel behaviour where the *amount of travel* depends only on duration and not on its direction and, therefore, describes a time-space, i.e., a generalised human-energy phase space. If equation 4.32 is an appropriate definition of effort, it should then be possible to fit equation 4.33 to the data to get numerical values for a and c which, in addition, can be seen as a qualitative test for the nature of the function.

4.3.7 Calibration and Application

The enormous difference in scale between a system of particles and a transport system should be recalled (Leung & Yan 1997). The verification of the travel distributions might therefore yield greater variations of parameters than such of particles. But as it can already be seen in relation to the values of Table 4.1, the variations should be within certain limits.

The number of degrees of freedom is related to the system as a whole. As assumed without considering the potential energy, most traffic activities take place on a two-dimensional surface area. In comparison to the two horizontal dimensions, the third dimension is relatively small in terms of travel. (This agrees with the assumption of the neglect of the potential energy.) Besides the NTS data do not provide any information in this respect. Hence, for this simple model s can be set to 2.

For the minimum numbers of calibration parameters and noting the relation between a and β in equation 4.33, it is convenient to define

$$b = \frac{1}{\beta a} \tag{4.34}$$

leading equation 4.33 to

$$\frac{\mathrm{d}N}{N_{tot}} = \frac{c}{b} e^{-\frac{t^c}{b}} t^{(c-1)} \mathrm{d}t \tag{4.35}$$

Equation 4.35 can also be indexed for different modes of transport, as equations 4.21, with the calibration parameters b and c obtained by curve fitting using the principle of minimising the least square error.

A first impression of possible values gives Figure 4.3 which are achieved when c takes the value of about 2. (In the title of Figure 4.3 'mse' refers to the 'mean square error'.)

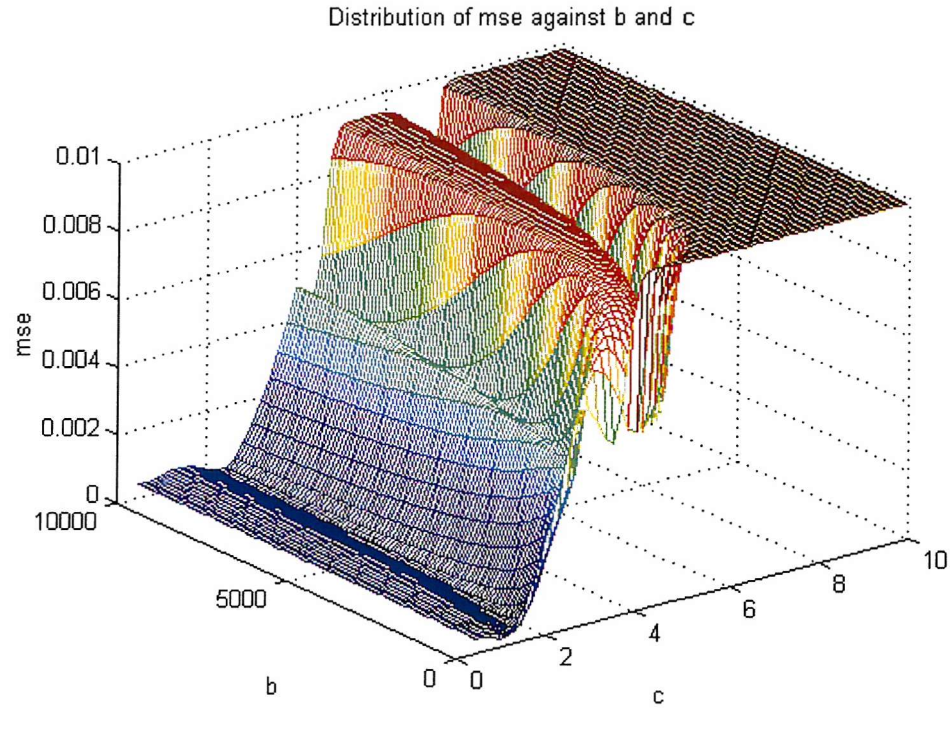


Figure 4.3: Calibration Parameters

The average parameters over all years for all modes and for the overall daily travelling are given in Table 4.3. For the Figures 4.4 to 4.9, walking, car-driver, car-passenger and bus were chosen from the seventh day data sets, whilst bicycle and rail were chosen from the data from first six days of observation, so as to combine the most realistic travel behaviour with best representation. (Further detailed tables and other figures are presented in Appendix C.)

For the recording of travel time in Section 3.1.4, a grouping of 10 is introduced for the figures. Figure 4.9 appears to be a just tolerable example in terms of variability

Mode	c	b	mse	c	b	mse
	Day 1-6			Day 7		
Daily Trip Parameters						
overall	1.54	697	0.00%	1.42	449	0.01%
walk	2.07	8795	0.05%	1.42	228	0.05%
bike	1.55	435	0.06%	1.50	529	0.12%
car-dr	1.57	744	0.01%	1.48	595	0.01%
car-p	1.44	257	0.01%	1.31	226	0.02%
bus	1.85	2922	0.02%	1.75	2814	0.04%
rail	1.75	15779	0.01%	1.48	8303	0.02%
Single Trip Parameters						
overall	1.53	93	0.02%	1.48	64	0.04%
walk	2.60	6643	0.15%	1.56	56	0.20%
bike	1.63	95	0.20%	1.78	195	0.35%
car-dr	1.59	81	0.03%	1.58	84	0.06%
car-p	1.58	80	0.05%	1.53	77	0.09%
bus	1.98	851	0.08%	1.88	1042	0.13%
rail	1.84	7126	0.02%	1.55	4801	0.04%
c,b ... Parameters, mse ... Mean Square Error						

Table 4.3: Average Parameters c and b over all years (1972 - 95)

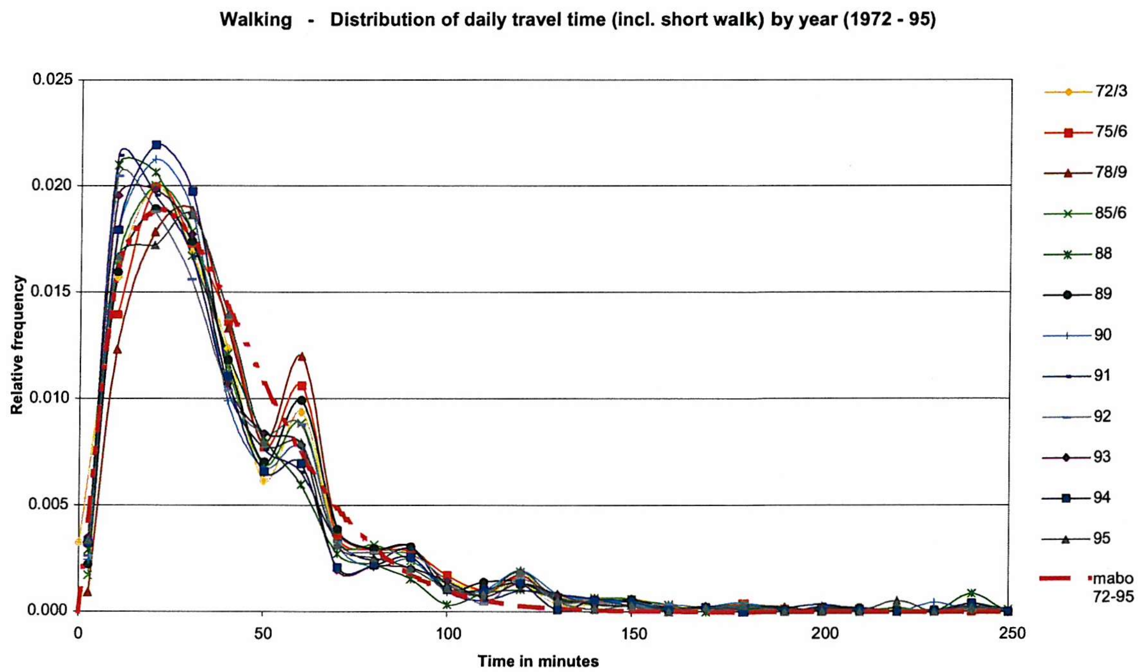


Figure 4.4: Maxwell-Boltzmann Distribution of Walking

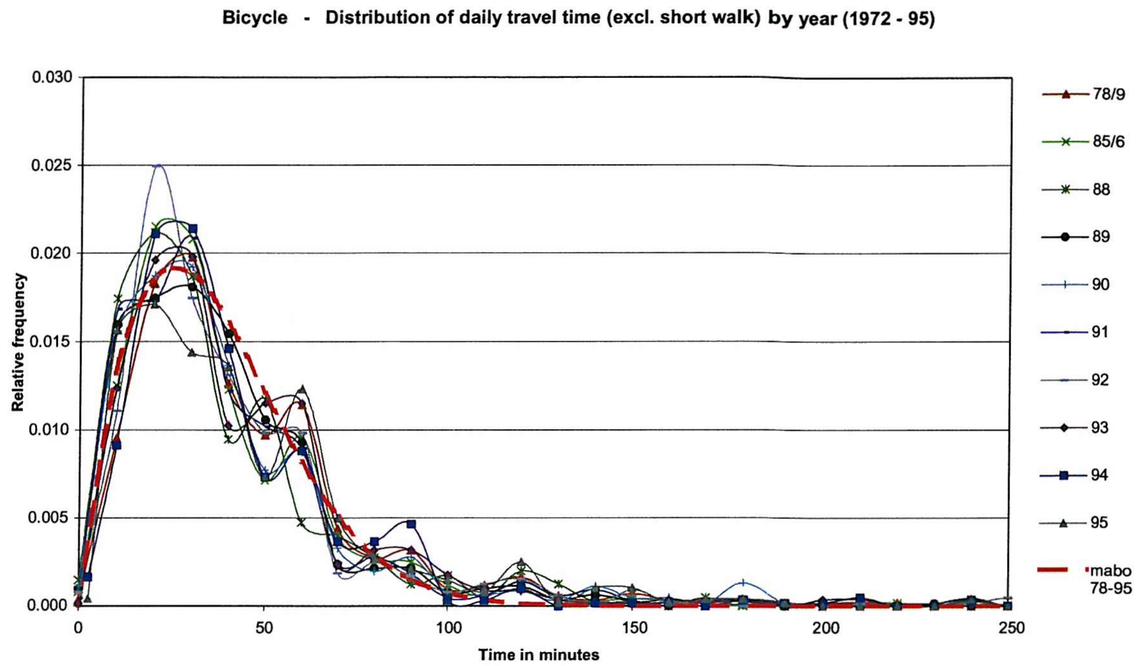


Figure 4.5: Maxwell-Boltzmann Distribution of Bicycle

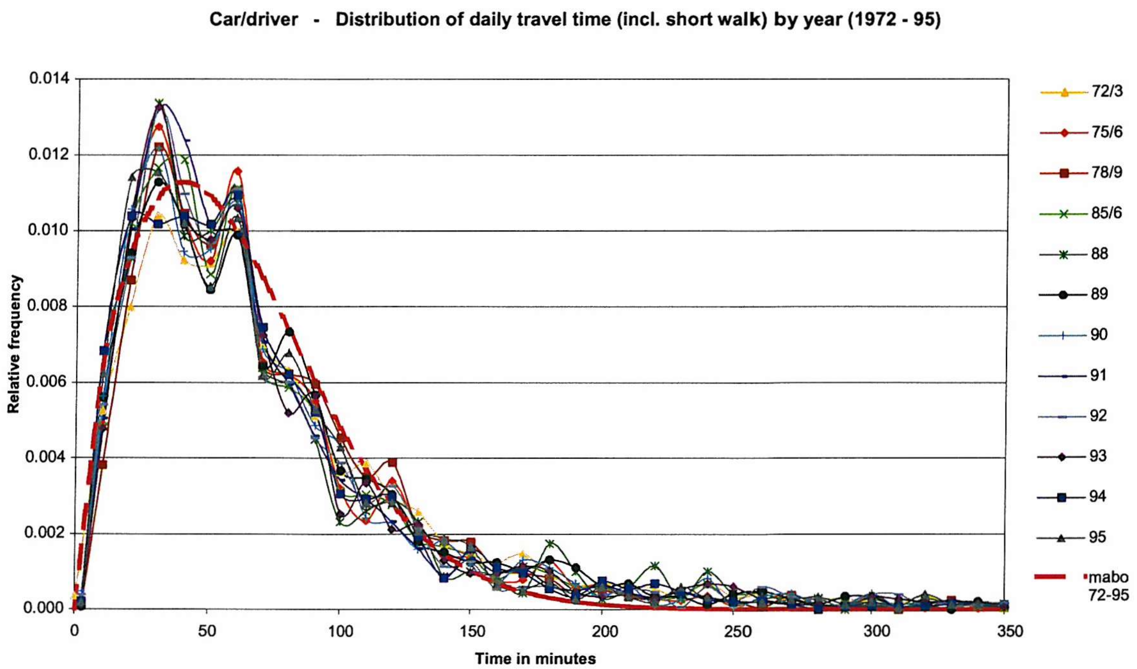


Figure 4.6: Maxwell-Boltzmann Distribution of Car/Driver

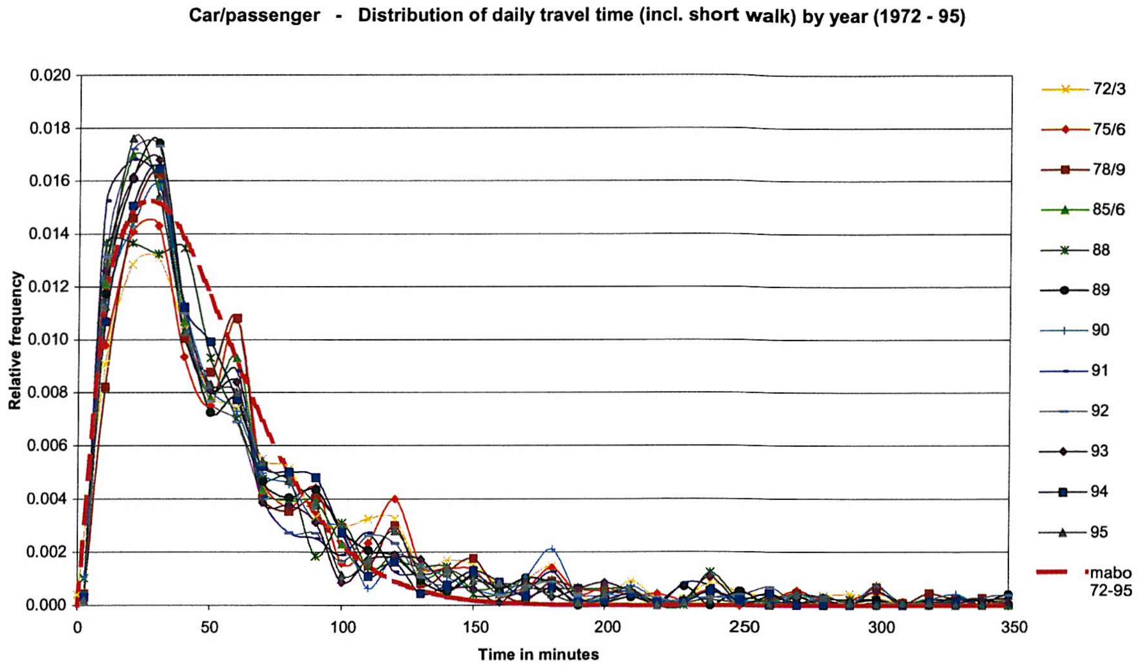


Figure 4.7: Maxwell-Boltzmann Distribution of Car/Passenger

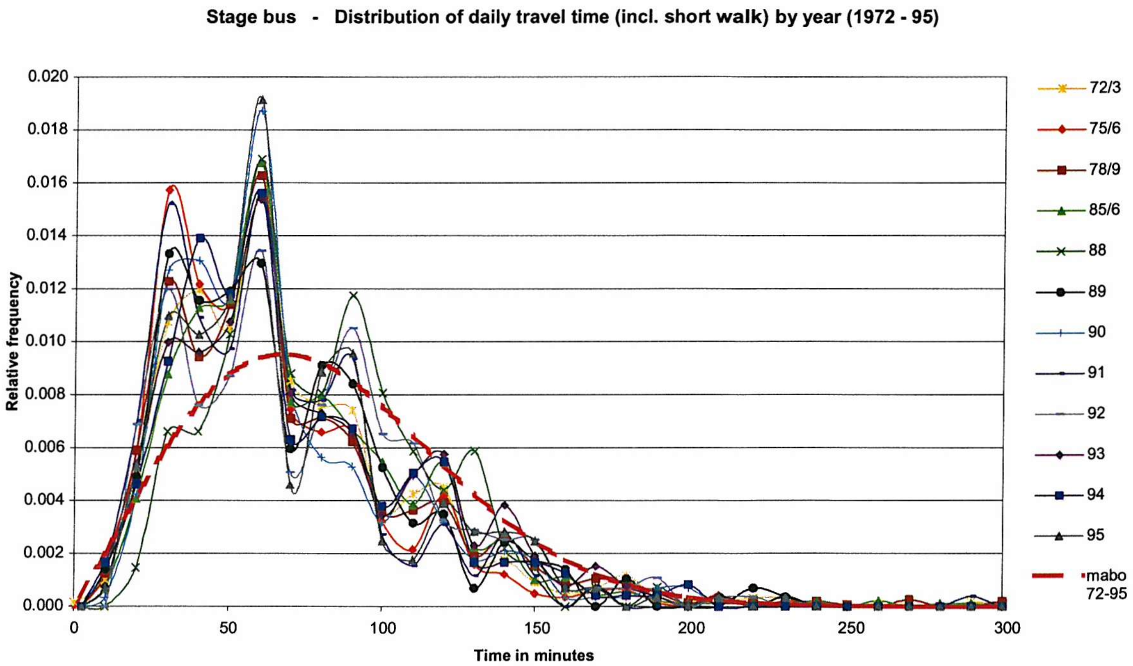


Figure 4.8: Maxwell-Boltzmann Distribution of Stage Bus

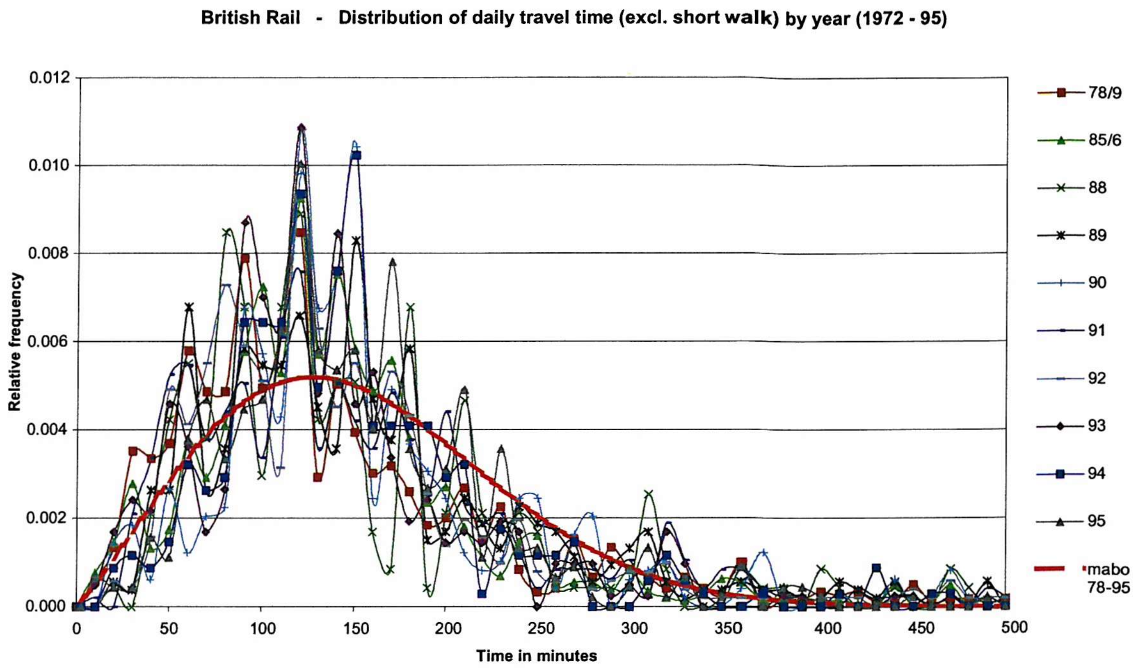


Figure 4.9: Maxwell-Boltzmann Distribution of Railway

which could be removed with bigger grouping intervals. The theoretical curves are composed of average parameters for all years. Table 4.3 shows non-grouped parameters. The visual closeness of the different distributions by year, supports the assumption of the system being in a steady state which could be found with the hypothesis of a constant modal TTB in Section 4.2.3. The different distribution functions show the emerging macroscopic behaviour where individuals fluctuate within the stability of the distributions.

The list of the parameters in Table 4.3 begins with the overall values of the different years and also divided into different modes. It contains the average values over each class and is complementary to the tables in Appendix C. The values show a consistent difference between the two recording methods. The influence can be observed in walking where the values of days 1-6 resemble more railway than any other mode. Similarly, the influence of the low numbers of observations cannot be detected so obviously by inspection, but it is apparent in terms of values with a high level of fluctuation within each group. The comparison of the parameters over years show that c is fairly stable whereas b varies to a greater extent which, most of all, may be a consequence of the lack of precision of the data sets. The overall values and the values of cars give an indication for the required size of data sets which is in accordance with 'large sampling'.

The numerical variation of the parameters shows the functional sensitivity. The large variations of the value of b, especially for rail, can be related to the counter-balancing between b and c in equation 4.35. An increase of around one tenth in c in the power position leads to an increase of one digit of b in the base position. If c could be equal for all modes, due to the strong stabilising position, the only varying parameter is b which would represent the proportions of the ergonomic power values. It should be noted that b appears always in the denominator so the inverse value represents the equivalent power value. Another reason, as mentioned earlier, lies in the lack of precision of the data sets, i.e., 'large sampling'.

An empirical interpretation for these variations may reflect a lower sensitivity of humans than the sensitivity of the function. This may be the case with low-energy-intensive means of transport, e.g. car transport, where an additional unit of time travelled makes little difference. On the other hand, the variation of the parameters can be reduced by decreasing the accuracy of fit. In that respect the values of c for daily and single travelling could be equal which would aid the understanding of the value of b. However, this would also involve a bio-physiological interpretation of a and c which was beyond the work described in this thesis.

The theoretical curve does not have smaller peaks on the right like the empirical distribution. Several reasons may be considered. The first one can be due to the nature of the trip rate which, in reality, may be discrete and not continuous. The travel time of single trips should then balance the discontinuity of the trip rate. However, there seems to be an intrinsic threshold value for trip making so that the product of trip rate and single travel time cannot fully smooth these peaks. Grouping can be another reason. Since these different peaks occur at approximately regular intervals the empirical curve might be comprised of several curves which, in turn, would reflect different threshold values. Another reason may lie in the partition of the area. In that respect the theoretical curve shows the distribution for smoothly distributed locations and in reality there are land-use settlement patterns. But the relationship between time and distance will be studied in Section 5.1 which will offer some clarification.

The power function in Figure 4.10 (and the energy function in Figure C.1) can provide additional scope for interpretation since they exhibit the dynamic dimension of the ergonomic values presented in Section 3.3.3. The graphs of the different power function show that two curves, walking at the top and rail at the bottom, are substantially different to those of the other mode of transport. The overall curve seems to be dominated by car-driver since these two curves run nearly parallel. Although walking and cycling seem to be quite close according to the numerical values for the average travel times and ergonomics, in terms of the power function, walking is graphically a much more demanding mode of travel than biking. Comparing the numerical values b and c with the figures, the difference in b between walking and car-passenger with an average of 3 is statistically insignificant. Thus, the difference comes basically with c, i.e., 0.11; the closeness can be found at low travel time levels but as time progresses the curves start to diverge greatly. A possible interpretation might be that car-passengers also have to walk at the onset of a trip but can relax after getting in the car. The 'odd one out' of this middle region is the bus, not only in value but also in its shape of the curve. The curve starts fairly low and then increases more than any other which might be an indication that riding a bus is not as comfortable as going by car or by train. The only comparable mode would be bicycle which runs fairly parallel to bus but starts off in the same region as car-driver. For long trips, the modal differences becomes visually more apparent with the energy functions in Figure C.1. Here, the potential growth shows the increasing demand in effort which can be found in the diminishing frequencies of the travel time distribution.

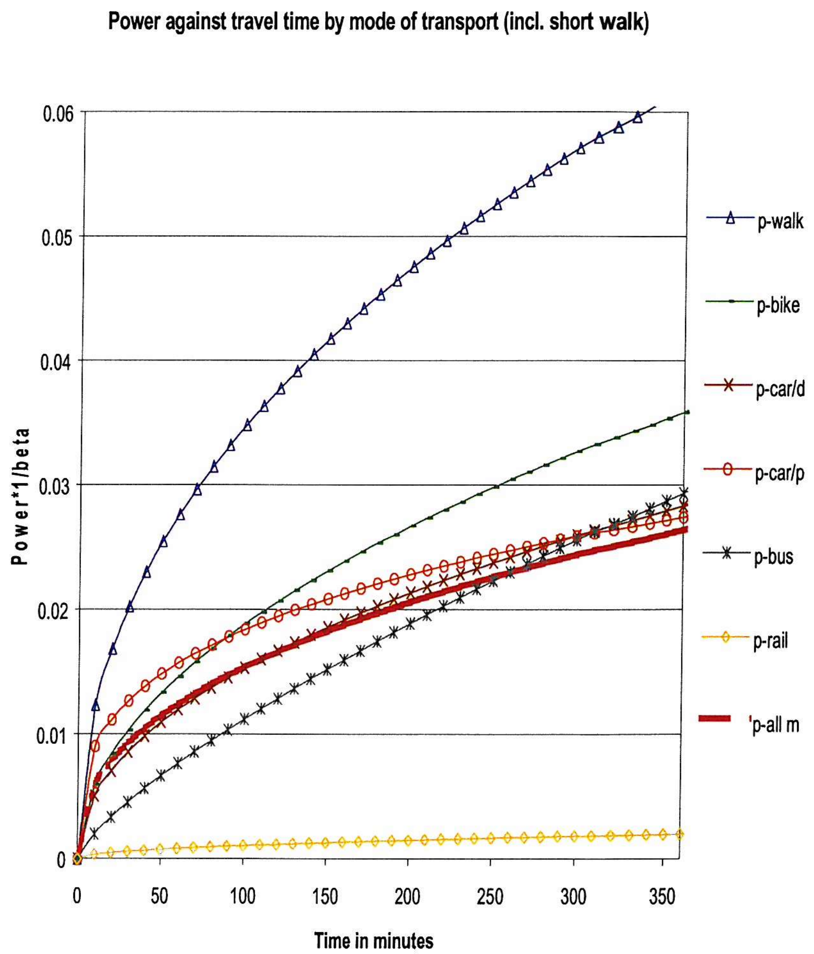


Figure 4.10: Distribution of Power by Mode of Transport

To conclude, the results presented are only a first assessment but they fit fairly well the empirical distribution of the NTS data. The power and energy functions allow a comparable interpretation to the statistical results and so reflect travel behaviour in a realistic way since the value of c is greater than 1 and the rate of increase of energy increases at a faster than linear rate than the rate of increase in power. However, the factor not determined is the parameter β, as will be discussed in the next section.

4.3.8 The Mean Energy and More Open Questions

The first Lagrangian multiplier α was determined as the normalisation parameter. The second Lagrangian, β, has to be identical - by definition (Section 4.3.3) - not only for all modes of transport but also for the overall travel behaviour. This can be determined by calculating the average energy of an agent. The average energy $\langle\epsilon\rangle$ times the number of agents equals the total energy and can be expressed as

$$\langle\epsilon\rangle = \int E_M \frac{\mathrm{d}N}{N_{tot}} \tag{4.36}$$

and with the substitution of equation 4.32 and 4.33 it forms

$$\langle\epsilon\rangle = \int_0^\infty at^c \frac{\beta^{\frac{s}{2}}}{\Gamma(\frac{s}{2})} ca^{\frac{s}{2}} e^{-\beta at^c} t^{(\frac{sc}{2}-1)} \mathrm{d}t. \tag{4.37}$$

With the solution of the integral the result can be given as

$$\langle\epsilon\rangle = \frac{s}{2\beta}. \tag{4.38}$$

Thus, the average turnover of daily energy is constant, i.e., a TEB, and independent of the mode of transport (since there is no modal dependent parameter involved).

