The state of mobility research

HEINZ HAUTZINGER and PETER KESSEL
Prognos, European Center for Applied Economic Research
Basel, Switzerland

INTRODUCTION

Mobility research is concerned with the description, explanation and forecast of the extent to which individuals carry out movements in space. For a large part, it thus stands for transport research as such. In an attempt to present a brief outline of this field, it will therefore hardly be possible to give a complete survey, and the selection of topics will always be somewhat arbitrary.

As a personal characteristic, mobility is usually measured by the number of trips a person completes during a specified time period. The necessity and urgency of making trips results from the compulsions and/or desires of an individual to carry out social and economic activities. Whether subjective mobility desires become an actual mobility demand is largely determined by the mobility opportunities of an individual, which are characterized by the availability of transport modes, the ability and inclination to buy transport services and the physical driving or riding capability.

Initially, mobility research was almost exclusively descriptive in nature and in transport planning the future level of mobility was treated as an exogeneous quantity like motorization. Although the necessity of a behavioural and causal explanation of mobility has been recognized at a fairly early stage, suitable models have been developed only in recent years. In order to evaluate what has been reached in mobility research up to now.

- the characteristics of mobility,
- the determinants of mobility and, finally,
- the state of the art in mobility modelling

are discussed in the remainder of this paper.

CHARACTERISTICS OF MOBILITY

As indicated above, the mobility of an individual is usually measured by its trip frequency. The total number of trips e.g. per day, however, is only a very crude measure since mobility is an extremely heterogeneous phenomenon. The various components of an individual mobility pattern may for instance be as different from each other as a charter flight to Majorca or a little walk to the cigarette automat on the corner. Trips as the natural elements of any mobility pattern can show quite divergent qualities and features and their completion may depend on quite different compulsions and choices regarding the purpose, spatial destination, transport mode and route.

Mobility research has therefore first of all to deal with these different features of trips. This refers mainly to the following detail aspects:

- The functional distribution of trips according to the various travel purposes
- The spatial distribution of trips (origin-destination relationships)
- The modal distribution of trips
- The distribution of trips according to length and duration
- The distribution of trips according to time of completion.

Since the empirical findings on the temporal, spatial, modal, and functional distribution of trips are generally well documented, it is not necessary to repeat them here. However, a few remarks should be made on the functional aspect i.e. the travel purposes. These are of particular importance as they predetermine to a large extent the mobility behaviour of individuals with regard to the choice of transport modes, and the other aspects of trip making. According to the purpose (motive) of a trip the following types of trips are usually distinguished: work, education, business, shopping, recreation, and passenger services. If a further division according to weekday and weekend travel is undertaken, the mobility components which have thus been defined are much more homogeneous in themselves than the heterogeneous overall mobility of an individual. The current situation in the Federal Republic of Germany (FRG) is characterized as follows [1]: work 29%, shopping 27%, recreation 21%, education 12%, business 7%, and service 4%.

According to the importance of travel purposes wide attention has been paid to this aspect within the scope of mobility research. The analysis of the "purpose structure" of travel behaviour is increasingly shifting from an isolated consideration of single trips to the investigation of complete daily travel patterns. For the transition from a certain transport purpose (activity) to the next – not necessarily different - purpose, specific transition probabilities can be identified. We shall refer to this again later on in more detail. An important starting base for further investigation of trip patterns is the empirical result that the daily trip sequences of individuals are strongly concentrated on only a few basic types. An analysis of the travel behaviour of approximately 16,000 persons yielded nearly 1,200 different trip patterns. Half of all mobile persons did however have one of the following six trip patterns:

home-work-home (20.6%)
home-shopping-home (10.1%)
home-education-home (9.8%)
home-education-home-recreation-home (3.4%)
home-recreation-home (3.2%), and
home-work-home-recreation-home (2.9%).

In the widest sense, all types of spatial movements including walks on foot should be considered as part of the individual mobility pattern. Such a comprehensive approach is becoming increasingly important in view of the potential substitutability and actual substitution of walks on foot by vehicular trips and vice versa. In spite of this fact, walks have up to now received relatively little attention in mobility research and few analyses have been made. Past data are almost exclusively available for vehicular trips.

These data indicate a strong growth of vehicular mobility in all industrialized countries. In the FRG, for instance, in 1950 only 0.5 daily trips per capita were carried out. In 1975, this figure was already 1.3 trips per person and day, i.e. the growth amounted to approximately 180%. The length of trips has also increased distinctly. In 1950, the average of length of a trip was about 10 km, in 1975 approximately 20 km [2]. A more detailed analysis shows that the development up to now has been marked by partially extreme changes in the relative and absolute importance of the various travel purposes. While the average number of work trips per person and weekday has been stagnating for quite some time, the business and recreational mobility in the FRG has alone during the last decade about doubled in volume. Shopping trips per person trebled and mainly due to specific developments in the German education system the number of school trips has grown fivefold [1,3].

DETERMINANTS OF MOBILITY BEHAVIOUR

A large number of different influential factors can be identified as the causes of the described development of mobility, depending on its multi-layered, multidimensional structure. From a macro viewpoint, the primary causes of the characteristics, scope, and development of the demand for mobility can be classified as follows:

– **Economic factors:** these are mainly the income of private households and growing labour division in the organization of economic processes.

