Traffic quarterly.

[Westport, Conn.] Eno Foundation for Transportation.

https://hdl.handle.net/2027/mdp.39015021323186

Urban Transportation Planning: Traffic Estimation

K. RASK OVERGAARD

Dr. Overgaard is a partner in the consulting firm of Hoff and Overgaard, in Copenhagen, Denmark, which specializes in physical and economic planning. He holds an M.S.C.E. degree, and a Ph.D. degree in transportation, from the Technical University of Denmark. As a NATO Science Fellow, he spent a year at the University of California, Berkeley, where he received an M.E. degree. While a traffic expert with the Danish consulting firm Kampsax he was assigned to the Brazil Transport Survey, sponsored jointly by the Government of Brazil and the International Bank for Reconstruction and Development. Dr. Overgaard is a member of the Institute of Danish Civil Engineers.

COMPREHENSIVE transportation planning, which considers all important modes of transport, traffic of persons and movements of goods, central cities and satellite cities, and which takes into account the relationship between land use and transport demand as well as the interactance between different parts of the transportation network, has been known for little more than ten years.

In the United States the Federal Aid Highway Act of 1962 has made continuing comprehensive transportation planning mandatory for cities with more than 50,000 population. A number of European cities have engaged in comprehensive planning on a voluntary basis.

The need for comprehensive transportation planning is most often due to rapid growth in urban population and increasing personal incomes combined with unsatisfactory conditions for both car and transit traffic. The objective of the planning may be stated as follows: "Plans should assure the maximum utilization of existing facilities; guide the development of new facilities to complement existing ones; obviate the need for widening local and collector

This article is a summary of the author's Doctor's dissertation, "Traffic Estimation in Urban Transportation Planning," Acta Polytechnica Scandinavica, Civil Engineering and Building Construction Series no. 37, Copenhagen, 1966.

streets through residential areas; balance capacities against future traffic demands; guide the logical and economical expenditures of available public funds; assure major route continuity regardless of corporate limits; provide for the most expeditious, efficient, and safe movement of people and goods; and serve as an effective guide and stimulus for orderly urban growth and development."[1]

As the authorities interested in comprehensive planning normally do not have a common organization at the outset, a completely new organization must be established. Heading the organization is a policy committee, which appoints a study director to be in charge of the staff and the day-to-day work. An advisory committee of technical experts is often established as an aid to the policy committee and the staff, and sometimes the interests of the public are also taken care of through an advisory committee of citizens.

Usually the planning comprises a period of about 20 years, and in general it takes three to four years to prepare the initial plans. The cost of this in the past may roughly be estimated at one dollar per inhabitant in the area, but the development of still more sophisticated methods and an increasing understanding of the importance of investing in planning will probably result in higher expenses in the future. After the approval of the initial plan, the detailed plans are worked out and the planning is turned into a continuous process during which the plans are adjusted according to the actual development.

The main steps in the methodology most commonly used in comprehensive transportation planning are the following:

1. *Data collection.* Information on land use and intensity measured in terms of floor space, number of employees, retail trade, etc. is collected on a zonal basis.

A home interview survey provides information on the households, e.g., type of housing unit; number of persons in the household, their age and occupation; number of cars owned by the household, and their trip making. With respect to the trips, information is obtained concerning origin and destination, time of day, trip purpose, travel mode, etc. Special surveys for truck trips, taxicab trips, and external trips are also carried out, as well as different

1. Wilbur Smith and Associates, *Future Highways and Urban Growth*, New Haven, Conn., 1961.

traffic counts. The existing street network is surveyed and characterized in terms of lengths, travel times, capacities, etc. Data on parking conditions are also collected. The mass transit network is characterized by the location of lines and terminals, and by travel times, frequencies, capacities, fares, etc. Many other types of information such as data on demographic and economic development must be collected too.

2. *Development of relationships*. The data collected are analyzed in order to find relationships and trends which may form the basis for forecasts.

3. *Determination of future land use, car ownership, etc*. As a basis for the planning, the size of the population and the level of economic activity in the future must be established. This estimate may vary from a simple extrapolation of a trend to a cumbersome forecast, as is the case when the economic activity is calculated through an input-output model. The determination of the location of the future increase in population and economic activity can be more or less rigid. In countries with strong city planning legislation, the location will presumably be taken from the adopted master plan, while the location in the United States is often determined by a model simulating the forces which are believed to influence locational patterns.