The result is identical to that of statistical physics and could have been expected for two additional reasons. The first reason lies in the assumptions, i.e., the assumption of a total number of agents, equation 4.10, and the assumption of a total energy budget, equation 4.12, so the average amount of energy is bound to be constant despite the variable energy turnover of a single agent. The second reason is related to the integral of the power function with the Maxwell-Boltzmann distribution, equation 4.37, which results in a constant value depending only on β and s. It could therefore be argued that the *constant* energy budget is just a coincidence due to the mathematical nature of the integral and not to the nature of the matter.

This problem can only be resolved by establishing a 'real' human energy function with the appropriate body-related variables. Nevertheless, the approach can still be taken as a valid verification because of the following methodological consistency: (i) the assumptions are reasonable and are verified through the derivation, (ii) the derivation itself satisfies and is integrated with the basic principles of physics, and (iii) the probability distribution function fits the data to a high degree of accuracy not only from an internal-microscopic perspective (ergonomic values) but also from an external-macroscopic perspective, i.e., the NTS data.

In physics, β is defined in relation to the temperature ($\beta = 1/kT$) of the system as a whole, and the temperature is defined in relation to the mean energy ($kT = \frac{1}{s}\overline{mv^2}$) (Landau et al. 1967). Thus, the result of the mean energy refers to a thermal motion, which is how travel motion may also be interpreted. Similarly, the other thermodynamic quantities, such as entropy, the 'pressure' and the 'heat capacity', which also depend on β, have to be considered later as the Boltzmann constant k plays an additional role.

The numerical determination of β has to be left to further research since β always appears in combination with a, i.e., β as the invariant unit within the variant and comparative parameter b; on the other hand, this is also tied up with the relationship to c. According to the additive property of energy, the daily turnover of energy ϵ_d equals the trip rate n multiplied with the energy turnover for a single trip rate ϵ_s, such that $\epsilon_d = n \times \epsilon_s$. If c is a mode-specific constant of energy then it should be equal to the daily energy function as well as to the single trip function, so that the daily b incorporates the trip rate as well as a representative power value. Consecutively, b or a and c would then require a physiological interpretation, for example, in terms of body-mass index or destructive metabolic rate, but this would be medical research.

In short, equation 4.33 gives the probability distribution of N_{tot} travellers over a region of energy-time space. The effort I, expressed in time units, gives an indication of the human's travel expenditure and limits travel behaviour from both power and time used. The mean energy budget $\langle\epsilon\rangle$ can quantitatively be regarded as being on average the same for all travellers, independent of the mode of transport. This supports the hypothesis of constant TEB or modal TTB as well as giving qualitative support for the hypothesis of overall TTB. Since the travel time is *dependent* on the mode of transport in connection with the *independent* TEB, the overall values of travel time can be regarded as a general first estimate.

Chapter 5

Discussion

In this chapter some of the conventional concepts and models raised in the previous chapters will be compared with the bio-physical model. Firstly, the *time-distance relationship* will be discussed and the modal influence on distance will be investigated, a major point of this analysis. Then, the *travel time budgets* will be revisited to look at travel patterns from the trip rate point of view. This will provide some guidelines for the following discussion about models of trip generation and trip distribution which are compared with those of Chapter 2. Although this thesis focuses more on the methodology and theory of these models, some indications are given for a practical implementation. A reflection will made on the unit of reference and the economic or rational behaviour. The chapter will finish with an outlook on several points raised in this thesis to provide some insight in the potential consequences of the bio-physical model to related subject areas.

5.1 Time-Distance Relationship

5.1.1 Linear Versus Non-Linear

One of the main assertions in Section 4.2.2 is the distinction between time and distance due to different sources, i.e., time as a human system's input and distance as a modal system's output. The metric connection between time and distance can be given by

$$l = v \times t \tag{5.1}$$

implying a linear relationship between length l, speed v and time t, as used in the regression analysis of Zahavi's TTB approach, equation 2.16. To assess the human/mode of transport influence, a connection can also be made over the energy functions, i.e., the human energy function is dependent on time and the kinetic energy is dependent on speed. Equation 4.4 can so be expressed as

$$\frac{s}{2}mv^2 = a \times t^c \tag{5.2}$$

Because of the kinetic energy of the mass m, equation 5.2 is only valid for walking and cycling in a strictly physical sense. Attempting an extension for other modes of transport, the parameter a could be interpreted as a modal mass-related factor. So if a is replaced by $a_m \times m$ and with $s = 2$, equation 5.2 becomes

$$\left(\frac{l}{t}\right)^2 = a_m \times t^c$$

so l can be expressed as

$$l = a_m^{\frac{1}{2}} \times t^{\frac{c}{2}+1} \tag{5.3}$$

This indicates that the effect of distance increases at a greater than linear rate with time, depending on the mode of transport used. If this result is compared with equation 5.1 then $a_m^{\frac{1}{2}}$ would correspond to the average speed of the mode of transport.

An important point is that 'distance' is positionally dependent. Unlike daily travel time, where the time spent on each single trip can be summed, the daily travel distance cannot be summed in terms of positional extent since, assuming a home-based travel pattern, the same trip distance between an origin and a destination is covered twice in two different directions, i.e., on the outward trip and on the return trip. For the following analysis the *single* trip distance has therefore to be considered and not the daily travel distance.

In the NTS data base, distance is given in classes, grouped with the following boundaries in miles: 1, 2, 3, 5, 10, 15, 25, 35, 50, 100 and 200. This almost logarithmic classification makes it impossible to achieve the detailed results as with unbanded time data. To obtain absolute values, the group values are exchanged with the group means; this might effect the long-distance travelling since for the group over 200 miles a class mean is assumed to be 300 which then forms the upper limit. Furthermore, the values of this group are bound to the have a greater variation because 99% of all trips made are shorter than 100 miles (Figure D.1).

The graphs in Figure 5.1 and Figures D.3 - D.8 show that all modes have in principle the same form, i.e., they start off in relation to the potential function but then level off. The most important area lies within 100 miles or $2\frac{1}{2}$ hours. (Figure D.2 provides an estimate of the time-distance functions in this range.) Generally, it can be inferred that the minor influence can be assigned to the non-linearity of the function but the major influence can be assigned to the mode of transport. This result can also be compared with the socio-economic variable 'car-ownership'; the differences in mode of transport may suggest that a consideration of only levels of car-ownership, as in equation 2.16, may be too imprecise for a quantitative analysis in spite of the non-stringent but necessary alterations in equation 5.2.

If the average single travel distance $\langle l_s \rangle$ is compared with the average single travel times $\langle t_s \rangle$ which results in the average trip speed $\langle v_s \rangle$ then the following values can be obtained:

Mode of Transport	walk	bike	car-dr	car-pas	bus	rail
$\langle t_s \rangle$ in min	14	16	21	23	32	83
$\langle l_s \rangle$ in miles	0.7	2.2	9	10	5	38
$\langle l_s \rangle$ in km	1.1	3.5	14	17	8	61
$\langle v_s \rangle$ in km / h	4.8	13.3	40	44	15	44

If the bicycle is again chosen as the reference mode, then the bus doubles the average travel distance and the car multiplies it by four. The car-passenger increases by 5 times and the rail trip by around 17 times. From a pedestrian perspective, all the multiplicators would have to be multiplied by 3 again. Although such a comparison might appear as an exaggeration in the first instance, if the historical context is taken into account, then the growth in cities and other land-use patterns could be

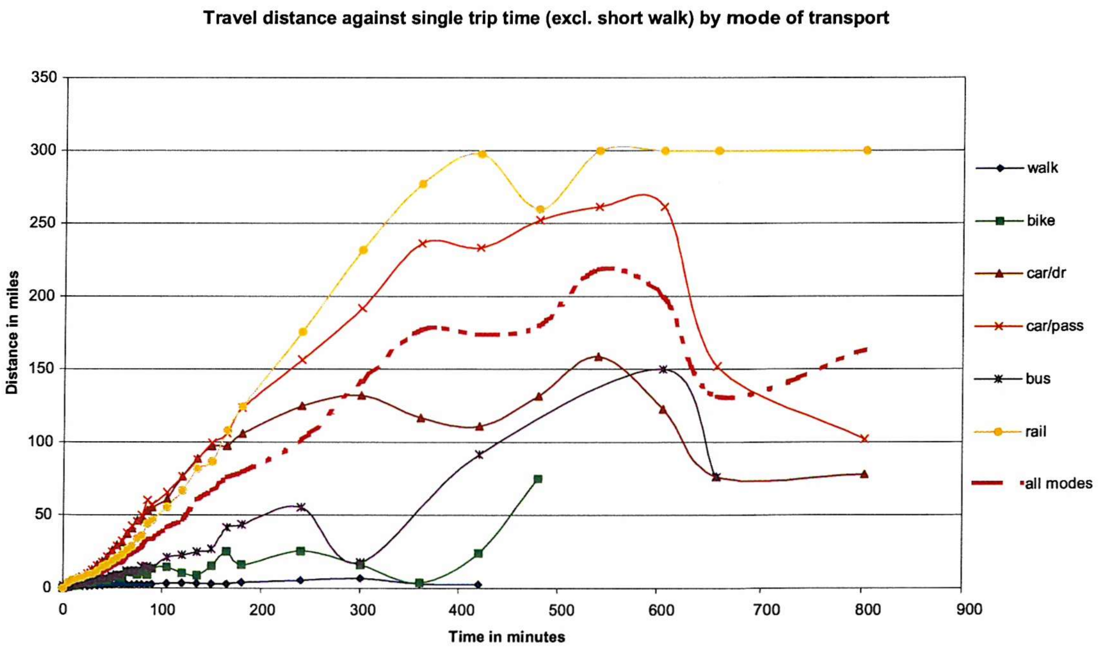


Figure 5.1: Single Travel Time Versus Travel Distance by Mode of Transport (DETR 1998b)

explored (independently of the number of inhabitants). An example is presented in Figure 5.5 of Section 5.4.

On the whole, the time-distance relationship may be regarded as a human evaluation function dependent on the mode of transport, where changes in time have a disproportionate effect in comparison to changes in distance. Thus, humans do not evaluate time-versus-distance in a metrical sense (Knoflacher 1987) but in a more non-linear sense depending on the mode of transport available. This flattening of the curves seen in Figure 5.1 may be interpreted as an approach to limit-values, i.e. a performance limit of travel effort. In addition, they indicate that the power function itself may be more complicated than a simple potential function. But this - as pointed out earlier - is outside the scope of this thesis.

5.1.2 Combining Time Versus Distance

Some remarks regarding the time-distance relationship have also been made in Section 4.3.7 where peaks along the distribution curves of the modes were interpreted - among others - not as a smoothly distributed area. Here, Figure 5.2 gives the distance-frequency distribution of the mode of transport and the overall case. The distance scaling is strictly logarithmic. (The detailed distance-frequencies by mode of transport over the years can be found in Appendix D which supports the stability of a modal travel pattern.) Walking and bicycle may represent a more 'intra-zonal' travel since their frequencies peak around one mile and their shape runs quite smoothly with only one peak. Bus and car compete on the middle range at around four miles whereas railway reaches its most frequent values between 12 and 20 miles. The curves of car and rail have two peaks which may display the 'inter-zonal' or 'inter-location' travel.

Figure 5.2 and Figures 4.4 to 4.9 are based on distance and time respectively. According to their dimension they are derived as a two-dimensional mapping from the combined three-dimensional distribution function. Figure 5.3 gives an example for the surface of the relative frequency in a time-distance space on an overall-mode level. (In principle this is correct but the actual difference is that Figures 4.4 - 4.9 are based on *daily* travel time whereas Figure 5.1 is based on *single* trip distance. Nevertheless, for the purpose of illustration of this concept this comparison will suffice.) In addition, Figure 5.1 represents the bird's eye view of Figure 5.3 and exhibits the traces of the most frequent values in relation to the mode of transport used, i.e., the third two-dimensional mapping but from the frequency dimension.

The peaks of Figure 5.3 may indicate different levels of thresholds, i.e., trade-offs between staying and investing no further effort on an additional journey, and moving on and achieving a higher level of satisfaction. An analysis in terms of

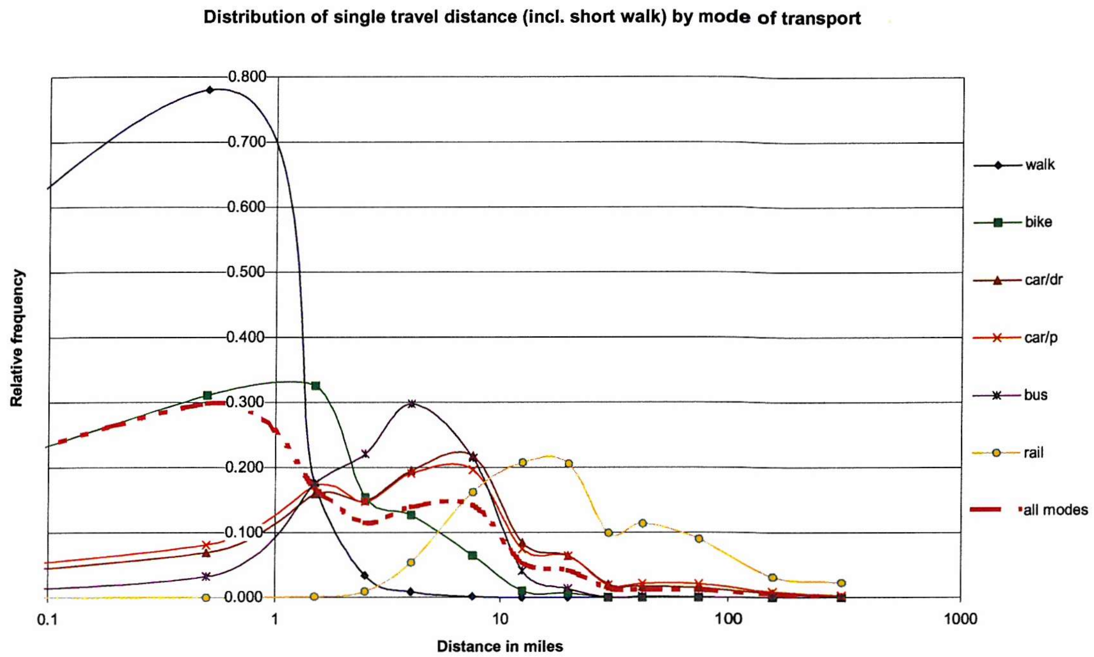


Figure 5.2: Distance Distribution by Mode of Transport (DETR 1998b)

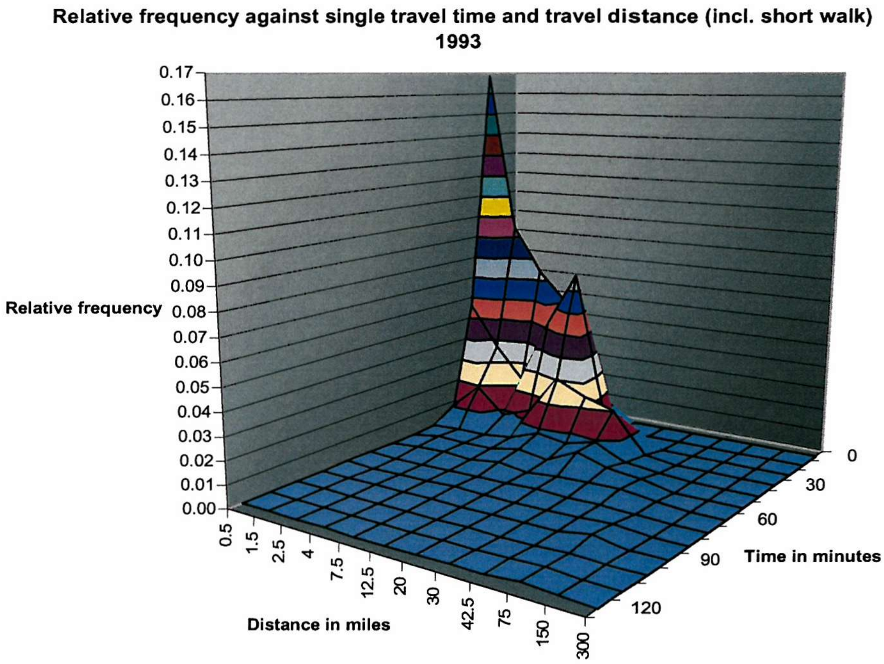


Figure 5.3: Frequency Distribution of Time-Distance Travel (DETR 1998b)

mode-independence would yield human effort values, i.e., a threshold value only in relation to the bio-physical energy. The values should then be tested in relation to settlement pattern so a simulation for their evolution may be obtained.

For a methodological understanding, this combination shows that time and distance are dependent or variable units and energy may be regarded as the independent or invariant unit. This can be exemplified in terms of human perception and understanding, since the notion of 'distance' is used as a measure not only in length or metres, but also in time or minutes (like in the concept of isochrones). 'Time' may constitute effectively the more tangible measure since it also coincides better with the daily rhythm, i.e., the energy turnover. This may also come across in the data accuracy since distance data is not as good in quality as time data because the length of a trip is more difficult to estimate than its time duration.

In this section a trip pattern has been assumed with outward and backward trips. The following section will tackle this problem regarding the trip rate in more detail.

5.2 Trip Rate Revisited

In this section an attempt is made to see how the number of trips correspond to the duration of single and daily trip time. This should give some insight into the pattern of trip making and also provide the empirical evidence for the subsequent attempt to construct a model of trip generation and trip distribution.

At first, the trip rate of daily travelling is examined where people use only one main mode of transport throughout the day. The trip rate can be separated into even and odd trip rates. Even trip rates may reflect travel behaviour as mentioned in Section 2.3.1 with home-based trips whereas odd trip rates may reflect more non-home-based trips or trip touring. As given in Table 5.1 a substantial difference between even and odd trip rates can be detected. On an overall level even trip rates account for 87% (whereas odd trip rates amount for only 13%). The even:odd ratio also varies relatively to the mode of transport. Walking, bicycle and bus share a similar measure with around 92:8, railway changes to 86:14, whereas the ratio for car is around 79:21.

As a special case the most frequent trip rate is 2. Around 85% of all railway and bus travelling is made within this rank; bicycle still accounts for 71% and for walking the trip rate 2 falls to 66%. For car-passenger trip rate 2 is still high with 60% whereas for car-driver the value drops to 42%. Comparing these values with Table 4.2 then, in general, the trip rate average lies approximately in this sector and only car-driver has an overall average trip rate over 3. From here it can be inferred that car-drivers adopt a different travel pattern in comparison to other mode users.

Trip Rate	Walk	Bike	Car-dr	Car-p	Bus	Rail
1	0.22%	0.03%	0.88%	1.44%	0.26%	0.17%
2	19.45%	1.43%	13.37%	12.81%	6.67%	1.03%
3	1.45%	0.08%	2.56%	2.03%	0.28%	0.01%
4	5.67%	0.35%	7.47%	3.20%	0.50%	0.01%
5	0.68%	0.03%	2.02%	0.79%	0.02%	0.00%
6	1.33%	0.07%	2.80%	0.68%	0.02%	0.00%
7	0.21%	0.01%	0.95%	0.18%	0.00%	0.00%
8	0.33%	0.01%	0.93%	0.15%	0.00%	0.00%
9	0.08%	0.00%	0.32%	0.04%	0.00%	0.00%
≥10	0.09%	0.00%	0.39%	0.02%	0.00%	0.00%
Sums	29.53%	2.02%	31.67%	21.35%	7.74%	1.21%
Total Ratio						
odd	2.65%	0.15%	6.83%	4.49%	0.56%	0.17%
even	26.88%	1.87%	24.84%	16.85%	7.18%	1.04%
Internal Ratio						
odd	8.98%	7.36%	21.58%	21.05%	7.18%	14.20%
even	91.02%	92.64%	78.42%	78.95%	92.82%	85.80%

Table 5.1: Number of Trips per Person per Day by Mode of Transport (DETR 1998b)

A more general interpretation would be a distinction between 'generated' trips and 'induced' trips. If it is assumed that each travel pattern satisfies the daily needs then the *difference* in trip rate between, for example, bicycle and car-driver can be defined as induced trips. Thus, 'trip generation' can be used for the absolute or primary trip pattern and 'trip induction' for the relative difference between the primary trip pattern.

An interpretation of the even:odd ratio could be that an even trip rate pattern is a more stable form of travel behaviour than odd ones. This becomes more apparent when the duration of travel is taken into account. To a great extent, days with even trip rates have less travel time than those with the smaller odd trip rate (see Figure 5.4 and E.1 - E.6). For example, the daily travel time of car-driver at a trip rate 3 is around 96 min and at trip rate 4 it takes only 76 min, i.e., although one trip less is made, the time spent is still higher. The value for car-driver indicates that even and odd daily travel times seem to lie respectively on two separate trajectories which converge at trip rate 10. The exception of this pattern is the bus where the single travel time decreases steadily and, through multiplication by the numbers of trips, the daily travel time increases up to 5 and then decreases again.

A closer look at the figures of Appendix E reveals a clear influence in terms of observational range, and therefore the quality of graphs. Travel times of even numbers lie closer together than those of odd numbers. This effect, seen in the daily

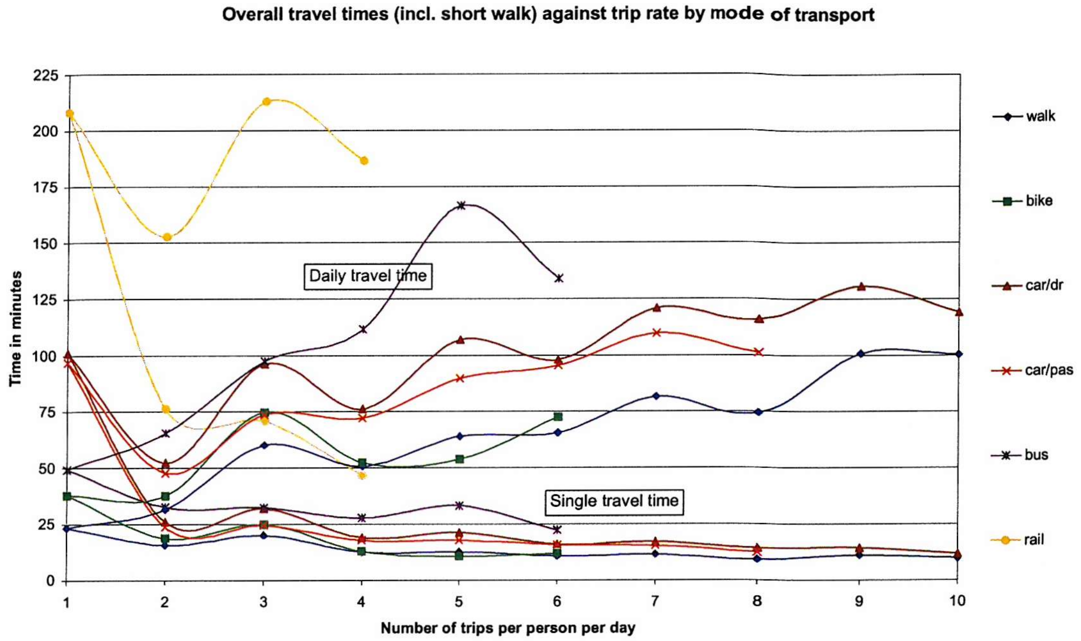


Figure 5.4: Different Modes of Transport -Travel Times Versus Trip Rate (DETR 1998b)

travel times, gets amplified through the multiplication with the number of trips. If the trip rate increases then this qualitative difference fades away. To obtain the most representative diagrams walking is composed from the seventh day data and the rest consists of data of the first six days include the time data from 1972 - 76 of the seventh day. (In terms of data division, these graphs show the next level since the overall modal averages have been split up in trip rate classes.)

From Figure 5.4 it can be deduced that a travel pattern based on an even trip rate has - according to the smaller time values - a lower threshold of trip making than that with odd trip rates. This even pattern of trip making seems to support this fact and therefore it appears to be a more stable one. The figures show that the modal travel pattern does not change over the years, i.e., a modal time-invariant behaviour, thus a stable travel pattern also from this angle.

In respect to the even:odd trip rate distinction, the modes except car-drivers seem to be more sensitive, i.e., more reluctant towards 'the odd trip', in comparison to car-drivers who are inclined to make more 'odd' journeys. Taking the ergonomic values of car-roads with 4.2 kJ / min as a comparative measure for the prospects of the trip effort, the car-driver value is three or four times lower than that of walking or biking. In that respect, the car-driver has a much lower threshold to overcome than the other modal agents and this would correspond to the higher odd-ratio value given above. Similarly, non-car-drivers may be considered to be more inhibited and more careful trip planning is needed. This shows that their scope for actual trip making is generally restricted to low trip rates with low travel times and this may be understood as an optimisation of an energy budget.

As already mentioned, a more complete explanation would involve the trip purpose linked up with origin-and-destination classification or home-based versus non-home-based trips, but this is then linked up with trip assignment or land-use planning. Nevertheless, some indications can be given for a bio-physical model to trip generation and trip distribution.

5.3 Another Trip Model

In this section the conventional trip models and other modelling approaches which were discussed in Chapter 2 are considered. Then, an attempt will be made to integrate the bio-physical approach into trip generation and trip distribution.

5.3.1 A Comparison of Modelling Preliminaries

In Section 2.2 the basic requirements for transport modelling are generally considered to be the unit of reference, the trip variables and the trip definition.

Unit of Reference and Trip Variables

A first result of Section 3.2 is that for the unit of reference a change from 'household' to 'individual' is essential otherwise the variations of the household size have to be considered. This influence with their functional form could be shown in Section 3.2.4. The other socio-economic variables are household structure, household income and car-ownership since they also coincide methodologically with the concept of cost. An individual traveller as a basic unit of reference cannot easily be assumed since the division of these variables into each household member is difficult to perform. Other variables, such as structural variables may also be encountered, especially in the ABA but they have not been examined.

With the individual as the unit of reference it is possible to introduce the energy variable as a variable of cause because, according to ergonomics, the daily life cycle and so all the other activities depend on it. This aspect could also be integrated in the following trip definition.

Trip Definition

Assuming that a definition should describe the basic units of an approach with its essential elements it was shown in Section 2.2.2 that there are some inconsistencies with the traditional trip definitions. One of them is a cost related feature which is not mentioned in the definition although an economic framework is presupposed.

Another one is that the main emphasis is usually on the means of transport, especially on vehicular mode, and less on the traveller. This leads to the problem where the traveller and the means of transport are envisaged as one unit and not as two separate units. Another concern is mentioned in regard to restrictions for specific measures such as the 300 metre (Ortúzar & Willumsen 1994) which could again be encountered in the NTS data sets where walks less than 1 mile are excluded from the first six days of recording or walks less than 50 yards are generally excluded. Such restraints impose an additional difficulty, for instance, for an objective comparison between different modes of transport. The (distance) data shown in Figure 5.2 may provide some additional evidence.

The trip definition given in Section 4.2.1 could be derived from a systems-theoretical framework. It makes a clear distinction between the traveller as the primary subject and the mode of transport as the secondary means. This separation also enables an application to several forms of trips so, for instance, walking can equivalently be described in terms of public transport trips or vehicular trips. In addition, the definition provides the context which elements still have to be considered if only a selection of them are used in a particular model, and it therefore exposes the predictive limitations of such models.

5.3.2 A Comparison of Transport Models

Travel Budget Approaches

The TTB models of Section 2.3.4 attempt to explain specific features of travel behaviour which appear to be independent of transport system, society or culture, e.g. the around-one-hour-travelling per person per day. Two branches can be identified, the economic one and the evolutionary one. The economic branch explains the constancy through generalised costs, which are again based on socio-economic variables and so retain their problems in explanatory value. In terms of the evolutionary branch, two approaches state physiological factors, in particular the human energy as variables in trip making (Goodwin 1976), (Knoflacher 1987). However, both remain descriptive because in terms of measures one uses an arbitrary points system and the other one takes the relative quantity of sensation but both types may not be objectively verifiable.

On the other hand, the bio-physical model is based on ergonomics where the main determinant for different activities is the energy turnover which can be objectively measured. Although there is some evidence that the general daily travel times remain fairly stable, statistically speaking this hypothesis could not be supported. If the modal influence is taken into consideration then those travel times become also statistically significant. This suggests that there is no constant travel time budget but a constant TEB. The theoretical approach is based on statistical physics where the hypothesis is further substantiated since the consistencies with the established principles of physics are taken into account. But further research is still necessary to fully confirm this approach.