– **Demographic structures:** the most important are the age structure of the population, activity and education rates, and size of households.

– **Settlement and spatial structure:** the impacts of these causal components are probably most easily discernible. Mobility demand results from the spatial separation of basic activities, i.e. place of residence, work, shopping and recreation. The way these activities are spatially mixed or disentangled determines the necessity and scope for each individual of connecting by trips his various activities during the course of a day.

– **Social behavior patterns:** in this context, the previous development has been marked by an increasing number of social positions and rôles of the individuum, not last on account of more leisure time. The growing number of positions inside the family, at the workplace, in societies, associations of political parties can be observed in all industrialized societies as typical accompaniment of the economic development. It increases quite inevitably the necessity of communication and integration and thus the demand for mobility [4].

– **Transport network and transport mode supply conditions:** the previous development in practically all industrialized countries was largely characterized by mass motorization, forced extensions of road networks and, at the same time, decreasing intensity of services in public passenger transport. These supply conditions have a direct and immediate impact on mobility, for instance by way of inducing trips through the initial purchase of a car, regardless of whether the resulting additional demand is actually "new" or whether it has already been latently existent. Indirectly, transport supply affects mobility by influencing also the other causal components mentioned above. Since without transport supply mobility cannot materialize, the demand for mobility is a "coupled" demand for trips, and for the means of transport they necessitate.

The possibilities to quantify the relations between the macro-type determinants as described above and the demand for mobility are very limited. Gross national product, income and motorization can be used only as crude indicators for the level of mobility. For example, the close connection between the mean number of daily trips per person and the motorization level of a certain town or region has already been identified during the early descriptive phase of mobility research [3, 5]. Any real explanation of mobility, however, presupposes a consideration of the socio-economic conditions of the individual. Despite this, personal and household characteristics have only recently been included in studies of mobility behaviour which utilize individual instead of zonal aggregated data.

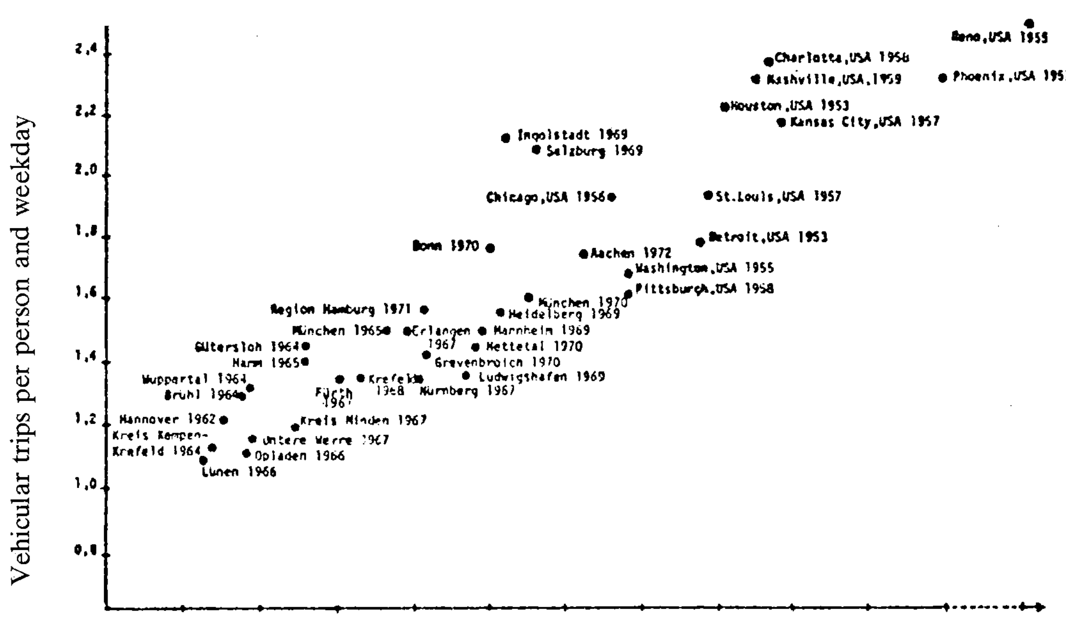

Figure 1 – Mean number of trips per person and weekday and motorization level in 38 towns and regions.

The analysis of major causal determinants of mobility which was initially undertaken rather qualitatively and globally from a macro viewpoint can be carried out much more concretely within a micro analytic framework with the individual as the study object. In several previous studies, the following central socio-economic factors have been identified [1, 6, 7, 8].

– Regularly recurring **demand compulsions,** as mainly characterized by the occupational status;

– The individual **mobility potential,** i.e. the ability to undertake trips, as for instance characterized by the possession of a driving license, of an automobile or by age;

– The **social status,** as for instance expressed by household income or the education level of an individual.

Of the socio-economic factors described in the foregoing, those which are closest related to the total number of daily trips, are – as expected – the most important factors of influence also in mode-specific analyses.

If the frequency of daily trips which an individual undertakes by car, public transit modes, bicycle or on foot, is analysed, in context with its socio-economic features, the following dependencies become apparent:

– The number of trips, which an individual undertakes is for each single transport mode largely determined by the same characteristics, above all by the possession of a driving license, possession of a car, and by occupational status.

