

**ANALYTICAL TRANSPORT PLANNING MODELS
(WITH SPECIAL REFERENCE TO
TRAVEL DEMAND FORECASTING):
A REVIEW OF LITERATURE**

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CHAPTER I

INTRODUCTION

Promoting economic development without planning is like attempting to reach home port in a rudderless ship. ... Economic growth per se of course does not depend on planning. Nor is planning a panacea for all economic ills; indeed, it can be overdone and impede attainable growth. Yet both the social and economic consequences of development can be greatly improved by intelligent planning. 1/

1.1 Need for Transport Planning

Transport is an important ingredient which ensures efficient and smooth functioning of any economy. The development of transport infrastructure has frequently been undertaken for promoting a host of economic as well as non-economic objectives. Without adequate transport facilities, much of a nation's natural resources would remain untapped, per capita consumption levels would remain meagre and there would be little scope for exchange of ideas. In short, communities would stagnate in isolation at low levels of living. As Lord Macaulay, the eminent British historian once remarked that of all inventions, the printing press excepted, transportation had done more than any other to advance the cause of civilization and understanding among peoples and nations.

1 Fromm, G. "Design of the transport sector," in Fromm, G. (ed.). Transport Investment and Economic Development (1965).

However, there is an ardent need to recognize that transport is only a necessary but not a sufficient condition for economic development. Transport can do little if the economy is deficient in other essential factors conducive to growth.

The degree to which transportation creates or compels new activity will surely depend upon the existence of other conditions within the economy, the quality of its administrative structure and social order, the character and drive of its educational system, the nature of legal and property relationships and all the other dimensions of a nation's "propensity to grow". ... 2/

Nevertheless, the existence of an economical and reliable transport system is considered to be a basic infrastructural requirement. Accordingly, since the mid-fifties attempts have been made to systematically organize the set up and functioning of the transport sector. This has been done in the framework of a planning exercise.

By its very nature, the transport sector has certain distinctive features which reinforces the need for planning. For instance, investment in transport infrastructure is invariably lumpy. Moreover, such projects begin to yield services only after long gestation periods, locking up a large amount of funds. Any misallocation could well jeopardize the efficient use of a nation's resources, retarding the

2 Heyman, H. Jr. "The objectives of transportation," in Fromm, G. (ed.). Transport, Investment and Economic Development (1965).

pace of economic growth. This issue holds special significance for the developing nations, where on the one hand, resources are scarce, while on the other there is an urgent need to hasten economic progress in order to combat problems such as unemployment, inequalities of income, low standards of living, etc. Further, when we consider the issue of optimum nature and location of transport facilities, the need for planning seems almost axiomatic. An in-depth survey of the unique characteristics of the region, including specific needs and values of the community, is a prerequisite if the aim is to derive far-reaching solutions. Blind adoption of sophisticated technology, ill adapted to local conditions can prove to be counter-productive.

1.2 The Scope of Transport Planning

The objectives of transport planning have undergone a radical change over time. To begin with, the aim was purely 'traffic functional'. Planners failed to look beyond the transport sector for ameliorating various aspects of the transport problem. Consequently, adhoc, project specific measures were rather common. Fortunately, since the mid-seventies, a comprehensive approach towards planning of the transport sector has been attempted.

Since transport is only one part of a total environmental complex, so transport planning is only one aspect of overall urban planning. The overall planning procedures must be ruled by an interdisciplinary approach which is undergoing continuous re-evaluation. 3/

³ Koelman, F.H.J. "Transport Planning Integrated in the Overall Planning Process," Traffic Quarterly, Vol.26 (1972).

Thus, the distinguishing features of this approach are, a comprehensive set of goals, an interdisciplinary approach to the problem and a continuous incorporation of short term plans within a well formulated long term plan.

The basic framework of the transport planning process has, however, remained the same. This is depicted in Figure 1.

Different phases of this process can be explained as follows:

- (i) In any systematic planning process the formulation of explicit goals and objectives is essential as the objectives become the criteria against which alternative plan proposals are evaluated.
- (ii) The survey, analysis and model building phase answers two important questions. First, what is the existing travel demand, and secondly, how is this demand satisfied on the basis of existing transport facilities? To answer these questions, a survey of the existing travel demand is undertaken with a view to establishing relationships between present demand and factors influencing it.
- (iii) The forecasting phase uses the relationships established in the analysis and model building phase to make estimates of future travel demand.
- (iv) Proposals to meet predicted travel demand are then put forward.

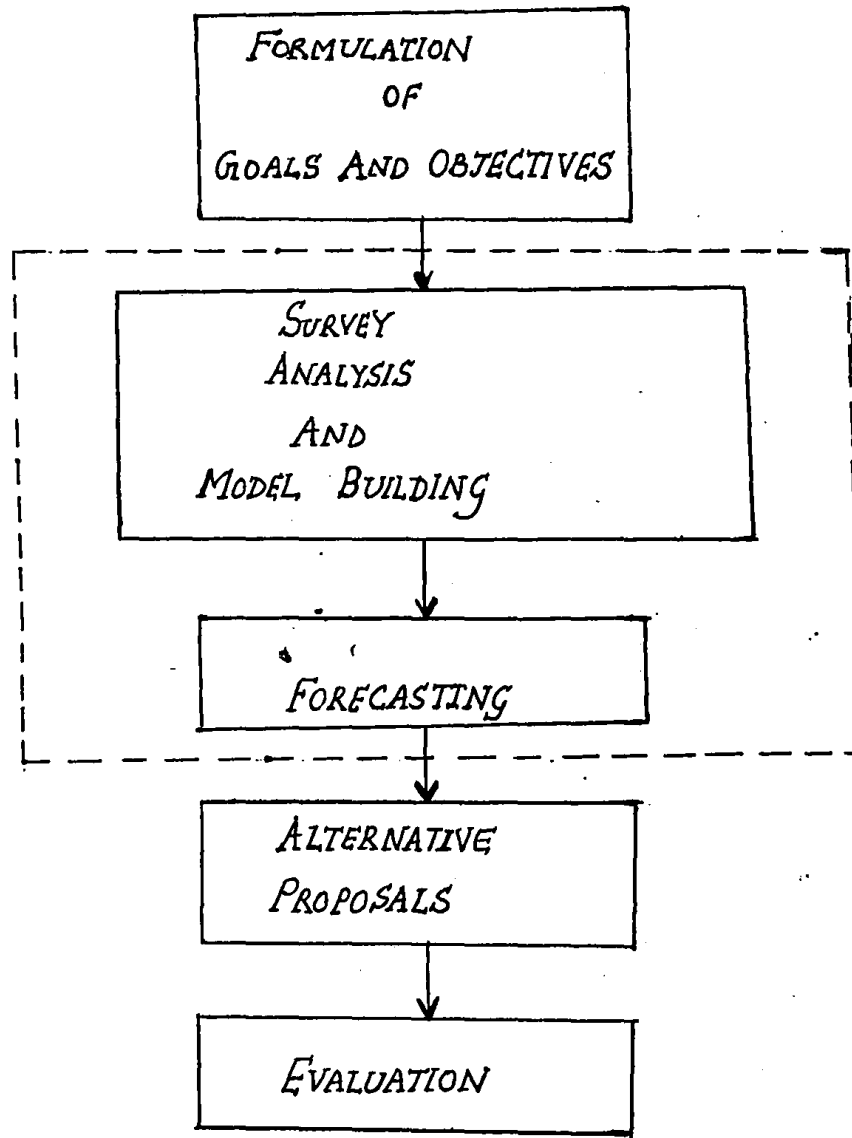


Figure 1 : The Framework of Transport Planning

- (v) The evaluation phase assesses these proposals to determine whether they satisfy defined social, economic and operational goals and objectives.

The survey, analysis and model building phase as well as the forecasting phase are the most important components of the transport planning process. The accuracy of the traffic forecasting model dictates the use that can be made of the transport planning process and the scope for evaluation. In this thesis an attempt will be made to review some of these models as they have evolved in the literature.

Chapter II discusses the most widely used aggregate sequential modelling techniques, wherein separate sub-models for trip generation, trip distribution, modal split and route assignment are examined in detail. Chapter III examines some of the transport related land use models, such as the Lowry model and its derivatives. Around the late sixties the aggregate sequential modelling techniques were severely criticised on the ground that these had few explanatory powers, though, as simple simulation models they reproduced a known situation quite well. Economic demand models emerged to overcome some of these shortcomings. These are discussed in Chapter IV. In Chapter V a brief review of application of travel demand models in the Indian context is attempted. Lastly, Chapter VI provides our concluding remarks.

CHAPTER II

AGGREGATE SEQUENTIAL MODELLING

2.1 Introduction

Aggregate sequential modelling evolved out of the significant contribution made by Mitchell and Rapkin, (Bruton, 1985)¹ regarding the relationship between land use and traffic flows. These models are based on the premise that a measurable, stable relationship exists between land use, socio-economic characteristics, the nature of the transport network and the generation and distribution of traffic flows.

The aggregate sequential modelling exercise comprises of four stages which can be outlined as follows:

- (i) Trip generation
- (ii) Trip distribution
- (iii) Modal split
- (iv) Route assignment

In the following sections each of these four stages will be examined more closely.

2.2 Trip Generation

Trip generation analysis is concerned with the estimation of trip magnitudes originating and terminating at each zone in the study area. Techniques developed for this

¹ Bruton, M. Introduction to Transport Planning (1985).

purpose are based on the hypothesis that land use patterns, socio-economic characteristics of the trip makers and the nature of the transport system in the study area are chief factors influencing travel.