Car density is the explanatory variable most often used in calculating the trips made by the households. Estimates of future car densities are usually based on expected income and kept fixed in the traffic calculations irrespective of the transportation system being tested.

4. *Proposals for the future transportation system*. The proposals for the future transportation systems which are to be evaluated emerge from existing conditions, from loading the existing network with the future traffic, from policy objectives, and from engineering experience and judgment.

5. *Calculation of future traffic flows*. Based on the proposed land-use plan and its related figures, i.e., car densities, etc., and the relationships or models developed from the traffic surveys, the future traffic flows for each of the proposed transportation systems may be calculated through four phases:

a. Trip generation
b. Trip distribution

c. Modal split

d. Traffic assignment.

To carry out the computations some assumptions must be made, e.g., on the travel times for the street sections. If they turn out to be unrealistic the process is repeated until a reasonable balance is reached.

The four phases in the estimation procedure described above will be treated in more detail in the following.

6. *Evaluation of proposals for the future transportation system.* With the future traffic flows assigned to the transportation systems under study, overloaded parts and poorly utilized parts are indicated and proper alterations may be introduced. During the assignment of traffic to the systems, the total trip length and the total travel time are also computed. These figures and construction costs constitute the main basis for an assessment of the different proposals in terms of such economic criteria as the benefit-cost ratio, the rate of return on total investments, the rate of return on marginal investment, etc.

TRIP GENERATION

Trip generation of a zone is the number of trips generated by the zone in a given period of time. *Trip attraction* is the number of trips attracted by a zone in a given period of time. While trip generation and trip attraction refer to areas, *trip production*, which is the number of trips made by a household or a car in a given period of time including trips taking place outside the home zone, refers to the trip-making unit. As location of the terminal points of the trips, i.e., origins and destinations, is important in planning the future transportation system, it is trip generation which is needed. This figure can, however, be found both directly and by using trip production as an intermediate step.

The trip generation forecast generally comprises the total daily traffic, the peak-hour traffic being taken as a percentage thereof. This procedure, however, is not satisfactory as the peak-hour percentage may be twice as high for one street as for another street. A main reason for this variation is that traffic on different streets does not have a uniform composition with respect to the kinds of trips observed, i.e., truck trips, passenger car trips to or from work, etc. A solution to the problem seems to be to make special forecasts for trip generation during peak hours. Such a method looks promising since there is a larger percentage of trips with a fixed pattern in this period than in the day as a whole, e.g., the home-to-work trips. However, the peak hour does not occur simultaneously for all streets, so in theory it may be necessary to make forecasts for different hours of the day and even of the week.

The number of trips generated in a zone or produced by its population has proved to be correlated to different characteristics of the area and the population. Based on observations it is possible to fix the relations quantitatively by means of correlation analysis. The future number of trips is then computed by substituting into the regression equation the estimated values of the independent variables. Thus it is assumed that the equation remains valid. Whether this in itself is a reasonable assumption will be discussed later.

In the following, different methods of computing trip generation on the assumption that the necessary data have been collected for the planning area will be outlined first, and thereafter the possibilities of applying to one city observations taken in other cities will be discussed.

A method much used in the past to obtain an estimate of the future trip generation of a zone is to multiply the present trips by a *growth factor*, which may be the product of the ratios between the future and the present population, the future and the present car density, and the future and the present car utilization.

Future trip generation may also be estimated roughly by applying *generation figures*, giving the number of trips generated per unit of area in a given period of time, to the future amounts of land in different uses such as residential, manufacturing, commercial, transportation, public buildings, and public open space. The generation figures are developed by relating observed numbers of trips to the amounts of land in the different categories. If individual figures are developed for the Central Business District (CBD) and the outskirts of the city, it will be seen that there is a decline in the generation figures for all land-use categories from the CBD toward the outskirts. This is due to the less intensive utilization of the land as the distance from the CBD rises. By relating the number of trips to the floor area instead of the area of land another set of generation figures may be obtained. These figures are generally more uniform over the city. For an adequate estimate it must be known how the generation figures change over the years as a result of increasing car density and other causes. In practice the method is used with constant generation figures in order to obtain a crude estimate of future travel demand.