– If a person is occupied and possesses both driving licence and a car, the individual number of automobile trips will, of course, be usually large. At the same time, total mobility tends also to be high.

– The number of trips a person undertakes on foot, by bicycle or public transport modes is chiefly determined by the automobile availability of that individual. The quality of supply with public transport facilities for instance has a much less significant influence on the usage of this mode. This confirms available experience from specific transport mode choice studies.

Table 1 – Relative importance of various determinants of trip frequency for different types of transport modes [1].

No.	Total trips	Walks	Bicycle trips	Car trips (Driver)	Bus trips
1	Licence poss.	Sex	Licence poss.	Car ownership	Licence poss.
2	Car ownership	Car ownership	Car ownership	Licence poss.	Car ownership
3	Occup. status	Housing conditions	Age	Occup. status	Age
4	Education	Occup. status	Occup. status	Pos. in household	Pos. in household
5	Age	Licence poss.	Pos. in household	Sex	Age (head of household)

Except age all variables appearing in this list are binary. No income data available.

In Table 1 various variables are ranked according to their importance in determining mobility. In interpreting these results it should be noted, however, that the occupational status was treated here as a binary variable (employed, not employed). If instead the full "range" of this characteristic (i.e. the categories employed, housewife, scholar, retired) was considered, the occupational status of a person proves to be the clearly dominating factor in most cases.

These empirical results have been obtained using a variety of statistical techniques. It seems, however, that the potential of methods of statistical inference has not yet been fully utilized. This is especially true for multivariate methods.

MODELS OF MOBILITY

General requirements for mobility models

By the "condensation" of available empirical knowledge about the study subject mobility into a number of *a priori* hypotheses, a mobility model is created. The development of such models must naturally be oriented by the concrete information needs of transport policy and planning. Statements on expected future developments of mobility and on the probable effect of measures which influence mobility will take a prominent position. From these two major functions, the standards can be derived which have to be required of models of mobility demand. They can be summarized as follows:

– **Explanatory value:** The model should be multivariate, i.e. it should contain statements on structural interrelations and thus provide the basis for an analysis of the effects of changing conditions.

– **Forecasting capacity:** The model should take into account the intrinsic dynamics of mobility behaviour and its interrelations with the relevant socio-economic and technical systems.

– **Policy sensitivity:** The model should, in an operational form, contain as variables all determining factors which can be influenced politically or by planning. Thus it should be suited to detect ways and means of achieving certain targets.

As shown by the following critical assessment of approaches which have been developed up to now, no comprehensive mobility model exists yet which meets all these requirements.

Currently existing models

Model typology

For a systematic study of currently existing models, a distinction should first of all be made between macro and micro models of transport mobility. While for *macro models,* spatial or socio-economic aggregates of individuals are the object of model design, *micro models* always attempt to reflect the behaviour of single individuals. With a micro model statements on behavioural characteristics of certain populations are therefore only possible after applying suitable aggregation methods. Macro models are estimated on the basis of aggregated data, while the statistical estimation of micro models requires disaggregated individual data.

A classification according to the time element leads to *static* and *dynamic* mobility models. While models of the first category contain no time-dependent variables, dynamic models are characterized by explicit time dependence of the variables. Temporal aspects can, within the scope of static models, at best be taken into account by comparative static analyses.

A third differentiation is finally undertaken according to the question to what extent the models are based on explicit behavioural hypotheses. Models which answer this qualification are usually called *behaviour-oriented.*

This classification results in altogether eight different categories of mobility models, to which the models developed so far can be assigned. As will be shown later, only six of these eight model categories have so far become apparent. Therefore, in the subsequent discussion a distinction will be made only between macro and micro models, the latter being additionally divided into static and dynamic approaches.

Macro-analytical mobility models

Seen from a historicalpoint of view, macro-analytical *zonal trip generation models* represent the first mobility models altogether. The issue of model design in this case is first of all the estimation of the relationship between the number T of trips starting out from a traffic zone and certain characteristics x_j ($j=1, \ldots, q$) of this zone (e.g. number of inhabitants or number of cars per zone). Typically, a linear stachastic relationship of the form

$$T = \alpha_o + \alpha_1 x_1 + \ldots + \alpha_q x_q + \varepsilon \qquad (1)$$

is assumed, with $\alpha_o, \alpha_1, \ldots, \alpha_q$ being parameters, and ε a random disturbance variable, representing all non-systematic influences on the number of zonal trips. On the further assumptions of the classical linear regression model, estimates $\hat{\alpha}_j$ for the unknown parameters can be determined from zonally aggregated random sampling data. Given forecast values x^*_j of the exogenous variable, the expected number $\hat{t}^*$ of trips starting out from an individual zone at a certain time interval in the future is estimated by means of the relation

$$\hat{t}^* = \hat{\alpha}_o + \hat{\alpha}_1 x^*_1 + \ldots + \hat{\alpha}_q x^*_q \qquad (2)$$

Zonal trip generation models have quite a number of weaknesses which have already been examined very thoroughly in the literature [9, 10]. The main points of this criticism have been the following:

– The assumptions of the classical linear regression model which form the basis of parameter estimation and testing of hypotheses, are in reality often violated to such an extent that the derived results are practically worthless.