Thus, if functional relationships, reflecting causal linkages, between the volume of trip ends and the land use and socio-economic characteristics of the population of zones can be established, then reliable forecasts of traffic generation can be made from land use and demographic forecasts. 2/

The rest of this section is devoted to a brief discussion of trip types used in various transportation studies, analysis of important techniques used to determine trip generation rates, followed by a review of the results of some empirical studies undertaken using these techniques.

2.2.1 Trip Classification

Trips are classified in various ways while obtaining trip end estimates, depending on the scope and objective of the study. Each of these trip types have their own spatial and temporal characteristics.

Firstly, there is a broad classification of trips into 'home-based' and 'non-home-based' trips. Home-based trips are those trips which either originate or terminate at home. For example, trips from home to work or trips from work to home. Non-home-based trips have neither origin nor destination at home. For instance, trips from work to shop.

In many studies, trip ends have been categorized into

² O'Sullivan, P., Holtzclaw, G.D., and Barber, G. Transport Network Planning (1979).

two classes. Ends from which trips originate are known as 'trip productions' and ends to which trips are attracted are 'trip attractions'. Since, in general, trips are produced at residences and attracted to non-residences, most studies treat trip production as residential trip generation and trip attraction as non-residential trip generation.

2.2.2 Analytical techniques for Forecasting Trip Ends

The principal methods used for trip generation analysis are:

- (i) Simple expansion method
- (ii) Regression analysis
- (iii) Category analysis

Though, all these methods are currently in use, they have evolved in the order enumerated above.

(i) Trip Generation by Simple Expansion: This is a crude method, wherein land-use type and intensity are considered to be sole determinants of trip generation. Thus, current data on travel is related to data on land use to obtain trip generation rates for different types of land uses. To illustrate, suppose a traffic zone consisting of 2000 acres of residential land generates 4000 trips today, the trip generation rate for this type of land use would be:

$$\frac{4000}{2000} = 2 \text{ trips per acre.}$$

The crucial assumption of this approach is that the trip generation rate obtained for the base year remains the same for the target year. Therefore, an estimate of future trip ends can be derived for this zone by applying the trip

generation rate to the residential land acreage predicted for the target area. Suppose, to continue our example, residential land area is expected to increase from 4000 to 5000 for the target year, then the number of trips likely to be generated are:

$$5000 \times 2 = 10,000 \text{ trips.}$$

As is evident from the above discussion, this method is simple. While it is unreasonable to assume that trip generation rates will remain unchanged over time, a more fundamental drawback of this method is that it fails to reflect the underlying causes of travel.

This method was widely used in early transportation studies and is still in use for making crude short term forecasts.

(ii) Regression Analysis: In an attempt to make up for some of the deficiencies of the crude 'expansion factor' method, this method tries to develop explicit quantifiable relationships between trip making and factors determining travel.

The general form of this relationship can be expressed as:

$$Y = f(X_1, X_2 \dots X_n)$$

where,

Y = Trips generated

$X_1 \dots X_n$ = Factors affecting trip generation.

If we assume that the relationship is linear then,

$$Y = a_0 + a_1X_1 + a_2X_2 + \dots + a_nX_n$$

where,

a_0, a_1, \dots, a_n = parameters, or regression coefficients determined by using the method of 'least squares'.

Use of this technique for obtaining trip-end estimates for the target year rests on the assumption that the parameters determined using base year data are unchanged over time. To illustrate, suppose the following relationship is estimated

$$Y = 0.467 + (0.831) X_1$$

where,

Y : number of person trips per household

X_1 : family size

If X_1 is estimated to be 5 in the target year, then the future number of trips per household,

$$Y = 0.467 + (0.831).(5) = 4.6$$

Multiple regression techniques have been used in most transportation studies for conducting trip generation analysis, with minor variations. Some studies have developed separate trip production and trip attraction equations. While others have developed distinct equations for different trip purposes.

Earlier studies such as the 'Cardiff Development and Transportation Study', (Bruton, 1985) developed relationships using variables representing average zonal characteristics. Dissatisfaction with this approach has led to the development of disaggregated models wherein the household is generally

taken as the unit of analysis. Generation rates are then aggregated to the zonal level after a consideration of the number of households in the zone under consideration. A study by Shuldiner³ in Modesto, California used these disaggregated models for analysis.

The chief weakness of the regression technique is that since the relationships are developed using cross-section data they are more correlative than causal in the sense that these attempt to simulate rather than explain trip making. The accuracy of predictions using a model where regression coefficients estimated today are assumed to hold good for any future date can well be questioned.

(iii) Category Analysis: Category analysis is an alternative to the regression approach in that it establishes an a priori hypothesis of trip making and then tests it against available data.

Essential aspects of the technique are:

- a) The household and not the traffic zone is the fundamental unit in the trip generation process. It is stressed that use of zonally aggregated measures of zonal characteristics tends to submerge important characteristics of travel at the household level.
- b) Journeys generated by the household depend on the characteristics of that household.

³ Shuldiner, P. Trip Generation and the Home. Highway Research Board, Bulletin No. 347 (1962).

- c) Households with different characteristics produce different mean trip generation rates.

There are essentially five steps involved in this technique. Firstly, variables which are considered to have maximum influence on trip making are identified, and categories are formed by a combination of these variables. Suppose work trip production is found to be influenced by the number of cars per household and the number of persons per household, then households with no cars and one person per household would constitute one category, households with one car and one person per household another, etc. Secondly, using survey data, households are classified into one of these categories and trips made by each of these households is recorded. The total number of households in each category and the total trips made by them are obtained by summing over all households assigned to each category. Thirdly, mean trip generation rates are derived for each category in the following way:

$$t(C_x) = \frac{T(C_x)}{H(C_x)}$$

where,

$t(C_x)$ = mean trip rate of category 'x'

$T(C_x)$ = total trips generated by category 'x'

$H(C_x)$ = total households in category 'x'.

Fourthly, trips generated by each category are estimated for the horizon year. Mean trip rates $t(C_x)$ are assumed to remain the same over time. In order to predict the number

of trips in each category, for some pre-determined date in future i.e. $T'(C_x)$, the total number of households in each category are predicted $H'(C_x)$ and the mean trip generation rates applied to the same.

$$T'(C_x) = [H'(C_x)].[t(C_x)]$$

Fifthly, to obtain zonal estimates of trip generation, estimates of trips are summed over all categories.

$$T'_z = \sum_x T'(C_x) = \sum_x [H'(C_x)].[t(C_x)]$$

where, T'_z = zonal estimates of trip generation.

A crucial assumption on which this model rests is that the mean trip rates are stable over time. This means that as long as a household remains in a particular category, its trip making activity will not change. Even if it moves to another category, it will emulate the behaviour of those households already in that category.

This technique is quite simple to compute and must be used where adequate data is available. Further, it is possible to examine the effects of any one independent variable at various levels of the others.

However, the assumption regarding constancy of mean trip rates may not hold good under conditions susceptible to rapid change. Predicting the number of households in each category could turn out to be a complex process. Lastly, there is no way of testing the statistical significance of variables affecting trip making.

2.2.3 Empirical Studies on Trip Generation

Empirical studies undertaken to test the validity of trip generation models can be grouped into two:

- i) Residential trip generation models,
- ii) Non-residential trip generation models.

An attempt will be made to review the results obtained for each group.

(i) Residential Trip Generation Models: A majority of studies have utilized regression techniques for estimating trip ends wherein land use and socio-economic characteristics of the trip makers seem to emerge the chief factors influencing travel.

T. Nakkash and W. Greco⁴ conducted a study to investigate the impact of activity accessibility⁵ variables on trip generation.

... it seems that trips produced by or attracted to a zone should be a function of the relative accessibility of the zone to different land uses in addition to characteristic of the zone itself.

The data was obtained from the Indianapolis Regional Transportation and Development Study. The basic unit of analysis was the zone and multiple regression techniques were used to determine trip ends. The novelty of this approach lies in the fact that independent variables included not only

⁴ Nakkash, T. and Greco, W. Activity-Accessibility Models of Trip Generation. Highway Research Board, Record No. 392 (1972).

⁵ Accessibility can be defined as the ease with which any land use activity can be reached from a given location using a particular transport system.

socio-economic and land use measures of the zone, but also measures of relative accessibility. Zones were stratified into central and non-central, since it was felt that the degree of accessibility differed considerably between these areas. This stratification was entered as a dummy variable into the analysis. Relative accessibility was computed as follows:

$$RA_{ik}(l) = \frac{A_{ik}(l)}{\sum_i A_{ik}(l)}$$

where,

i = zone under consideration ($i = 1, 2, \dots, n$)

k = activity under consideration ($k = 1, 2, \dots, m$)

l = trip purpose ($l = 1, 2, \dots, p$)

$RA_{ik}(l)$ = relative accessibility of zone 'i' to activity 'k' for purpose 'l'

$A_{ik}(l)$ = accessibility of zone 'i' to activity 'k' for purpose 'l'.

$$\text{Now, } A_{ik}(l) = \sum_j S_{jk} \cdot F_{ij}(l)$$

where,

j = any zone in the study area

S_{jk} = size of activity 'k' in zone 'j'

$F_{ij}(l)$ = friction factor from zone 'i' to 'j' for purpose 'l'.