Many European studies have estimated future trip generation from the number of *residents and employees* in the zones. This may be regarded as a special case of the land-use method just described with only two land-use categories being considered, namely, residential areas and areas of employment. In the same way as trip-generating capability differs widely between different land-use categories, the number of vehicle trips generated per employee depends strongly on the kind of employment in question. It has been suggested that a stratification of land use for business purposes is superfluous since it has proved possible to set up models based on residents and employees which reproduce fairly accurately the number of trips generated by each zone. It should be kept in mind, however, that a good statistical fit does not assure a good forecasting model, and in any case the possibilities of testing realistically the effects of different land-use plans disappear if such a crude model is employed.

Future trip generation of the zones may also be found by calculating trip production of the households and then distributing the end points of the trips geographically. Future *trip production* per household is usually determined from a regression equation using such explanatory variables as car density, distance to the CBD, residential density, income, etc. With a proper combination of these variables it is often possible to develop from survey data an expression for trip production which is correlated significantly, in the statistical meaning of the word, to the observed number of trips. Unfortunately, this does not mean that an ideal forecasting model has been found, since such a model must rely on causal relations, and these are far from clarified. What, for example, is cause and what is effect with regard to the number of trips and the number of cars per household?

When developing regression equations based on the above-mentioned variables it should be remembered that these quantities are interrelated. Just how strong the interrelation is and which of the quantities are the relevant ones is not yet fully understood. The regression equations apply to *average* figures, e.g., the average number of cars per household for a zone. However, in the application of averages some possibilities of errors are inherent, as the following example will show. In a survey in Detroit in 1955, the following numbers of trips per day were found for households with three persons and no car, one car, and two or more cars respectively: 3.32, 6.92, and 8.82.

Suppose now that two zones both have 100 households and on the average one car per household. Suppose furthermore that one of the zones has 100 households with one car, and the other zone 50 households with no car and 50 with two cars. The corresponding numbers of trips are then $100 \cdot 6.92 = 692$ and $(50 \cdot 3.32 + 50 \cdot 8.82) = 607$ respectively. This result suggests that the trip production calculations should be based on a stratification of the households with respect to the number of cars owned as well as other household characteristics.

Recent studies have pointed to household size as an even more important variable than car ownership in explaining trip production of *individual* households. How much better trip production estimates will be if a stratification of the households according to size and number of cars owned is used than when equations based on zonal averages are used will depend on the accuracy with which the distribution of households with respect to size and car ownership may be predicted for individual zones. Knowing the trip production of the households the next problem is to determine *where* the trips are generated. In studies which employ a division of the trips into home-based and non-home-based trips, the points of generation for the home-based trips are already known, while the points of generation for the non-home-based trips may be found by means of an index. This index is developed from the observed distribution of the non-home-based trips between the different land-use categories. When no distinction is made between home-based and non-home-based trips the index method may be applied to the total trip production.

The methods for calculating trip generation described in the foregoing apply only to person trips. The question of how to determine *goods movements* remains. So far this problem has not been given as much consideration as that of estimating person trip generation. Very often the numbers of truck trips generated by different land-use categories are computed from the person trips by assuming a certain number of truck trips per 1,000 person trips. A justification for relating the two kinds of trips to one another is that the number of person trips expresses the level of activity of a zone and this level again depends on the number of truck trips.

As the collection of the data needed to develop individual parameters for the city under study is both time-consuming and expensive, it is very challenging to look for relationships and parameter values of general validity. Although it is too early to say anything definite about the outcome of this search, forecasts have been carried out in a number of cases based on figures considered sufficiently universal. In such applications the procedure is to substitute into the model parameter values from a comparable city or from a small-scale local survey, to simulate the present travel pattern. Comparing the traffic flows derived in this way to counts from different points in the area, the initial parameter values may be adjusted until computed values and counts agree sufficiently well. It is possible that traffic estimates obtained by means of general models as described above may be comparable to results from individual models, but important parts of the solution to the problem under investigation are usually found during the analysis of the survey data.

The transportation study reports published so far reveal that the relationships derived from the analysis quite frequently have been applied directly to the target year without any *adjustment* of the parameters. This procedure must be considered a first approximation since at least some of the parameters obviously change over the years. A decreasing number of trips per unit of floor space may be caused by a smaller employment density in new buildings than in old ones. Increasing use of telecommunication also tends to make invalid parameter values derived from traffic surveys. It is therefore necessary to estimate the future value of the parameters before the models are used to estimate future traffic. This requires human intuition and imagination.

In order to plan the transportation system so the best possible connections between the different parts of the city are achieved, the demand for travel between the zones, i.e., the trip frequencies, must be known. The trip distribution models may be divided into growth factor methods (in which observed trip frequencies occur explicitly), gravity models, and opportunity models.