Another inference can be drawn for transport modelling. According to probability calculus and equation 3.3, trip rate and travel time are independent. This means that the number of trips and travel times can be treated in a separate way, as it is common practise with trip generation and trip distribution respectively. But if a 'generalised travel budget' is taken into consideration then the problem can only be approached by a combination of both since the notion of 'budget' is intrinsically confined to an upper limit and so the product of both - the number of trips and trip time - constitutes the restrictive factor. But this consideration will be analysed further in the sections below.

Activity Based Approaches

The ABA discussed in Section 2.3.3 is based on a variety of variables. In general, a definite answer to actual travel behaviour may be difficult to achieve because of the extensiveness of variables simultaneously combined in several submodels, despite increasing computing power. The claim of replacing conventional trip modelling could not been verified.

Physical capacity constraints in terms of time-space are discussed in geographic models but the stringencies seem to equalise with the complexity of the prism concept or of AMOS. Some properties of economic behaviour, e.g. satisficing, could be found again in these approaches. In the economic model of Goodwin, the notion of equilibrium is defined in a similar way as the steady state of the bio-physical model. Statistically, the equilibrium or steady state could be found in the modal TTB over the years and, analytically with the interpretation of the mean travel energy expenditure, i.e., TEB. The dynamic calculation may be viewed as an additional extension whereas the bio-physical model and the statistical analysis is assessed at discrete periods of time.

In practical terms, the modal influence could be shown with their trip rates and travel times. This means that the modal choice is the decision making of travelling which is made before the onset of the trip. Sequentially, modal choice models should then come before trip generation models as pointed out by some ABAs. This consequence is also important for conventional models of trip generation, as discussed in the next section.

Trip Generation

As described in Section 2.3.1 the modelling of trip generation, i.e., the determination of number of trips in an area, is based on the socio-economic variables mainly related to vehicular traffic. The growth-factor analysis simply relates past and future traffic events without giving further insight into trip generation. The regression analysis attempts to measure correlation between the trip variables and number of trips per area but, independent of the goodness of fit, a causation of trip making cannot be established by this method despite the termination of the independent variables as explanatory (Kendall & Stuart 1973). The cross-classification or category analysis is based on the category values which represent average numbers of trips in relation to certain socio-demographic person groups. The model is only supported by the 'art' of choosing the categories, which is subjective to the investigator, and by the goodness of fit with the actual data, i.e., a subjective model in relation to the available data, and remains therefore phenomenological.

For the bio-physical model of trip generation the problem of modal choice has to be taken into account which has already been mentioned in relation to ABA. At the onset of a trip the availability of mode of transport influences the decision making of 'relative trip making', i.e., the relative difference in the modal trip rates (Table 4.2). For the purpose of calculation this means that a modal variation should be considered. A connection to the TTB approaches can be achieved if a 24-hour travel pattern in the model is assumed.

For the bio-physical model the numbers of trips have two main dependencies: firstly, the number of inhabitants, and secondly, the modes of transport used or the 'modal mix'. For a first estimate the total number of trips T of an area with z zones or cells can be given by

$$T = \sum_{i=1}^{z} T_i \qquad \text{with} \tag{5.4}$$

$$T_i = \sum_{m=1}^{k} N_{im} \times \langle n \rangle_m + \sum_{m_{1,2}=1}^{k'} N_{im_{1,2}} \times \langle n \rangle_{m_{1,2}} + \ldots + \sum_{m_{1,..,l}=1}^{k''} N_{im_{1,\ldots,l}} \times \langle n \rangle_{m_{1,\ldots,l}}$$

where N_{im} represents the number of inhabitants in zone i using the mode m throughout the day, and $\langle n \rangle_m$ is the average trip rate. The second and the last term represent the two or more mode of transport used per day. If these terms are not available then an estimate can be given with factors of adjustment, i.e., the percentages of modes in question p_{im} and the percentage $p_{i1m/d}$, where only one mode is used. So,

$$T = \sum_{i=1}^{z} \left(\frac{1}{p_{im} \times p_{i1m/d}} \sum_{m=1}^{k} N_{im} \times \langle n \rangle_m \right)$$

The layout of the model is similar to a cross-classification or category analysis, but here, no choice of categories is necessary since travel behaviour is dependent only on the number of individuals and the average trip rates are pre-determined as values from the TEB approach. The distinction in original and destination travel, O_i and D_i, can already be regarded as a question of trip distribution since the number of trips going from O_i to D_i is already dependent on the time-distance between these zones.

Trip Distribution

With regard to Section 2.3.2, there are two dominating branches of modelling trip distribution, the Gravity Model and the Opportunity Model. The Gravity Model is adopted from physics where the gravity function is replaced by a deterrence function. For example, the Wilson Model, uses the same method as statistical mechanics but replaces the energy term with a generalised cost term so the equilibrium condition results in a total expenditure of travel costs of a region. Although causal in the physical layout, the model becomes again descriptive since no direct connection to travel behaviour can be established. The Opportunity Model is based only on empirical observations, so the resulting isochrones constitute a practical estimate without further explanation of trip distribution. Before the bio-physical model of trip distribution can be developed a clarification is needed in relation to the trip matrix.

The trip matrix describes trips according to their origin and destination, i.e., their positions in the area. However, in the bio-physical model the zonal positions of the inhabitants and their positions are not required. But this has already been considered in the trip generation model by the marginal sums of the trip matrix. This means that the distribution model should divide daily trip making into single trips in relation to the cell positions and determine the number of trips between different cells. Practically speaking, the positions have to be expressed in single trip time, i.e., the time-distance or isochrones, demanding that the structural condition is also expressed in single trip parameters.

The bio-physical model can now be developed in two steps. The first step is similar to the conventional Gravity Model where only equation 4.35 is substituted as a modal deterrence function:

$$f_{ij} = \frac{c_m}{b_m} e^{-\frac{t_{ij}^{c_m}}{b_m}} t_{ij}^{(c_m-1)} \tag{5.5}$$

where t_{ij} is the single modal trip time between cell i and j, b_m and c_m are the mode specific parameters, and equation 5.5 gives so the probabilities of trips between these cells. The second step consists of an iteration process where the results of trip generation, i.e., equation 5.4, are used where the marginal sums ensure the mathematical boundary conditions for trip matrix (Lohse & Lätzsch 1997). The initial state for the calculation process could be described in a symmetrical matrix, i.e., dividing the total number of trips per cell T_i into O_i and D_i, since, as noted in Section 5.2, 87% of all trips are made on an even trip rate.

As a result trip generation and trip distribution have to be solved together since the trip matrix satisfies three conditions, the marginal sums from trip generation, the matrix elements from trip distribution, and the structural condition from TTB approach, so all three models are intrinsically interconnected. The superposition of the different probability distributions should yield the time-space of the area which can be exhibited, for instance, in form of probability occupation of isochrones.

A simplified process can be performed without a modal distinction where the overall parameters of single trips have to be considered. This means that the original sequence of trip generation - trip distribution - the modal split is preserved.

To enhance the level of description in terms of area, a parametric adjustment of b and c should be made according to type of area, e.g. region or city; this influence can be noticed in Table 3.3 with the ergonomic values of car between road 4 and city 13. Another practical adjustment could be made according to the investigated area. If a territorial radius of around 25 miles is considered then according to Figure D.1 the through-traffic can be neglected. Since no additional influx or efflux has to be taken into account the region may be considered as 'partially closed' and being in a steady state.

Comparing the distribution functions in Section 2.3.2 using the Maxwell-Boltzmann distribution of travelling (MaBoT), some differences can be detected. The most obvious difference is in the shape, where only the combined function resembles the MaBoT which combines the classical model and the Wilson model. Another difference can be found in the scale of the ordinate; there, the values on the ordinate are of magnitude of one tenth and centre around 1 whereas MaBoT finds its highest value at around 0.025. The argument regarding the value of 1at 0 is used as an improvement in relation to the classical model which has a value of infinity, or as a validity restriction in relation to the EVA model where Lohse et al. clearly note that the function is strictly valid only for pedestrians and partially for cyclists; but this might not be the case for pedestrians as MaBoT suggests, even with the considerations of walking length under 50 yards. Another reason may lie in relation to the variables in question since the ordinate is then described as a 'probability of assessment' (Lohse & Lätzsch 1997, p214) or as a deterrence function (Ortúzar & Willumsen 1994) and not as a probability function. Therefore, similar magnitudes may be reached after a calibration of the deterrence functions. On the other hand, MaBoT is based on the unmodified variable of time in relation to the actual probability of occurrence and therefore may not require calibration. But a practical verification would clarify these points.

Simply, the way of modelling is characterised by progressing from considering the individual with its means of transport to the total number of trips T and back to the level-in-between with the determination of trips per cell T_{ij}; this combines trip generation with trip distribution based on the TEB approach as the common core. This means that all three perspectives are complementary since the absolute number of trips in relation to the single trip time constitutes the boundary condition for the distributional iteration and the double constrained model may reflect the steady state of the system as a whole. However, trip generation and trip distribution models attempt to explain only one aspect of trip making, i.e., the amount of daily travelling, where only some of the essential variables are considered. The other variables, i.e., the trip purpose and the route with origin and destination, will find their implementation in trip assignment or land-use models.

5.3.3 The Bio-Physical Homo Economicus

The concept of cost as described in Section 2.1 is often used as a framework in most current transport models. It assumes an idealistic rationality of behaviour, i.e., perfect information, immaculate computing and ideal decision making, which is difficult to justify in an absolute sense. But rationality has to be assumed otherwise an explanation would not be achievable and, idealism is necessary in combination with the rational methodology, to provide an unambiguous understanding. This normative approach has been criticised which lead to concepts such as that of the relative Homo Economicus or Simon's satisficing models but with the disadvantage of diluting the stringency of the absolute Homo Economicus. Nevertheless, the following parallels can be drawn in relation to the conventional trip models and to the bio-physical model; most of the following parallels are related to Section 2.1.1 where the unit of reference is either the individual, the household or the firm.

The absolute Homo Economicus can be found in the 'Average Traveller' as used in the cross-classification or category analysis, where a constant pattern of behaviour with an invariant decision making is assumed. The methodological influence can be found on the 'social level', with the concept of equilibrium and the maximisation of self-interest. A traffic system is assumed to be in equilibrium, a condition, which seems generally difficult to satisfy because of the continuous changes in network and rolling stock or in travel demand and, therefore, equilibrium is treated more as a methodological-mathematical prerequisite. The maximisation of self-interest can be found in the analytical selection of one particular mode of transport, i.e., the vehicles, because most problems (e.g. congestion, accidents or pollution) are associated with that particular mode. This exclusive concentration can again be found, for example, in the trip definition so other modes of transport and their interactions, which are essential for a more complete understanding of travel behaviour, do not receive the same attention.

For the bio-physical model the economic principles can be applied to travel behaviour because on the one hand, the basic needs have to be satisfied, i.e., a trip has to be made which is trip generation/trip distribution, and on the other hand, the choice of how this satisfaction can be obtained, i.e., modal choice. Economic rationality is understood in terms of maximising utility under budget constraints. The equivalent budget constraints are those of the travel energy and the equivalent maximisation can be given primarily on the ordinal scale of the power values, i.e., beginning with the lowest energy demanding mode, which is the car. The tendency towards the same choice of means of travel can be shown in the trend towards the means with the lowest power values in combination with the travel times, exemplified in the modal split of Figure 4.1. The equivalent to the general utility function can be found in the MaBoT where all travellers behave within the same probability distribution. The assumption of general equilibrium can also be satisfied by the steady state condition where the TEB of a population remains constant. (The satisficing model, bounded or procedural economics are more relativistic in nature and therefore may satisfy the requirements of decision making in modal split with monetary constraints.)

These economic interpretations of bio-physical travelling are consistent from a methodological point of view. They even satisfy the idealistic economic assumptions in a realistic physical way. However, this is in contradiction to economic rationality which is understood in saving money or time. For example, the trend towards increasing car usage cannot be considered as the cheapest way of travel and one may not even save time in the long run. Furthermore, in terms of rational expectations: first, the agent thinks he could save time by using quicker means of transport, i.e., less energy-intensive means of transport, but then he spends more time travelling by using the same amount of energy. This means that the assumption of a rationalised economic behaviour is dominated by the bio-physical constraint behaviour. In addition, the energy behaviour on an unconscious level could be considered as rational (because of minimising the power value) and conscious economic reasoning may be regarded as a process of rationalised justification. Economic rationality approached from such a perspective would receive completely new dimensions, i.e., what can be regarded as physically or biologically determined and what can be regarded as economically determined.

5.4 An Outlook

Whilst further investigation is required to fully confirm the bio-physical approach, some considerations are presented to show possibilities and implications for further applications.

- **Traffic Engineering and Land-Use**
  A fundamental advantage of the approach is a common definition of a trip, i.e., what constitutes a trip and what describes it in its essential features. As in physics, where certain quantities have to be considered, the new trip definition could constitute a common base in a similar way.
  Conventional relationships, such as the time-distance relationship, would need to be re-considered if human influence is taken into account. This relationship

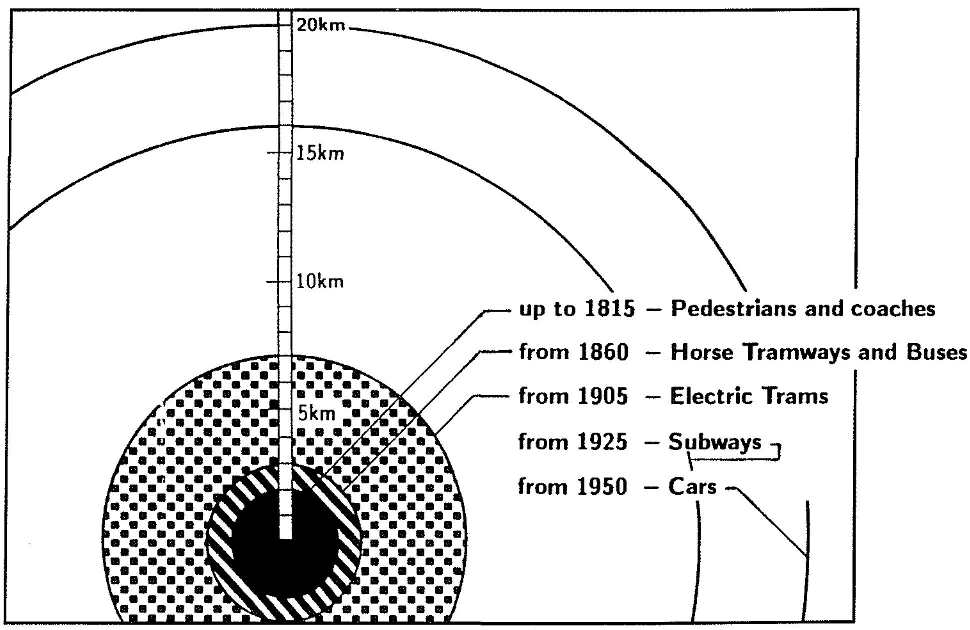


Figure 5.5: The Evolution of Berlin in Comparison to the Mode of Transport (Marchetti 1993)

shows the increase in land-use distribution in relation to the mode of transport. This effect may also be reflected in settlement patterns, as depicted in Figure 5.5. Marchetti states in the original caption to this figure: "The fact that the 'daily radius' depends on the speed of transportation is clearly manifested by the evolution of the size of the city of Berlin. The 1800 Berlin was very compact with a radius of 2.5 km pointing to a speed of 5 km / h, the speed of a man walking. With the introduction of faster and faster means of transportation the radius of the city grew *in proportion* to their speed, and is now about 20 km pointing to a mean speed of transport of about 40 km / h. The center of the city can be defined then as the point which the largest number of people can reach in less than 30 min. Reducing the access to the geometric center, e.g., through zoning, can displace the functional center elsewhere, e.g., outside the city" (Marchetti 1993)[1].

To elucidate or neutralise the influence of means of transport, the spatial changes should be compared with the number of inhabitants, i.e., increase or steadiness, or with conurbation, i.e., integration of suburb villages into the sphere of a city, or a change of life style, i.e., increase in individual living space. This would give further clarification in terms of mode specific travel patterns and their stability.

A comparison between the socio-economic variables and land-use measures on a modal base could also give an insight into settlement patterns and settlement requirements. This would provide a different understanding of travel demand in relation to transport systems.

- **Trip Generation and Trip Distribution**

  The distribution function is fully compatible with the methodology of classical trip distribution models. However, the Maxwell-Boltzmann distribution function describes a particular condition of the system, i.e., the steady state. With further extensions it could be integrated in a dynamic model such as a feedback or control system with the traveller acting as the controller.

- **Modal choice and trip assignment**

  Modal choice may be understood as a conscious process of decision making constrained by the available means of travel, which results in an adoption of certain travel patterns. The 'means' can be considered not only in modal terms, but also in terms of route, cost or comfort. The comprehending notion of this complex problem could be defined as 'accessibility'. Some indication

[1] It must be noted that such a historical analysis should not imply a 'backward development'. Such a comparison should only consolidate the understanding between transport and land-use with its consequential effects.

for modal choice can be found according to the percentages of modal split (Section 4.2.4).

From a physical point of view, a first indication of the ascendancy of the vehicular means of transport can be given with a comparison of the power values (Table 3.3): car-driving is three times as attractive as cycling, and four times as attractive as walking, particularly at the onset of a trip, where no congestion can be perceived; and at this point the power value is as low as travelling by train. Even in the city during rush hours, the value still remains lower than walking or cycling, but then it is more likely that people will change over to public transport. Train (and express bus) are already prevalent over longer distances. In addition, this would involve the problem of modal mix such as park-and-ride which has not been tackled here, and the problem of route choice.

Modal choice, as in Section 2.3.3, can also be approached from a psychological perspective. Since the energy turnover is not consciously measured but experienced through sensation, the energy function could be interpreted as a function of 'sensation'. If a person invests too much effort in trip making (s)he would then experience a *sensational* dissonance which eventually will be expressed in psychological terms as *cognitive* dissonance which can be understood as a connection between traffic physiology and traffic psychology. There seems to be a relationship between mode of transport and cost or income, as a provider of means of transport. This could be found in the TMB (Section 2.3.4) where a fairly fixed amount of income is spent on mobility. In that respect, it would be interesting to compare the socio-economic variables with the modal split. The modal choice might also be dependent on the available route with an additional influence e.g. of ticket prices or road pricing. The trip purpose should also be considered since the destination, e.g. working place, should coincide with the primary aim of the trip, e.g. work. Thus, all these interdependencies would come together in modelling of trip assignment.

- **Transport Economics and Transport Policy**

  The concept of a bio-physical Homo Economicus would shed new light on transport economics in terms of travel demand and supply with its elasticities. Daily travelling (due to the daily purposes and due to the physiological-health related necessity) is relatively inelastic since these activities have to be undertaken. However, modal choice is relatively elastic since modes of transport can be seen as secondary means to fulfil the primary purpose of a trip. According to the trip rate, non-vehicular modes of transport show higher inelasticities than vehicular modes of transport. This means that a modal change to the former would demand quite a distinguished planning.

Transport policy on the other hand, is more concerned with the 'social level' where such decisions are made in relation to society, land-use and environment. For example, if a modal shift to non-vehicular modes of transport is proposed as in the White Paper (DETR 1998a), then some policy directives can be envisaged in monetary terms. Taking into consideration the development of modal split in Figure 4.1 (and in Table B.1 - B.6) during the 1970's where the two oil-crises occurred (in the years 73/4 and 78/9), the slowing down in car-use and short term increase in bus travel may give an indication for the magnitude of response of taxational policies. Nevertheless, some other policies have already been realised, for example, increasing pedestrianisation or demand management. In practical terms the power values may be used as an indicator for the magnitude of effect of restriction.

Overall, it should be possible to infer some criteria for a sustainable human transport system. To obtain the full extent, an involvement of medical, economic and environmental measures would be required.

- **Human Perception**

Subjective perception or apparent cognition does not always coincide with objective measurements of a theoretical analysis, and therefore does not reveal the objective patterns which eventually determine actual behaviour. Methodologically, this problem could be identified on a microscopic level, where a traveller is described in terms of a physical movement, and on the macroscopic level, where a region with travellers is examined. The analysis showed that a performance pattern in form of the MaBoT emerges which cannot be detected on an individual level. Faster moving means of transport does not necessarily mean quicker in terms of absolute time. For example, with car or train (39 and 44 km / h) more time is spent on daily travelling (between 1.8 and 3.9 fold) than with walking or cycling (4.8 and 13.3 km / h) (Section 4.2.3 and 5.1.1). (The speeds refer to the average trip speeds and the ratios are calculated in relation to the latter modes. Both measures are taken from the seventh recording day.) At the macroscopic level, origin and destination are generally perceived to be fixed so such settlement changes may escape the subjective-conscious recognition, whereas from an objective-analytical perspective both vary in relation to the mode of transport.

This problem of perception or cognition is also connected to the question of rationality since an axiomatic theory constitutes the objective criterion of a rational and consistent methodology (Arrow 1987). An epistemological study may provide some elucidation to this problem.

- **Health Implication**
  Out of the four physiological factors of body energy consumption, i.e., gender, age, height and weight, only the latter can (actively) vary. Land-use/transport plans could be used to support healthy life-styles since physical activity is an essential necessity. In terms of analysis, this problem could be solved if an appropriate function for energy usage could be developed which includes these physiological variables. But this tasks falls into the field of physiology or medicine. Until this medical research can be implemented, the parameter in the Table 4.2 may serve as descriptive index values for land-use planning.
- **Transport Science**
  The systems-theoretical framework may be able to provide more insight into the complexity of transport. It supplies a schema where different disciplines such as biology, physics and transportation could be combined in a stringent and consistent way, so, for example, the bio-physical causes can be separated from economic influences. If this framework is applied in a more general way, it should eventually be possible to derive an evaluation system allowing an interdisciplinary or 'discipline-neutral' comparison which is the prerequisite for an objective understanding. This fundamental understanding of travel behaviour should subsequently lead to better assessments and forecasts, not only from a quantitative point of view but also from a qualitative one.

Chapter 6

Conclusions

This thesis has attempted to develop a new approach to trip generation and trip distribution which may provide a better understanding of the fundamental drives which govern travel behaviour. The main findings below follow the logic of the thesis, moving from the methodology to the preliminaries and actual bio-physical model, through to the development and application of the approach.

Methodological Findings

The structure for this thesis is given by the systems-theoretical function model of scientific development which defines a scientific discovery in four stages: 1. the problem, 2. the hypothesis, 3. the theory, 4. the prognosis and application. Although Oeser depicts the process as a circle, the epistemological process is not circular but rather spiral, since after going through the different stages new information has been gained, i.e., the scientific progress, so the next round starts off at a different height or, in other words, the (spiral) pitch equals the obtained information.

This methodology is necessary to demonstrate that subjective perception may differ from objective analysis. Subjective perception in terms of the methodology means to observe a situation or a problem and infer a hypothesis from it. As an example, socio-economic variables may describe travel behaviour of the conventional approaches but they could not statistically determine daily trip time and the trip rate. Hence, a different hypothesis is developed based on ergonomics and the energy turnover of physical activities, which leads to the hypothesis of a constant TEB. Also, an objective analysis can be understood as the constructive method of placing the hypothesis in a systematic and consistent way in relation to more general theories. In this thesis, this is done by using an analogy of statistical physics with its established principles and by applying them to travel behaviour. The MaBoT could so be developed which would be impossible to perceive from just a microscopic perspective.

Since the different stages with their results are described in more detail below one practical result should suffice to illustrate this subjective-objective contrast. For example, 'faster' modes of transport do not necessarily mean 'lesser' time spent on daily travelling, or 'time saving' as it is defined in economic terms (Section 4.2.3 and 5.1.1). This kind of travel may escape subjective perception and so an objective analysis is required to detect such patterns.

Preliminary Findings

- **The Unit of Reference**
  The household is used as the unit of reference in most travel models. In Section 3.2.1 it could be shown that the household size is subject to variations. This fact is important because such variations have to be taken into account in the data analysis. Therefore, the individual is proposed as the unit of reference since it is independent of household size and also enables a consideration of traveller-specific variables such as the bio-physical energy.
- **Travel Time and Trip Rate**
  The three most important measures for this approach are daily travel time, single trip time and the trip rate, i.e., the number of trips per day per person, which could be connected mathematically in Section 3.2.2. According to statistical calculus the three measures are shown to be independent. In methodological terms this means that the trip rate and therefore trip generation models (i.e., determining the number of trips in an area) can be treated separately from single trip time and therefore trip distribution models (i.e., determining the number of trips between different zones of an area in relation to single trips). The empirical evidence of the data analysis also suggests this independence because the three measures are always calculated separately. However, from a point of view of travel budgets, trip rate and single trip time should be treated in combination since the connection of both constitutes the boundary condition.
- **UK NTS Data**
  The data sets used in this thesis are taken from the NTS which has been compiled by the OPCS. As described in Section 3.1 the survey is carried out according to a rigorous schema to ensure the quality of the data. One aspect which is of special importance to this approach, is concerned with the recording method. Travel data are collected in one week where on the first six days walks shorter than 1 mile are ignored, and on the seventh day only walks shorter that 50 yards are ignored. This qualitative influence has been taken into account throughout the analysis and so the different measures are

labeled with R-day 1-6 or R-day 7. The data analysis is based on the source or raw data between 1972 and 1995. Two statistical methods were used in this thesis, the analysis of variance and a confidence interval estimate for means. The second method did not yield significant results and therefore it will be neglected in this summary.

The preliminary data analysis should verify firstly, the assertions of the travel time budget (TTB) approaches, i.e., the hypothesis of a constant travel time budget, and secondly, the explanatory influence of the socio-economic variables in relation to daily travel time and trip rate, i.e., their evaluation in terms of trip generation/trip distribution models and activity based approaches (ABA).

- ***Daily Travel Time*** The TTB approaches attempt to explain the constancy of daily travel time which can be observed throughout the world (Schafer 1998). So the aim of the data analysis in Section 3.2.3 is verify this constancy. On an overall level, the daily travel time ranges between 64.5 and 87.2 min with an average of 81.3 min. The average single trip time is 22.1 min and the average trip rate is 3.7; all measures are taken from the seventh day. The analysis of variance resulted in a rejection of the constancy hypothesis with $F = 80.12$, i.e., greater than $F_{.95} = 1.79$ and $F_{.99} = 2.25$. Although the statistical test reveals a quantitative rejection, from a qualitative point of view the constancy still remains somehow intriguingly appealing because of its global observability and because of the fact that "a statistical relationship, however strong and however suggestive, can never *establish* a causal connexion" (Kendall & Stuart 1973).
- ***Socio-Economic Variables*** The socio-economic variables are used as explanatory variables in various trip models. In Section 3.2.4 the four chosen variables are household size, household structure, car-ownership and household income because they are well defined in relation to the unit of reference, i.e., household or family. The variables are described in three dimensions: on the x-axis is the dimension of the actual variable, on the y-axis is the year (i.e., to capture the dynamic behaviour) and on the z-axis is daily travel time or trip rate as the comparative measure. In terms of dynamic behaviour all four variables follow the trend of the overall daily travel time and trip rate. All variables display a certain non-linear behaviour in relation to travel time as well as trip rate. Only household income exhibits a fairly linear relationship in relation to the trip rate. But the question of intercept, i.e., general appearance of travel

time and trip rate, remains unanswered. This means that the socio-economic variables influence daily travel time and trip rate to a limited extent but they cannot offer a statistical explanation in terms of daily trip making or the 'one-hour' travel phenomenon related to the travel time budget approaches (Section 2.3.4).

- **The Ergonomic Data**

  Ergonomics evaluates work-related stress mainly on the basis of the energy turnover for activities (Spitzer et al. 1982). The energy turnover can be measured through the amount of oxygen of breathing which cannot be stored in the body. Various measures for travel activities can be given in [kJ / min]. In this thesis the ergonomic concept is used as an alternative to the socio-economic one. As a result of Section 3.3 it could be shown in principle that the energy concept describes not only the effort of activities but also the integration of activities in a person's daily life cycle. The latter can be supported further by bio/physiological studies which state that daily physical activities constitute an essential part of a healthy life style (Kujala et al. 1998) which are biologically regulated through the central nervous system (Rowland 1998). In terms of the approach, a certain amount of the daily energy turnover for such activities can then be interpreted as a daily travel energy budget (TEB). It should be noted that this concept is not in conflict with an economic understanding because the same trip can be understood on a conscious-economic level to fulfil the trip purpose, and on an unconscious-biological level to satisfy the physiological need.