The results obtained revealed that the stratification of zones into central and non-central areas improved the statistical strength of trip generation models, in general. The introduction of relative accessibility variables, however, seemed to improve the statistical strength of trip attraction

models more than that of trip production models.

Inclusion of accessibility variables might make the modelling exercise quite complex. In an operational transport study, future forecasts of trip generation would determine the nature of the horizon year transport network. However, by affecting relative accessibility, this proposed network is likely to modify horizon year estimates of trip generation in turn. Therefore, in order to incorporate this bi-directional relationship between trip generation and the transport system, a complicated iterative process would be necessary. This aspect has not been taken into account in any of the models.

Shuldiner, (1962), developed a trip generation model wherein the household was the basic unit of analysis. The purpose of his study was to analyse the effect of variations in several household and neighbourhood characteristics on urban trip generation. Data on travel and household characteristics was obtained from the O - D study conducted by the California Division of Highways in the Modesto area for the year 1956. Neighbourhood characteristics were described in terms of a social area typology developed by E. Shevky and W. Bell from data published in the U.S. Decennial Census of Population.

The household characteristics, whose effects on travel were being examined, were

- (a) family size
- (b) vehicle ownership

- (c) distance to the C.B.D.
- (d) type of dwelling unit
- (e) occupation of the head of the household.

Neighbourhood characteristics included,⁶

- (a) social rank
- (b) degree of urbanization
- (c) extent of segregation.

The household was taken as the main unit of analysis since it was considered to provide a much more sensitive and unbiased measure of existing relationships. Regression techniques were used for developing functional relationships between travel, household and neighbourhood characteristics.

The study revealed that household characteristics of family size and car ownership had the greatest effect on trip production. The estimated regression equation was:

⁶ Social Rank: This index contains two elements (a) the proportion of blue collar workers, defined as craftsmen, operatives and labourers to all employees; and (b) education level as measured by the proportion of persons 25 years old and above who have completed eight or fewer years of schooling. The social rank index is inversely related to both ratios.

Degree of Urbanization: This index contains three elements (a) fertility rate, defined as ratio of children under five years of age to the female population of childbearing age "14 to 45" years of age; (b) female labour-force participation rate, meaning the percentage of women over 14 years of age who are in the labour force and (c) the percentage of single dwellings to total dwelling units. The degree of urbanization is inversely related to fertility rate and the proportion of single dwelling units, while it is directly related to the female labour force participation rate.

Extent of Segregation: This index is defined as the proportion of an area's residences which belong to certain minority groups. It measures the extent to which these minority groups live in relative isolation.

$$T = -0.137 + 0.632 P + 0.950 V \quad \dots (1)$$

where,

T = average number of person trips made from the home per day

P = number of persons living in the dwelling unit

V = number of vehicles per dwelling unit.

The coefficient of variation turned out to be 23.3%.

The effect of distance on trips independent of variations in family size and car ownership, appeared to be negligible. In order to study the independent influences of dwelling unit type and occupation of the head of the household, the relationship (1) above was adjusted. This adjustment procedure is not quite clear. Hence it is difficult to comment on the effect of these variables on trip generation. Regarding neighbourhood characteristics, only the urbanization index, seemed to exert some influence on trip generation rates.

This study is quite systematic and it brings out the significance of conducting analysis at the household level. Guidelines for selecting the most appropriate variables to be included in a model can also be obtained.

Wooton and Pick⁷ were the main proponents of the category analysis outlined earlier. Data from Greater London Council, London Traffic Survey and West Midlands Transport

⁷ Wooton, A.J. and Pick, G.W. "A model for trips generated by households," *Journal of Transport Economics and Policy*, No. 2 (1967).

Study was used to build the model. Car ownership, income, family structure and size were identified as the three most important variables affecting trip generation. Car ownership was further divided into three classes and income and family structure into six classes each. Thus, 108 (3 x 6 x 6) categories were obtained by combining these three factors and mean trip rates were derived for each of these categories, by three modes and six trip purposes. In order to obtain estimates of trip ends for each category, in the horizon year, forecasts of the number of households in each category are obtained and the corresponding mean trip rates applied to them. In this study, discrete distributions (gamma, poisson, binomial) were used to forecast households in each category.

The analysis progresses step by step highlighting the influence of each of the factors on trip making. However, there seems to be lack of clarity while distributing future estimates of households into each category. For instance, allocation of households is determined only by taking family structure into account. There is no attempt to determine the distribution when all three variables are simultaneously present.

(ii) Non-residential Trip Generation Models: Trips attracted to a particular area, are likely to depend on the type and intensity of land use activities in that area. Hence, in the case of non-residential trip generation models, the importance of the interrelationship between land use and

trip making becomes most apparent. Measures of land use include floor area, employment, sales, school enrolment, etc. While conducting a study using data collected by the Chicago Area Transportation Study, Black (1966) has tried to indicate that a single measure would be unsuitable for all land use categories.

Floor area seems best for commercial, employment for manufacturing and land area for public buildings, public open space and transportation. 8/

A wide variety of methods have been used to estimate non-residential travel. These may be briefly discussed.

In the land-use based models,

... trip generation is assumed to be related to the kinds, amounts, intensities and locations of a limited set of land use classes. ... 9/

Trip rates per acre are obtained for different land uses and this rate is assumed to hold constant into the future. In the Chicago study of 1956 (Dickey, 1975)¹⁰ mean trip rates were obtained for different categories of land uses (manufacturing, commercial, transportation, public buildings and public open space) and their distance from the central business district (CBD).¹¹ In order to obtain future

8 Black, A. Comparison of Three Parameters of Non-residential Trip Generation. Highway Research Board, Record No. 114, (1966).

9 Schuldiner, P. Land Use Activity and Non-residential Trip Generation. Highway Research Board, Record No.141, (1966).

10 Dickey, J.W. Metropolitan Transport Planning, (1975).

11 The central business district is one where major employment establishments are located.

estimates of trip attractions, the mean trip rates were employed in conjunction with exogenously predicted land acreage figures for each category of land use, at given distances from the CBD.

The most important aspect of land use activity trip purpose models is that trips are estimated separately by purpose.

Once trip making is differentiated on a trip purpose basis, relatively less reliance is placed on land use per se as the basis for trip generation and more use is made of employment, retail sales and other measures of land-use activity which are more directly related to trip purpose. 12/

Functional relationships are developed between trips for different purposes and land-use activity factors. Table 2.1 summarizes land-use activity factors employed in estimating trip attractions in some of the transportation studies.

Multiple regression techniques have been widely used for obtaining non-residential trip generation rates. The main explanatory variables that have been incorporated into these models include land use acreage, employment, number of households, etc.

The purpose of competitive distribution models is to determine measures of attractiveness rather than to estimate the number of trips attracted to zones in the study area. These measures of attractiveness are applied to trips produced by various zones and trip interchanges between zones are

12 Schuldiner, P., (1966).

Table 2.1 : Factors Used to Estimate Trip Attractions

Study, Year, Population	Trip Purpose Category					
	Home-based					Non-home-based
	Work	Shop	Social-Recreation	Other	Special	
Washington, D.C. 1963 - 2,900,000	E	S _R	S _R DU	E, S _R , DU	*** A _{SC} , DU	E, S _R , DU
New Orleans, 1960 - 645,000	NRD, DU, S _R E, A _C , I, DRD	NRD, DU, C, S _R , DRD	DU, P, C, P ₅ , S _R	* C, E, DRD	*** NRD, P, C, S _R , E, I, H, DRD	NRD, DU, C, S _R , E, A _C , S _C
Kansas City, 1959 - 643,000	E, D	S _R , D	P, DU	-	*** P	D
Fort Worth, 1964 - 540,000	E	E _C	-	P, E _C , E _M , E _O	-	P, E _C , E _M , E _O
Charleston, 1965 - 250,000	E, E _V	E _R , S _C , S _P	-	S _V , E _V , DU, A _R , S _C , I **	*** S _C , I	E, E _V , S _C , S _C , DU, A _R , I
Nashville, 1961 - 250,000	E, E _W , E _B	A _C , D	P, I	A _C **	*** S _C , I	A _C , D
Chattanooga, 1962 - 240,000	E	A _C	P, I	A _C **	*** S _C , I	A _C
Waterbury, 1963 - 190,000	E	E _R	-	P, E _C , E _M , E _O	-	P, E _C , E _M , E _C
Erie, 1963 - 140,000	E	E _R	P, E _R , E _O	-	-	P, E _R , E _M , E _O
Greensboro, 1964 - 130,000	E	E _R	-	P, E _C , E _M , E _O	-	P, E _C , E _M , E _O
Fargo, 1965 - 70,000	E, E _R	P, E _R , E _O	-	P, DU, C, E	* DU, E _R , E _O	DU, E, E _R
Appleton, 1965 - 55,000	E, D, A _{PU} , A _I	-	-	DU, A _{PU} , A _I , A _C ; E	-	D, E, A _C , A _I , A _{PU} , DU

Comments: * Personal business trips. ** Business trips. *** School trips.

Key to Entries

Employment : E = Total employment; E_R = Retail employment; E_M = Manufacturing employment; E_O = Employment other than retail and manufacturing; E_W = White collar employment; E_B = Blue collar employment; E_V = Various specialized employment, E_C = Commercial employment.

Sales : S_R = Retail sales; S_C = Convenience goods retail sales; S_P = Personal service sales; S_V = Retail sales by various specialized categories.