TRIP DISTRIBUTION

One of the *growth factor methods* most easily understood is the average growth factor method, which computes the future trip frequency between two zones as the product of the existing trip frequency between the zones and the average of the growth factors for the two zones. The growth factor of a zone is the ratio between the future and the present number of trips to and from the zone. When the trips from a zone to all other zones are computed by means of the average growth factor method and summed up, the result generally deviates from the total trip generation of the zone already known. To obtain identity, a new growth factor for each zone has to be computed and the calculations must be repeated until sufficient correspondence is reached.

The remaining growth factor methods employ other combinations of the growth factors.

In the United States the following general traffic model is generally applied.[2]

$$T_{i-j} = G_i \frac{A_j \cdot f(d_{i-j})}{\sum_x A_x \cdot f(d_{i-x})}$$

where

T_{i-j} = the number of trips of a certain category generated at zone i and attracted to zone j.

G_i = the total number of trips of the category in question generated at zone i.

A_j = a measure of the attractiveness of zone j with respect to the trips in question.

$f(d_{i-j})$ = an expression for the effect of distance on the number of trips between zones i and j.

The different variants of the general model mainly arise from differences in: 1. The classification of trips according to purpose;

2. A. M. Voorhees, "A General Theory of Traffic Movement," Institute of Traffic Engineers, New Haven, Conn., 1955.

2. the measure of attractiveness of the zones; 3. the distance function $f(d)$.

A classification of the trips into eight groups has been suggested for larger cities, while three groups are considered sufficient for small cities. Even with eight groups, however, some groups may be fairly inhomogeneous. As a measure of the attractiveness of the zones different quantities may be used, depending on which trip purpose is being considered. It is most often some combination of the number of residents and the number of employees in various business categories.

The distance function is the element of the gravity model which, thus far, has been examined most thoroughly. The following quantities have been employed to measure the distance: the straight line distance, the road distance, the travel time, and even others. Today the travel time plus terminal times, such as the walk at each end of a trip, is in common use.

No general agreement has yet been reached as to the type of the distance function. Power functions and exponential functions with different parameter values are suggested most often. Some of the distance functions deviate considerably from one another for small distances. Thus, the power function becomes infinitely large as the distance approaches zero, while others, such as the exponential function, take on a definite greatest value when the distance is zero, and still others become zero as the distance becomes zero. Arguments in support of each of these functions may be put forward.

In the United States analytical expressions are now frequently avoided, and a table of travel time factors corresponding to one-minute intervals is used instead. The travel time factor expresses the effect of the travel time on the trip frequency between two zones. Survey results generally reveal distance functions which approach zero for small distances. It is, nevertheless, quite possible that the true distance function has a definite greatest value when the distance is zero, as the exclusion of trips on foot and by bicycle may be responsible for the observed result.[3]

The Bureau of Public Roads has suggested a gravity model which may be considered an extension of the aforementioned

3. An example supporting this hypothesis is presented in the author's dissertation, *op. cit.*

general model as it includes an adjustment factor for each pair of zones. The introduction of adjustment factors has turned out to be necessary because the travel time and the land use are not sufficient to explain an observed travel pattern. For example, in some cases special socioeconomic relations which influence the trip frequencies do exist between zones. The adjustment factors are determined from observed data and assumed valid for the future. So far little is known about how these factors may be explained, but they open up the possibility of taking economic and social conditions into account explicitly.

Numerous other gravity models have been presented over the years. Most of these are analytical expressions, but the so-called interactance model may be characterized as a graphic gravity model. Many of the gravity models employ a balancing procedure to ensure that the computed numbers of trips from or to a zone add up to the predetermined trip generation or trip attraction of the zone.

The *opportunity models* are interesting as they attempt to explain the travel pattern through basic considerations about the individual's behavior. In the intervening opportunity model the basic assumption is that the traveler wishes to make his trips as short as possible. Furthermore it is assumed that when the traveler considers the possibility of stopping at a potential destination there is a constant probability that he actually stops. To obtain a mathematical expression of the principle it is additionally assumed that the traveler examines the possible destinations in a certain order, say, according to the travel time from the origin. The travel times between the zones do not occur explicitly in the opportunity models, but they constitute the basis for ranking the zones.

MODAL SPLIT

If a rational transportation system is to be established it is not sufficient to know how many persons will be traveling between the different zones of the urban area. It is necessary also to know how the trips will distribute themselves over the different modes of travel. This distribution is known as the modal split.