– Zonal trip generation models explain only the variation of travel behaviour between different zones and thus not the real causes of the observed behaviour discrepancies. High values of the multiple correlation coefficient (R=0.95 is not rare) pretend a non-existing explanatory quality.

– The results – in particular the parameter estimates – depend heavily on the division into traffic zones and are therefore not spatially transferable.

– Macro-analytical trip frequency models of the type (1) do on account of their zonal aggregated character as a rule not contain policy sensitive variables in a form which would make an analysis of the effects of alternative measures possible.

A recent *two-stage mobility forecasting model* [11] can also be classified as macro approach. In this model the mean daily trip frequency T of the inhabitants of a town or region is assumed to depend on the prevailing car density x (number of cars per 1000 inhabitants):

$$T = \alpha_o + \alpha_1 x + \varepsilon \qquad (3)$$

The car density is largely regarded as an indicator variable for the individual transport mode supply conditions and the general economic status of the area under survey. The parameters α_o, α_1 of the regression model (3) have been estimated on the basis of the values indicated in Figure 1 ($\hat{\alpha}_o=.118$, $\hat{\alpha}_1=.006$). By means of the Gompertz-function

$$x_t = \xi \exp(-\beta_o \beta_1^t) \qquad (4)$$

a forecast of the car density has been carried out for the Federal Republic of Germany, with t denoting the time (the base year (t=1) was 1952). With an exogenously given saturation level of $\xi=400$ cars per 1000 inhabitants the parameter estimates $\hat{\beta}_o=3.682$ and $\hat{\beta}_1=.906$ resulted. A combination of the results of the regression analysis and the car density forecast yielded

$$\hat{t}^*_t = \hat{\alpha}'_o + \hat{\alpha}_1 x^*_t = .188 + 2.400 \exp\{(-3.682)(.906)\} \qquad (5)$$

i.e. the forecasted value of the average daily vehicular trip frequency for the FRG in year t. Naturally, $\hat{t}^*_t$ has the character of a conditional point forecast of the mean trip frequency for a given car density forecast x^*_t. Starting out from a current mobility level of 1.9 vehicular trips per person and day (weekdays) this number rises according to (5) to 2.2 by 1980 and to 2.4 trips per person and day by 1985. For the year 1990 the value 2.5 follows, with the saturation level of average daily trip frequency being at just 2.7 trips per day. In addition to this point forecast, the limits of the respective (conditional) forecast intervals for arbitrary future dates have been determined. See Figure 2.

This approach has the advantage of being fully dynamic, since the temporal development of mobility is described by means of the saturation model (5). Its effectiveness is of course limited mainly due to the high aggregation level of this model. In principle however further refinements seem to be possible, for instance by means of stronger disaggregation and introduction of additional (causal) explanatory variables.

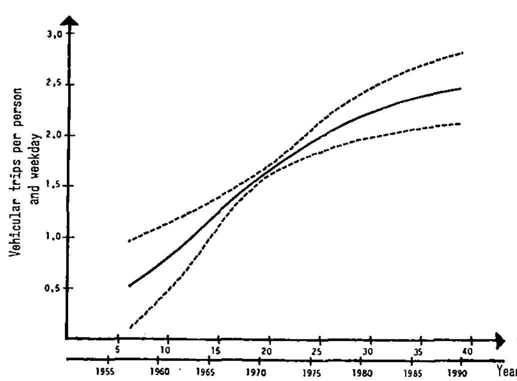

Figure 2 – Point and interval forecast of mean number of vehicular trips per person and weekday for the Federal Republic of Germany.

With some reservations, also *category analysis* [12] can be regarded as a mobility model. In order to characterize the mobility behaviour of households, these are first of all broken down into individual categories by means of household characteristics which have a significant influence on mobility (e.g. household income, car ownership, family structure). To these household categories specific mean trip rates will then be attributed. Accordingly, in category analysis for forecasting purposes the shares of individual household categories, on the one hand, and the related mean trip frequencies, on the other hand, must be estimated.

The category analysis approach is only to be classified with reservations as a mobility model in as much as it does not yield an explicit relation between mobility and its determinants. There is in particular, no possibility within the scope of this approach to assess the relative significance of the various influential factors. The major forecasting steps (forecast of category shares and specific categorial mobility levels) are taking place outside the actual "model".

Static micro-analytical mobility models

Contrary to the macro approach, in micro-analytical mobility models the individual or the household represent the study unit whose mobility behaviour is to be explained. *Linear regression models of individual trip* *frequency* are based on a stochastic relation of the type (1) with the exception that in this case T denotes the daily trip frequency of a person or a household, and the variables $x_1, \ldots, x_q$ represent characteristics of individuals or households (occupational status, car ownership, age, etc.), characteristics of the supply with public transport facilities (e.g. distance to stops) as well as characteristics of the opportunity potential (e.g. number of accessable leisure time institutions). For an estimation of the constant α_o as well the variable weights $\alpha_1, \ldots, \alpha_q$ disaggregated random sampling data on persons or households are necessary.