Area : A_{PU} = Acres of public and semi-public land; A_I = Acres of industrial land; A_C = Acres of commercial land; A_R = Acres of residential land; A_{SC} = Areas of school land.

School Enrolment: SC = Total school enrolment; S_C_V = School enrolment by various grade levels.

Household Characteristics : P = Population; P₅ = Persons five years of age or older; H = Persons per dwelling unit; DU = number of dwelling units; NRD = Persons per net residential acre; DRD = Dwelling units per net residential acre; I = Income; C = Number of automobiles.

Miscellaneous : D = Distance from CBD; T = Truck ownership.

Source : Dickey, J.W. Metropolitan Transportation Planning, (1975).

obtained by using the gravity model. In the Fort Worth Study (Schuldiner, 1966) a combination of factors were used to determine relative attractiveness of each zone, namely, population, commercial employment, industrial employment and other employment.

In spite of the different approaches to trip generation analysis that have been developed, the regression technique has been used most extensively. This is because it is easy to estimate using available data. While growth factor techniques are crude, the method of category analysis is too complex to serve as an efficient operational technique.

2.3 Trip Distribution

The next stage in the aggregate sequential modelling process is to determine how the trips generated in a particular zone are distributed between zones in the study area. This stage is commonly referred to as the 'trip distribution' stage. In this section an attempt will be made to review important trip distribution models. Throughout the analysis, emphasis will be on highlighting desirable aspects of these models as well as their weaknesses. We may enumerate these models as follows:

- i) Growth factor techniques
 - ii) Synthetic methods : the gravity model; the intervening opportunities model; the competing opportunities model
 - iii) Linear programming approach
 - iv) Multiple linear regression techniques.

Despite the diversity of formulation used in the various mathematical procedures developed, the underlying principle in all trip distribution models (except growth factor-methods) is the same : Travel between any two points will increase with increase of attraction for such travel but decrease as the resistance to travel increases. 13/

The aim of trip distribution analysis is to estimate elements T_{ij} of the matrix referred to as the 'origin destination' matrix or 'trip distribution matrix'. This is illustrated in Figure 2 below.

		DESTINATION ZONES					
		ZONES	1	2	...	n	COLUMN TOTALS
ORIGIN ZONES	1	T_{11}	T_{12}	...	T_{1n}	P_1	
	2	T_{21}	T_{22}	...	T_{2n}	P_2	
	
	
	n	T_{n1}	T_{n2}	...	T_{nn}	P_n	
ROW TOTALS		a_1	a_2	...	a_n		

Figure 2 : ORIGIN DESTINATION MATRIX

where,

- T_{ij} = trips from zone 'i' to zone 'j'
 (i = 1, 2, ... n; j = 1, 2, ... n)
 p_i = number of trips produced in zone 'i'
 a_j = number of trips attracted to zone 'j'

Trip productions (p_i) and trip attractions (a_j) are estimated in the trip generation stage. To ensure consistency between trip generation and trip distribution estimates, the following constraints must be satisfied while determining interzonal and intrazonal trips:

$$p_i = \sum_j T_{ij}$$

$$a_j = \sum_i T_{ij}$$

$$\text{Note, } T = \sum_i p_i = \sum_j a_j = \sum_i \sum_j T_{ij}$$

where,

T = total number of trips generated by the study area.

With this brief introduction, we may now proceed to examine trip distribution models in detail.

2.3.1 Growth Factor Techniques.

Early transport studies relied upon simple growth factor techniques for conducting trip distribution analysis. The essence of this technique lies in extrapolating existing interzonal flows to some date in the future by applying growth factors. There are three growth factor methods: uniform factor method, average factor method and the Fratar growth factor technique. However, in general, all growth factor methods can be reduced to the following form:

$$T_{ij}^h = T_{ij}^b \cdot E$$

where,

T_{ij}^h = estimates of horizon year trip interchanges between zones 'i' and 'j'.

T_{ij}^b = base year trip interchanges between zones 'i' and 'j' obtained from origin destination survey.

E = growth factor

(i) Uniform Growth Factor Method: In the uniform growth factor method, a single growth factor is computed for the entire study area. This is applied to base year inter-zonal movements in order to obtain estimates of future inter-zonal flows.

Symbolically,

$$T_{ij}^h = T_{ij}^b \cdot E$$

where,

$$E = \frac{T^h(G)}{T^b}$$

$T^h(G)$ = total horizon year trips estimated at the trip generation stage

T^b = total base year trips obtained from O-D survey.

Since a uniform growth factor is applied to the entire study area, the inherent assumption of this method is that the expected growth in movement for the area, as a whole, reflects adequately the expected growth in movement between any specific pair of zones. This assumption is unrealistic since development is not likely to be uniform over the study area. This will inevitably result in different rates of growth in movement and the use of a single growth factor could result in poor forecasts.

(ii) Average Growth Factor Method: The average growth factor method attempts to overcome weaknesses of the uniform growth factor method by incorporating differential rates of development and hence movement for different zones. Thus, growth factors are zone specific. This is evident from the following formulation:

$$T_{ij}^h = T_{ij}^b \cdot \left(\frac{E_i + E_j}{2} \right) \quad \dots (2)$$

where,¹⁴

$$E_i = \frac{O_i^h(G)}{O_i^b} \quad \text{i.e. growth factor for zone 'i'}$$

$$E_j = \frac{D_j^h(G)}{D_j^b} \quad \text{i.e. growth factor for zone 'j'}$$

$O_i^h(G)$ = horizon year trip origins estimated at the trip generation stage

O_i^b = base year trip origins obtained from O-D survey

$D_j^h(G)$ = horizon year trip destinations estimated at the trip generation stage

D_j^b = base year trip destinations obtained from O-D survey.

Once trip interchanges have been estimated using (2) above, it is most likely that computed trip ends do not tally with trip ends estimated during the trip generation stage or, symbolically,

$$\sum_j T_{ij}^h \neq O_i^h(G)$$

$$\text{and } \sum_i T_{ij}^h \neq D_j^h(G)$$

In order to remove this inconsistency an iterative procedure is adopted. This may be illustrated as follows:

To begin with, we have

¹⁴ Throughout this analysis, trip production 'p_i' and trip origins 'O_i' will be used interchangeably. Similarly, trip attractions 'a_j' and trip destinations 'D_j' will be used interchangeably.

$$[T_{ij}^h]_1 = T_{ij}^b \cdot \left[\frac{(E_i)_1 + (E_j)_1}{2} \right]$$

Such that,

$$(E_i)_1 = \frac{O_i^h(G)}{O_i^b} \quad \text{and} \quad (E_j)_1 = \frac{D_j^h(G)}{D_j^b}$$

where subscript '1' refers to iteration number. At this stage, it is necessary to check whether,

$$\sum_j [T_{ij}^h]_1 = O_i^h(G) \quad \text{i.e. the horizon year trip origins from the model equal those obtained from the trip generation stage,}$$

and $\sum_i [T_{ij}^h]_1 = D_j^h(G)$ i.e. the horizon year trip destinations from the model equal those obtained from the trip generation stage.

If a discrepancy exists, then a second iteration is to be carried out as follows:

$$[T_{ij}^h]_2 = T_{ij}^b \cdot \left[\frac{(E_i)_2 + (E_j)_2}{2} \right]$$

$$\text{where, } (E_i)_2 = \frac{O_i^h(G)}{\sum_j [T_{ij}^h]_1} \quad \text{and} \quad (E_j)_2 = \frac{D_j^h(G)}{\sum_i [T_{ij}^h]_1}$$

and subscript '2' denotes iteration number.

If the discrepancy persists, then a third iteration, similar to the second, is undertaken. This iterative procedure is continued until $\sum_j T_{ij}^h$ converges to $O_i^h(G)$ and $\sum_i T_{ij}^h$ converges to $D_j^h(G)$.

(iii) Fratrar Growth Factor Method: The Fratar growth factor method was developed by T.J. Fratar while attempting to make travel forecasts for the Cleveland Metropolitan region.

The method can be expressed as follows:

$$T_{ij}^h = T_{ij}^b \cdot E_i \cdot E_j \cdot \frac{(L_i + L_j)}{2}$$

where,

L_i and L_j are locational factors for zones 'i' and 'j' respectively.

$$L_i = \frac{O_i^b}{\sum_j T_{ij}^b \cdot E_j} \quad \text{and} \quad L_j = \frac{D_j^b}{\sum_i T_{ij}^b \cdot E_i}$$

Other variables have been defined earlier. The hypothesis is that trip interchanges between zones 'i' and 'j' in the horizon year are directly proportional to base year trip interchanges between these zones, modified by growth factors of the zones under consideration, and inversely proportional to the average attracting pull of all other zones. [$\frac{(L_i + L_j)}{2}$ is the reciprocal of average attracting pull of surrounding zones.]

An iterative procedure may be necessary in order to remove discrepancies between trip ends estimated from the trip generation stage and the trip distribution stage.

A modification of the Fratar method (Bruton, 1985) was suggested by the Urban Planning Division of the U.S. Bureau of Public Roads so as to incorporate ten different trip purposes and to apply growth factors by mode and times of the day. However, this only seemed to further complicate the procedure.

The principal advantage of the growth factor methods is that they are simple to comprehend as well as easy to apply. However, the essence of this technique that future

trip interchanges will be simply an extrapolation of existing trip patterns may not be justified in a rapidly changing environment. Further, these methods fail to incorporate the effect of changes in the transport network on trip interchanges. Lastly, intrazonal trips cannot be estimated.