The modal split computations may be put into the four-phase estimation procedure followed in this article in three ways:

1. In connection with the trip generation calculations—this means that trips using different modes of travel are calculated separately—the estimation procedure consists of only three phases.

2. Between the trip generation and the trip distribution calculations—this means that the trips generated in each zone are split between modes of travel before the points of attraction are found.

3. After the calculation of the trip distribution—this means that the trips between each pair of zones are being split.

In many studies combinations of these possibilities are used, as the modal split for trips of different purposes is carried out in different computational phases.

The calculation of the number of trips on different modes of travel has been done most often by computing the trip generation separately for each mode. A calculation according to this principle may be based on the number of trips per car per day and the number of trips by mass transit per person per day. Although the discussion of trip generation presented earlier in this article referred mainly to the total number of trips, corresponding methods and variables may be used in determining the trip generation for each mode of travel.

It may be completely sound to generate the trips for each mode of travel separately as long as the modes meet different demands for transportation. However, this is generally no longer the case in large cities in the United States and Europe, where increasing car densities and resulting traffic difficulties have made the use of the mass transit system where available a realistic alternative to car riders, at least for work trips to the CBD. Most of the models which perform the modal split after the total person trips are calculated but before the trip distribution is carried out rely on the same explanatory variables as the trip generation models for total person trips or trips by individual modes of travel, i.e., car density, residential density, income, distance to the CBD, etc. The models are usually presented in the form of curves, the dependent variable being the percentage of transit trips and the independent variable(s) one or more of the quantities just mentioned.

This group of models generally does not reflect the competition between the different modes of travel. However, one of the most recent models for splitting the person trips from a zone into car and transit trips may be considered a linkage between the models which carry out the modal split before the determination of the trip frequencies and those which do it after, as this recent model takes into consideration characteristics of the generating zone as well as overall characteristics of the transportation networks. The model consists of curves which give the percentage of trips using transit in relation to the accessibility ratio for the zone in question, i.e., the ratio between transit accessibility and car accessibility calculated according to the expression in the denominator of the general gravity model presented in the section on trip distribution. There is a set of curves corresponding to different income ranges for each of the trip purposes considered.

If the modal split is postponed until the trip frequencies are calculated, the models may be based on variables which characterize the different modes such as travel time, travel cost, level of service, etc. This means that the modal split is considered a problem in a competitive market. As this type of model illustrates the effects on the modal split of changes in the transportation system, it may be a very important planning tool. The kind of model most often used in splitting the trip frequencies between cars and mass transit uses the travel time ratio as the only explanatory variable. The travel time should include walking times and waiting times.

It is well known, however, that many factors other than travel time play a role in the choice of mode. One of the most sophisticated modal split models seems to be the model developed for Washington, D.C.[4] This model splits the number of person trips between a pair of zones by means of five explanatory variables:

1. *Trip purpose*, i.e., work trips and other trips, except school trips which are handled separately.

2. *Income level* of the zone of generation.

3. *Relative travel cost* defined as the ratio of the travel cost using mass transit to the out-of-pocket costs of riding a car, i.e., cost of gas, oil, lubrication, and half the parking fee divided by the number of persons per car trip.

4. *Relative excess travel time* defined as the ratio of the amounts of time lost by using the modes of travel in question, i.e., total time

4. T. B. Deen, W. L. Mertz, and N. A. Irwin, "Application of a Modal Split Model to Travel Estimates for the Washington Area," Washington, D.C., 1963.

spent walking to and from transit stops and time spent waiting and transferring, divided by the time spent on parking and walking to the destination. No time consumption is considered at the beginning of a car trip. This ratio is also known as the *service* ratio.

5. *Relative travel time* defined as the ratio of the door-to-door travel times by mass transit and by car.

Three of the variables are considered only at certain levels. There are five income levels, four levels of relative travel cost, and four service levels. This means that for each of the two trip purposes there are 80 curves which give the percentage of transit trips as a function of the travel time ratio. Although the curves are valid only for Washington, D.C. it is considered reasonable to assume that the same variables govern the modal split in other cities.