As to whether the individual or the household are the better suited study unit, opinions differ. In an empirical study by the authors [1], the characteristics of the individual (in particular the occupational status) were distinctly confirmed as major determinants of the individual mobility level and accordingly the individual as the best suited study unit. From other sides, however, it has been requested to make the household the subject of analysis [13], since household characteristics, as for instance income and car ownership, are also of considerable importance for the mobility behaviour of individuals. The fact that mobility models on the household level leave a considerable part of total variability of trip frequency (i.e. behaviour variability within households) unexplained, is borne out by the fact that the coefficient of determination which reaches up to $R^2 \approx 0.4$ with household regression models [14] is generally distinctly below 0.3 with individual models.

It is evident that the problems of multiple regression analysis (non-normality, heteroskedasticity, multicollinearity) which are sufficiently known from statistical literature, also occur in the development of regression models of travel mobility. A discussion of relevant questions can be found in [13, 14, 15], where in addition specification problems and further aspects, as for instance the use of dummy variables and stepwise multiple regression, are dealt with.

On the whole, it can be observed that a micro approach of the type mentioned has considerable advantages over macro analytical regression models of mobility. The most important advantage is to be seen in its causal character and in the fact that it is much more easily transferable, spatially as well as temporally, due to its independence of special zonal divisions. On account of these stability properties it is particularly suited for forecasting purposes.

The linear regression model of individual mobility behaviour explains the observed behaviour divergencies by inter-personal differences of the values of certain variables – or more precisely – it assumes a linear dependence of the expected individual trip frequency on its determining factors. It does, on the other hand, not contain any explicit hypotheses on the origin of these behaviour patterns. This theoretical weakness is at least partially overcome by the so-called *behaviour-oriented trip frequency models*, which are based on the theory of qualitative choice behaviour [16].

It is not necessary to deal in detail with this approach which in the meantime is very much in use within the field of transport research. Models of this type explain the probability

$$p_j = P\{T=j\} \quad (j=0,1,\ldots,n) \tag{6}$$

that an arbitrary person undertakes exactly j trips for a certain purpose during a specific time interval as follows: The individual attributes to each "alternative" j a certain utility U_j, depending on the characteristics of this alternative which are combined in a vector x_j, and on the vector s of the socio-economic characteristics of the individual, i.e. $U_j = U(x_j,s)$. It is assumed that the individual chooses that alternative which offers the greatest utility. Of course, for a randomly selected individual, U_j is a random variable. According to the decision rule mentioned above, we have

$$\{T=j\} \text{ if and only if } \{U_j = \max_{0 \leq k \leq n} U_k\} \tag{7}$$

Without loss of generality, U_j may be represented in the form $U_j = u(x_j,s) + \varepsilon(x_j,s)$ where u is non-stochastic and ε is a random variable. If the value of the h_{th} explanatory variable for alternative j is denoted by y_{hj} where y_{hj} depends on x_j and s, and if it is assumed that for $u_j = u(x_j,s)$ we have

$$u_j = \sum_{h=1}^{q} \alpha_h y_{hj} \quad (j=0,1,\ldots,n) \tag{8}$$

it can be shown that under the additional assumption of independent Weibull-distributed variables $\varepsilon_o, \varepsilon_1, \ldots, \varepsilon_n$ the multinomial logit model

$$p_j = \exp(u_j) / \sum_{k=0}^{n} \exp(u_k) (j=0,1,\ldots n) \tag{9}$$

results. The unknown parameters $\alpha_1, \ldots, \alpha_q$ of this model can be estimated according to well-known statistical methods [16].

The expected value of the individual trip frequency is given by

$$\tau = E(T) = \sum_{j=0}^{n} j p_j \tag{10}$$

According to (8) and (9) it depends on the alternative-specific values y_{hj} of the explanatory variables as well as on the parameters α_h, which express the relative importance of the individual variables.

As compared with other aspects of travel behaviour (in particular transport mode choice) logit models have up to now only rarely been used for the estimation of trip frequency. Referring to initial applications as, for instance, described in [17] it seems promising to further develop trip frequency models of the type and to analyze the influence especially of socio-economic variables on an improved sampling data basis. The potential range of application of choice models is to be seen mainly in non-compulsatory travel (i.e. shopping and recreational trips) since the completion of work and school trips is almost completely determined by the occupational status of a person.

Dynamic micro-analytical mobility models

Owing to the exceptional importance of travel purposes in the analysis of mobility it is advisable to formulate separate trip frequency models for each travel purpose. With such a breakdown of the overall mobility of a person, of course, the sequential aspect of trip making cannot be captured. Since quite a number of mobility phenomena can, however, only be explained by the optimizing behaviour of the individual in the planning of his daily activity program it seems only logical to develop appropriate dynamic models. Currently three different approaches can be roughly distinguished in this field:

- Markov chain models of the linking of activities,
- models which are based on hypotheses on the length of trip chains, and
- models which assume a trip generating process of need accumulation

If the activities carried out by a person are interpreted as states of a stochastic process, and his trips as transitions between subsequent states, a highly developed mathematical instrumentarium can be resorted to for the description of the mobility behaviour. Particularly specific statements are achieved if it is assumed that the described stochastic process is a finite homogenous Markov Chain. By means of such *Markovian trip chain models*, the distribution of population consisting of n persons over the set of various activities after completion of their i^{th} trip can be determined by using the recursion formula