The Bio-Physical Model

- **The Hypothesis of a Constant Travel Energy Budget**

  Instead of an economic framework, a systems-theoretical framework is adopted, from which an *alternative trip definition* is derived in Section 4.2.1. From a qualitative point of view it becomes clear that distinction between the traveller as the prime subject of travel and the mode of transport as a secondary means is essential. The other consequence of the definition is that the energy variable and thus the bio-physical effort can be regarded as an essential component. A more detail investigation of Section 4.2.2 into the energy variable with the conservation of energy reveals that distance is a mode dependent unit (and not an independent unit as in physics) and time is the only unit that may be used for the purpose of comparison.

  To obtain a connection between the external travel measures of the NTS data and the internal energy measure of ergonomics, the former have to be sorted out into 'pure modes of transport', i.e., where one *main* mode is used through the day. This is the case in 80% of all daily travelling since walking is part of nearly every other mode, i.e., walking to the car park or bus stop. The main modes considered in Section 4.2.3 were walking, cycling, car-driver, car-passenger, stage bus and railway since together they amount for more than 90% of all modes. The quickest modes of transport, i.e., the mode with the least time spent on daily travelling, are walking and cycling with around 41 min, followed by car-passenger with 60 min and bus by 69 min. The slowest modes are car-driver with 76 min and railway with 156 min. (These values are averages over all years from R-day 7.) If these averages are tested for constancy then the analysis of variance yields F-values between 6.10 (for car-passenger) and 2.27 (for bicycle). Although none of these values pass the test even on $F_{.99} = 2.25$ there is a clear indication that the modal travel times are statistically more stable than the overall values. Also, taking the differences in absolute terms (up to 116 min) into consideration, it becomes difficult to speak of a constant TTB without a modal distinction. Therefore, the hypothesis should now be termed one of a constant *modal* daily travel time.

In Section 4.2.4 the average modal travel times were combined with the ergonomic values to explain the differences in their value. Since a daily TEB has not been measured in *absolute* terms, one reference mode has to be chosen so that only the *relative* difference has to suffice for establishing a hypothesis of a constant TEB. In the case of the thesis, the reference mode is bicycle because of its detailed analysis in ergonomics. The correct values for equivalent energy turnovers can be found in all modes. Whilst for public transport no ergonomic values are given, good agreement can be found with certain body positional measures. This supports the fact that the bio-physical energy turnover can explain the difference in daily modal travel time and - in comparison to the socio-economic variables - that the energy variable can be regarded as a variable of cause, i.e., 'cause' understood in a strictly physical sense.

- **The Maxwell-Boltzmann Distribution of Travelling**

In advance, it should be noted that this method has already been applied in transport, i.e., the trip distribution model by A. Wilson. The only difference is that here the energy term is exchanged for generalised costs (Wilson 1967). Whereas the hypothetical approach describes travel behaviour in a *quantitative* way (with the data analysis and the statistical tests) the theoretical approach describes it in a *qualitative* way with statistical physics and its derivations, i.e., the theory outside statistics (Kendall & Stuart 1973). Before the theoretical approach is summarised, a brief digression to 'the free fall' should convey the idea for understanding the MaBoT (which again shows the influence of subjective perception versus objective understanding).

In physics, the law of free fall is strictly valid only in vacuum. Under real circumstances if a stone is now compared with a feather then the stone obeys the formula fairly accurately, i.e., the air resistance has a minor influence under relative slow velocity. The feather on the other hand, seems to disobey the law because it falls more slowly, i.e., the air resistance becomes predominant according to the speed. However, because only the feather falls at a slower pace does not mean that the law of free fall is invalid. In the same way this theoretical approach is to be understood. Here, the MaBoT corresponds to the law of free fall and the air resistance corresponds to other influences. These influences have been ignored because statistical analysis shows that their magnitude is of minor importance and, to speak in physical terms, because of the concept of aggregated states.

In general, the MaBoT describes daily travel in its boundary conditions and the mean energy supports the hypothesis of a constant TEB (Section 4.3). A physical methodology is employed for the consistency and systemisation with already established theories of physics. In detail, conceptual parallels could be drawn in Section 4.3.2 which substantiate the feasibility of certain underlying assumptions. The mathematical derivation reveals that there is, on average, a constant TEB which should be valid irrespective of the mode of transport used. In Section 4.3.7 it can be shown that the functional form (as a qualitative measure) fits the different modal travel time distributions with high accuracy. However, the unsolved problem is the mathematical function of the human energy expenditure which could be verified in respect to the physical methodology, but not in respect to the physiological explanations. (The problem here lies with medical physiology which should provide a function with explanatory, body-related variables. This is beyond the scope of this research.)

The main findings of this approach are firstly, that it is possible to derive a mathematical function for macroscopic travel behaviour which describes the bio-physical boundary conditions consistent with physical principles which otherwise would have to be assumed in a statistical analysis; and secondly, that it is possible in principle to infer a deterministic and physical-causal relationship for the amount of travel behaviour despite probabilistic assumptions.

According to the actual travel values and parameters, these may vary in a similar way as the gravitational constant varies around the earth (if the analogy of the free fall is briefly adopted once again). Here, the travel data are only from the UK and ergonomic data are only from Germany. But Figure 2.2 gives an indication for a worldwide context with which the travel values obtained in this thesis agree.

- **Bio-Physical Trip Generation/Trip Distribution**

  In Section 5.1 some empirical evidence was given for the assertion of distance being dependent on the mode of transport. In the time-distance diagram the gradient which should show a linear form according to the metric relationship of speed, exhibits a non-linear form that could partly be assessed through the human energy function. But the main influence on the gradient comes from the mode of transport where the single trip distance increases in relation to bicycle by a ratio of 2 for bus, 4 for car and 17 for railway.

  In Section 5.2 it can be shown that 87% of daily travelling is based on an even trip rate, which can be interpreted that an 'even' travel pattern is a more stable one. The exception is the car which has a higher share of 'odd' trips. The suggested reason for this is that car has a lower threshold towards trip making due to its low value of effort.

  Bio-physical trip generation in Section 5.3.2 has the basic form of a category analysis with two dependencies: firstly, the number of inhabitants per zone and secondly, the proportion of mode of transport used. The second point suggests that the modal split should not come after trip distribution - as is practised in the conventional four-stage approach - but before trip generation since the modal choice has a direct influence on the number of trips (Section 4.2.3). However, a simplified version can be made using the overall values (without a modal distinction), where the only explanatory variable would be the number of inhabitants. This would again be in the conventional sequence.

  The structural condition for the bio-physical model of trip distribution comes from the MaBoT. The problem is that the trip matrix is positionally dependent so the parameters of the single (modal) trips have to be used for bio-physical trip distribution, which is exactly its basic idea, i.e., to distribute the single trips in terms of daily travelling. From this it can be seen that all three models are inter-connected through the trip matrix, i.e., trip generation in relation to the marginal sums, trip distribution in relation to the matrix elements and the structural condition from the travel time budget approach. The model provides a coherent analysis for the amount of daily travelling.

However, this approach could only be demonstrated in principle but a practical application would help to verify its validity.

The data analysis of this approach spans over more than two decades where fundamental changes in the transport system, e.g. changes in road network and means of transport, and where two oil crises have taken place. During this time an invariant pattern could be detected which is developed into a consistent schema based on a physical methods and which provides a fundamental understanding of human travel behaviour and a basis for its forecasting. However, this approach is only a first attempt to shed new light on the problem of trip generation and trip distribution. There may be several opinions about such a *bio-physical* perspective in relation to *human* travel behaviour but its concept, its methodology and its quantification may prove to be more powerful arguments than those which sound convincingly to practitioners of the traditional way. Irrespective of this, the final assessment of this approach will inevitably come with time, where time will put it to the test over and over again.

References

Arrow, K. J. (1987). Economic theory and the hypothesis of rationality, *in* J. Eatwell, M. Milgate & P. Newman (eds), *The New Palgrave - A Dicionary of Economics*, Macmillan Press Limited, London and Basingstoke.

Axhausen, K. W. & Polak, J. W. (1991). Transportation planning: Activity-based approach, *in* M. Papageorgiou (ed.), *Concise Encyclopedia of Traffic & Transportation Systems*, Pergamon Press, Oxford, pp. 564–569.

Becker, U. J., Schneider, R. & Schwartzmann, R. (1991). Transportation planning: Microscopic approach, *in* M. Papageoriou (ed.), *Concise Encyclopaedia of Traffic & Transportation Systems*, Pergamon Press, Great Britain.

Bertalanffy, L. v. (1968). *General System Theory*, George Braziller, New York.

Borgers, A. W. J., Hofman, F. & Timmermans, H. J. P. (1997). Activity-based modelling: Prospects, *in* D. Ettema & H. Timmermans (eds), *Activity-Based Approaches to Travel Analysis*, Pergamon Press, Oxford.

Chapin, F. S. (1974). *Human Activity Patterns in the City*, John Wiley & Sons, New York.

Dasgupta, M., Raha, N. & K., S. (1996). Review of trip generation studies, *Technical report*, Transport Research Laboratory.

DETR (1995). *National Travel Survey*, 2. edn, The Data Archive, Essex.

DETR (1998a). *A New Deal for Transport: Better for Everyone*, TSO, London.

DETR (1998b). Nts7273 sn2852, nts7576 sn2853, nts7879 sn2854, nts8586 sn2855, ntsd sn3288, CD-ROM. The Data Archive, Essex.

DKS, A. (1994). Travel model development and refinement - trip generation, *Final report*, Puget Sound Regional Council, NTL.

Ettema, D. & H., T. (1997). Theories and models of activity patterns, *in* D. Ettema & H. Timmermans (eds), *Activity-Based Approaches to Travel Analysis*, Pergamon Press, Oxford.

Fischer, L. (1997). Induced traffic and the theory of the constant travel time budget, *Internationales Verkehrswesen* **49**(11): 551–6.

Forrester, J. W. (1975). *Collected Papers of Jay W. Forrester*, Wright Allen Press, Inc., Cambridge, Massachusetts.

Frisch, K. v. (1977). *Aus dem Leben der Bienen*, Springer-Verlag, Berlin Heidelberg New York.

Goodwin, P. B. (1976). Human effort and the value of travel time, *Journal of Transport Economics and Policy* **10**: 3–15.

Goodwin, P. B. (1981). The usefulness of travel budgets, *Transpn. Res.-A* **15A**: 97–106.

Goodwin, P. B. (1990). Some principles of dynamic analysis of travel behaviour, *in* P. M. Jones (ed.), *New Developments in Dynamic and Activity-Based Approaches to Travel Analysis*, Gower Publishing, England.

Hargreaves-Heap, S. & Hollis, M. (1987). Economic man, *in* J. Eatwell, M. Milgate & P. Newman (eds), *The New Palgrave - A Dicionary of Economics*, Macmillan Press Limited, London Basingstoke.

Hettinger, T. (1989). Physiologische leistungsgrundlagen, *in* H. Schmidke (ed.), *Handbuch der Ergonomie*, 2. edn, Vol. 1, Carl Hanser Verlag, München - Wien.

Hettinger, T., Kaminsky, G. & Schmale, H. (1980). *Ergonomie am Arbeitsplatz*, 2. edn, Friedrich Kiehl Verlag, Ludwigshafen (Rhein).

Hägerstrand, T. (1970). What about people in regional science?, *Reg. Sci. Assoc.* **24**: 7–21.

Hupkes, G. (1982). The law of constant travel time and trip-rates, *Futures* (February): 38–46.

ITE (1991). *Trip Generation*, 5. edn, Institute of Transportation Engineers, Washington D.C.

Jones, P., Koppelman, F. & Orfeuil, J.-P. (1990). Activity analysis: State-of-the-art and future directions, *in* P. M. Jones (ed.), *New Developments in Dynamic and Activity-Based Approaches to Travel Analysis*, Gower Publishing, England.

Kendall, M. G. & Stuart, A. (1973). *The Advanced Theory of Statistics*, Vol. 2, 3. edn, Charles Griffin & Company Limited, London.

Kirby, H. R. (1981). Forward, *Transpn. Res.-A* **15A**: 1–6.

Kölbl, R. (1995). *Ein Bauplan der allgemeinen Systemtheorie mit Anwendung im Verkehrswesen*, Diplomarbeit, TU Vienna.

Klir, G. (1991). *Facets of System Science*, New York.

Knoflacher, H. (1981). Human energy expenditure in different modes: Implications for town planning, *International Symposium on Surface Transportation System Performance*, Vol. II, U.S. Department of Transportation.

Knoflacher, H. (1987). *Verkehrsplanung für den Menschen*, Orac, Vienna.

Knoflacher, H. (1995). Das Lill'sche Reisegesetz - das Weber-Fechner'sche Empfindungsgesetz - und was daraus folgt, *Mobilita* (195). Bratislava.

Kujala, U. M., Kaprio, J., S. S. & M., K. (1998). Relationship of leisure-time physical activity and mortality, *JAMA* **279**(6): 440–444.

Landau, L. D., Akhiezer, A. I. & Lifshitz, E. M. (1967). *General Physics*, Pergamon Press, Oxford.

Leung, Y. & Yan, J. (1997). A note on the fluctuation of flows under the entropy principle, *Transpn Res.-B* **31**(5): 417–23.

Lifshitz, E. M. & Pitaevskii, L. P. (1980). *Statistical Physics*, Pergamon Press, Oxford.

Lill, E. (1889). Die grundgesetze des personenverkehrs, *Zeitschrift für Eisenbahnen und Dampfschiffahrt* **35/36**.

Lohse, D. & Lätzsch, L. (1997). *Verkehrsplanung*, Vol. 2 of *Grundlagen der Strassenverkehrstechnik und der Verkehrsplanung*, Verlag für Bauwesen, Berlin.

Lorenz, K. (1976). *Behind the Mirror*, London.

Marchetti, C. (1993). On mobility, *Final Status Report Contract No. 4672-92-03 ED ISP A*, International Institute for Applied Systems Analysis (IIASA).

Oeser, E. (1976). *Struktur und Dynamik erfahrungswissenschaftlicher Systeme*, Vol. 3. of *Wissenschaft und Information*, R. Oldenbourg Verlag, Vienna, Munich.

Ortúzar, J. d. D. & Willumsen, L. G. (1994). *Modelling Transport*, 2. edn, John Wiley & Sons, Chichester New York Brisbane Toronto Singapore.

Peperna, O. (1982). *Die Einzugsbereiche von Haltestellen öffentlicher Nahverkehrsmittel im Strassen- und Busverkehr*, Diplomarbeit, TU Vienna.

Popper, K. (1995). *Objective Knowledge: An Evolutionary Approach*, 9. edn, Oxford University Press, Oxford, New York.

RDC, I. (1994). Further comparative analysis of daily activity and travel pattern & development of a time-activity-based traveler benefit measure, *Technical report*.

RDC, I. (1995). Activity based modeling system for travel demand forcasting, *Technical report*, U.S. Department of Transportation.

Riedl, R. (1985). *Die Spaltung des Weltbildes*, Verlag Paul Parey, Berlin und Hamburg.

Rohmert, W. & Ulmer, H.-V. (1983). Energetik des menschlichen körpers, *in* W. Rohmert & J. Rutenfranz (eds), *Praktische Arbeitsphysiologie*, 3. edn, Georg Thieme Verlag, Stuttgart New York.

Roth, G. J. & Zahavi, Y. (1981). Travel time "budgets" in developing countries, *Transpn. Res.-A* **15A**: 87–95.

Rowland, T. W. (1998). The biological basis of physical activity, *Medicine & Science in Sports & Exercise* pp. 392–9.

Schafer, A. (1998). The global demand for motorized mobility, *Transpn Res.-A* **32**(6): 455–477.

Sen, A. K. (1987). Rational behaviour, *in* J. Eatwell, M. Milgate & P. Newman (eds), *The New Palgrave - A Dicionary of Economics*, Macmillan Press Limited, London Basingstoke.

Simon, H. A. (1987). Behavioural economics, *in* J. Eatwell, M. Milgate & P. Newman (eds), *The New Palgrave - A Dicionary of Economics*, Macmillan Press Limited, London Basingstoke.

Smith, J. A. & Ross, W. D. (eds) (1908). *Metaphysica*, Vol. VIII of *The Works of Aristotle*, Clarendon Press, Oxford.

Sommerville, D. M. Y. (1929). *An Introduction To The Geometry Of N Dimensions*, Methuen & Co. Ltd., London.

Spiegel, T. (1992). *Die Empfindung des Widerstandes von wegen unterschiedlicher Verkehrsmittelbenützung und deren Auswirkungen auf das Mobilitätsverhalten*, Ph.d., TU Vienna.

Spitzer, H., Hettinger, T. & Kaminsky, G. (1982). *Tafeln für den Energieumsatz bei körperlicher Arbeit*, 6. edn, Beuth Verlag GmbH, Berlin Köln.

Supernak, J. & Zahavi, Y. (1982). Travel-time budget: A critique (discussion), *Transportation Research Record* **28**(879): 15–28.

Tanner, J. C. (1981). Expenditure of time and money on travel, *Transpn. Res.-A* **15A**: 25–38.

Tolman, R. C. (1938). *The Principles of Statistical Physics*, Clarendon Press, Oxford.

Tomazinis, A. (1962). A new method of trip distribution in an urban area, *Technical report*, Highway Research Board Bulletin 347.

Wilson, A. G. (1967). A statistical theory of spatial distribution modes, *Transpn. Res.-A* **1**: 253–269.

Wilson, A. G. (1970). *Entropy in urban and regional modelling*, Pion, London.

Wootton, H. J. & Pick, G. W. (1967). A model for trips generated by households, *Journal of transport economics and policy* pp. 137–153.

Zahavi, Y. & Ryan, J. (1980). Stability of travel components over time, *Transportation Research Record* **750**: 19–26.

Zahavi, Y. & Talvitie, A. (1980). Regularities in travel time and money expenditure, *Transportation Research Record* **750**: 13–19.

Zipf, G. K. (1949). *Human Behaviour and the Principle of Least Effort*, 2. edn, Hafner Publishing Company, New York and London.

Glossary

ABA	Activity-Based Approach
MaBoT	Maxwell-Boltzmann Distribution of Travelling
DETR	Department for the Environment, Transport and the Regions
NTS	National Travel Survey
OPCS	Office of Population Census and Surveys
TE	Travel Effectivity
TEB	Travel Energy Budget
TTB	Travel Time Budget
TMB	Travel Money Budget

Appendix A

Tables of TTB and the Socio-Economic Variables

This appendix contains the complementary tables relating to Section 3.2. Table A.2 gives the complete data for Table 3.2 and for Figure 3.2 and describes the basic travel measures (i.e. daily and single travel time and trip rate), percentage of journeys per day and stages per journey. Table A.3 - A.6 present the numerical values for Figure 3.4 - 3.7 in terms of number of observations, daily travel time and trip rate. Table A.1 provides the detailed values for Section 3.3.3.

The empirical comparison investigates travel time and trip rate from an angle of the approaches of travel time budget and from an angle of trip generation, trip distribution and activity-based approach with the socio-economic variables, i.e. household size, structure, car-ownership and income. The data analysis shows that the influence of the socio-economic variables on daily travel time and trip rate is limited.

BM kg	ET kJ / min	RC ET %	ET/BM J / m kg	RC ET/BM %
35	8.1	-	2.89	30.0
45	9.5	17.3	2.64	18.9
55	11.1	37.0	2.52	13.5
65	12.4	35.1	2.38	7.2
75	13.8	70.4	2.30	3.6
85	15.1	86.4	2.22	-
95	16.9	108.6	2.22	-
BM ... Body Mass, ET ... Energy Turnover RC ... Relative Change Against The Lowest Value				

Table A.1: An Ergonometric Comparison of Walking (Spitzer et al. 1982)

Year	$\langle t_d \rangle$	σ_{t_d}	$\langle t_s \rangle$	σ_{t_s}	$\langle r \rangle$	σ_r	1m/d	2m/d	≥3m/d	1st/j	2st/j	≥3st/j
	[min]		[min]		[no]			[%]			[%]	
day 1-6												
72/3	n.a.	n.a.	n.a.	n.a.	2.9	1.5	84.1	14.6	1.3	95.7	3.6	0.7
75/6	n.a.	n.a.	n.a.	n.a.	2.9	1.5	82.6	15.8	1.6	96.7	2.8	0.6
78/9	74.3	66.4	24.5	29.1	3.0	1.7	78.5	19.2	2.2	97.1	2.4	0.5
85/6	77.0	80.7	24.9	37.8	3.1	1.6	78.1	19.4	2.5	97.2	2.2	0.5
88	78.6	79.9	24.3	36.2	3.2	1.8	76.5	20.6	2.9	97.1	2.4	0.5
89	80.2	82.4	24.7	37.9	3.2	1.8	76.9	20.0	3.0	97.4	2.0	0.6
90	78.5	81.4	24.0	37.0	3.3	1.8	77.7	19.7	2.6	97.3	2.1	0.6
91	78.2	80.6	24.5	37.0	3.2	1.7	78.1	19.3	2.6	97.5	2.0	0.4
92	75.6	80.1	23.7	37.4	3.2	1.8	80.3	17.6	2.1	97.7	1.9	0.4
93	75.3	80.5	24.2	38.1	3.1	1.7	81.5	16.8	1.7	97.8	1.8	0.4
94	76.5	84.1	24	40.3	3.2	1.8	81.0	16.8	2.1	n.a.	n.a.	0.0
95	74.8	73.1	23.7	33.4	3.2	1.7	81.3	16.9	1.9	n.a.	n.a.	0.0
day 7												
72/3	74.8	80.6	20.9	31.7	3.6	2.0	70.3	25.4	4.3	80.3	9.0	10.7
75/6	64.5	63.7	19.5	26.5	3.3	1.8	69.2	26.0	4.8	78.8	14.3	6.9
78/9	76.8	67.6	20.8	25.8	3.7	2.1	63.0	28.9	8.1	92.2	5.3	2.6
85/6	85.4	86	22.8	35.4	3.7	2.0	59.9	31.3	8.8	90.2	5.6	4.2
88	86.0	85.0	22.7	34.9	3.8	2.1	59.7	31.2	9.1	88.6	6.5	4.9
89	87.5	86.2	22.7	35.1	3.9	2.2	59.1	31.4	9.5	89.4	6.8	3.8
90	87.2	88.4	23.1	37.1	3.8	2.1	61.1	30.1	8.8	89.7	6.5	3.8
91	84.7	87.9	22.7	35.6	3.7	2.0	60.6	30.7	8.6	89.8	6.0	4.2
92	84.3	94.4	23.3	41.4	3.6	2.0	63.1	29.7	7.3	90.9	5.8	3.3
93	82.8	89.1	22.7	38.3	3.6	2.0	63.3	29.7	7.0	91.5	4.9	3.6
94	81.7	89.2	21.9	36.5	3.7	2.1	61.9	30.7	7.4	n.a.	n.a.	n.a.
95	79.3	76.3	21.9	32.2	3.6	2	65.3	28.2	6.5	n.a.	n.a.	n.a.
difference												
72/3	n.a.	n.a.	n.a.	n.a.	0.7	0.4	-13.8	10.9	3.0	-15.4	5.4	10.0
75/6	n.a.	n.a.	n.a.	n.a.	0.4	0.3	-13.4	10.2	3.2	-17.9	11.5	6.3
78/9	2.5	1.2	-3.7	-3.3	0.7	0.4	-15.5	9.7	5.8	-4.9	2.9	2.1
85/6	8.3	5.3	-2.1	-2.4	0.6	0.4	-18.2	11.8	6.3	-7.0	3.3	3.7
88	7.4	5.1	-1.6	-1.3	0.6	0.3	-16.8	10.6	6.2	-8.5	4.1	4.4
89	7.4	3.7	-2.0	-2.8	0.6	0.3	-17.8	11.3	6.5	-8.0	4.8	3.1
90	8.8	7.0	-0.8	0.0	0.5	0.3	-16.6	10.4	6.2	-7.6	4.4	3.3
91	6.6	7.3	-1.8	-1.4	0.5	0.3	-17.5	11.4	6.1	-7.7	4.0	3.7
92	8.7	14.3	-0.5	4.0	0.4	0.2	-17.3	12.1	5.2	-6.8	3.9	2.9
93	7.5	8.6	-1.5	0.2	0.5	0.3	-18.3	12.9	5.4	-6.4	3.1	3.2
94	5.3	5.1	-2.1	-3.9	0.6	0.3	-19.1	13.8	5.3	n.a.	n.a.	n.a.
95	4.6	3.3	-1.8	-1.2	0.5	0.3	-16.0	11.3	4.7	n.a.	n.a.	n.a.