Therefore to sum up:

For short term predictions in stable areas, or for updating recent origin and destination survey data, these methods can be used with success. However, they cannot satisfy the requirements of modern urban transportation studies, which are usually designed to cater for conditions of continual and rapid change in the patterns of development, and the way of life of the population generally. 15/

2.3.2 Synthetic Methods

The gravity model, the intervening opportunities model and the competing opportunities model have often been grouped together under 'synthetic methods'. These models are based on the hypothesis that causal relationships giving rise to movement patterns can best be understood if they are considered to be similar to certain laws of physical behaviour. Since it is essential to comprehend the underlying causes of travel before making accurate forecasts, these models attempt to simulate existing travel patterns by relating trips to the distribution of activities as well as characteristics of the transport system.

These models need to be calibrated until base year travel behaviour is accurately simulated. Only after this

has been achieved can the models be utilized as forecasting tools. The inherent assumption is that if the calibrated model simulates existing patterns of travel effectively, it can be used as a tool for predicting future trip patterns as well.

Although the calibration procedure differs from model to model, the trip length frequency curve¹⁶ obtained from any of the calibrated models must closely approximate the trip length frequency curve constructed using base year origin-destination survey data.

We may now proceed to discuss the essential aspects of the three synthetic models.

(i) Gravity Model: The gravity model was developed by analogy with Newton's law of gravitational force. Newton's law essentially states that the gravitational force between two bodies varies directly with the mass of these bodies and inversely with the distance separating them. Accordingly, the gravity model of trip distribution is based on the hypothesis that trip interchanges between two zones 'i' and 'j' is directly proportional to the number of trips produced in zone 'i' and the number of trips attracted to zone 'j', and is inversely proportional to some function of spatial separation between the zones. In its most simple form the model can be expressed as:

$$T_{ij} = K \frac{O_i \cdot D_j}{f(S_{ij})}$$

¹⁶ Refer to Appendix 2.1 of this chapter for a description relating to construction of trip length frequency curves.

where,

K = constant

T_{ij} = trip interchanges between zones 'i' and 'j'

O_i = trip origins at zone 'i'

D_j = trip destinations at zone 'j'

$f(S_{ij})$ = some function of spatial separation between zones 'i' and 'j'

According to Heggie (1972)¹⁷ distance was initially used as a measure of spatial separation. More specifically,

$$f(S_{ij}) = d_{ij}^{-n}$$

where,

d_{ij} = distance between zones 'i' and 'j'

n = a constant

Use of $\exp(-d_{ij})d_{ij}^{-n}$ was suggested as an alternative to the simple inverse power of distance since it was found to be more attractive theoretically as well as on the ground that it provided an appreciably closer fit to empirical data. Recent studies have used a 'generalized cost' function consisting of various elements that are likely to influence travel impedance. Generalized cost is a function of the following elements: time associated with travel, distance, excess travel time, terminal costs at the destination end of the journey, such as parking charges, etc.

The first application of the gravity model technique in transportation studies was made by H.J. Casey, Jr., while

17 Heggie, I.G. Transport Engineering Economics (1972).

determining the magnitude of trips between residential areas and retail centres (Bruton, 1985). Further studies undertaken, emphasized the need to modify the deterrence function, $f(S_{ij})$, in accordance with trip purpose. Production constrained gravity models were also formulated. In these models,

$$\sum_j T_{ij} = O_i$$

Now,

$$T_{ij} = K \frac{O_i \cdot D_j}{f(S_{ij})} \quad \dots (3)$$

$$\sum_j T_{ij} = K \cdot O_i \sum_j \left[\frac{D_j}{f(S_{ij})} \right]$$

$$\frac{\sum_j T_{ij}}{O_i} = K \cdot \sum_j \left[\frac{D_j}{f(S_{ij})} \right]$$

$$1 = K \cdot \sum_j \left[\frac{D_j}{f(S_{ij})} \right]$$

Therefore,

$$K = \frac{1}{\sum_j [D_j / f(S_{ij})]}$$

Substituting for K in (3) we get,

$$T_{ij} = \frac{1}{\sum_j [D_j / f(S_{ij})]} \cdot \left[\frac{(O_i) (D_j)}{f(S_{ij})} \right]$$

The lack of a theoretical base was often cited as a major weakness of the gravity model. A.G. Wilson (1967)¹⁸

¹⁸ Wilson, A.G. "A statistical theory of spatial distribution models," *Transportation Research*, Vol. 1 (1967).

attempted to provide such a base to the gravity model using a probability maximizing method. J. Niedercorn and B. Bechdolt Jr., (1969)¹⁹ illustrated that the gravity model formulation could be derived on the basis of economic theory. Consequently, the gravity model, now has a fairly firm theoretical foundation, which has served to reinforce its validity as a model for estimating trip interchanges.²⁰

The most widely used procedure for calibrating the gravity model is the one developed by the 'Bureau of Public Roads' Washington, D.C. (Bouchard and Pyres, 1965).²¹ An attempt will be made to outline this procedure and also critically examine its application in the context of the use of the gravity model to determine trip interchanges in Washington D.C. Metropolitan area. Specifically, the gravity model formulation used by the Bureau of Public Roads is given by

$$T_{ij} = \frac{O_i \cdot D_j \cdot F_{ij} \cdot K_{ij}}{\sum_j [D_j \cdot F_{ij} \cdot K_{ij}]} \quad \dots (4)$$

where,

F_{ij} = some function of spatial separation between zones i and j, referred to as the travel time factor or friction factor

19 Niedercorn, J.H. and Bechdolt, B.V.Jr. "An economic derivation of the 'gravity law' of spatial interaction," Journal of Regional Science, Vol. 9, No. 2, (1969).

20 Refer to Appendix 22 for a rigorous theoretical formulation of the gravity model provided by Wilson and Niedercorn and Bechdolt.

21 Bouchard, R.J. and Pyres, C.E. Use of Gravity Model for Describing Urban Travel. Highway Research Board, Record No. 88 (1965).

K_{ij} = specific zone to zone adjustment factor to allow for incorporation of effect on travel patterns of socio-economic linkages not otherwise considered in the model

Other variables have been defined earlier.

The calibration of the gravity model essentially involves three phases.

In the first phase, travel time factors F_{ij} 's are estimated by an iterative procedure. For the first iteration, the trip distribution matrix is derived by using the gravity model formula (4) above. O_i and D_j are obtained from base year O-D survey data, while F_{ij} ²² and K_{ij} are assumed to be equal to 1. The trip length frequency distribution and mean trip length for trips computed by the model are determined and these are compared with the trip length frequency distribution and mean trip length for base year O-D data. If (i) the shape and position of the two trip length frequency distribution curves are relatively close to one another when compared visually, and (ii) the difference between the mean trip lengths is within $\pm 3\%$, then it is assumed that an acceptable set of travel time factors has been obtained. If this is not the case, then the travel time factors used for the first iteration needs to be adjusted in the following manner:

22 Operationally, a more satisfactory starting point for determining travel time factors would be to use factors obtained from other urban areas of similar size and character. Therefore, if such data is available, this should be used for the first iteration, instead.

$$F_{ijz}^{(A)} = F_{ijz}^{(1)} \times \frac{[T_z/T]_{O/D} \times 100}{[T_z/T]_{GM} \times 100}$$

where,

z = particular intercentroid travel time category

$F_{ijz}^{(A)}$ = adjusted travel time factor

$F_{ijz}^{(1)}$ = travel time factor used for the first iteration

$[T_z/T]_{O/D} \times 100$ = percentage of total trips in the intercentroid travel time category ' z ', computed using O-D survey data

$[T_z/T]_{GM} \times 100$ = percentage of total trips in the intercentroid travel time category ' z ', computed using the gravity model.

These adjusted travel time factors $[F_{ijz}^{(A)}]$ are then plotted against their corresponding travel time category (z) and lines of best fit through these plotted points are drawn. A new set of travel time factors to be used in the next iteration, $F_{ijz}^{(2)}$ is read from this graph. A hypothetical illustration is given in Figure 3.

The trip distribution matrix is then derived using $F_{ijz}^{(2)}$ in the gravity model formulation and the tests undertaken. This sequence of activities is repeated until the synthesized and observed trip length frequency distributions are in close agreement.