The modal split methods discussed so far have handled all trips leaving a zone in the same way although quite a few individuals may have no real choice. It has been suggested that a distinction should be made between captive trips and choice trips by mass transit. Captive trips are defined as trips made by persons belonging to households owning no cars, by persons having no driver's license, or by persons who did not have the opportunity to drive because the family car was not available when the trip was started. All other transit trips are choice trips. The definitions imply that a person in the captive category very well may go by car, either as a passenger or as a driver of a borrowed or a rented car. However, the total trips made by persons belonging to this group are split between car trips and transit trips in quite another way than the trips made by persons having a real choice.

The criteria which determine the modal split of the two groups are not the same. Therefore, the modal split model should take the existence of the different groups into account explicitly, contrary to what has been the case in previous models. Such a model may well lead to improved estimates of the effects of a future mass transit system.

TRAFFIC ASSIGNMENT

After the person trips are split between cars and mass transit it remains to assign the car traffic to the street network and the mass transit trips to the transit network. Most theories suggested so far for assigning traffic to a network have considered car traffic. However, similar principles may quite frequently be applied to mass transit traffic. In cities which offer a number of realistic alternative transit routes, the assignment of transit trips ought to be given more consideration than has been the case until now. In the following, the assignment problem will be discussed in terms of car trips and street networks. The simplest way of assigning traffic to a network is to have an engineer with a good knowledge of the area choose one route connecting each pair of zones. This route is then supposed to convey all traffic between the corresponding pair of zones. An extension of the method consists in choosing more than one route between two zones and estimating roughly the distribution of the traffic over the selected routes.

These subjective methods are no longer in use for transportation planning in big cities. When a trip is going to be made the traveler chooses his route from a number of criteria which he is more or less conscious of. If the trip is made repeatedly he does not review his choice every time. According to a British survey about 70 percent of the traveling public study their choice of route fairly frequently.[5]

It is observed in practice that not all travelers follow identical routes between two points. This fact may be explained through either one or both of the following circumstances:

1. Alternative routes are evaluated differently by different persons.

2. The distribution over a number of routes arises because the total traffic situation tends to reach some state of equilibrium.

When traffic flows are small compared to street capacities, point 1 is presumably the most important reason why a number of routes are used. When the traffic becomes more dense the importance of point 2 increases.

The factors which play a role in the choice of route are related to the three classical elements of traffic engineering:

1. The road and its environment;
2. The vehicle;
3. The driver, including circumstances related to the trip.

The most important circumstances related to the road are: trip

5. J. A. Hillier, "Use of Computers for Traffic Analysis, Forecast, and Assignment," *International Road Safety and Traffic Review*, vol. xi, no. 1, 1963.

distance, travel time, fees, e.g., tolls at toll roads, type of road, and traffic flow conditions. Distance, travel time, and fees may all be quantified immediately though not in the same unit. Very often they are combined into a travel cost from a cost per vehicle mile and a value for one hour spent on the road.

All road conditions other than distance, travel time, and fees are generally disregarded in the models. Nevertheless, alignment, gradients, intersections, traffic signals, roadside development, etc. probably also have considerable influence on the choice of route. The different operating characteristics for cars and trucks may result in different route choices for these vehicle categories. Local ordinances preventing trucks from using certain streets also cause car and truck drivers to take different routes. The subjective element in the choice of route is due to the driver's individual evaluation of the road characteristics, which depends on his sex, age, temperament, economic status, etc.

According to available information individual factors have not been taken into account in any assignment calculation thus far. It is assumed that groups of travelers considered on the average react in a fairly uniform way.

A problem very often faced by traffic engineers is that of estimating the amount of traffic which may be diverted to a new freeway, e.g., a bypass. This problem has lead to the development of a great number of so-called diversion curves which express the percentage of traffic between two zones that may be expected to use the freeway depending on the characteristics of the freeway, i.e., length, travel time, etc., compared to the characteristics of the best existing road. Some of the early diversion curves used the difference in distance or the distance ratio as the explanatory variable, others the difference in travel time or the travel time ratio. As different drivers, however, base their choices of route on different characteristics, more representative diversion curves may be obtained by employing several explanatory variables in the same model. The travel cost combines time and distance and eventually fees such as tolls on roads or bridges. Diversion curves with the travel cost ratio as the explanatory variable have often been used to assess the amount of traffic which may be expected on a new toll facility. Other models comprising a system of diversion curves use both the distance ratio or the distance difference and the time difference as explanatory variables. Still other models take three or more characteristics into consideration.