R-day ... Recording Day, t_d ... Daily Travel Time, t_s ... Single Travel Time,
r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation
m/d ... Modes of Transport Used per Day, st/j ... Stage per Journey (Single Trip)
diff ... Difference between R-day 1-6 and R-day 7

Table A.2: Overall Journey Data by Year (DETR 1998b)

	Persons per household												
Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Number of observations													
72/3	802	3100	2656	3673	1847	855	402	166	81	19	42	10	12
75/6	1349	5710	4360	5516	2833	1202	486	173	91	28	4		
78/9	1334	4521	3395	5321	2551	986	460	162	70	24			
85/6	1742	5368	4094	5850	2286	663	264	60	11	7	2		
88	341	928	784	944	318	129	42	14					
89	701	2068	1453	1921	838	246	64	25		12			
90	701	1979	1357	1836	699	250	98	24	7	10			
91	673	1904	1480	1945	690	202	80	37	9				
92	682	1885	1423	1769	664	194	40	45	12				
93	715	1832	1302	1688	643	222	61	30		11			
94	690	1938	1233	1598	708	183	97	42					
95	657	1734	1276	1695	604	164	39	16	15				
Daily travel budget													
72/3	79.9	78.7	78.3	76.0	67.6	68.9	59.8	62.3	61.3	62.4	61.3	50.1	62.9
75/6	62.0	68.1	64.1	64.7	62.1	62.2	57.7	54.6	53.2	25.0	25.0		
78/9	77.5	82.1	78.5	76.0	69.0	76.4	72.0	58.6	66.6	75.5			
85/6	96.7	92.3	83.8	80.3	80.3	80.3	67.9	72.9	58.2	30.0	60.0		
88	96.3	94.5	91.4	74.2	77.8	68.9	75.6	147.2					
89	94.9	92.0	90.3	85.1	76.1	66.0	109.8	96.0		42.8			
90	93.2	95.5	88.0	84.2	74.2	73.2	63.3	69.2	32.3	60.2			
91	92.4	87.1	86.6	81.6	72.3	94.8	80.5	107.4	59.4				
92	87.7	87.7	85.7	81.0	85.4	58.8	98.1	69.5	19.0				
93	92.1	87.5	83.1	80.2	75.9	67.5	53.1	44.1		55.0			
94	86.4	86.0	83.2	77.3	73.5	79.8	91.9	58.3					
95	87.6	81.6	79.7	78.1	73.3	63.6	57.6	62.6	53.3				
ave.	87.2	86.1	82.7	78.2	74.0	71.7	74.0	75.2					
Trip rate													
72/3	3.51	3.50	3.64	3.71	3.62	3.47	3.26	3.25	3.31	3.68	3.00	2.10	2.08
75/6	3.10	3.24	3.33	3.42	3.44	3.21	3.04	2.86	2.45	2.50	2.00		
78/9	3.31	3.60	3.74	3.86	3.72	3.72	3.50	3.41	4.13	3.13			
85/6	3.78	3.68	3.73	3.81	3.74	3.70	3.48	3.23	2.09	2.00	2.00		
88	3.60	3.78	3.84	3.85	3.91	3.51	3.38	3.14					
89	3.74	3.70	3.95	3.98	3.96	3.63	3.70	4.32		2.67			
90	3.84	3.73	3.82	3.92	3.62	3.18	3.31	3.08	2.29	4.50			
91	3.82	3.66	3.63	3.87	3.77	3.84	3.56	2.97	3.11				
92	3.62	3.68	3.60	3.66	3.59	3.38	3.25	2.98	2.00				
93	3.65	3.68	3.69	3.65	3.58	3.47	3.28	3.07		3.55			
94	3.59	3.76	3.71	3.86	3.72	3.40	3.09	4.00					
95	3.60	3.48	3.65	3.80	3.54	3.46	3.18	3.50	3.20				
ave.	3.60	3.62	3.69	3.78	3.68	3.50	3.34	3.32					

Table A.3: Household Size per Year (DETR 1998b)

Household structure													
Year	01	02	03	04	05	06	07	08	09	10	11	12	13
Number of observations													
72/3	420	380	412	1790	894	1293	1360	2467	680	529	2275	1159	6
75/6	660	657	666	2756	1579	2102	1978	3889	1159	923	3368	1706	207
78/9	616	718	706	2342	1473	1975	1420	3753	896	672	2536	1469	248
85/6	966	776	911	2960	1497	2113	1981	3710	1052	1088	1895	1088	310
88	173	168	166	506	256	423	361	628	129	187	320	154	29
89	381	320	353	1065	650	781	672	1138	381	402	763	333	89
90	387	314	299	1079	601	689	668	1233	281	322	710	292	86
91	382	291	301	1015	588	774	706	1199	358	388	642	302	74
92	384	298	297	1027	561	749	674	1115	323	331	613	249	93
93	400	315	278	1039	515	701	601	1174	235	279	606	323	38
94	383	307	313	1097	528	654	579	1086	293	219	682	280	68
95	394	263	228	990	516	726	550	1133	267	295	568	218	52
Daily travel budget													
72/3	96.2	62.3	98.0	80.3	66.5	78.9	77.6	71.3	81.6	90.9	62.9	73.5	70.3
75/6	69.4	54.5	71.7	70.5	62.9	64.5	65.0	60.7	69.2	76.7	58.6	64.3	65.3
78/9	85.3	70.8	86.4	83.1	78.3	73.7	85.1	71.3	86.4	88.3	67.2	75.2	80.0
85/6	106.4	84.6	99.9	94.4	83.5	77.9	90.0	75.8	83.7	92.5	71.7	86.1	98.5
88	105.2	87.2	95.8	94.2	94.5	87.4	96.1	69.0	84.2	84.8	64.7	89.3	151.4
89	103.9	84.2	100.0	92.4	87.1	85.9	95.4	79.7	90.3	95.3	75.2	75.5	83.5
90	101.1	83.5	89.9	100.9	88.6	84.5	91.6	80.0	92.4	92.9	73.0	71.7	70.8
91	103.3	78.2	98.1	85.9	83.4	79.4	94.4	75.7	82.3	99.5	70.9	87.3	109.3
92	96.0	76.9	86.1	91.9	80.9	83.1	88.7	75.9	81.6	97.6	81.8	72.3	77.6
93	98.9	83.5	83.6	89.0	86.3	79.1	87.8	77.8	77.1	92.9	64.2	82.6	88.0
94	93.8	77.2	82.8	93.1	73.2	81.1	85.6	73.4	88.8	81.3	75.6	79.0	63.8
95	94.6	77.0	91.9	82.9	74.5	79.6	79.8	73.8	89.9	84.0	68.4	77.2	59.2
ave.	96.2	76.6	90.4	88.2	80.0	79.6	86.4	73.7	83.9	89.7	69.5	77.8	84.8
Trip rate													
72/3	3.90	3.08	4.07	3.58	3.07	3.69	3.58	3.73	3.67	3.70	3.37	3.74	3.33
75/6	3.46	2.73	3.63	3.32	2.91	3.34	3.36	3.43	3.36	3.40	3.28	3.32	3.27
78/9	3.74	2.94	4.03	3.71	3.24	3.69	3.80	3.87	3.84	3.86	3.60	3.84	3.64
85/6	4.13	3.34	3.86	3.76	3.40	3.67	3.79	3.79	3.88	3.81	3.65	3.77	3.71
88	3.80	3.39	3.76	3.90	3.55	3.74	3.96	3.86	3.68	3.95	3.62	4.03	3.52
89	4.08	3.35	4.02	3.69	3.55	3.95	3.94	3.95	4.14	3.90	3.94	3.71	3.81
90	4.22	3.37	3.90	3.87	3.40	3.73	3.91	3.95	4.05	3.68	3.34	3.82	3.47
91	4.11	3.44	3.93	3.73	3.39	3.49	3.77	3.89	3.97	3.72	3.75	3.69	3.74
92	3.87	3.30	3.82	3.80	3.37	3.55	3.66	3.67	3.40	3.87	3.51	3.37	3.61
93	3.95	3.26	3.86	3.76	3.42	3.64	3.74	3.73	3.31	3.61	3.33	3.85	3.68
94	3.98	3.09	3.59	3.91	3.56	3.72	3.70	3.81	4.01	3.85	3.65	3.59	3.41
95	3.97	3.05	3.57	3.61	3.20	3.67	3.61	3.76	3.80	3.96	3.54	3.50	3.08
ave.	3.9	3.20	3.84	3.72	3.34	3.66	3.74	3.79	3.76	3.78	3.55	3.69	3.52

Table A.4: Househod Structure by Year (DETR 1998b)

Cars per household						
Year	0	1	2	3	4	≥ 5
Number of observations						
72/3	5400	6743	1330	192		
75/6	7269	11338	2815	251	63	
78/9	6969	9674	1974	181	26	
85/6	5212	10044	4230	735	106	20
88	809	1818	721	134	14	4
89	1660	3461	1833	283	73	18
90	1474	3347	1788	282	60	10
91	1396	3343	1857	353	45	26
92	1323	3139	1890	293	52	17
93	1378	3086	1676	301	61	2
94	1358	3047	1724	264	79	17
95	1287	2789	1760	269	86	9
Daily travel budget						
72/3	67.7	78.7	81.9	93.1		
75/6	59.5	65.9	71.0	72.0	67.2	
78/9	73.5	77.7	82.5	92.4	64.0	
85/6	83.5	83.3	89.4	100.3	103.2	80.7
88	86.1	86.5	81.7	98.2	127.6	96.8
89	85.7	85.4	92.9	86.7	91.7	118.8
90	84.4	85.6	89.4	108.4	88.0	77.7
91	83.9	79.4	89.8	107.3	105.4	111.4
92	77.9	81.3	90.8	102.7	82.4	89.1
93	76.7	80.6	90.5	84.6	102.2	
94	75.6	78.9	90.1	96.1	74.8	59.4
95	74.6	76.9	84.5	86.8	97.5	87.9
ave.	77.4	80.0	86.2	94.0	91.3	90.2
Trip rate						
72/3	3.18	3.80	4.03	4.31		
75/6	2.95	3.45	3.59	3.79	3.75	
78/9	3.31	3.89	4.09	4.23	4.62	
85/6	3.41	3.79	3.95	4.03	4.31	4.70
88	3.33	3.90	3.95	4.28	3.14	4.75
89	3.40	3.94	4.06	4.22	3.71	3.72
90	3.32	3.83	3.97	4.17	3.83	3.90
91	3.33	3.71	3.96	4.30	4.16	4.46
92	3.21	3.66	3.82	3.80	4.13	3.06
93	3.26	3.65	3.87	3.92	4.72	3.00
94	3.19	3.80	3.99	4.08	3.59	4.06
95	3.24	3.64	3.80	3.87	4.06	2.56
ave.	3.26	3.75	3.93	4.08	4.00	3.80

Table A.5: Car-Ownership by Year (DETR 1998b)

Income per household									
Year	1	2	3	4	5	6	7	8	9
Number of observations									
72/3	380	550	1375	937	2106	1742	3455	664	557
75/6	39	1624	493	3327	2008	7695	2719	3268	579
78/9	77	1178	916	1896	2743	1570	4024	5122	1298
85/6	462	2149	2021	3379	2571	2134	3453	2287	1891
88	20	326	334	424	272	338	593	599	594
89	55	578	618	717	550	643	1331	1496	1340
90	22	530	477	752	487	518	1144	1362	1669
91	33	411	526	713	507	497	1098	1333	1902
92	33	374	604	478	829	1023	1279	1085	1009
93	27	340	623	484	856	961	1231	1031	951
94	23	300	560	440	845	821	1221	985	1060
95	18	237	496	605	553	800	1793	824	752
Daily travel budget									
72/3	67.6	65.6	66.2	69.1	71.3	75.3	80.7	84.2	85.5
75/6	70.3	58.2	50.0	59.3	59.7	64.3	68.3	72.7	78.6
78/9	88.2	73.5	75.8	72.0	75.2	75.4	74.1	81.0	83.5
85/6	81.5	80.9	80.4	80.4	83.1	82.0	89.3	91.7	97.7
88	75.6	86.7	79.6	81.8	90.6	76.6	88.0	82.6	97.5
89	73.6	75.1	88.3	83.9	90.5	82.4	84.9	91.3	94.8
90	87.1	79.3	92.8	80.3	81.3	78.3	78.4	88.9	100.5
91	103.1	75.0	77.1	76.2	75.5	74.1	84.6	85.8	96.4
92	92.7	72.2	78.7	69.9	75.3	82.0	86.2	86.6	103.3
93	99.2	82.1	73.4	72.9	77.6	80.5	81.0	86.8	98.9
94	103.7	69.2	76.9	67.6	75.3	81.3	82.1	90.1	93.5
95	81.9	68.0	72.0	69.8	76.5	70.6	85.1	78.4	89.1
ave.	85.4	73.8	75.9	73.6	77.7	76.9	81.9	85.0	93.3
Trip rate									
72/3	2.95	3.11	3.37	3.53	3.50	3.64	3.81	3.61	4.02
75/6	2.64	2.77	2.91	3.16	3.17	3.35	3.50	3.52	3.95
78/9	2.84	3.06	3.27	3.40	3.57	3.80	3.83	3.87	4.11
85/6	3.31	3.47	3.46	3.64	3.84	3.75	3.80	3.98	4.07
88	3.15	3.33	3.57	3.62	4.10	3.91	3.68	3.90	4.09
89	3.40	3.19	3.61	3.64	3.87	3.77	4.05	3.90	4.17
90	3.68	3.40	3.23	3.45	3.40	3.73	3.75	4.00	4.13
91	3.79	3.30	3.35	3.56	3.46	3.81	3.78	3.85	3.95
92	3.09	3.15	3.31	3.41	3.49	3.57	3.70	3.81	3.97
93	3.11	3.56	3.30	3.27	3.56	3.64	3.83	3.74	3.86
94	4.35	3.26	3.29	3.39	3.67	3.72	3.88	3.93	4.01
95	4.33	3.28	3.36	3.20	3.38	3.59	3.78	3.74	3.82
ave.	3.39	3.24	3.34	3.44	3.58	3.69	3.78	3.82	4.01

Table A.6: Household Income by Year (DETR 1998b)

Appendix B

Tables of Modes of Transport

This appendix contains the detailed tables relating to Section 4.2. Table B.1 - B.6 complement Table 4.1 and Figure 4.1 and give the basic travel measures, percentages of stage per journey and the power values according to the mode of transport and year. The following modes are used in this study: walking, bicycle, car-driver, car-passenger, stage bus and railway. The data analysis shows that the travel measures depend on the mode of transport used for daily travelling and daily travel times are directly proportional to the power values thus, supporting the hypothesis of a constant travel energy budget.

Walking											
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
R-day 1-6												
72/3	14.3	n.a.	n.a.	n.a.	n.a.	2.2	0.7	99.7	0.3	0.0	0.0	n.a.
75/6	14.8	n.a.	n.a.	n.a.	n.a.	2.3	0.8	99.6	0.4	0.0	0.0	n.a.
78/9	13.2	66	43	29	19	2.3	0.8	99.7	0.3	0.0	0.0	9.4
85/6	8.9	67	45	29	21	2.3	0.8	99.4	0.5	0.1	0.0	9.2
88	7.5	68	48	31	24	2.2	0.6	100.0	0.0	0.0	0.0	9.1
89	7.9	69	53	31	28	2.2	0.8	99.7	0.3	0.0	0.0	8.9
90	6.9	67	44	30	20	2.3	0.9	99.9	0.1	0.0	0.0	9.2
91	7.4	71	58	31	27	2.3	0.9	99.7	0.3	0.0	0.0	8.7
92	6.1	66	41	30	20	2.2	0.6	99.9	0.1	0.0	0.0	9.4
93	5.9	67	42	30	18	2.2	0.7	99.9	0.1	0.0	0.0	9.2
94	5.8	68	45	31	21	2.2	0.8	n.a.	n.a.	n.a.	n.a.	9.1
95	6.1	67	43	30	20	2.2	0.7	n.a.	n.a.	n.a.	n.a.	9.2
R-day 7												
72/3	40.4	42	40	14	14	3.0	1.5	99.7	0.1	0.1	0.0	14.7
75/6	36.4	42	34	15	13	2.8	1.4	99.8	0.1	0.1	0.0	14.5
78/9	34.8	43	36	15	14	2.8	1.4	99.9	0.1	0.0	0.0	14.1
85/6	31.4	42	39	15	16	2.9	1.4	99.9	0.1	0.0	0.0	14.7
88	28.1	38	41	14	17	2.8	1.3	99.6	0.4	0.1	0.0	16.3
89	27.9	41	34	14	15	2.9	1.4	99.9	0.1	0.0	0.0	15
90	27.8	40	37	14	16	2.8	1.4	100.0	0.0	0.0	0.0	15.5
91	26.2	38	37	14	17	2.3	0.9	99.8	0.2	0.0	0.0	16.2
92	25.2	40	55	15	48	2.7	1.3	100.0	0.0	0.0	0.0	15.4
93	27.0	37	33	13	14	2.7	1.3	99.9	0.1	0.0	0.0	16.6
94	26.1	36	34	13	12	2.8	1.4	n.a.	n.a.	n.a.	n.a.	16.8
95	24.3	40	36	14	14	2.8	1.4	n.a.	n.a.	n.a.	n.a.	15.5
difference												
72/3	26.1	n.a.	n.a.	n.a.	n.a.	0.8	0.8	0.0	-0.2	0.1	0.0	n.a.
75/6	21.6	n.a.	n.a.	n.a.	n.a.	0.6	0.6	0.3	-0.3	0.1	0.0	n.a.
78/9	21.6	-22	-7	-13	-5	0.5	0.6	0.1	-0.2	0.0	0.0	4.7
85/6	22.5	-25	-6	-15	-6	0.6	0.6	0.5	-0.4	-0.1	0.0	5.5
88	20.6	-30	-6	-17	-7	0.6	0.7	-0.4	0.3	0.1	0.0	7.2
89	20.0	-28	-19	-17	-13	0.6	0.6	0.2	-0.2	0.0	0.0	6.1
90	20.8	-28	-7	-16	-4	0.6	0.6	0.1	-0.1	0.0	0.0	6.3
91	18.8	-33	-21	-17	-10	0.0	0.0	0.1	-0.1	0.0	0.0	7.5
92	19.1	-26	14	-15	28	0.5	0.6	0.1	-0.1	0.0	0.0	6
93	21.1	-30	-9	-17	-4	0.5	0.6	0.0	0.0	0.0	0.0	7.4
94	20.3	-31	-11	-17	-8	0.6	0.7	n.a.	n.a.	n.a.	n.a.	7.7
95	18.2	-28	-7	-16	-6	0.6	0.6	n.a.	n.a.	n.a.	n.a.	6.3

R-day ... Recording Day, M.S. ... Modal Split, t_d ... Daily Travel Time, t_s ... Single Trip Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation, st/j ... Stages per Journey (Single Trip), P_m ... Power by Mode.

Table B.1: Trip Data by Year of Walking (DETR 1998b)

Bicycle												
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
day 1-6												
72/3	3.7	n.a.	n.a.	n.a.	n.a.	2.5	1.0	99.9	0.1	0.0	0.0	n.a.
75/6	4.0	n.a.	n.a.	n.a.	n.a.	2.7	1.2	99.8	0.1	0.1	0.0	n.a.
78/9	3.2	46	40	17	16	2.7	1.2	99.8	0.0	0.2	0.0	13.4
85/6	3.1	42	41	16	19	2.6	1.2	99.6	0.2	0.2	0.0	14.7
88	2.9	40	41	14	15	2.7	1.3	100.0	0.0	0.0	0.0	15.6
89	2.7	40	35	15	15	2.6	1.2	100.0	0.0	0.0	0.0	15.6
90	2.2	41	38	16	16	2.6	1.3	99.8	0.2	0.1	0.0	14.9
91	2.2	41	41	17	18	2.4	1.0	100.0	0.0	0.0	0.0	15.1
92	2.3	42	41	17	22	2.4	0.9	99.7	0.1	0.2	0.0	14.7
93	2.1	42	31	17	14	2.5	1.0	99.7	0.3	0.0	0.0	14.8
94	2.2	41	33	17	16	2.4	0.9	n.a.	n.a.	n.a.	n.a.	15
95	1.8	45	39	19	20	2.4	1.0	n.a.	n.a.	n.a.	n.a.	13.6
day 7												
72/3	2.8	40	30	15	12	2.7	1.2	97.5	2.0	0.6	0.0	15.3
75/6	3.1	39	32	14	11	2.7	1.2	99.1	0.8	0.1	0.0	15.9
78/9	2.4	45	34	16	13	2.7	1.3	99.5	0.3	0.3	0.0	13.7
85/6	2.2	40	32	16	16	2.6	1.1	99.1	0.6	0.3	0.0	15.4
88	2.1	37	27	14	14	2.4	0.9	100.0	0.0	0.0	0.0	16.4
89	2.1	33	24	13	11	2.5	1.1	99.2	0.8	0.0	0.0	18.4
90	1.7	45	47	17	22	2.6	1.0	98.5	1.5	0.0	0.0	13.6
91	1.5	40	29	18	15	2.4	1.0	98.6	1.4	0.0	0.0	15.3
92	1.3	40	23	16	11	2.4	0.8	100.0	0.0	0.0	0.0	15.1
93	1.5	40	27	15	11	2.5	0.9	98.8	1.2	0.0	0.0	15.4
94	1.9	54	45	21	22	2.4	0.8	n.a.	n.a.	n.a.	n.a.	11.4
95	1.8	47	40	20	21	2.3	0.8	n.a.	n.a.	n.a.	n.a.	13
difference												
72/3	-0.9	n.a.	n.a.	n.a.	n.a.	0.2	0.2	-2.5	1.9	0.6	0.0	n.a.
75/6	-0.8	n.a.	n.a.	n.a.	n.a.	0.0	-0.1	-0.7	0.7	0.0	0.0	n.a.
78/9	-0.7	-2	-6	-1	-3	0.0	0.1	-0.3	0.2	0.1	0.0	0.4
85/6	-0.9	-2	-9	0	-3	-0.1	-0.1	-0.5	0.4	0.0	0.0	0.7
88	-0.8	-2	-14	0	-2	-0.3	-0.5	0.0	0.0	0.0	0.0	0.7
89	-0.6	-6	-11	-2	-4	-0.1	-0.2	-0.8	0.8	0.0	0.0	2.8
90	-0.5	4	10	1	5	0.0	-0.3	-1.3	1.4	-0.1	0.0	-1.3
91	-0.7	-1	-12	1	-3	0.0	0.0	-1.4	1.4	0.0	0.0	0.2
92	-1.0	-2	-19	-1	-11	0.0	-0.1	0.3	-0.1	-0.2	0.0	0.4
93	-0.5	-2	-4	-1	-3	0.1	-0.1	-0.9	0.9	0.0	0.0	0.6
94	-0.3	13	12	4	6	0.0	-0.1	n.a.	n.a.	n.a.	n.a.	-3.6
95	0.0	2	1	1	0	-0.1	-0.2	n.a.	n.a.	n.a.	n.a.	-0.6

R-day ... Recording Day, M.S. ... Modal Split, t_d ... Daily Travel Time, t_s ... Single Trip Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation, st/j ... Stages per Journey (Single Trip), P_m ... Power by Mode.

Table B.2: Trip Data by Year of Bicycle (DETR 1998b)

Car-Driver												
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
day 1-6												
72/3	29.3	n.a.	n.a.	n.a.	n.a.	3.5	1.9	99.3	0.5	0.2	0.0	n.a.
75/6	32.0	n.a.	n.a.	n.a.	n.a.	3.4	1.8	99.2	0.7	0.1	0.0	n.a.
78/9	29.0	74	67	20	26	3.7	2.1	99.7	0.3	0.0	0.0	8.3
85/6	37.5	75	81	21	36	3.6	1.9	99.7	0.3	0.0	0.0	8.3
88	39.6	76	78	20	32	3.7	2.0	99.8	0.2	0.0	0.0	8.2
89	39.8	76	78	21	34	3.7	2.0	99.6	0.3	0.1	0.0	8.1
90	41.4	75	78	20	33	3.7	2.0	99.7	0.2	0.0	0.0	8.3
91	41.8	74	75	21	33	3.6	1.9	99.6	0.3	0.0	0.0	8.3
92	42.3	74	78	20	35	3.6	2.0	99.7	0.3	0.0	0.0	8.4
93	42.7	74	82	21	36	3.5	1.9	99.6	0.4	0.0	0.0	8.3
94	41.9	76	84	21	38	3.6	2.0	n.a.	n.a.	n.a.	n.a.	8.1
95	43.0	72	69	20	30	3.5	2.0	n.a.	n.a.	n.a.	n.a.	8.5
day 7												
72/3	22.1	85	103	22	35	3.8	2.1	86.7	10.0	2.9	0.4	7.2
75/6	24.4	73	67	22	30	3.5	1.8	85.6	13.7	0.3	0.4	8.4
78/9	24.5	74	62	19	24	3.8	2.2	96.9	3.0	0.1	0.0	8.3
85/6	31.0	78	82	22	36	3.6	2.0	96.0	3.8	0.2	0.0	7.8
88	33.0	74	69	20	28	3.6	2.0	95.5	4.1	0.4	0.0	8.3
89	33.4	79	77	22	35	3.6	2.0	94.0	5.6	0.4	0.0	7.7
90	33.8	75	73	21	32	3.5	1.9	94.7	5.1	0.2	0.0	8.2
91	36.3	73	78	21	35	3.6	1.9	94.3	5.3	0.3	0.0	8.3
92	35.3	75	76	22	33	3.5	1.9	95.6	4.3	0.1	0.0	8.1
93	35.5	76	74	22	33	3.5	1.9	96.1	3.5	0.4	0.0	8.1
94	35.7	73	75	21	32	3.5	2.0	n.a.	n.a.	n.a.	n.a.	8.4
95	36.7	73	69	21	30	3.4	1.9	n.a.	n.a.	n.a.	n.a.	8.4
difference												
72/3	-7.2	n.a.	n.a.	n.a.	n.a.	0.3	0.2	-12.6	9.5	2.7	0.4	n.a.
75/6	-7.6	n.a.	n.a.	n.a.	n.a.	0.1	0.0	-13.6	13.0	0.2	0.4	n.a.
78/9	-4.5	0	-5	0	-1	0.1	0.1	-2.8	2.7	0.1	0.0	0
85/6	-6.5	4	1	1	0	0.1	0.1	-3.7	3.5	0.2	0.0	-0.4
88	-6.6	-2	-9	0	-5	-0.1	-0.1	-4.3	3.9	0.4	0.0	0.1
89	-6.4	3	-1	1	1	0.0	0.0	-5.6	5.3	0.3	0.0	-0.4
90	-7.6	0	-5	1	-1	-0.2	-0.1	-5.1	4.9	0.2	0.0	-0.1
91	-5.5	-1	3	0	2	0.0	0.0	-5.3	5.0	0.3	0.0	0
92	-7.0	2	-2	1	-3	-0.2	-0.1	-4.1	4.0	0.1	0.0	-0.2
93	-7.2	1	-8	1	-4	0.0	0.0	-3.4	3.0	0.4	0.0	-0.2
94	-6.2	-3	-9	0	-6	-0.1	0.0	n.a.	n.a.	n.a.	n.a.	0.2
95	-6.3	0	0	1	0	-0.1	0.0	n.a.	n.a.	n.a.	n.a.	-0.1

R-day … Recording Day, M.S. … Modal Split, t_d … Daily Travel Time, t_s … Single Trip Time, r … Trip Rate, $\langle\rangle$ … Average, σ … Standart Deviation, st/j … Stages per Journey (Single Trip), P_m … Power by Mode.

Table B.3: Trip Data by Year of Car-Driver (DETR 1998b)

Car-Passenger												
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
day 1-6												
72/3	24.4	n.a.	n.a.	n.a.	n.a.	2.3	1.0	97.7	1.7	0.5	0.1	n.a.
75/6	25.1	n.a.	n.a.	n.a.	n.a.	2.2	1.1	97.3	2.2	0.5	0.1	n.a.
78/9	25.6	60	65	23	32	2.6	1.2	99.1	0.8	0.1	0.0	10.4
85/6	27.9	54	62	21	32	2.6	1.2	99.2	0.7	0.1	0.0	11.4
88	29.0	55	59	21	31	2.7	1.3	99.3	0.7	0.1	0.0	11.3
89	29.3	58	67	22	34	2.7	1.4	99.2	0.7	0.2	0.0	10.7
90	29.7	57	64	21	32	2.7	1.4	99.2	0.8	0.0	0.0	10.8
91	29.4	58	67	22	35	2.6	1.2	99.3	0.6	0.1	0.0	10.7
92	30.2	55	61	21	31	2.6	1.3	99.2	0.7	0.0	0.0	11.3
93	30.3	58	68	22	37	2.6	1.3	99.6	0.4	0.0	0.0	10.7
94	31.1	56	65	21	35	2.7	1.4	n.a.	n.a.	n.a.	n.a.	11
95	30.9	53	55	20	27	2.6	1.3	n.a.	n.a.	n.a.	n.a.	11.6
day 7												
72/3	16.6	66	79	25	34	2.4	1.2	81.9	13.0	4.3	0.8	9.3
75/6	17.8	67	70	26	39	2.8	1.4	80.8	16.4	1.2	1.6	9.2
78/9	18.5	65	67	25	34	2.6	1.3	95.9	3.8	0.3	0.0	9.4
85/6	20.6	56	60	22	32	2.6	1.3	94.9	4.8	0.3	0.0	10.9
88	23.1	60	67	22	31	2.6	1.3	94.0	5.2	0.7	0.1	10.2
89	22.3	56	55	21	28	2.7	1.3	93.5	6.3	0.2	0.0	11
90	22.2	64	71	24	41	2.6	1.4	92.5	7.3	0.2	0.0	9.6
91	22.3	55	60	20	29	2.6	1.2	95.1	4.7	0.1	0.1	11.2
92	24.3	58	64	22	31	2.6	1.2	93.2	6.2	0.6	0.1	10.6
93	22.6	61	78	23	44	2.6	1.2	95.9	4.0	0.1	0.0	10
94	22.8	57	60	21	30	2.7	1.3	n.a.	n.a.	n.a.	n.a.	10.8
95	23.7	57	59	22	32	2.7	1.4	n.a.	n.a.	n.a.	n.a.	10.8
difference												
72/3	-7.7	n.a.	n.a.	n.a.	n.a.	0.2	0.1	-15.8	11.3	3.8	0.7	n.a.
75/6	-7.2	n.a.	n.a.	n.a.	n.a.	0.5	0.4	-16.4	14.2	0.7	1.5	n.a.
78/9	-7.1	6	3	1	2	0.1	0.1	-3.3	3.0	0.2	0.0	-1
85/6	-7.3	2	-2	0	-1	0.0	0.1	-4.3	4.1	0.2	0.0	-0.5
88	-5.9	5	8	2	1	0.0	0.0	-5.2	4.5	0.6	0.1	-1.1
89	-7.0	-2	-12	-1	-6	0.0	0.0	-5.7	5.6	0.0	0.0	0.3
90	-7.5	7	7	3	9	-0.1	0.0	-6.7	6.5	0.2	0.0	-1.2
91	-7.0	-3	-7	-2	-6	0.0	0.0	-4.2	4.1	0.1	0.1	0.5
92	-5.9	3	3	1	0	0.0	-0.1	-6.1	5.4	0.6	0.1	-0.7
93	-7.8	4	10	1	7	0.0	-0.1	-3.7	3.6	0.1	0.0	-0.7
94	-8.3	1	-5	0	-5	0.0	-0.1	n.a.	n.a.	n.a.	n.a.	-0.2
95	-7.2	4	4	1	5	0.0	0.0	n.a.	n.a.	n.a.	n.a.	-0.8

R-day ... Recording Day, M.S. ... Modal Split, t_d ... Daily Travel Time,
t_s ... Single Trip Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation,
st/j ... Stages per Journey (Single Trip), P_m ... Power by Mode.