Phase two also involves an iterative procedure for balancing the trip destinations ' D_j ' obtained from the gravity model and that from the O-D survey data. This becomes necessary in the case of a production constrained

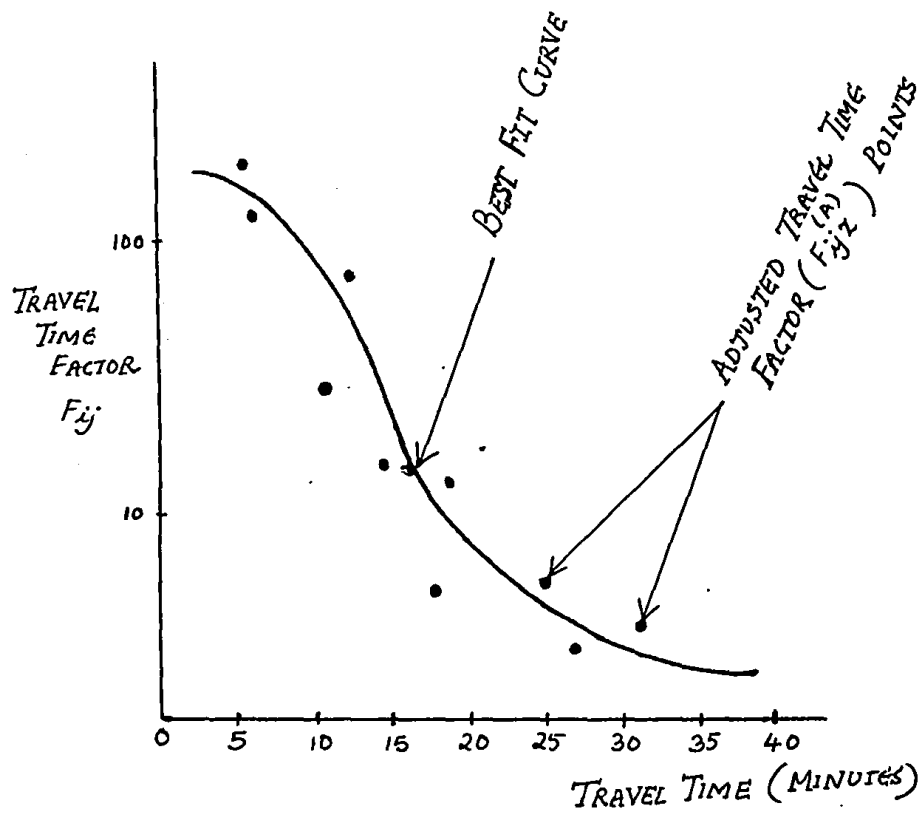


Figure 3 : Determination of Travel Time Factor Functions

gravity model where $\sum_j [T_{ij}]_{GM} = [O_i]_{O/D}$ but equality between $\sum_i [T_{ij}]_{GM}$ and $[D_j]_{O/D}$ is not ensured. The adjustment procedure is carried out by using the following formula:

$$D_j^{(n)} = \frac{[D_j]_{O/D}}{[\sum_i T_{ij}]_{GM}^{n-1}} \times [D_j]^{(n-1)}$$

i.e., D_j 's to be used for the nth iteration. $[D_j]^{(n)}$ is arrived at by multiplying D_j 's used in the n-1th iteration $[D_j]^{(n-1)}$ by the ratio of the observed O-D survey ' D_j 's $[D_j]_{O/D}$ to the trip destinations obtained by using the gravity model for the n-1th iteration $[\sum_i T_{ij}]_{GM}^{n-1}$. The adjusted ' D_j 's are used in the formula (4) above to compute trip interchanges. This procedure is continued, until, $\sum_i [T_{ij}]_{GM}$ converges to $[D_j]_{O/D}$. Note, in this phase, trip origins $[O_i]_{O/D}$, the final travel time factors obtained in phase one and a value of unity for K_{ij} are used along with the adjusted D_j 's for each of the iterations.

The final phase of the calibration procedure is the development of zone to zone adjustment factors K_{ij} 's which incorporates the effect of socio-economic linkages on travel patterns. These factors are calculated using the following expression:

$$K_{ij} = R_{ij} \frac{(1 - X_i)}{(1 - X_i \cdot R_{ij})} \dots (5)$$

where,

$$R_{ij} = \frac{[T_{ij}]_{O/D}}{[T_{ij}]_{GM}} \text{ i.e., the ratio of trip interchanges between zones 'i' and 'j' obtained from O-D survey to those computed using the gravity model}$$

$$K_{ij} = \frac{[T_{ij}]_{O/D}}{[O_i]_{O/D}}$$
 i.e., the trip interchanges between zones 'i' and 'j' as proportion of total trip origins of zone 'i' obtained from base year O-D survey.

These K_{ij} 's are incorporated into the model (4) above to obtain a new set of trip interchanges.

These three phases are generally essential for calibrating the gravity model. However, it may often be necessary to modify intercentroid travel times between zones due to the existence of special topographical barriers whose effects may not have been considered earlier. Further, the model may be developed and calibrated separately for different trip purposes, if required.

After all phases of calibration have been computed, the final results obtained are tested to determine how accurately the model simulates base year travel patterns. The Bureau of Public Roads utilized the following tests:

- a) Comparison of mean trip lengths of O-D survey data and model results.
- b) Visual inspection of trip length frequency distributions of O-D survey data and computed model results.

If these tests indicate that the calibrated gravity model simulates base year travel patterns reasonably well, then it can be used for forecasting future trip interchanges. For this purpose, the gravity model formulation would appear as :

$$T_{ij}^h = \frac{O_i^h(G) \cdot D_j^h(G) \cdot F_{ij}^h \cdot K_{ij}^h}{\sum_j D_j^h(G) \cdot F_{ij}^h \cdot K_{ij}^h}$$

$O_i^h(G)$ and $D_j^h(G)$ are the horizon year trip and estimates obtained from the trip generation phase. Horizon year inter-centroid travel times have to be estimated, and based on the relationship established during the second phase of the calibration procedure, new horizon year travel time factors for each pair of zones is derived [F_{ij}^h]. Although attempts have been made to develop relationships in order to estimate horizon year socio-economic factors [K_{ij}^h], the results have not been very satisfying. However, we may illustrate the method used by the Bureau of Public Roads. To arrive at a method for estimating future K_{ij} factors, several items of socio-economic data related to the zones was identified. Of these, income group was selected. A plot of the relationship between K_{ij} s used in the calibration process and income groups of the zones corresponding to these was obtained. Depending on the income group to which the zones belonged to in the horizon year, estimates of K_{ij} were derived from this relationship which was assumed to remain unchanged.

After T_{ij}^h has been estimated, a balancing procedure⁴ described in phase two above must be resorted to until $[\sum_i T_{ij}^h]_{GM}$ converges to $D_j^h(G)$.

In order to test and calibrate the gravity model trip distribution technique, the Bureau of Public Roads in co-operation with the Washington Metropolitan Area Transport study used 1955 survey data relating to the Washington D.C.

metropolitan area. This calibrated model was used to estimate trip interchanges for the year 1948. Results were obtained separately for six trip purposes (work, shopping, social-recreation, school, miscellaneous, non-home-based).

The final results indicated that the gravity model can adequately simulate present travel patterns. ... The level of accuracy obtained by forecasting trip distribution patterns in 1948 was comparable to the level of model accuracy for the base year (1955). ... 23/

In spite of the numerous computational steps involved, the gravity model has been widely used. However, a few observations regarding the model are in order. Firstly, the use of travel time factors (F_{ij} s) which are not 'i'-'j' specific but averages for all trip interchanges which fall within a certain intercentroid travel time category may not be adequate. Travel time factors which reflect unique deterrence characteristics between a specific pair of zones need to be incorporated. Secondly, the K_{ij} factors (refer to equation (5) above) which are supposed to reflect the effect of socio-economic factors on travel do not appear to depict this influence adequately.

We may conclude our discussion of the gravity model with the following comment:

The gravity model will give satisfactory results if properly calibrated and tested. 24/

23 Bouchard, R.J. and Pyres, C.E., (1965)

24 Ibid.

(ii) The Intervening Opportunities Model: The intervening opportunities model rests on the premise that a trip will remain as short as possible, lengthening only as it fails to find an acceptable destination nearer at hand. If D_j represents the total number of destinations at zone 'j' and D , the intervening destinations or opportunities between zones 'i' and 'j' then,

$T_{ij} \propto \frac{D_j}{D}$ i.e., the number of trips T_{ij} between zones 'i' and 'j' is directly proportional to the number of destinations at zone 'j', D_j and inversely proportional to the number of intervening destinations or opportunities, D .

This idea was first developed in 1930 by S.A. Stouffer²⁵ while analysing the pattern of migration of families in Cleveland (Ohio). He found that migration of families over a given distance was proportional to the number of opportunities available at this distance for satisfaction of the migrants, while it varied inversely with the number of intervening opportunities available. A number of extensions of the Stouffer hypothesis have been proposed. We will discuss the model developed by M. Schneider (Wilson, 1967).

Let all destination zones away from the zone of origin under consideration (i) be ranked in order of increasing travel time from zone 'i'. Let 'j' denote the jth destination zone away from 'i' in this ranking.

²⁵ Stouffer, S.A. "Intervening opportunities: A Theory Relating Mobility and Distance," American Sociological Review, Vol. 5, No. 6, (1940).