$s_i = s_{i-1}P \quad (i=1,2,\ldots)$ (11)

The j^{th} component s_{ij} of the row vector s_i is the number of persons who carry out an activity of type j (j=1,...,m) before undertaking the $(i+1)^{th}$ trip, and the elements p_{jk} ($p_{jk}=0$) of the (m x m) matrix P denote the probability of a person's passing on to an activity of type k (k=1,...,m) as next state, if it is just occupied with an activity of the type j. Apparently

$$\sum_{j=1}^{m} s_{ij} \doteq n \qquad \text{and} \qquad \sum_{k=1}^{m} p_{jk} = 1$$

for all i=0,1,2,... and j=1,...,m, respectively. The vector s_0 is called initial state and P is referred to as transition matrix of the process.

If the state (activity) "home" is split into two states, "from home" and "to home" (the latter being absorbing), this model yields the expected frequency of trip chains of any type, the expected frequency of the incidence of a certain trip purpose within a trip chain, and the expected "length" of a trip chain (number of trips until the return to the home). For the calculation of these expected values, merely the initial state s_0 and the transition matrix P must be known, since these two quantities completely determine the Markov chain.

The weak points of this simple Markovian model are obvious and are, for one thing, due to the Markov property of the model, i.e. to the assumption that the probability of a trip to a certain activity only depends on the last previous activity, and for another, to the homogeneity assumption that this transition probability is independent of the fact where the particular trip in question is ranking within the trip chain. Another weakness is the fact that temporal aspects (travel time, duration of an activity) are not taken into account. The first papers which were published as early as the 1960s [18, 19, 20] have in the meantime been generalized into various directions [21, 22].

The basic inadequateness of this type of model however is its descriptive nature: Transition probabilities must always be determined empirically, the model does not offer the possibility of estimating them on the basis of land-use, transport supply, and socio-economic data. A critical evaluation of these models should however not underestimate the fact that Markovian trip chain models represent the first approaches into a direction of research which is today regarded as the right one.

Besides Markovian trip chain models which build up on hypotheses regarding the linking of activities by trips, a second type of dynamic micro mobility models is based on assumptions on the probability of returning home from a non-home activity [24, 25]. Starting out from the empirically proven fact that short trip chains occur more frequently than long ones, in [24] the following assumption is made on the probability p(t) of carrying out an additional trip to a non-home activity (in this instance: shopping) given that t trips have already been carried out since the last stay at home:

$p(t) = \exp(-t/\lambda) \quad (t=1,2,\ldots)$ (12)

In (12) the parameter λ is identified with the mean length of a trip chain and has to be determined empirically.

The model developed in [25] is mainly concentrated on the connexion between the process of linking trips and the number of daily activities outside the home. If this number is denoted by n and it is assumed that an individual is just staying at its k^{th} non-home activity ($k \leq n$), the destination of the next trip may be one of the n-k places which have not yet been visited or the home, i.e. altogether n-k + 1 destinations. If p (k|n) denotes the probability of the event "trip back home from the k^{th} non-home activity provided that altogether n activities outside the home are carried out", the fundamental hypothesis of the model can be depicted as follows:

$p(k|n) = 1/(n-k+1)$ (13)

i.e. the probability of a return to the home is the smaller the more unattended activities are still on the daily program of the person in question. Since from (13) it follows for the expected value of the number C_n of daily trip chains of a person visiting n non-home activities

$$E\{C_n\} = \sum_{i=1}^{n} \frac{1}{i}$$

the model is called *harmonic seris trip chain model.* Under the hypothesis (13) the distribution of the length of trip chains and the expected value of the individual daily trip frequency can be obtained in dependence on n.

The advantages of the harmonic series model are to be seen in the fact that it seeks to describe the entire daily mobility pattern of persons in a distinct manner and not only single trip chains from such a pattern. Moreover, it creates an immediate connexion between travel behaviour and number of daily activities. On the other hand, it is a disadvantage that the model is based on an assumption (Eq. (13)) which seems very specific, that no activities of differing types are taken into account, and that the ultimate results depend only on the distribution of the number n of non-home activities. If the model is calibrated, only the distribution of n, but not the observed mobility behaviour would be taken into consideration. The model also has a descriptive character, since it does not contain any explanatory variables. This criticism indicates at the same time possible approaches toward an improvement of the model.

A third, very interesting approach starts out from a classification into so-called "fixed" and "substitutable" activities [26, 27]. While activities of the first kind are carried out regularly at certain times and certain places (e.g. work), the latter are marked by free choice of time and place – at least within certain limits. Their occurence depends on whether the respective need has exceeded a certain threshold value. This threshold value depends on the expected utility which is connected with the activity in question, and on the distance from the place where the activity is carried out. While the expected utility of each substitutable activity can be regarded as fixed, the distance of the individual from the places of substitutable activities changes in the course of its movements in space which are induced by the fixed activities. In this context it is assumed that given the expected utility of a substitutable activity the threshold of the need increases with the distance from the activity place. Consequently, for each distance there is a minimum strength of the need required to incite a trip to the respective substitutable activity, One of the focal points of the model is the assumption that, starting out from a zero position, the intensity of need grows as long as it takes to reach the threshold value. After that, the respective activity will be carried out and the need drops to the starting value to begin accumulating again.