Table B.4: Trip Data by Year of Car-Passenger (DETR 1998b)

Stage Bus												
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
day 1-6												
72/3	21.1	n.a.	n.a.	n.a.	n.a.	2.2	0.7	89.6	9.8	0.4	0.2	n.a.
75/6	16.7	n.a.	n.a.	n.a.	n.a.	2.2	0.6	92.6	6.9	0.4	0.0	n.a.
78/9	20.0	64	39	29	19	2.2	0.7	92.9	6.7	0.4	0.0	9.7
85/6	13.1	63	40	29	19	2.2	0.7	94.4	5.1	0.4	0.0	9.8
88	11.6	67	38	32	19	2.1	0.6	93.0	6.8	0.1	0.1	9.2
89	10.5	64	43	30	21	2.2	0.7	94.7	4.7	0.5	0.1	9.7
90	10.7	64	41	29	19	2.2	0.7	95.7	4.2	0.1	0.0	9.7
91	9.7	62	40	29	19	2.1	0.6	95.2	4.5	0.3	0.0	9.9
92	10.5	65	43	31	21	2.1	0.6	95.3	4.5	0.2	0.0	9.5
93	10.5	64	40	30	20	2.1	0.6	96.0	3.9	0.1	0.0	9.6
94	10.4	65	45	31	25	2.1	0.6	n.a.	n.a.	n.a.	n.a.	9.5
95	10.0	64	40	30	20	2.1	0.6	n.a.	n.a.	n.a.	n.a.	9.7
day 7												
72/3	12.5	71	48	31	20	2.2	0.7	6.6	28.7	56.1	8.5	8.6
75/6	9.9	62	36	29	17	2.1	0.6	18.3	40.4	38.4	2.9	9.9
78/9	12.7	71	47	32	22	2.2	0.6	59.8	25.1	13.1	2.1	8.6
85/6	7.2	72	40	33	20	2.1	0.6	36.1	24.3	37.4	2.2	8.6
88	6.5	77	32	35	16	2.0	0.3	20.6	30.7	47.0	1.7	8
89	6.6	67	38	32	17	2.1	0.6	33.7	34.0	30.0	2.3	9.1
90	6.7	66	36	31	19	2.1	0.5	28.0	36.3	33.6	2.2	9.3
91	6.0	62	35	29	16	2.1	0.6	35.6	28.0	36.0	0.4	9.8
92	6.5	73	39	34	19	2.2	0.6	38.4	25.0	35.0	1.7	8.4
93	6.3	72	39	35	20	2.1	0.4	35.2	27.1	36.6	1.1	8.5
94	5.9	67	36	32	19	2.1	0.5	n.a.	n.a.	n.a.	n.a.	9.1
95	7.0	68	36	33	17	2.0	0.4	n.a.	n.a.	n.a.	n.a.	9
difference												
72/3	-8.6	n.a.	n.a.	n.a.	n.a.	0.0	0.0	-83.0	18.9	55.7	8.4	n.a.
75/6	-6.8	n.a.	n.a.	n.a.	n.a.	0.0	-0.1	-74.3	33.5	38.0	2.8	n.a.
78/9	-7.3	8	8	3	4	0.0	-0.1	-33.1	18.4	12.7	2.0	-1.1
85/6	-5.9	9	0	4	1	0.0	-0.1	-58.3	19.1	36.9	2.2	-1.2
88	-5.1	10	-7	4	-4	-0.1	-0.3	-72.4	23.9	46.9	1.7	-1.2
89	-3.9	4	-5	2	-3	0.0	-0.1	-61.1	29.3	29.5	2.2	-0.6
90	-4.1	2	-4	2	-1	0.0	-0.1	-67.7	32.1	33.5	2.2	-0.4
91	-3.7	0	-5	0	-3	0.0	0.0	-59.6	23.5	35.7	0.3	-0.1
92	-4.0	8	-3	3	-2	0.0	0.0	-56.9	20.5	34.8	1.7	-1.1
93	-4.2	8	-1	4	1	0.0	-0.2	-60.8	23.2	36.5	1.1	-1.1
94	-4.5	2	-9	1	-6	0.0	-0.1	n.a.	n.a.	n.a.	n.a.	-0.4
95	-3.1	4	-4	2	-3	-0.1	-0.2	n.a.	n.a.	n.a.	n.a.	-0.7

R-day ... Recording Day, M.S. ... Modal Split, t_d ... Daily Travel Time, t_s ... Single Trip Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation, st/j ... Stages per Journey (Single Trip), P_m ... Power by Mode.

Table B.5: Trip Data by Year of Stage Bus (DETR 1998b)

Railway												
Year	M.S. [%]	$\langle t_d \rangle$ [min]	σ_{t_d}	$\langle t_s \rangle$ [min]	σ_{t_s}	$\langle r \rangle$ [no.]	σ_r	1st/j [%]	2st/j	3stj	≥4st/j	P_m [kJ / min]
day 1-6												
72/3	1.9	n.a.	n.a.	n.a.	n.a.	1.9	0.3	36.4	37.8	23.0	2.8	n.a.
75/6	1.7	n.a.	n.a.	n.a.	n.a.	1.9	0.3	38.4	37.2	21.5	2.9	n.a.
78/9	1.6	141	98	74	65	1.9	0.4	35.7	41.1	19.6	3.6	4.4
85/6	1.8	146	92	76	63	1.9	0.3	31.9	41.3	23.6	3.2	4.2
88	1.7	152	95	81	63	1.9	0.3	28.7	44.8	20.2	6.3	4.1
89	1.8	158	95	85	66	1.8	0.4	32.0	38.2	25.2	4.7	3.9
90	1.7	160	97	83	67	1.9	0.3	24.3	44.7	29.2	1.9	3.8
91	1.6	154	107	81	72	1.9	0.4	33.9	44.0	18.4	3.7	4
92	1.8	142	82	75	59	1.9	0.4	39.5	42.4	17.0	1.1	4.3
93	1.5	137	82	72	53	1.9	0.3	34.6	44.7	19.5	1.3	4.5
94	1.2	151	81	81	55	1.8	0.4	n.a.	n.a.	n.a.	n.a.	4.1
95	1.7	153	82	81	59	1.9	0.4	n.a.	n.a.	n.a.	n.a.	4
day 7												
72/3	1.2	174	144	87	76	1.9	0.3	0.0	8.1	44.8	47.1	3.5
75/6	0.7	119	75	63	55	1.9	0.3	6.8	18.4	52.9	21.8	5.1
78/9	1.1	158	96	88	74	1.8	0.4	8.0	32.9	35.4	23.6	3.9
85/6	1.3	145	74	75	47	1.9	0.3	5.3	12.8	58.2	23.7	4.2
88	1.0	125	72	68	43	2.0	0.2	0.0	7.3	70.7	22.0	4.9
89	1.3	186	135	98	97	1.8	0.4	3.0	8.1	47.5	41.4	3.3
90	1.2	173	81	92	60	1.9	0.3	2.1	12.4	60.8	24.7	3.5
91	1.4	166	91	91	71	1.9	0.4	1.9	13.1	43.9	41.1	3.7
92	1.5	160	73	82	42	1.9	0.3	4.0	16.1	41.1	38.7	3.8
93	1.3	149	62	77	44	1.9	0.3	0.0	17.6	54.9	27.5	4.1
94	1.2	173	95	101	66	1.7	0.5	n.a.	n.a.	n.a.	n.a.	3.5
95	1.4	148	68	78	39	1.9	0.3	n.a.	n.a.	n.a.	n.a.	4.1
difference												
72/3	-0.7	n.a.	n.a.	n.a.	n.a.	0.0	0.0	-36.4	-29.7	21.8	44.3	n.a.
75/6	-1.0	n.a.	n.a.	n.a.	n.a.	0.0	-0.1	-31.6	-18.7	31.4	18.9	n.a.
78/9	-0.5	17	-2	14	9	-0.1	0.0	-27.7	-8.2	15.9	20.0	-0.5
85/6	-0.5	-1	-18	-1	-16	0.0	0.0	-26.6	-28.5	34.7	20.5	0
88	-0.7	-27	-23	-13	-20	0.1	-0.1	-28.7	-37.5	50.6	15.7	0.8
89	-0.5	29	41	13	32	-0.1	0.0	-29.0	-30.1	22.3	36.8	-0.6
90	-0.6	13	-15	9	-7	0.0	0.0	-22.2	-32.3	31.7	22.8	-0.3
91	-0.3	11	-16	9	-2	0.0	0.0	-32.1	-30.9	25.5	37.5	-0.3
92	-0.3	17	-9	7	-17	0.0	-0.1	-35.5	-26.3	24.2	37.6	-0.5
93	-0.2	11	-21	5	-9	0.0	0.0	-34.6	-27.0	35.4	26.2	-0.4
94	0.0	23	13	20	11	-0.2	0.1	n.a.	n.a.	n.a.	n.a.	-0.6
95	-0.3	-5	-14	-4	-20	0.1	-0.1	n.a.	n.a.	n.a.	n.a.	0.1

R-day ... Recording Day, M.S. ... Modal Split, t_d ... Daily Travel Time,
t_s ... Single Trip Time, r ... Trip Rate, $\langle\rangle$ ... Average, σ ... Standart Deviation,
st/j ... Stages per Journey (Single Trip), P_m ... Power by Mode.

Table B.6: Trip Data by Year of Railway (DETR 1998b)

Appendix C

Tables and Figures of the Maxwell-Boltzmann Distribution of Travelling

This appendix contains the detailed tables and figures relating to Section 4.3. Figure C.1 depicts the modal energy functions (in comparison to Figure 4.10 which depicts the modal power functions). Table C.2 and Table C.3 complement Table 4.3 and give the parameters of the active Maxwell-Boltzmann distribution with the mean square error with respect to daily travelling and single trips. Figures C.2 - C.7 exhibit the empirical mode-specific distribution of daily travel time with the theoretical Maxwell-Boltzmann distribution. These figures round off the comparison to Figures 4.4 - 4.9 with respect to the record day (i.e. including or excluding short walk).

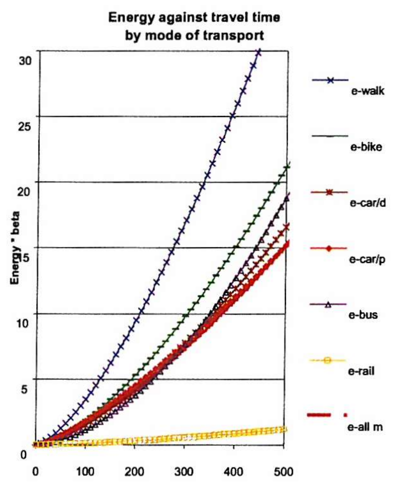


Figure C.1: Energy Functions by Mode of Transport

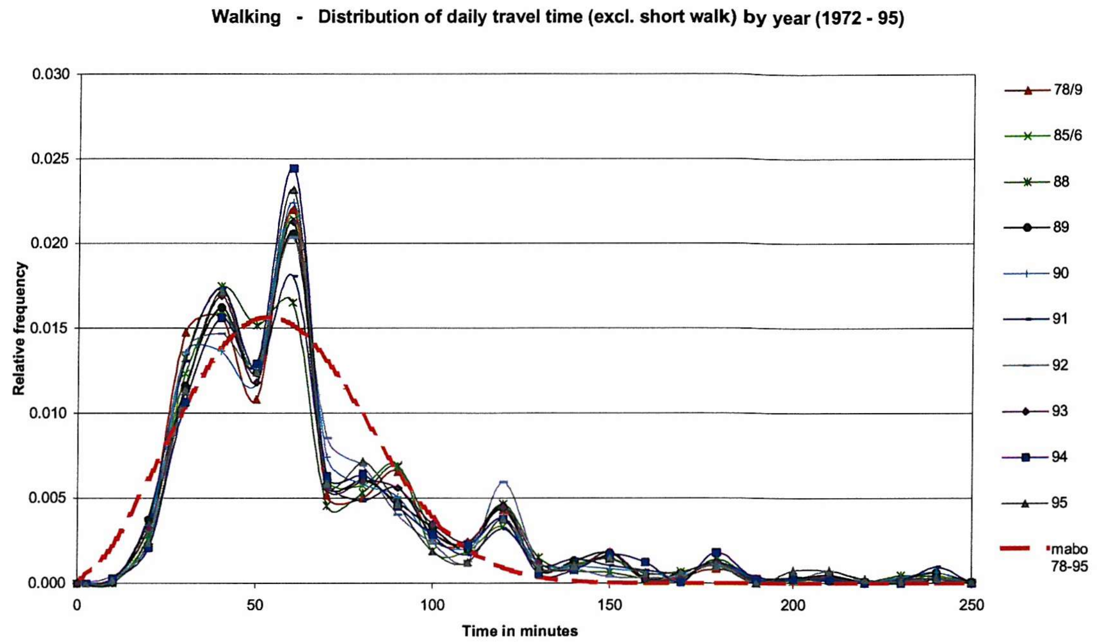


Figure C.2: Maxwell-Boltzmann Distribution of Walking

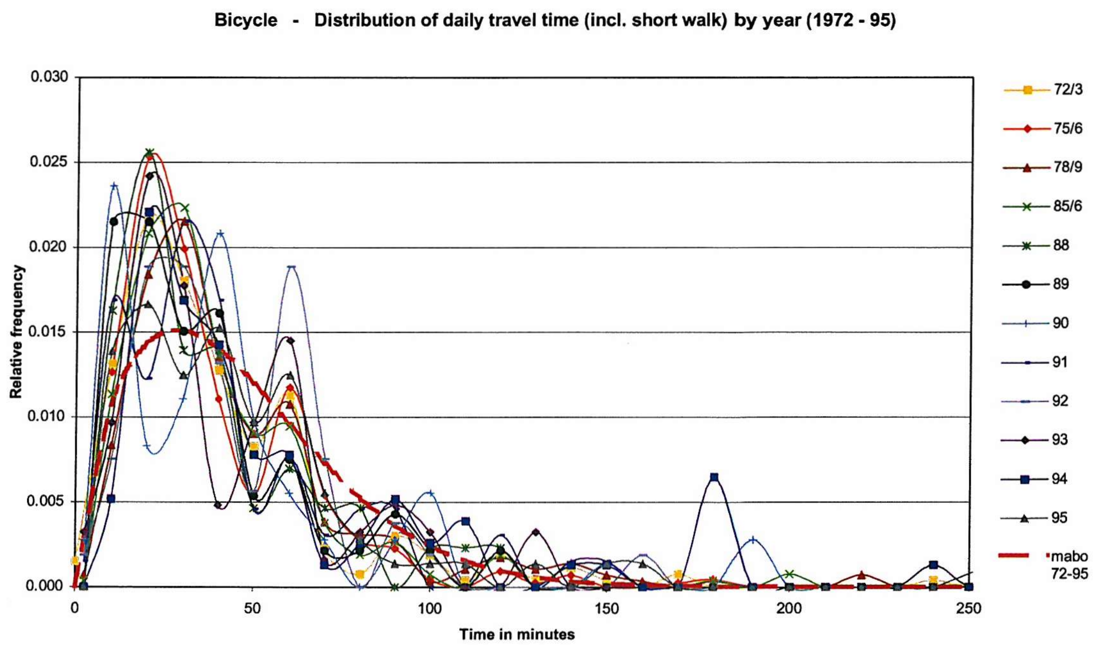


Figure C.3: Maxwell-Boltzmann Distribution of Bicycle

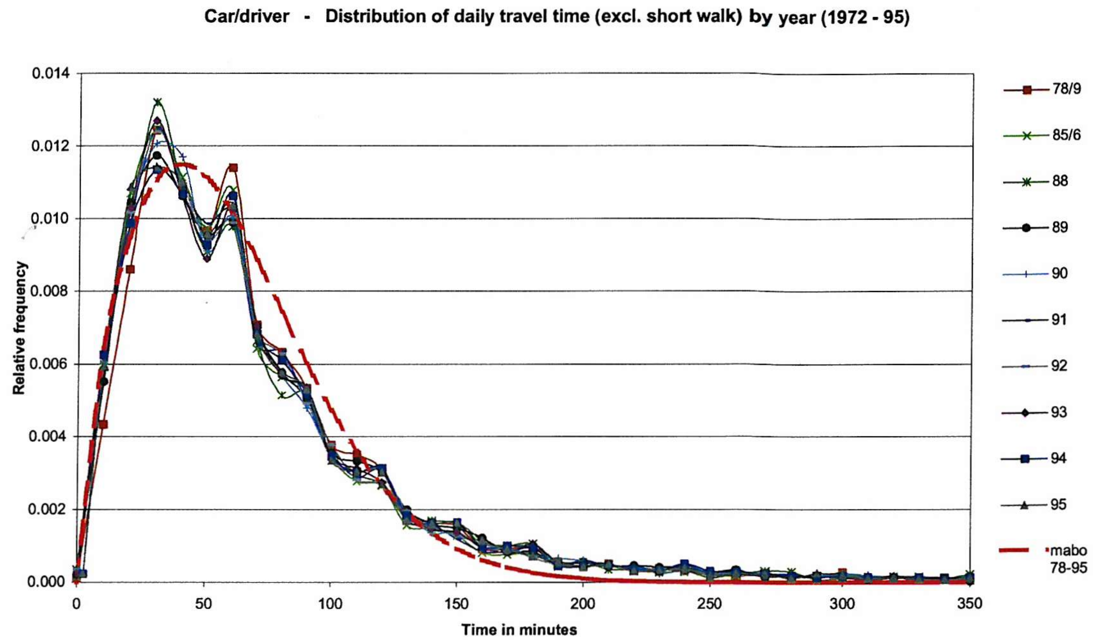


Figure C.4: Maxwell-Boltzmann Distribution of Car/Driver

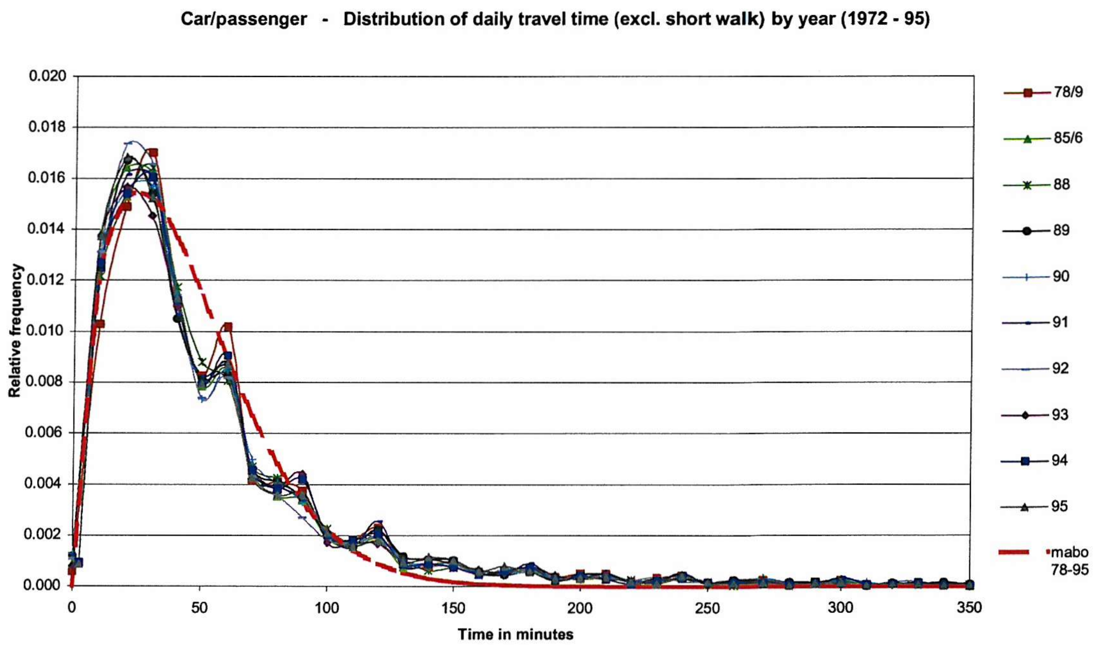


Figure C.5: Maxwell-Boltzmann Distribution of Car/Passenger

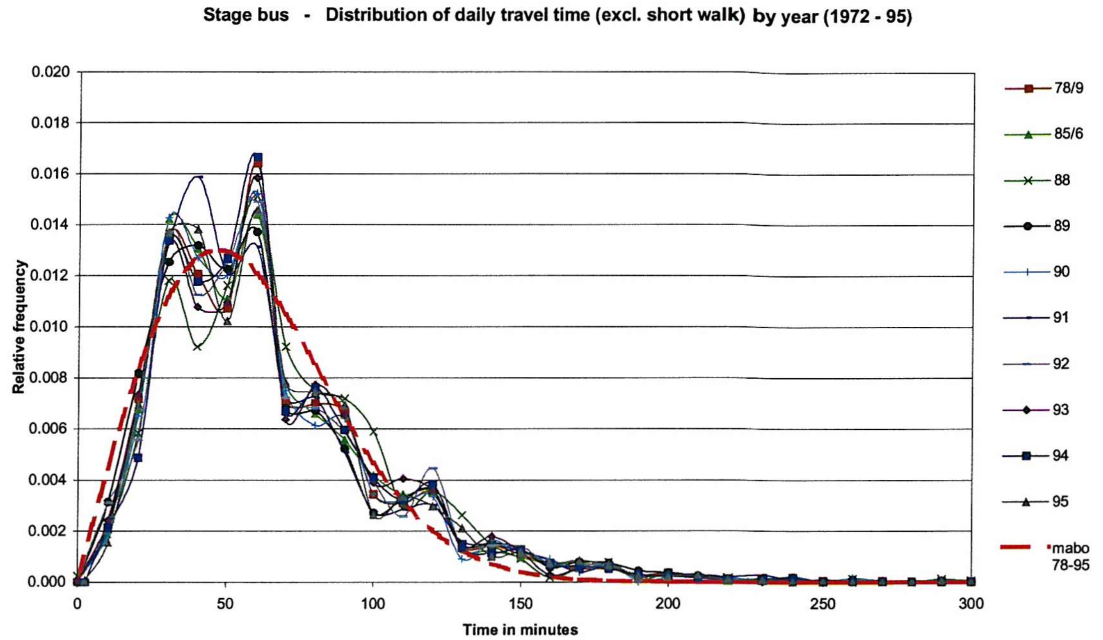


Figure C.6: Maxwell-Boltzmann Distribution of Stage Bus

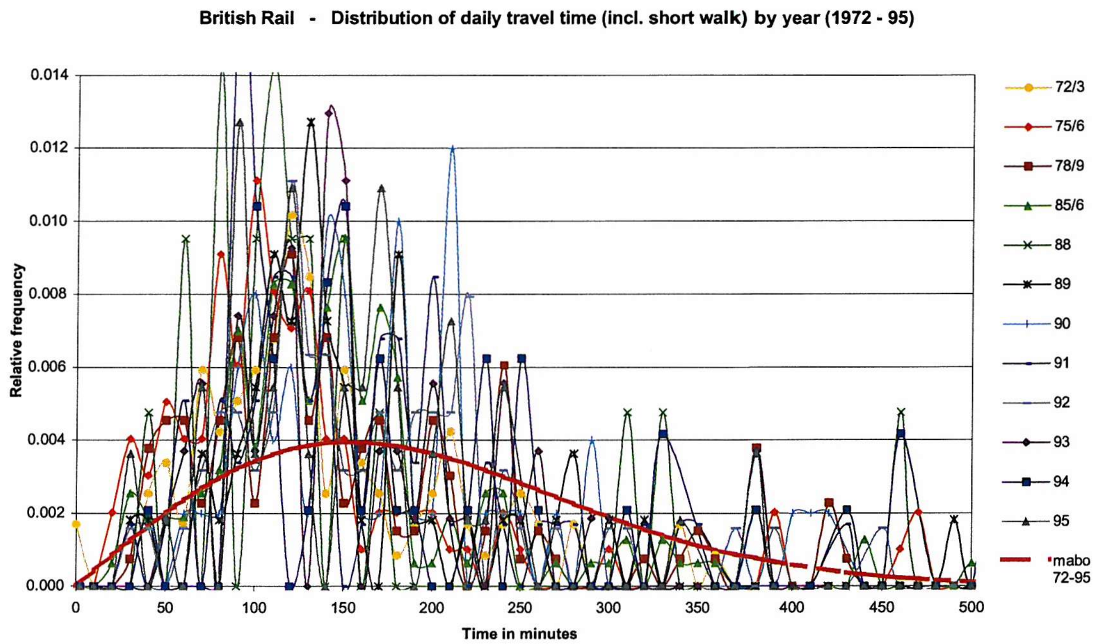


Figure C.7: Maxwell-Boltzmann Distribution of Railway

Year	c	b	mse	c	b	mse
	Day 1-6			Day 7		
Overall Daily Trip Parameters						
72/3	n.a.	n.a.	n.a.	1.45	440	0.01%
75/6	n.a.	n.a.	n.a.	1.53	545	0.01%
78/9	1.73	1435	0.01%	1.55	770	0.01%
85/6	1.56	710	0.00%	1.4	425	0.00%
88	1.53	650	0.00%	1.3	310	0.01%
89	1.5	590	0.00%	1.43	510	0.00%
90	1.51	600	0.00%	1.39	410	0.00%
91	1.53	625	0.00%	1.33	315	0.00%
92	1.51	575	0.00%	1.4	410	0.01%
93	1.51	580	0.00%	1.4	410	0.00%
94	1.53	620	0.00%	1.41	425	0.01%
95	1.51	585	0.00%	1.41	420	0.01%
ave	1.54	697	0.00%	1.42	449	0.01%
Overall Single Trip Parameters						
72/3	n.a.	n.a.	n.a.	1.43	55	0.04%
75/6	n.a.	n.a.	n.a.	1.58	90	0.05%
78/9	1.63	140	0.03%	1.56	85	0.05%
85/6	1.55	100	0.02%	1.48	65	0.03%
88	1.53	90	0.03%	1.39	50	0.04%
89	1.51	85	0.02%	1.46	60	0.03%
90	1.5	80	0.02%	1.44	55	0.03%
91	1.55	95	0.02%	1.49	65	0.03%
92	1.51	80	0.02%	1.46	60	0.03%
93	1.51	85	0.02%	1.44	55	0.04%
94	1.51	85	0.02%	1.5	65	0.04%
95	1.51	85	0.03%	1.49	65	0.04%
ave	1.53	93	0.02%	1.48	64	0.04%
c, b ... Parameters, mse ... Mean Square Error.						