The underlying assumption of the model is that the tripper considers each opportunity as reached, in turn, and has a definite probability that his needs will be satisfied. 26/

Let 'L' denote a measure of the probability that a random destination will satisfy the needs of a particular tripper. Let 'D_j' denote the number of destinations at zone 'j'. Let 'U_{ij}' denote the probability that a tripper does not stop at zone 'j' or goes beyond zone 'j'. For the first set of destinations in the ranked sequence, then,

$$U_{11} = (1 - LD_1)$$

$$U_{12} = U_{11}(1 - LD_2)$$

$$U_{13} = U_{12}(1 - LD_3)$$

In general,

$$U_{ij} = U_{ij}(1 - LD_j) \quad \dots (6)$$

Rearranging,

$$\frac{U_{ij} - U_{ij+1}}{U_{ij-1}} = -LD_j \quad \dots (7)$$

Let 'A_j' denote the number of destinations upto and including zone 'j'.

$$\text{i.e. } A_j = \sum_{x=1}^j D_x \quad \dots (8)$$

$$\text{Then, } A_{j-1} = \sum_{x=1}^{j-1} D_x = D \quad \dots (9)$$

Using (8) and (9),

$$D_j = A_j - A_{j-1} \quad \dots (10)$$

Substituting for 'D_j' in (7) we get,

$$\frac{U_{ij} - U_{ij-1}}{U_{ij-1}} = -L(A_j - A_{j-1}) \quad \dots (11)$$

Assuming continuous variation, (11) may be written as

$$\frac{dU}{U} = -L A \quad \dots (12)$$

which integrates to,

$$\text{Log } U = -LA + K \quad \dots (13)$$

$$\therefore U_{ij} = K_i \exp(-LA_j) \quad \dots (14)$$

where 'K_i' is a constant.

$$\text{Now, } T_{ij} = (O_i \cdot U_{ij-1}) - (O_i \cdot U_{ij}) \quad \dots (15)$$

where O_i are the number of trip origins at 'i'. From (15) it is seen that the number of trips between zones 'i' and 'j' is obtained by deducting the number of trips going beyond zone 'j' from the number of trips going beyond zone 'j-1'.

$$\text{Therefore, } T_{ij} = O_i(U_{ij-1} - U_{ij}) \quad \dots (16)$$

Substituting for 'U's in (16) from (14) we get,

$$T_{ij} = K_i O_i \cdot [\exp(-LA_{j-1}) - \exp(-LA_j)] \quad \dots (17)$$

Substituting for 'A's in (17) from (8) and (9)

we get,

$$T_{ij} = K_i O_i \cdot \left\{ \exp(-LD) - \exp[-L(D + D_j)] \right\} \quad \dots (18)$$

Equation (18) gives the final form of the intervening opportunities model.

Thus, we find that spatial separation is measured in terms of the number of intervening opportunities. Impedances do not appear explicitly as they do in the gravity model. For instance, friction factors (F_{ij}) are not explicitly incorporated in the model.

The calibration procedure involves four phases.

Firstly, to simulate base year travel patterns, an iterative procedure is used, wherein, 'L' values are adjusted until the observed and synthesized trip length frequency distributions and mean trip lengths are as close as possible.

Secondly, a balancing procedure is necessary to ensure that the correct number of trips are being sent or, $\sum_j T_{ij}$ converges to O_i .²⁷ Similarly, the 'D_j's need to be adjusted so that trips received by each zone of the area are in close agreement with O-D survey trip attractions. Lastly, the synthesized trips to the central business district (C.B.D.) and those across topographical barriers are checked for any bias and appropriate adjustments made to travel times between zones.

The Bureau of Public Roads, while conducting trip distribution analysis in the Washington D.C. metropolitan area, experimented with two methods for calibrating this model. Both methods used the following relationship to obtain 'L' values to be used in the first run of iterative procedure:

27 This model does not have an in-built procedure (like a production constrained model) to ensure that the correct number of trips are being sent. This can be illustrated as follows:

$$T_{ij} = O_i [e^{-LD} - e^{-L(D+D_j)}]$$

$$\sum_j T_{ij} = O_i \sum_j [e^{-LD} - e^{-L(D+D_j)}]$$

$$\frac{\sum_j T_{ij}}{O_i} = \sum_j [e^{-LD} - e^{-L(D+D_j)}] \neq 1$$

$$\bar{r} = K \cdot \sqrt{1/(P \cdot L)}$$

or

$$L = \left(\frac{K}{\bar{r}}\right)^2 \cdot \frac{1}{P}$$

where,

K = a constant = 2

\bar{r} = mean trip length in minutes

P = density of the study area expressed as trip ends per square mile.

Implicit in this relationship is the idea that the probability that a random destination will satisfy the needs of a particular tripper will decline as trip length and density increases and intervening opportunities keep mounting. The Bureau used a single 'L' value for the entire study area. Therefore, ' \bar{r} ' and 'P' may be interpreted as averages for the study area. In both methods, trip origins ' O_i ' were adjusted by applying an appropriate factor before these could be used in the model. Further, trip destinations were adjusted by the following.

$$(D_j)_{\text{Adjusted}} = \frac{[D_j]_{O/D}}{\sum_i T_{ij}} \times D_j^*$$

where,

D_j^* = trip destinations used in the previous iteration.

The manner in which trips are stratified differed in the two methods. In the first method, trip ends were classified into six trip purposes: home based work, home based shop, home based school, home based social-recreation, home based other and non-home based. 'L' values were determined

separately for each of the six trip purposes. These 'L' values were adjusted until the mean trip lengths for each trip purpose was close to observed mean trip lengths corresponding to that purpose. In spite of several runs, the model failed to simulate base year travel patterns adequately. Further, intrazonal trips seemed to be underestimated. To overcome these problems a new trip purpose stratification was used namely, long residential, long non-residential and short.²⁸ Again, 'L' values were determined separately for each of the three trip purposes. The model was run several times and after the fourth run, the synthesized and observed mean trip lengths were close to each other. Unlike the first method, 'L' values were adjusted to ensure that the total all-purpose actual and estimated trip length frequency curves closely approximated one another. Thus, the second approach was preferred.

The results clearly indicate that this model will provide an adequate duplication of travel patterns for the present period of time. 29/

While conducting the Honolulu Metropolitan Area Traffic Survey, the Bureau of Public Roads observed that the use of

²⁸ Long residential: Trips from home to work and from home outside the C.B.D. to the C.B.D. for any other purpose.

Long non-residential: Trips from work to home and trips for any other purpose which originate at the CBD and have destinations at home outside the CBD.

Short: All other trips.

²⁹ Pyres, C.E. Evaluation of Intervening Opportunities Trip Distribution Model. Highway Research Board, Record No. 114 (1966).

single area wide 'L' values, by purpose, failed to produce desirable results. 'L' values were found to be quite sensitive to the trip end density. Hence, if the trip-end density varied over the study area, the 'L' values would be expected to vary over this region. Therefore, a variable 'L' method was resorted to. The study area was divided into a number of districts and two sets of 'L' values were established for each of these districts (one for long trips and the other for short trips). The initial 'L' values were first obtained for each zone. For this purpose a 'trip decay curve' was constructed using O-D survey data. A hypothetical curve is illustrated in the Figure 4. A least square fit of the form e^{-bx} was used to represent the hand plotted decay curve adequately. The slope of this least square fit gave zonal 'L' values. The zonal 'L' values were adjusted to obtain district 'L' values, one for short and the other for long trips. The adjustment was carried out in the following way.³⁰

$$L_{ds} = \sum_z \frac{(L_{zs} \times D_{zs})}{D_{ds}}$$

L_{ds} = district short 'L'

D_{ds} = total district short trip destinations

L_{zs} = zonal short 'L'

D_{zs} = zonal short trip destinations.

³⁰ Jarema, F.E., Pyres, C.E., Reed, H.A., Evaluation of Trip Distribution and Calibration Procedures. Highway Research Board, Record No. 191 (1967).

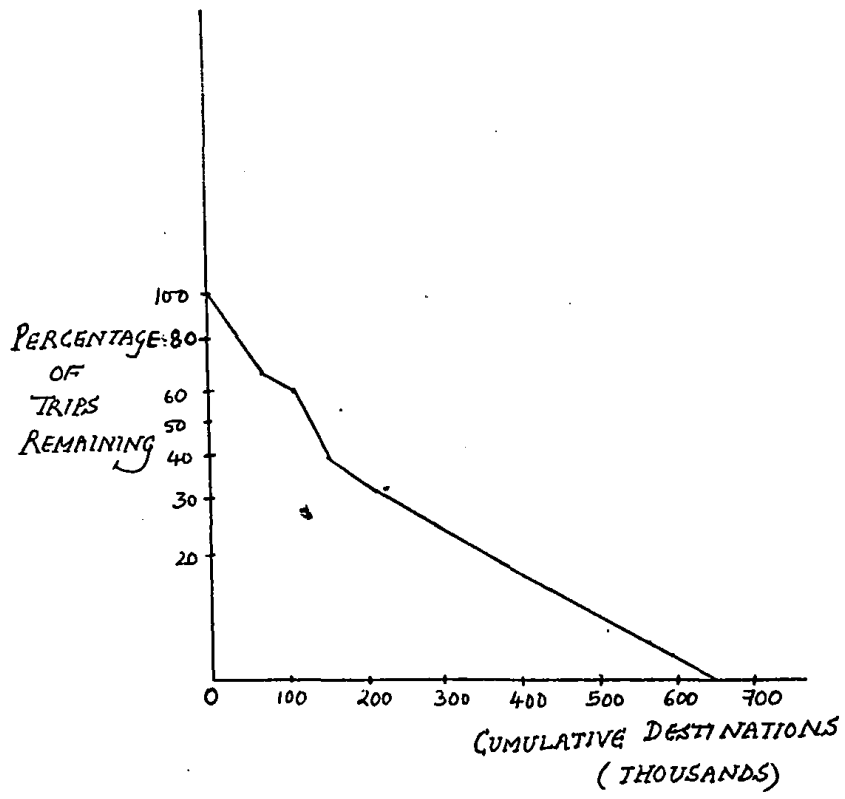


Figure 4 : A Hypothetical Trip Decay Curve

$$LdL = \sum_z \left[\frac{(Lznr \times Dzr) + (Lzr \times Dznr)}{Ddr + Ddnr} \right]$$

LdL = district long 'L'

Lznr = zonal non-residential 'L'

Lzr = zonal residential 'L'

Ddr = total district long residential trip destinations

Ddnr = total district non-residential trip destinations

Dzr, Dznr = zonal residential and non-residential destinations.