The diversion curves are all more or less influenced by the local conditions of the area at the time for their development. Such factors as the traffic volume and the trip distance distribution, the number of and the quality of alternative routes, etc. affect the percentage of traffic on the new road. This implies that the application of the models to other areas is somewhat questionable. Some of the models, however, contain parameters which may be adjusted to fit a factual situation. By applying a diversion curve successively it is possible to distribute traffic between more than just the two routes being compared each time, but it is not quite obvious that diversion curves may be used in this way. In studies which employ diversion curves the routes being compared are usually selected manually or even predetermined as in the case of a bypass round a small town.

In long-range transportation planning it is necessary to assign traffic to complete networks comprising hundreds of road sections. This has been made possible only by the introduction of electronic computers which may determine optimal routes, e.g., fastest routes, between some hundred zones, and load the trip frequencies onto these routes in a couple of hours or less. If all traffic between each pair of zones is assigned to the optimal route some road sections will probably be overloaded. Because of the reduced service offered by a facility when the flow approaches capacity, part of the traffic will therefore in practice prefer other routes. The most recent methods of calculating the distribution of traffic over a network take into account this restriction in the travelers' choice of route by redistributing the traffic until a certain balance is achieved. Some theoretical methods compute this condition directly. The balanced condition represents the best estimate of the traffic flows in the target year under the assumptions made, e.g., concerning the street network.

Some planners have apparently misunderstood this procedure. They claim that using this method one writes off the possibility of directing the traffic flows, but this is certainly not the case. What happens when the flows are redistributed is just that the drivers are allowed to react on the conditions in the network suggested by the planners. The reactions are in accordance with theoretically and/or practically founded principles. If the traffic flows do not correspond to what the planner has pursued he may change the master plan or the traffic system and repeat the calculations.

In the following, some network assignment models which do not take into account the street capacity will be discussed first, and thereafter the models which allow the capacities of the streets to affect the distribution of traffic over the network will be treated. Assignments according to the all-or-nothing principle in which all traffic between two zones is assumed to follow the optimal route, e.g., the fastest route, may provide valuable information on the location of new streets and the design volumes to be used.

Two types of assignment models which are founded on probability theory and electric circuit analogy respectively divide traffic between different routes on the basis of the following expression:

$$p_i = \frac{A_i}{\sum_{x=1}^{n} A_x}$$

where

P_i = percentage of traffic to be assigned to route i.
A_i, A_x = attractiveness of route i and x respectively.
n = the number of routes considered.

The attractiveness of a route is measured as the inverse of the travel cost or a combination of travel distance and travel time raised to some power.

Models like the one just described have been used both with and without the so-called capacity restraint, i.e., the relationship between traffic flow and travel time for a street. When capacity restraint is not used, the routes to be considered are generated under the assumption of fixed travel times and then loaded.

The capacity restraint may be introduced by initially assigning all traffic to the optimal routes, after which the travel times are adjusted according to the obtained loading and the appropriate time-flow relationship. Another set of optimal routes results, and the traffic is then divided between the original route and the new one according to the above formula. This process may be repeated until a satisfactory balance is reached.

The first major transportation study to consider the relationship between travel time and traffic flow was the Chicago Area Transportation Study, which employed the following assignment model:

Based on travel times at zero flow the fastest routes from a certain zone to all other zones are found and loaded with the traffic from that zone. Thereafter the travel times are adjusted according to the loadings, and the fastest routes from a second zone to all other zones are found and loaded. Traffic from the two loadings is summed for each street section, and the travel times are adjusted once more. The process is repeated until all zones have been treated. To achieve a uniform increase in travel times all over the network, the Chicago study treated the zones in a certain order, while a study in Pittsburgh picked the zones at random.

In 1952 Wardrop suggested two theoretical principles for the distribution of traffic over a network:[6]

1. The principle of equal travel times;
2. The principle of minimization of the total travel time.

If the principle of minimization of the total travel time does hold, travelers must behave in such a way that they consider the overall situation and not just what suits themselves. Such behavior probably does not correspond to what actually happens. But the principle might have an application in establishing traffic control schemes.