Table C.1: Average Parameters b and c

Daily Trip Parameters												
	Day 1-6			Day 7			Day 1-6			Day 7		
Year	c	b	mse	c	b	mse	c	b	mse	c	b	mse
	Walking						Bicycle					
72/3	n.a.	n.a.	n.a.	1.45	205	0.04%	n.a.	n.a.	n.a.	1.33	210	0.10%
75/6	n.a.	n.a.	n.a.	1.59	370	0.05%	n.a.	n.a.	n.a.	1.69	655	0.13%
78/9	2.24	10810	0.04%	1.59	445	0.05%	1.69	665	0.07%	1.8	1410	0.08%
85/6	2.25	12505	0.04%	1.45	215	0.04%	1.6	385	0.07%	1.74	765	0.12%
88	1.78	2410	0.04%	1.45	250	0.07%	1.45	345	0.04%	n.a.	n.a.	n.a.
89	1.75	2040	0.04%	1.36	215	0.05%	1.6	465	0.05%	1.54	505	0.07%
90	1.99	5310	0.06%	1.45	225	0.06%	1.49	345	0.10%	1.04	115	0.15%
91	2.25	12695	0.05%	1.28	105	0.06%	1.41	310	0.04%	1.48	270	0.15%
92	1.99	5710	0.05%	1.21	115	0.06%	1.65	610	0.05%	1.31	335	0.16%
93	2.25	15335	0.04%	1.4	200	0.06%	1.49	370	0.07%	1.78	730	0.13%
94	2.25	16125	0.07%	1.46	210	0.06%	1.63	515	0.07%	n.a.	n.a.	n.a.
95	1.99	5010	0.05%	1.31	185	0.06%	1.49	340	0.06%	1.34	290	0.08%
	Car-Driver						Car-Passenger					
72/3	n.a.	n.a.	n.a.	1.45	525	0.01%	n.a.	n.a.	n.a.	1.18	155	0.02%
75/6	n.a.	n.a.	n.a.	1.56	785	0.02%	n.a.	n.a.	n.a.	1.31	285	0.03%
78/9	1.71	1410	0.06%	1.54	735	0.01%	1.51	360	0.00%	1.36	300	0.02%
85/6	1.58	695	0.07%	1.54	665	0.01%	1.45	250	0.01%	1.4	245	0.03%
88	1.51	565	0.01%	1.28	350	0.01%	1.44	265	0.01%	1.26	220	0.03%
89	1.55	680	0.01%	1.45	560	0.01%	1.43	245	0.01%	1.33	235	0.03%
90	1.56	680	0.01%	1.48	545	0.01%	1.39	215	0.02%	1.26	190	0.02%
91	1.56	690	0.00%	1.53	615	0.01%	1.44	255	0.01%	1.34	210	0.03%
92	1.56	685	0.01%	1.56	740	0.01%	1.46	255	0.01%	1.28	180	0.02%
93	1.55	655	0.01%	1.54	705	0.01%	1.4	230	0.01%	1.29	200	0.02%
94	1.55	685	0.00%	1.44	480	0.01%	1.44	260	0.01%	1.34	235	0.02%
95	1.56	695	0.01%	1.4	440	0.01%	1.43	235	0.01%	1.35	255	0.02%
	Bus						Railway					
72/3	n.a.	n.a.	n.a.	1.75	2375	0.02%	n.a.	n.a.	n.a.	1.48	8910	0.02%
75/6	n.a.	n.a.	n.a.	1.78	2110	0.04%	n.a.	n.a.	n.a.	1.74	6710	0.02%
78/9	1.99	4110	0.01%	1.73	1920	0.03%	1.51	3095	0.02%	1.1	810	0.02%
85/6	1.99	3910	0.01%	1.78	2610	0.03%	2	27000	0.03%	2	32110	0.01%
88	1.78	2505	0.02%	2.01	8310	0.06%	1.75	7695	0.01%	1.21	1555	0.03%
89	1.71	1425	0.02%	1.73	1810	0.04%	1.51	3710	0.01%	1.2	2710	0.02%
90	1.99	4110	0.03%	1.78	2095	0.04%	1.75	10735	0.01%	1.75	22370	0.04%
91	1.74	1795	0.02%	1.73	1815	0.05%	1.49	2420	0.01%	1.29	1410	0.02%
92	1.78	1960	0.02%	1.54	1210	0.04%	2	24930	0.01%	1.51	6510	0.01%
93	1.99	5210	0.03%	1.74	3350	0.03%	1.48	2810	0.01%	1.75	12585	0.02%
94	1.78	2085	0.02%	1.48	855	0.03%	2	29915	0.01%	1.21	1610	0.02%
95	1.78	2110	0.02%	2.01	5310	0.07%	2	45480	0.01%	1.49	2340	0.03%

c, b ... Parameters, mse ... Mean Square Error.

Table C.2: Daily Travel Parameters c and b by Year

Single Trip Parameters												
	Day 1-6			Day 7			Day 1-6			Day 7		
Year	c	b	mse	c	b	mse	c	b	mse	c	b	mse
	Walking						Bicycle					
72/3	n.a.	n.a.	n.a.	1.46	45	0.18%	n.a.	n.a.	n.a.	1.51	90	0.31%
75/6	n.a.	n.a.	n.a.	1.63	80	0.19%	n.a.	n.a.	n.a.	1.78	170	0.41%
78/9	2.49	3490	0.15%	1.68	85	0.20%	1.85	155	0.16%	1.75	215	0.38%
85/6	2.74	8310	0.11%	1.58	55	0.15%	1.69	85	0.15%	1.69	100	0.35%
88	2.28	2070	0.15%	1.50	40	0.25%	1.49	55	0.34%	3.28	830	0.63%
89	2.74	8510	0.12%	1.60	60	0.18%	1.53	65	0.19%	1.44	65	0.38%
90	2.74	8810	0.13%	1.65	60	0.22%	1.75	100	0.20%	1.53	65	0.32%
91	2.51	3950	0.11%	1.50	45	0.22%	1.51	70	0.18%	2.25	325	0.20%
92	2.51	4110	0.18%	1.43	45	0.20%	1.59	80	0.20%	1.58	155	0.36%
93	2.51	4610	0.14%	1.56	50	0.20%	1.51	75	0.18%	1.73	135	0.39%
94	2.75	11465	0.19%	1.64	60	0.25%	1.79	160	0.21%	1.19	55	0.28%
95	2.75	11100	0.18%	1.51	50	0.20%	1.61	100	0.18%	1.61	140	0.18%
ave	2.60	6643	0.15%	1.56	56	0.20%	1.63	95	0.20%	1.78	195	0.35%
	Car-Driver						Car-Passenger					
72/3	n.a.	n.a.	n.a.	1.56	75	0.06%	n.a.	n.a.	n.a.	1.53	85	0.08%
75/6	n.a.	n.a.	n.a.	1.66	110	0.09%	n.a.	n.a.	n.a.	1.51	85	0.09%
78/9	1.68	105	0.04%	1.68	105	0.08%	1.61	100	0.05%	1.61	105	0.10%
85/6	1.64	90	0.03%	1.63	90	0.06%	1.60	85	0.05%	1.55	75	0.08%
88	1.56	75	0.04%	1.54	75	0.09%	1.58	80	0.06%	1.33	55	0.12%
89	1.59	80	0.03%	1.60	90	0.05%	1.58	75	0.04%	1.58	75	0.10%
90	1.58	75	0.03%	1.55	75	0.06%	1.51	65	0.05%	1.49	65	0.07%
91	1.59	80	0.03%	1.59	80	0.05%	1.61	90	0.04%	1.59	75	0.10%
92	1.58	75	0.03%	1.56	80	0.05%	1.59	75	0.05%	1.55	75	0.08%
93	1.56	75	0.03%	1.54	75	0.06%	1.55	75	0.05%	1.48	65	0.09%
94	1.55	75	0.03%	1.55	75	0.06%	1.61	85	0.05%	1.56	80	0.09%
95	1.56	75	0.04%	1.56	80	0.06%	1.55	70	0.06%	1.55	80	0.10%
ave	1.59	81	0.03%	1.58	84	0.06%	1.58	80	0.05%	1.53	77	0.09%
	Bus						Railway					
72/3	n.a.	n.a.	n.a.	2.05	1200	0.12%	n.a.	n.a.	n.a.	2.01	8710	0.03%
75/6	n.a.	n.a.	n.a.	2.01	945	0.10%	n.a.	n.a.	n.a.	1.78	1985	0.05%
78/9	2.01	870	0.08%	1.91	810	0.10%	1.49	705	0.02%	1.16	345	0.04%
85/6	2.01	855	0.08%	1.80	625	0.21%	2.25	21525	0.02%	2.01	7410	0.04%
88	1.94	925	0.08%	2.28	3310	0.12%	2.00	5565	0.03%	1.23	375	0.07%
89	1.98	775	0.08%	1.66	420	0.12%	1.55	1300	0.02%	1.20	770	0.04%
90	1.99	790	0.09%	2.05	1210	0.16%	1.76	3090	0.02%	1.51	2545	0.05%
91	1.98	785	0.09%	1.93	1010	0.11%	1.55	1205	0.02%	1.08	185	0.05%
92	1.95	820	0.08%	1.76	680	0.11%	1.78	2610	0.02%	2.25	31335	0.04%
93	1.94	810	0.08%	1.79	1310	0.13%	1.73	2235	0.03%	1.54	1360	0.04%
94	2.05	1095	0.08%	1.58	385	0.17%	2.00	9135	0.02%	1.06	275	0.03%
95	1.95	780	0.09%	1.74	600	0.13%	2.25	23885	0.03%	1.76	2315	0.07%
ave	1.98	851	0.08%	1.88	1042	0.13%	1.84	7126	0.02%	1.55	4801	0.04%
c, b ... Parameters, mse ... Mean Square Error.												

Table C.3: Single Trip Parameters c and d by Year

Appendix D

Figures Related to Distance

This appendix contains figures relating to Section 4.3.2 and Section 5.1. Figure D.1 shows the cumulative distribution by mode of transport. Figure D.2 shows Figure 5.1 in greater detail including an estimate of the time-distance function. Figures D.3 - D.8 show the mode-specific graphs of Figure 5.1 and depict relationships of single travel time-distance by year. (It should be noted that the sharp increase of 0.5 in walking is most probably due to the assumed average value of 0.5 for the lowest class, since the data base contains only banded distance data.) Figure D.9 - D.14 show the mode specific graphs relating to Figure 5.2 and depict the frequencies of single travel distance by year.

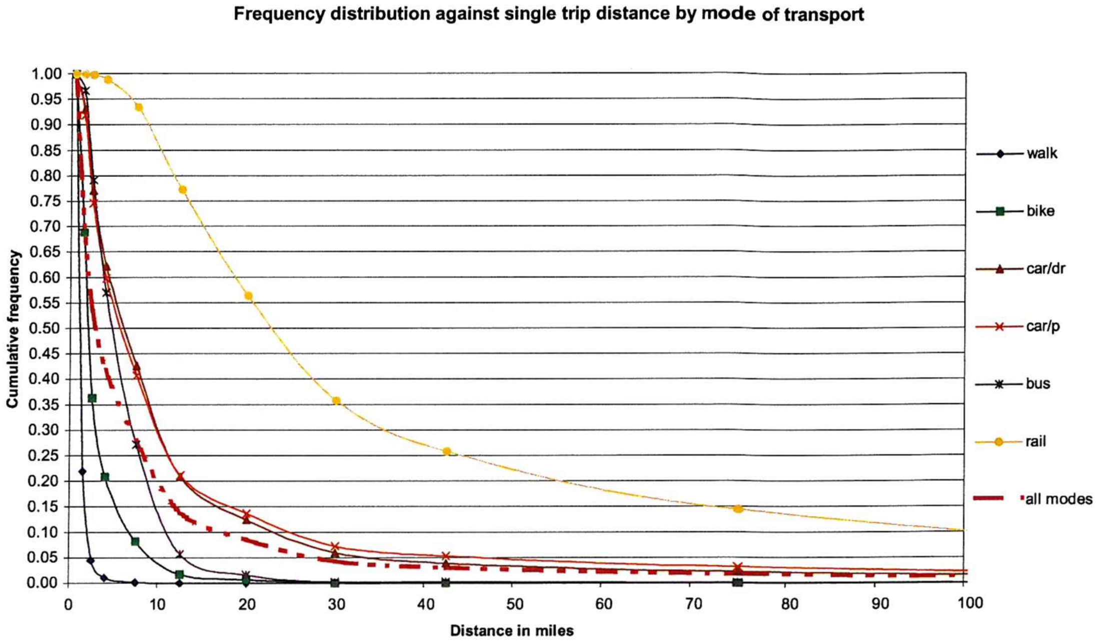


Figure D.1: Cumulative Distance Distribution by Mode of Transport (DETR 1998b)

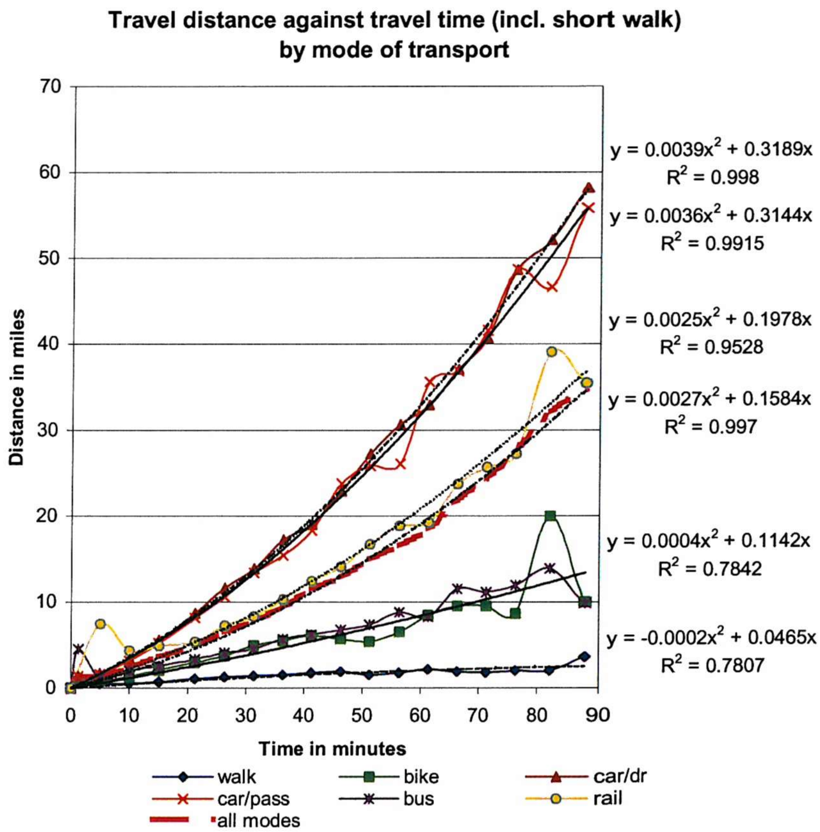


Figure D.2: Time-Distance Function by Mode of Transport (DETR 1998b)

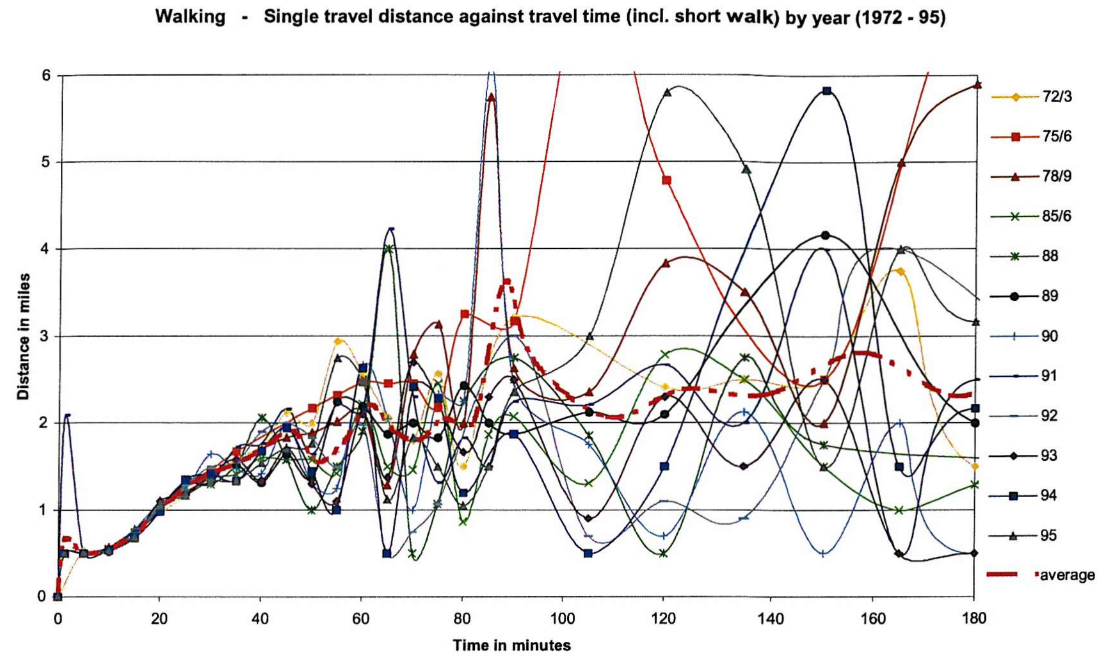


Figure D.3: Time-Distance Relationship by Year of Walking (DETR 1998b)

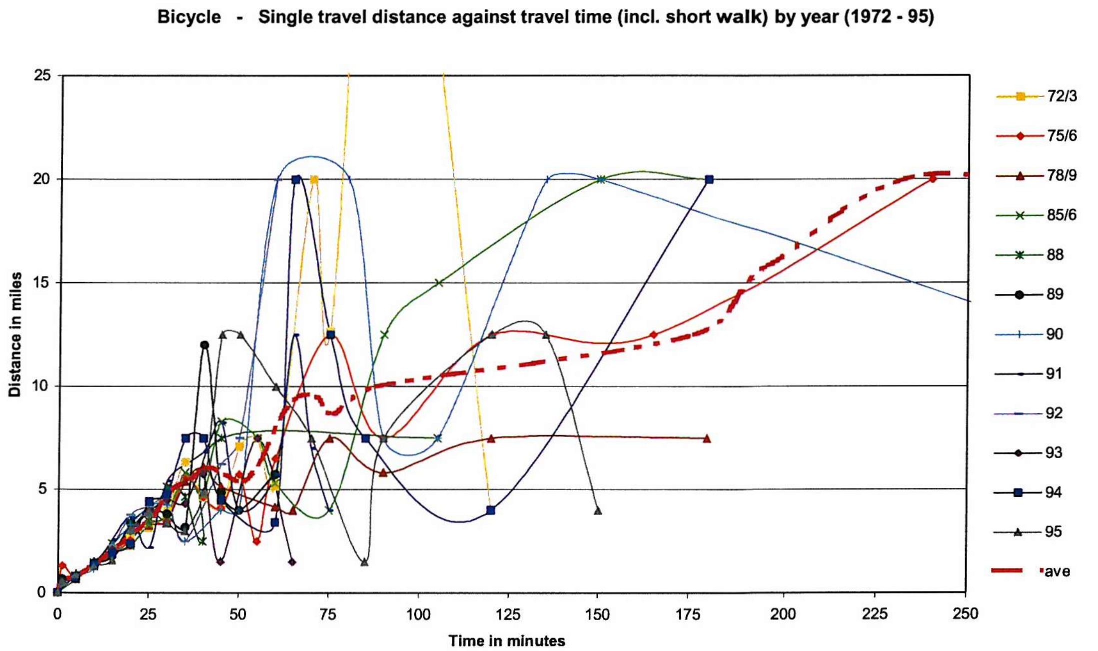


Figure D.4: Time-Distance Relationship by Year of Bicycle (DETR 1998b)

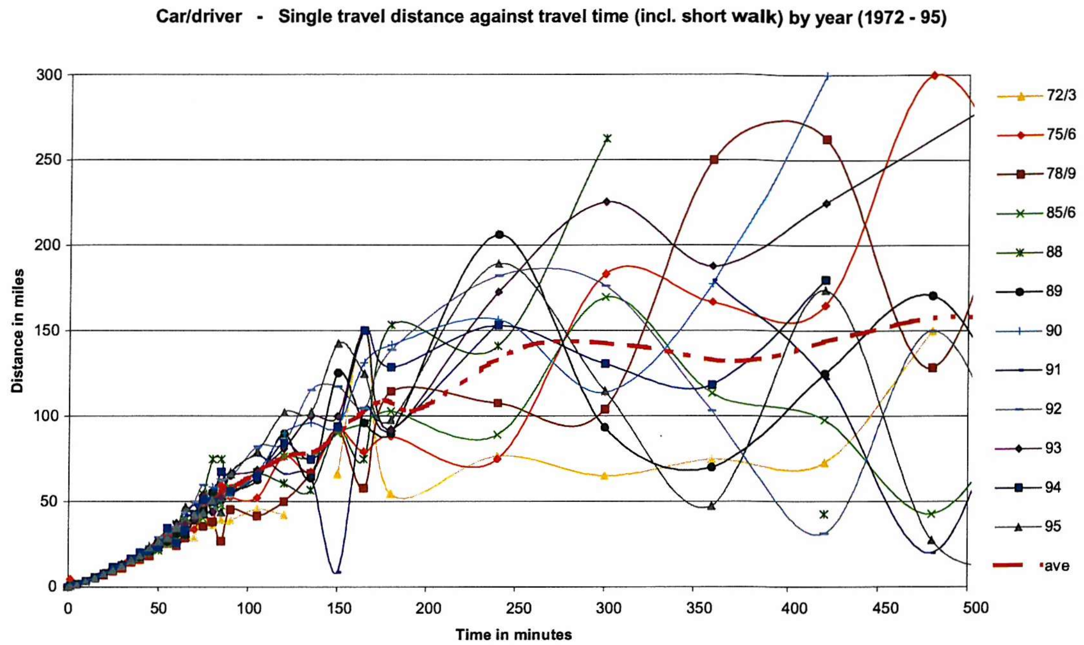


Figure D.5: Time-Distance Relationship by Year of Car/Driver (DETR 1998b)

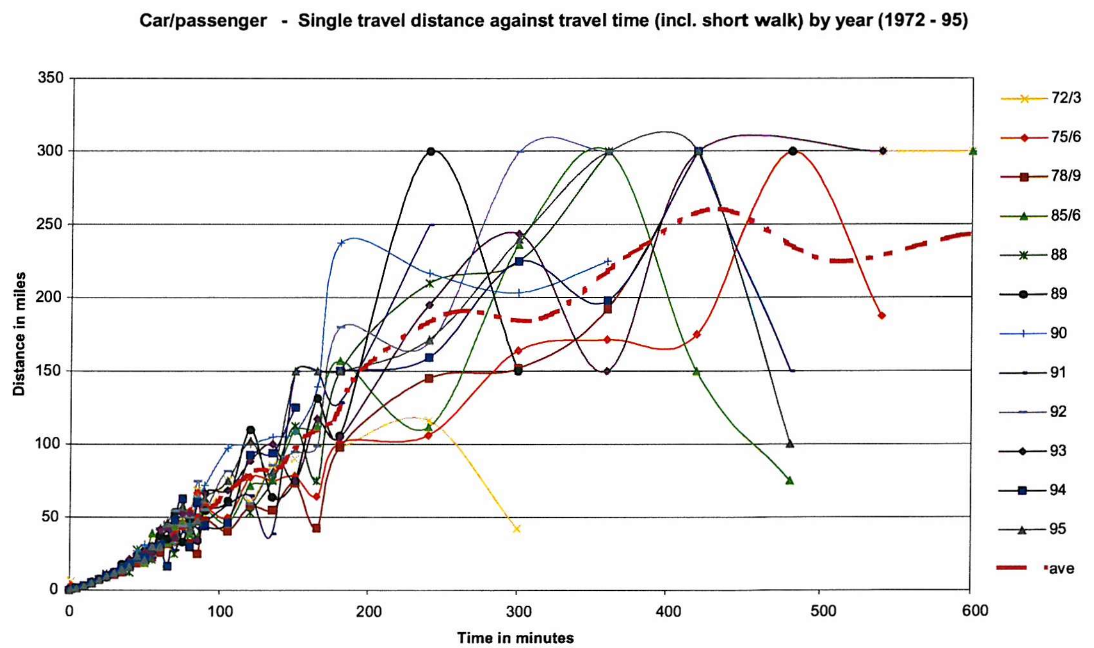


Figure D.6: Time-Distance Relationship by Year of Car/Passenger (DETR 1998b)

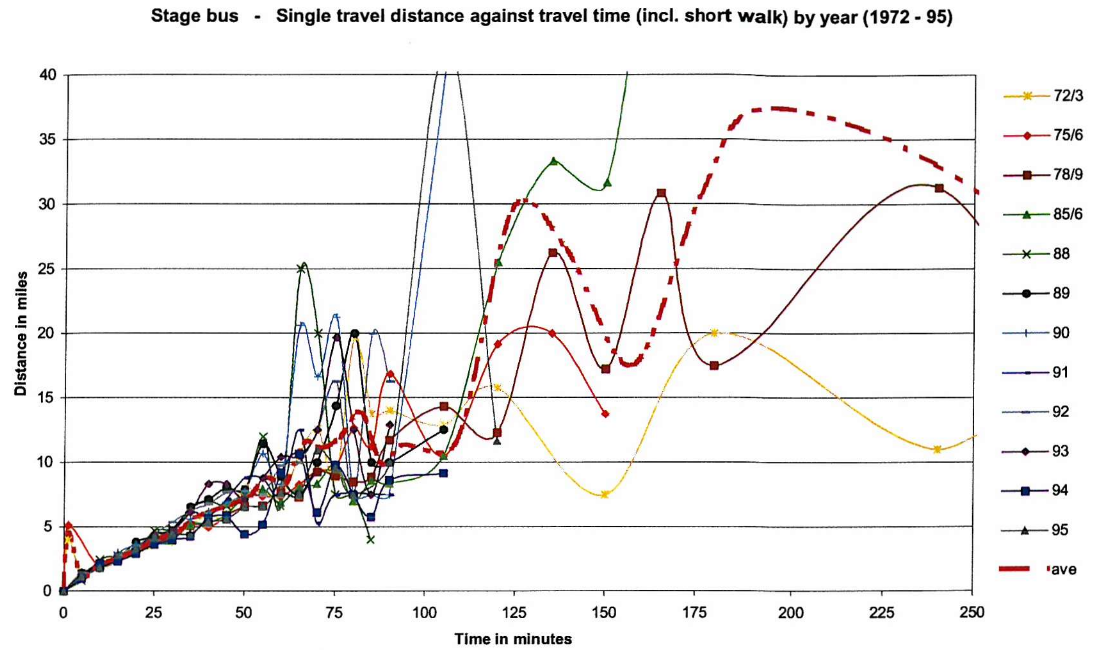


Figure D.7: Time-Distance Relationship by Year of Stage Bus (DETR 1998b)

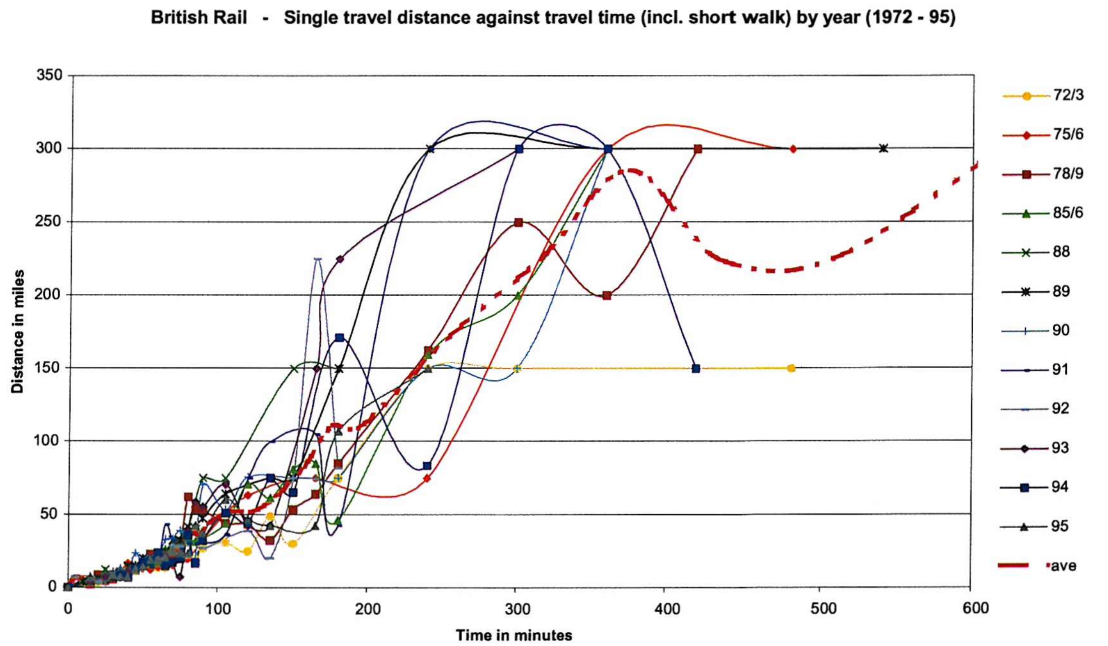


Figure D.8: Time-Distance Relationship by Year of Railway (DETR 1998b)