This principle of accumulation of need results in the fact that in the demand for substitutable activities, two alternative types of demand can be distinguished. In those cases where a person is staying at a "base place" (e.g. its home), and the need has been accumulated long enough to exceed the respective threshold value, we may speak of an autonomous demand. A controlled demand is the case when the accumulation of need is not far enough advanced to incite an autonomous demand, but that during the course of a trip from the base to a fixed activity, the distance of the person from the place of the substitutable activity is reduced to such an extent as to make the accumulated need exceed the lower threshold of need attributed to this distance.

In [26] several travel pattern models of this type have been developed with varying degrees of complexity. The case of exponentially distributed time intervals between two subsequent fixed activities and an accumulation of need following a Poisson process has for instance been discussed. After complete specification, such a model yields, besides a number of interesting expected values (e.g. length of a trip chain, time interval between two trip chains, and frequency of trips of a certain type during a time interval), also estimates for the probability of a trip chain to contain certain types of activities. These quantities could however only be determined in simpler cases by analytical methods. For the more complicated models this was not possible, and simulation techniques had to be resorted to.

Without doubt, the *need accumulation model* represents an important contribution to the development of mobility models since it explains the generation of travel demand by the needs of persons for certain activities and by the individual utility resulting therefrom. In its present state of development it is however still as far removed from practical applicability as the other trip chain and travel pattern models. The problem of integration of personal and activity characteristics as explanatory variables is also still unsolved to a large extent.

Summary of Model Evaluation

The review of currently existing models in the field of transport mobility has demonstrated the great variety of all hitherto developed approaches. As shown in Table 2 with the exception of behavioural macro models all categories in the sense of the typology used here can be found.

If it is now attempted to assess in the form of a summary to what extent these models fulfill the three requirements of explanatory quality, forecasting capacity and policy sensitivity, the following can be said:

– Explanatory quality: This characteristics, as far as the integration of causal explanatory variables is concerned, is most markedly present in multinomial logit and individual regression (multivariate linear) trip frequency models. The explanatory potential of trip chain models is currently still very limited due to lacking consideration of socio-economic variables. Only a light explanatory quality can be accorded to all macro models.

– Forecasting capacity: This characteristic can probably at best be attributed to the regression model of the micro type and the dynamic macro mobility forecasting model. In the case of the logit model, the questions connected with the aggregation problem have not yet been solved to complete satisfaction. The zonal regression model is not very suitable on account of its parameter instability. Trip chain models can at the moment not be considered at all for longer-term forecasts, mainly due to their descriptive character.

– Policy sensitivity: The integration of policy sensitive variables in an operational form seems at best possible with micro models of the multinomial logit and multivariate linear type. With macro models, this is more difficult due to their high degree of aggregation, and with trip chain models, not even first approaches exist at the present time.

Table 2 - Classification of existing mobility models.

Type of model	Static		Dynamic	
	Behavioural	*Non behavioural*	*Behavioural*	*Non behavioural*
Macro	—	Zonal regression model (Category analysis)	—	Two-stage mobility forecasting model
Micro	Multinomial logit model	Individual regression model	Need accumulation model Harmonic series model	Markovian trip chain model

DIRECTIONS OF FUTURE MOBILITY RESEARCH

This survey of the present state of mobility research has made two major issues quite clear. For one thing, it could be demonstrated that empirical knowledge of the characteristics and determining factors of mobility have already reached a comparatively high standard. For another, it has become apparent that mobility research is suffering from a deficit in theories which should not be underestimated: no really satisfactory model of travel mobility exists yet.

Behavioural micro-analytical trip frequency models, for instance, have the advantage of being based on explicit behavioural hypotheses and containing the significant socio-economic explanatory variables. Their weakness, on the other hand, is the oversimplified description of individual mobility behaviour merely by daily trip frequency. The dynamic trip chain models, for their part, characterize mobility much more precisely, but are at the present time still lacking in the integration of causal determining factors.

From this disproportion between the empirical and theoretical state of knowledge the emphases of future theoretical mobility research are directly derived. The aim should in this case plainly be the development of models which explain the mobility behaviour of persons by the pattern of daily activities with the help of plausible assumptions on the individual decision behaviour. Approaches of this kind could for instance be the further development of the harmonic trip chain model or the need accumulation model. It would in this context also appear a promising undertaking to follow up the travel time budget approach [28] as well as the journey structures approach [29].

All currently existing micro models are of a short-term nature. No method exists so far which shows how to use these short-term behavioural models for long-term forecasts. A stronger concentration of research activities on the long-term forecasting problem should bring the necessary complementation of the aspect of model calibration which has been strongly emphasized up to now.

Applied mobility research should in the future be more concentrated on actual mobility problems of our society. Of particular urgency in this context seems to be the identification of individual social groups, which are at a particular disadvantage on account of insufficient mobility opportunities, and the investigation of their mobility problems. The analysis of the possibilities of influencing mobility in order to reach an overall social optimum distribution of mobility should also be seen in this context.