PROGRAM AND TEST RUN

The principle of equal travel times states that trips between two zones are distributed over the different routes in such a way that travel times over routes used are equal, while travel times over routes not used are greater. When the principle is fulfilled no traveler can benefit from changing his route. A distribution corresponding to such an equilibrium seems to be more realistic than a distribution according to the principle of minimization of the total travel time. The principle of equal travel times may be formulated as a mathematical programming problem. Though the theory for solving this problem is known, it is not yet developed into computationally feasible methods. It is, however, the author's belief that the so-called Wayne Arterial Assignment Method converges

6. J. G. Wardrop, "Some Theoretical Aspects of Road Traffic Research," Proceedings of the Institute of Civil Engineers, 1952.

towards a situation in which the requirements of the principle are met.[7]

In order to examine the Wayne method in general and its relationship to the equal travel times principle in particular it was decided to write a computer program and to test the program by means of data from a Danish city. The computational procedure of the program actually developed, which deviates from the Wayne method in a number of ways, is the following:

1. Using travel times corresponding to zero flow the fastest route between every pair of zones is found.

2. Traffic between every pair of zones is assigned to the route found and traffic is summed for every street section.

3. Travel time for every street section is revised according to a formula of the type:

$$t^{(i)} = a\left(\frac{q^{(i)}}{C}\right)^{b} \cdot t_o \cdot L$$

where

$t^{(i)}$ = travel time in the i'th iteration (min.)
$q^{(i)}$ = flow in the i'th iteration (vph)
C = practical capacity (vph)
t_o = travel time per mile at zero flow (min./mi.)
L = length of street section (mi.)
a and b = parameters.

Eight sets of values for C, t-, a, and b, corresponding to different types of streets, were developed from time-flow relationships proposed by Irwin and von Cube.[8] "a" expresses the ratio between travel time at practical capacity and travel time at zero flow. Values used range from 1.0 (travel time independent of flow—used for artificial street sections) to 1.7. This represents the main departure from the Wayne method, which has a ratio of e (=2.718) between travel time at capacity and travel time at zero flow for all types of streets. The value of the ratio used in the Wayne method is high and, furthermore, the ratio is known not to have the same value for all street types, so it was felt that the method would be improved by

7. R. B. Smock, "A Comparative Description of a Capacity-Restrained Traffic Assignment," Highway Research Record, no. 6, Highway Research Board, 1963.

8. N. A. Irwin and H. G. von Cube, "Capacity Restraint in Multi-Travel Mode Assignment Programs," Highway Research Board Bulletin 347, 1962.

introducing a more realistic time-flow relationship into the algorithm.

4. Using the new travel times the fastest route between every pair of zones is found.

5. Traffic between every pair of zones is divided equally between the two routes found so far, and traffic is summed for every street section.

6. Travel time for every street section is revised, and a third set of fastest routes is determined. This time traffic is divided into thirds, each part being assigned to one of the three routes found until now (if the same route is found more than once it receives a corresponding number of shares of the traffic).

7. The process is repeated until changes in flows and travel times from one iteration to another are sufficiently small.

The network used for testing the procedure with respect to the principle of equal travel times was made up of 52 intersections and 130 directed street sections. Trips between 35 zones were assigned to the network by running the program through 20 iterations. Sixty-six pairs of zones, between which more routes seemed likely to be used, were selected for inspection in advance. Because of the small size of the network only three pairs of zones used three routes, 45 used two routes, and 18 used only one route.

For each of the three pairs of zones using three routes, travel times on the different routes were in fact the same, e.g., 4.25—4.26—4.25 min.

In 26 cases out of the 45 using two routes, travel times were not identical. Closer examination showed that of the two routes found in each case, one was found only in one iteration, usually in the second, while the other was found in nineteen iterations. This means that one-twentieth of the traffic between the zones used one route, while the rest of the traffic used the other route.

In the case of an infinite number of iterations the limiting distribution is zero traffic on one route and all traffic on the other route. This implies that the principle of equal travel times does in fact apply here also as the "extra" route may be looked at as an unused route. Thus the test run has given a practical indication that the modified Wayne method used (and certainly also the original Wayne method) may be considered an iterative procedure for solving the traffic assignment problem in accordance with the principle of equal travel times. The questions that remain are whether traffic actually distributes itself over a network according to this principle, and if not, what then is the principle?

SUMMARY

This article has presented an outline for the urban transportation planning process and given a general description of the four phases in the traffic estimation procedure, i.e., trip generation, trip distribution, modal split, and traffic assignment. A particular traffic assignment program, which was developed and tested by the author, has also been described.[9] For more specific information such as formulas, diagrams, evaluations, references, etc. on the matters dealt with in this article the reader is referred to the author's dissertation.[10]

9. K. R. Overgaard, "Testing a Traffic Assignment Algorithm," Third International Symposium on Theory of Traffic Flow, New York, 1965.
10. *Op. cit.*