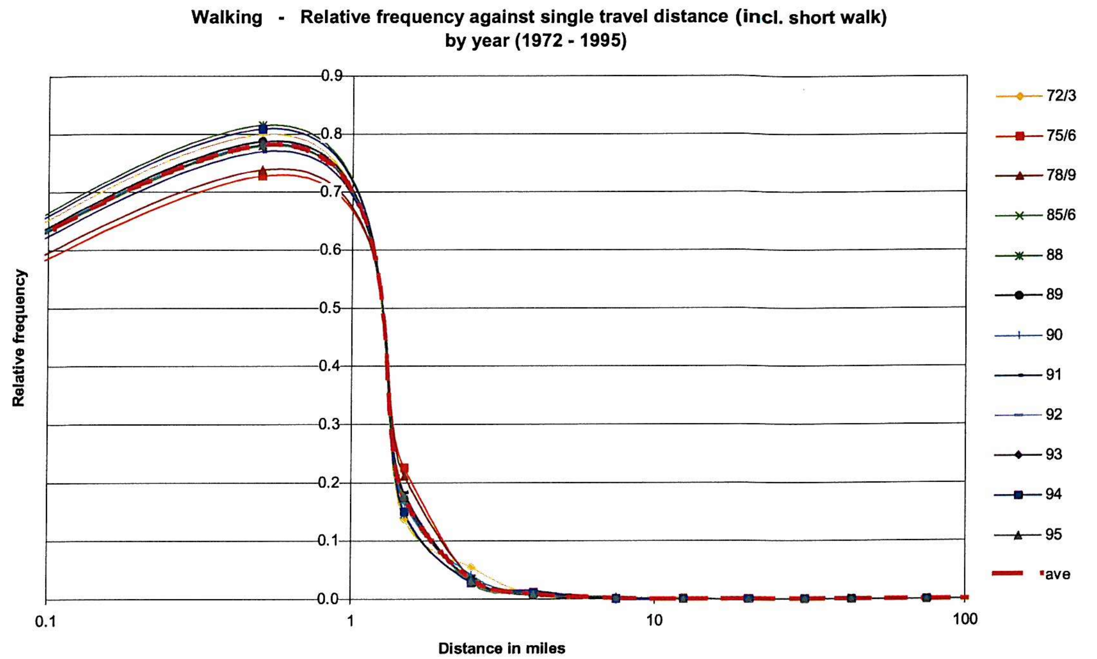


Figure D.9: Distance Distribution of Walking Trips (DETR 1998b)

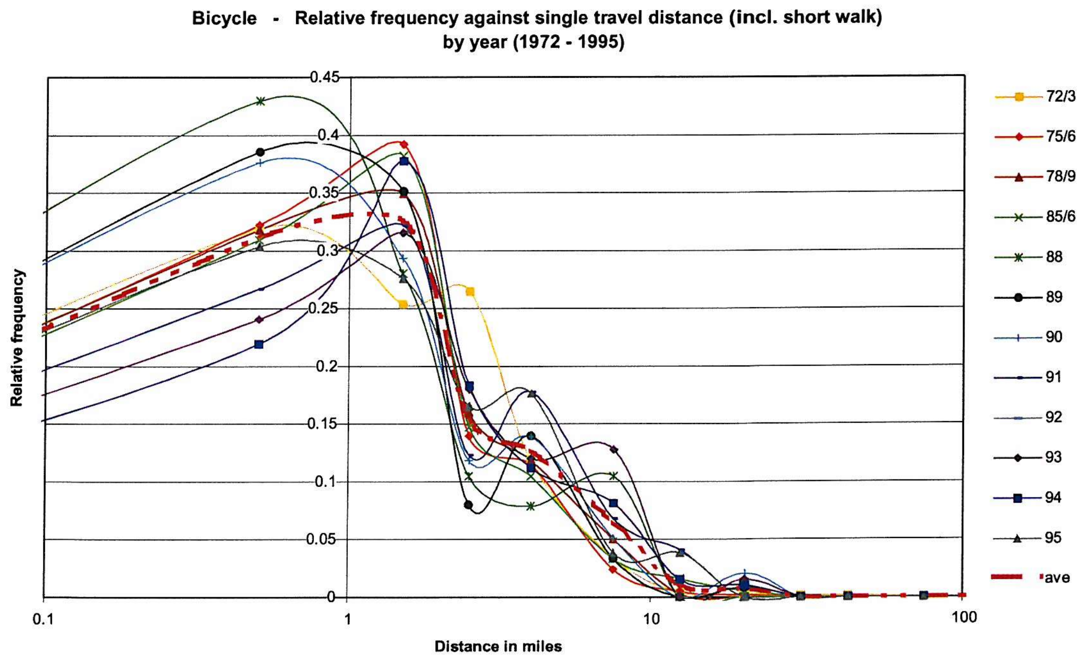


Figure D.10: Distance Distribution of Bicycle Trips (DETR 1998b)

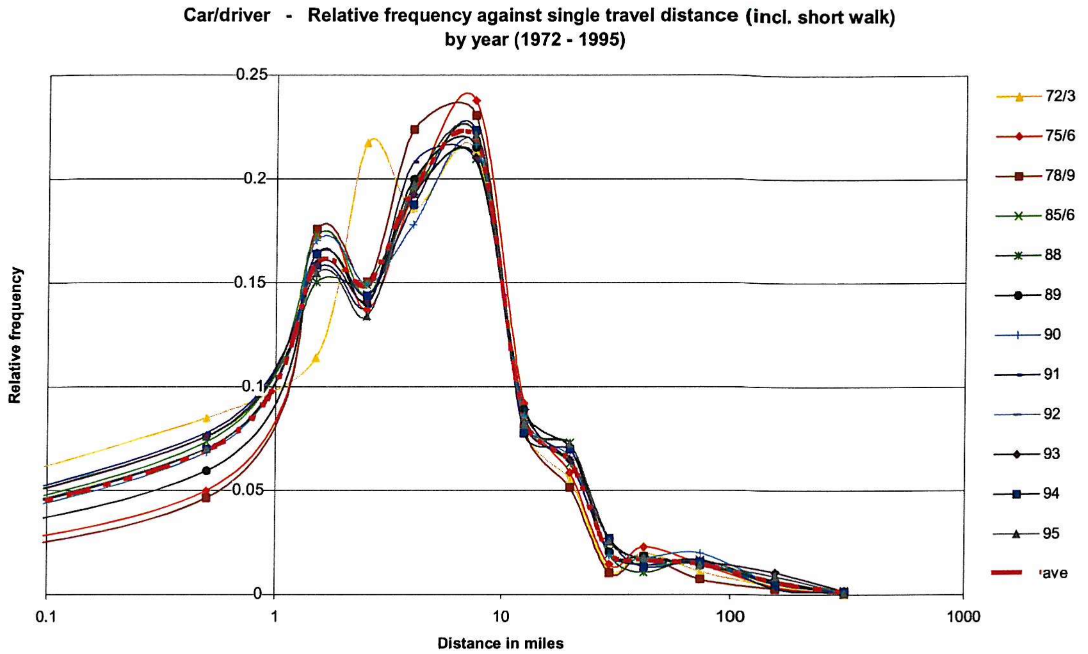


Figure D.11: Distance Distribution of Car/Driver Trips (DETR 1998b)

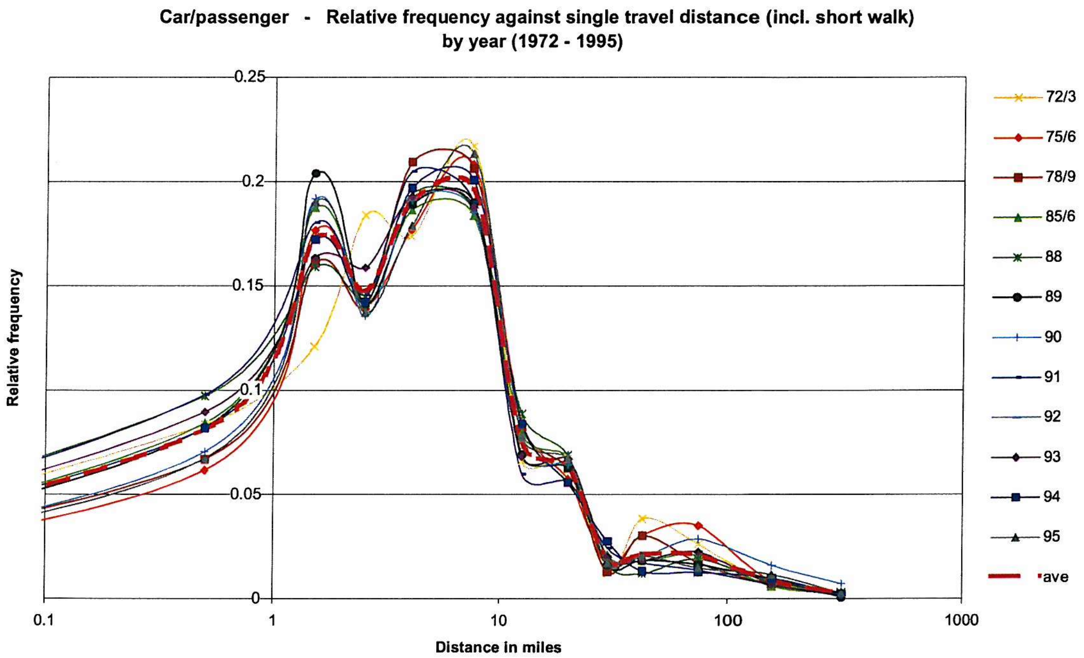


Figure D.12: Distance Distribution of Car/Passenger Trips (DETR 1998b)

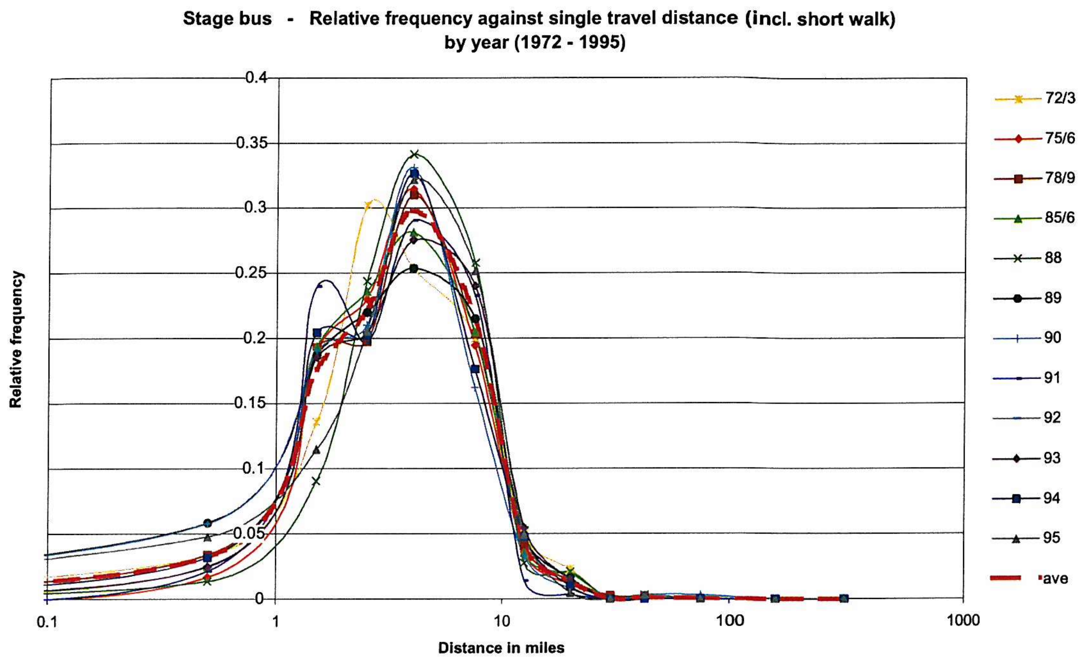


Figure D.13: Distance Distribution of Stage Bus Trips (DETR 1998b)

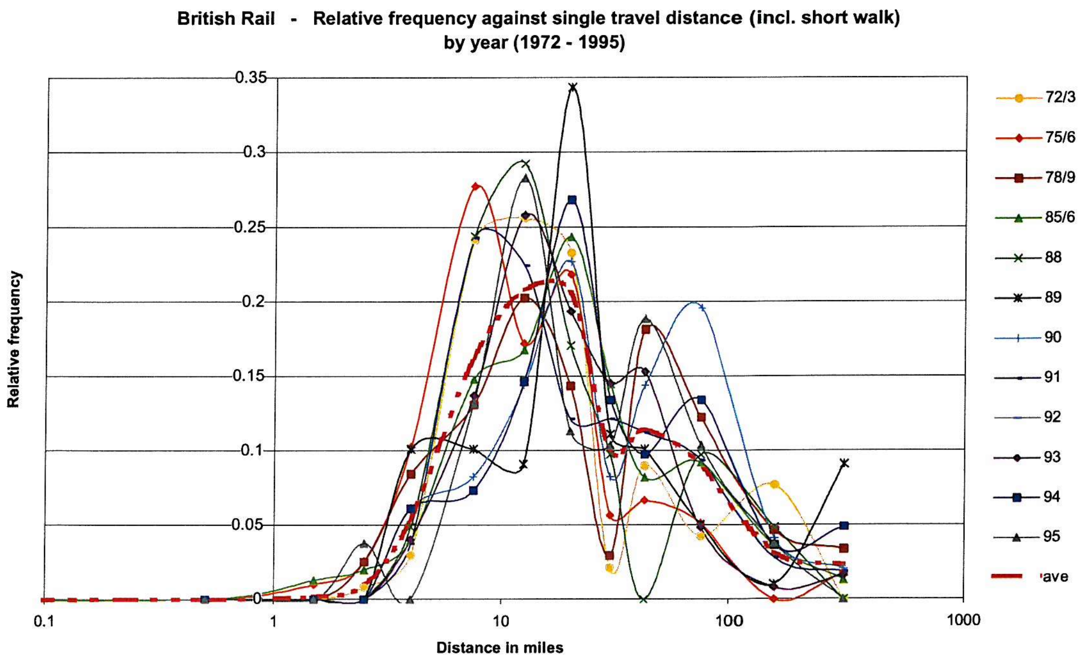


Figure D.14: Distance Distribution of Railway Trips (DETR 1998b)

Appendix E

Figures of Trip Rate

Figures E.1 - E.6 complement Figure 5.4 of Section 5.2 and show travel times against trip rate with respect to mode of transport. The comparison shows that a daily trip pattern based on even trip rates takes up less time than a pattern based on the (smaller) odd trip rates.

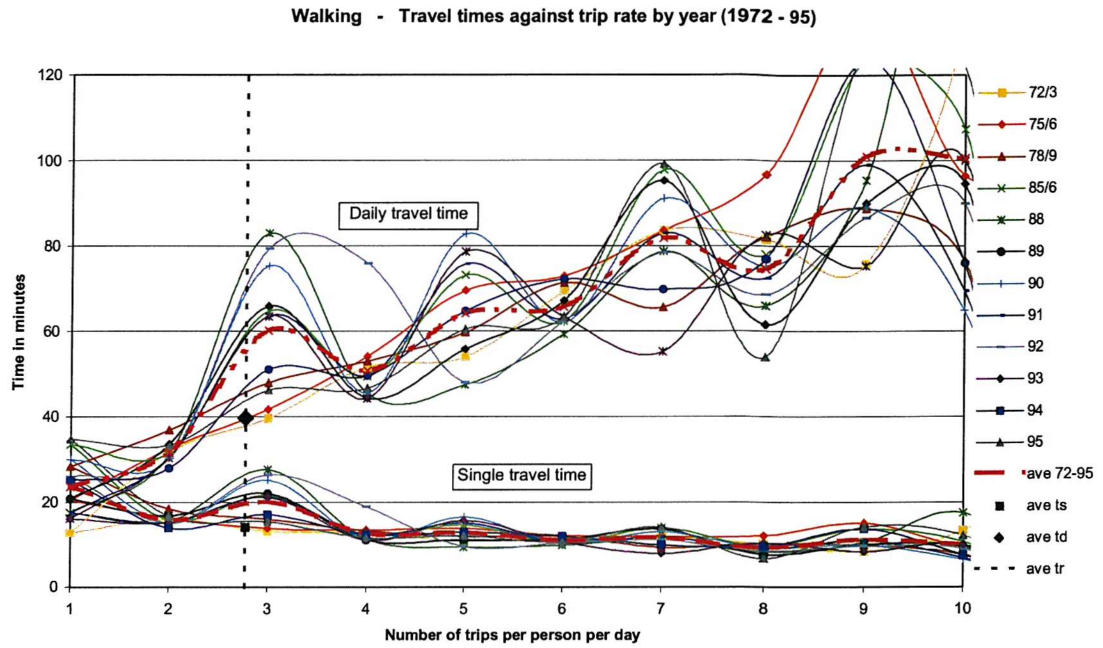


Figure E.1: Travel Times Versus Trip Rate of Walking Trips (DETR 1998b)

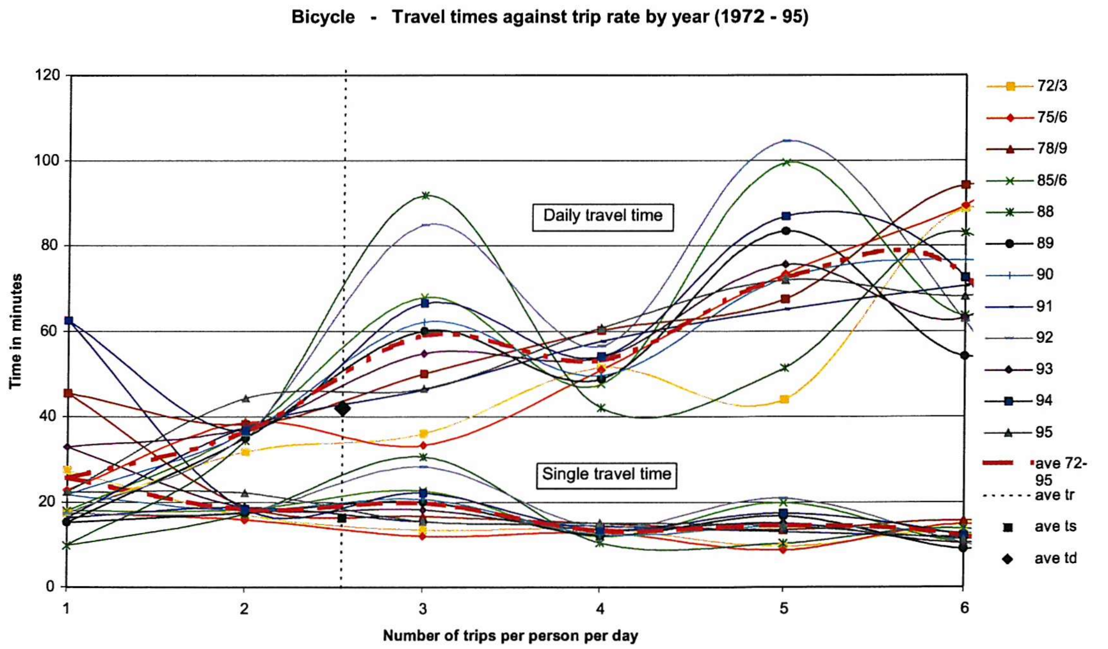


Figure E.2: Travel Times Versus Trip Rate of Bicycle Trips (DETR 1998b)

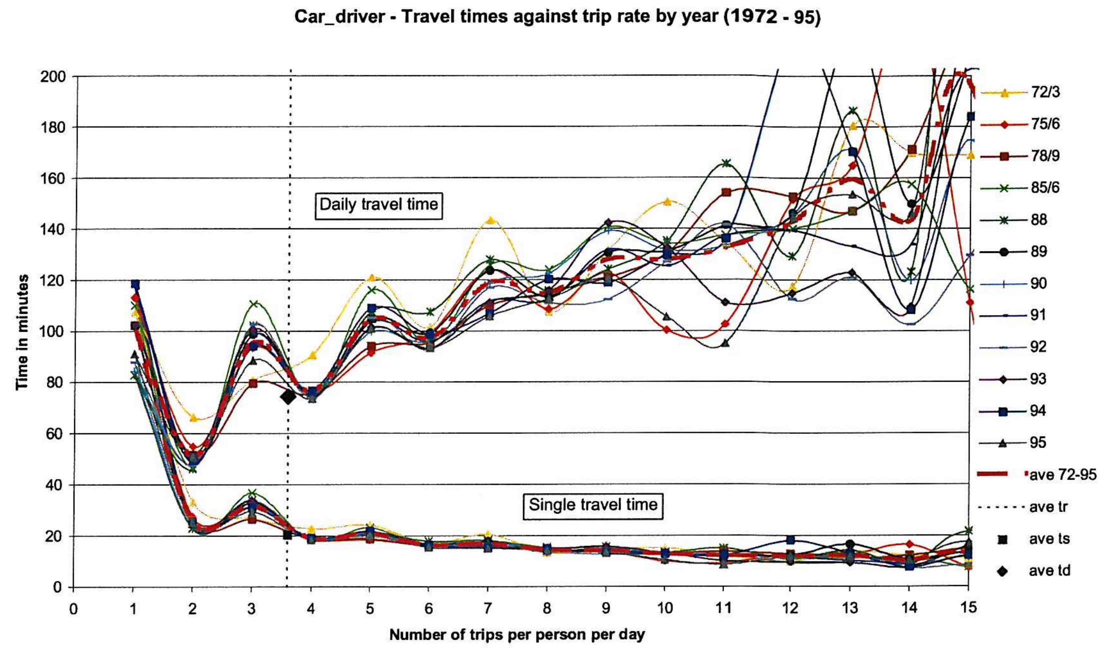


Figure E.3: Travel Times Versus Trip Rate of Car-Driver Trips (DETR 1998b)

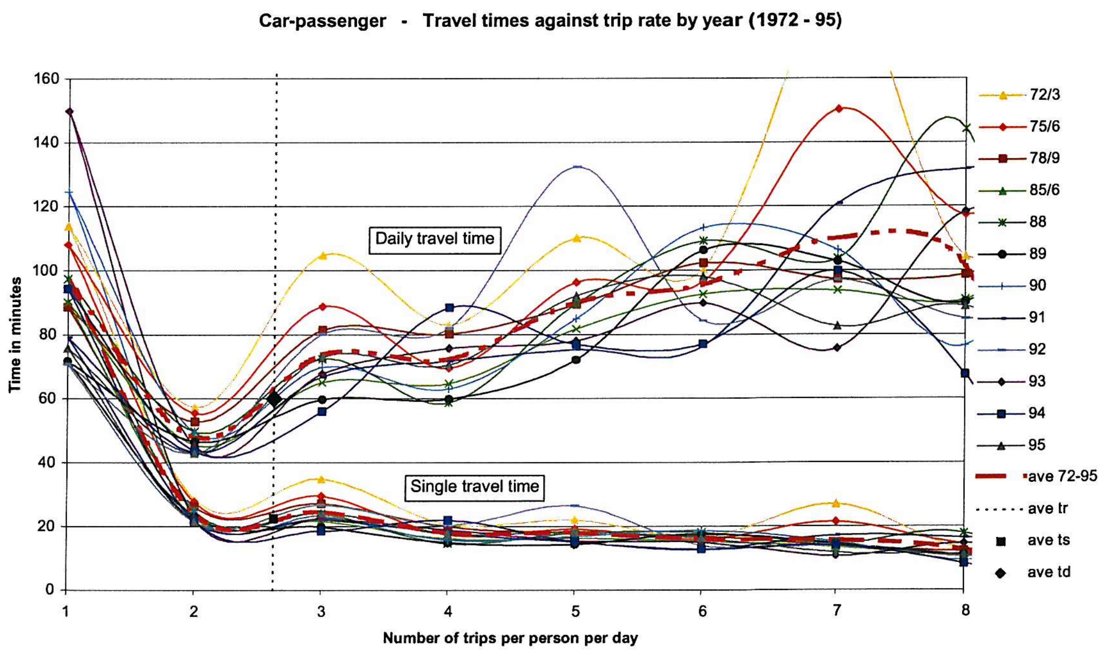


Figure E.4: Travel Times Versus Trip Rate of Car-Passenger Trips (DETR 1998b)

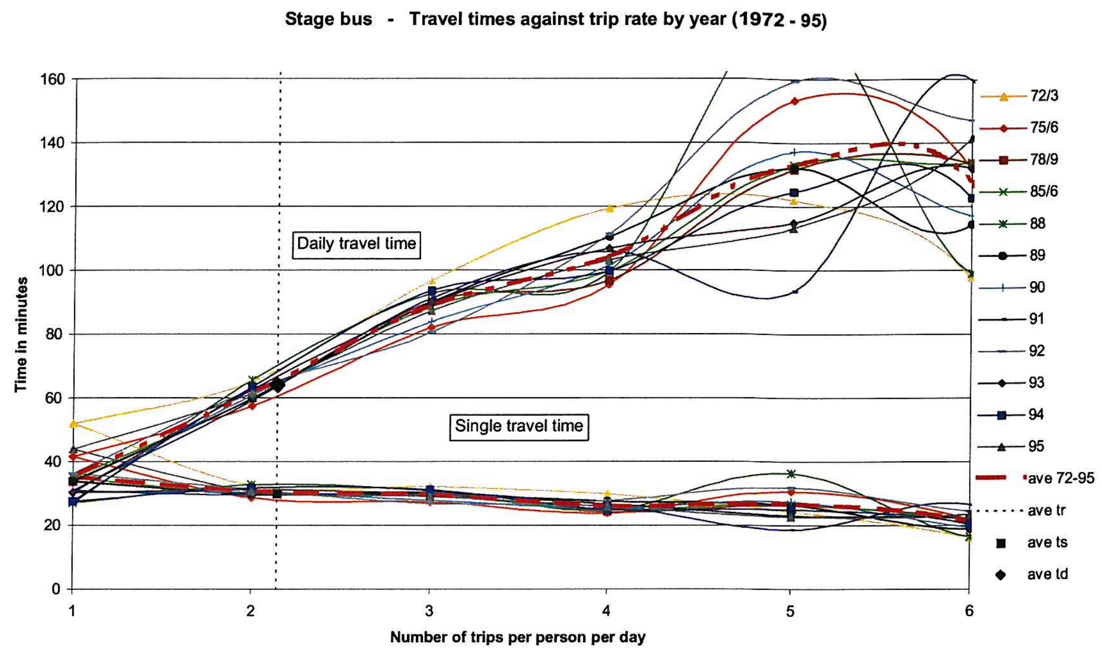


Figure E.5: Travel Times Versus Trip Rate of Stage Bus Trips (DETR 1998b)

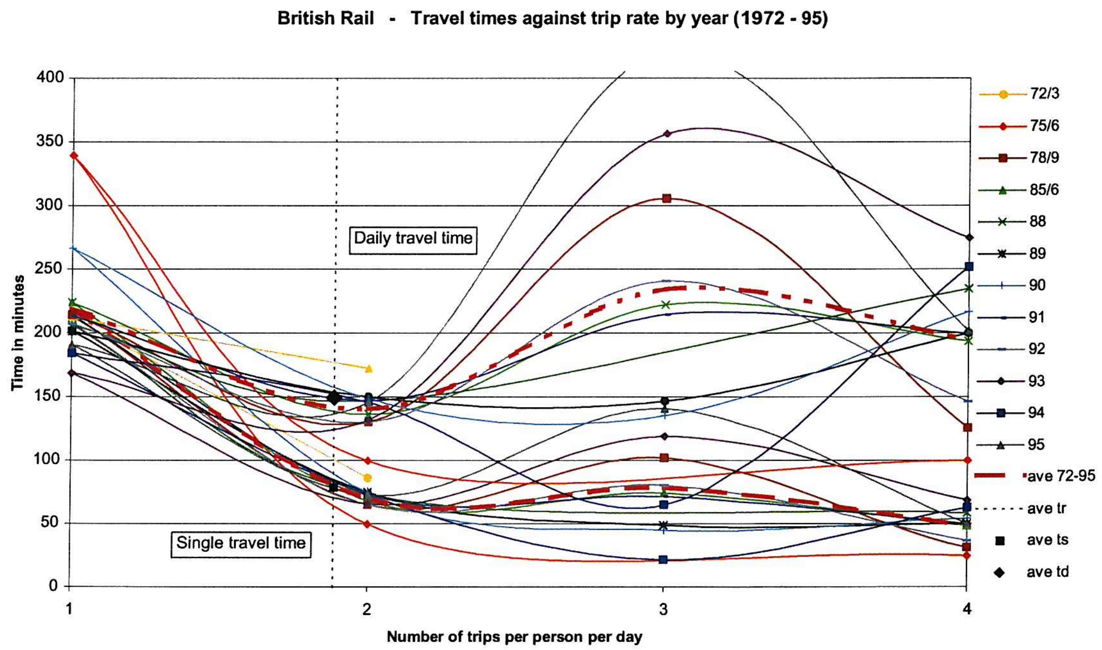


Figure E.6: Travel Times Versus Trip Rate of Railway Trips (DETR 1998b)