REFERENCES

[1] Hautzinger, H., and P. Kessel: **Mobilität im Personenverkehr,** Untersuchung im Auftrag des Bundesverkehrsministeriums, Bonn, Prognos AG, Basel, 1976.

[2] Der Bundesminister für Verkehr: Verkehr in Zahlen 1976, Bonn, 1976.

[3] Kessel, P.: Verhaltensweisen im werktäglichen Personenverkehr, **Strassenbau und Strassenverkehrstechnik,** Heft 132, Bonn, 1972.

[4] Spiegel, E.: Stadtstruktur und Gesellschaft, in: **Zur Ordnung der Siedlungsstruktur,** Veröffentlichungen der Akademie für Raumforschung und Landesplanung, Hannover, 1974.

[5] Curran, and Stegmaier: Travel patterns in 50 Cities, **Highway Research Record,** No. 230, 1958.

[6] Mossman, F., and A.J. Faria: Mobility Index Based on the Socioeconomic Characteristics of Households, Traffic Quarterly, Vol. 29, 347-367, 1975.

[7] Tardiff, T.J.: Comparison of Effectiveness of Various Measures of Socioeconomic Status in Models of Transportation Behavior, **Transportation Research Record,** No. 534, 1975, 1-9.

[8] Kannel, E.J., and K.W. Heathington: Structural Model for Evaluating Urban Travel Relationships, **Transportation Research Record,** No. 526, 73-82, 1974.

[9] McCarthy, G. M.: Multiple-Regression Analysis of Household Trip Generation - A Critique, **Highway Research Record,** No. 298, 31-43, 1969.

[10] Lewis, R.J., and A.A. Douglas: Trip Generation Techniques, **Traffic Engineering and Control,** Vol. 12, 428-431, 1970.

[11] Kessel, P., and H. Hautzinger: Verkehrsmobilität: Meinungen – Analysen – Prognosen, **Zeitschrift für Verkehrswissenschaft,** 47. Jahrgang, Heft 1, 1976, 31-44.

[12] Wootton, H.J., and G.W. Pick: A Model for Trips Generated by Households, **Journal of Transport Economics and Policy,** Vol. 1, No. 2, 1967, 137-153.

[13] Douglas, A.A., and R.J. Lewis: Trip Generation Techniques, **Traffic Engineering and Control,** Vol. 12, 477-479, 1971.

[14] White, M.T.: An Examination of Residual Distributions in Ordinary Least Squares (OLS) Household-Based Trip Generation Models, **Transportation Research,** Vol. 10, 249-254, 1976.

[15] Hautzinger, H.: Statistical Analysis of Travel Behaviour, (forthcoming).

[16] McFadden, D.: Conditional Logit Analysis of Qualitative Choice Behaviour, in: Zarembka, P. (ed.): **Frontiers in Econometrics,** Academic Press, New York, 1974.

[17] Charles River Associates: **A Disaggregate Behavioral Model of Urban Travel Demand,** Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1972.

[18] Hemmens, G.C.: **The Structure of Urban Activity Linkages,** Center for Urban and Regional Studies, Chapel Hill, 1966.

[19] Horton, F.E., and W.E. Wagner: A Markovian Analysis of Urban Travel Behavior: Pattern Response by Socioeconomic-Occupational Groups: **Highway Research Record,** No. 283, 1969, 19-29.

[20] Marble, D.F.: A Simple Markovian Model of Trip Structures in a Metropolitan Region, **Papers of the Regional Science Association,** Western Section, 1964.

[21] Kondo, K.: Estimation of Person Trip Patterns and Modal Split, in: Buckley, D.J. (ed.): **Transportation and Traffic Theory,** Elsevier, New York, 1974.

[22] Gilbert, G., G.L. Peterson and J.L. Schefer: Markov Reneval Model of Linked Trip Travel Behaviour, **Transportation Engineering Journal,** Proceedings of the American Society of Civil Engineers, TE 3, 1972, 691-704.

[23] Jones, P.M.: **The Analysis and Modelling of Multi-Trip and Multi-Purpose Journeys,** Transport Studies Unit/University of Oxford, Working Paper No. 6 (Revised), May, 1976.

[24] Nystuen, J.D.: A Theory and Simulation of Intraurban Travel, in: Garrison, W.L., and D.F. Marble (ed.): **Quantitative Geography,** Northwestern University, Studies in Geography, No. 13, 1967, 54-83.

[25] Vidakovic, V.S.: A Harmonic Series Model of the Trip Chains, in: See Ref. 21.

[26 Westelius, O.: **The Individual's Pattern of Travel in an Urban Area,** National Swedish Building Research, Document D 2, 1972.

[27] Westelius, O.: **The Individual's Way of Choosing Between Alternative Outlets,** National Swedish Building Research, Document D 17, 1973.

[28] Zahavi, Y.: **Travel Time Budgets and Mobility in Urban Areas,** Final Report No. PL 8183, prepared for the U.S. Federal Highway Administration, Washington, D.C., 1974.

[29] Hensher, D.A.: **The Structure of Journeys and Nature of Travel Patterns: Some Conceptual Issues,** Transport Studies Unit/University of Oxford, Working Paper No. 15, January, 1976.