For each iteration the 'L' values were adjusted using

$$(Ls)_n = (Ls)_{n-1} \cdot \left[\frac{VMT \text{ model}}{VMT \text{ O-D}} \right]^2$$

where,

$(Ls)_n$ = calculated district short 'L' for nth iteration

$(Ls)_{n-1}$ = district short 'L' used in n-1th iteration

VMT model = district vehicle miles of travel resulting from assignment of estimated short trips, and

VMT O-D = district VMT resulting from assignment of actual short trips.

For the long 'L'

$$(Ll)_n = (Ll)_{n-1} \cdot \left[\frac{VMT \text{ model}}{VMT \text{ O-D}} \right]^2$$

where,

$(Ll)_n$ = calculated district long 'L' for nth calibration

$(Ll)_{n-1}$ = district long 'L' used in calibration n-1

VMT model = district vehicle miles of travel resulting from assignment of estimated long trips

VMT O-D = district vehicle miles of travel resulting
from assignment of actual long trips.

It was observed that a satisfactory estimate of travel patterns was simulated. For forecasting future trip interchanges the following was used:

$$T_{ij}^h = K_i \cdot O_i^h \cdot \{ \exp[-L^h \cdot D^h] - \exp[-L^h(D^h + D_j^h)] \}$$

Horizon year trip end estimates O_i^h , D_j^h , D^h are obtained from the trip generation stage. The horizon year 'L' values also need to be estimated. The Bureau of Public Roads observed from trends in the past that the trip end density was likely to grow in future. Thus, the probability that any one of these destinations will be acceptable to any given origin will fall. Accordingly, the horizon year 'L' values were revised downwards for the study. It was felt that forecasting of 'L' values would be strengthened with additional knowledge of trends in trip length, either in time or distance.

The intervening opportunities model was amongst the first to utilize the concept of probability in trip distribution analysis. The notion of intervening opportunities as an implicit measure of spatial separation was quite novel. However, as is evident from the numerous calibration techniques experimented with, there seems to be an ardent need for refinement of the same. Further research needs to be undertaken for estimating 'L' values for the horizon year. The failure to take into account the effect of socio-economic factors can be considered to be a limitation of the model. However, complexities arising out of incorporation of these

factors are avoided. We have already seen while discussing the gravity model that the influence of such factors is difficult to measure and predict.

(iii) Competing Opportunities Model: The competing opportunities model was proposed by A.R. Tomazinis³¹ for use in the Penn-Jersey transportation study. Once again, elementary notions of probability theory form the basis of this model.

An attempt will be made to derive this model with the help of hypothetical study area as developed by Tomazinis. This study area consisting of 21 zones is illustrated in Figure 5. Let 'T' denote the total number of destinations in the study area.

$$\therefore T = \sum_{j=1}^{21} D_j$$

Let 't' denote a particular time band. Now, given inter-centroid travel times between zone 'i' and other zones in the study area, it is possible to categorize zones within a particular time band, that have the same travel time from zone 'i' which the time band represents. For example, in Figure 5, zones 1 to 6 fall within time band-1, zones 7 to 15 fall within time band-2 and so on. Let 'D_t' denote the cumulative trip destinations lying within time band 't'. Let 'D_{j(t)}' denote the trip destinations in zone 'j' which belongs to time band 't'.

³¹ Tomazinis, A.R. A New Method for Trip Distribution in an Urban Area. Highway Research Board, Record No. 347 (1962).

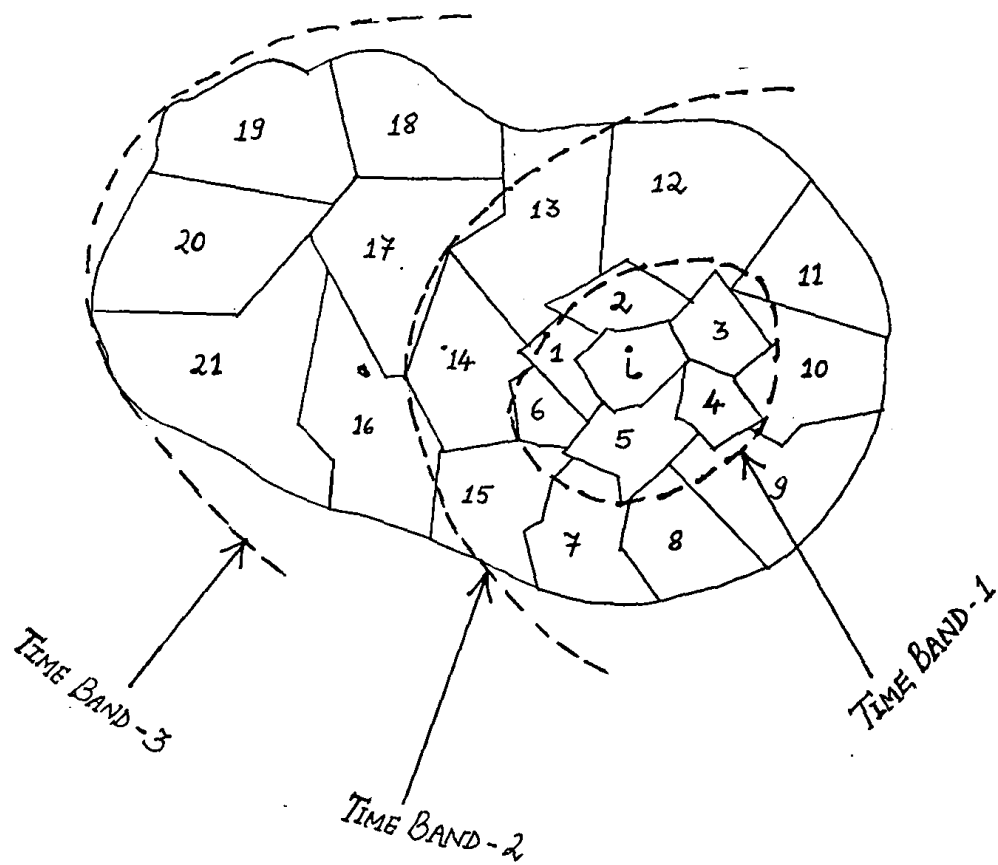


Figure 5 : A Hypothetical Study Area for Trip Distribution Analysis Using Competing Opportunities Model

In our example,

$$D_1 = D_{1(1)} + D_{2(1)} + D_{3(1)} + \dots + D_{6(1)}$$

i.e. cumulative destinations lying within time band-1.

$$D_2 = D_1 + D_{7(2)} + D_{8(2)} + \dots + D_{15(2)}$$

i.e. cumulative destinations lying within time band-2.

In general,

$$D_k = D_{k-1} + \sum_j D_{j(k)} \quad \dots (19)$$

i.e. the cumulative destinations lying within time band 'k'.

The probability that a trip originating in zone 'i' will go to a particular zone 'j' lying in time band 't' is given by the conditional probability,³²

$$P(D_{j(t)}/D_t) = \frac{D_{j(t)}}{D_t}$$

or, in other words, this probability depends on the ratio between trip opportunities in the zone and its competing opportunities within the same time band. Now, the sum of all such conditional probabilities of all zones must be equal to 1 because total trips distributed should be equal to trips available in the district of origin. Therefore, in order to ensure this, (19) above needs to be adjusted as:

$$32 \quad P(D_{j(t)}/D_t) = \frac{P[D_{j(t)}]}{P(D_t)} = \frac{[D_{j(t)}]/T}{D_t/T} = \frac{[D_{j(t)}]}{D_t}$$

$$P(D_j(t)/D_t)^* = \frac{P(D_j(t)/D_t)}{\sum_t \sum_j P(D_j(t)/D_t)} \quad \dots (20)^{33}$$

The final form of the competing opportunities model is given by

$$T_{ij} = O_i \cdot [P(D_j(t)/D_t)^*]$$

The application of the model for determining trip interchanges is quite straightforward. For simulating base year flows, the model is calibrated by varying the width of the time bands until base year travel patterns are adequately simulated. The calibrated model is then used to estimate horizon year trip interchanges. For this purpose, trip end estimates are obtained from the trip generation stage,

33 Denominator of (20) is derived as

$$\begin{aligned} P(D_j(1)/D_1) &= D_j(1)/D_1 \\ \therefore \sum_j P(D_j(1)/D_1) &= \sum_j D_j(1)/D_1 = \frac{1}{D_1} \cdot \sum_j D_j(1) = 1 \\ \sum_j P(D_j(2)/D_2) &= \sum_j D_j(2)/D_2 = (D_2 - D_1)/D_2 = 1 - (D_1/D_2) \\ &\vdots \\ &\vdots \\ \sum_j P(D_j(k)/D_k) &= \sum_j D_j(k)/D_k = (D_k - D_{k-1})/D_k = 1 - (D_{k-1}/D_k) \end{aligned}$$

$$\begin{aligned} \therefore \sum_t \sum_j P(D_j(t)/D_t) &= \sum_j P(D_j(1)/D_1) + \sum_j P(D_j(2)/D_2) \\ &\quad + \sum_j P(D_j(3)/D_3) + \dots + \sum_j P(D_j(k)/D_k) \\ &= K - \sum_{t=2}^K D_{t-1}/D_t \end{aligned}$$

horizon year intercentroid travel times estimated and time bands predicted.

The probability approach in this model is simpler to comprehend as compared to the intervening opportunities model. Much, however, depends on the careful development of time bands.

This model has not been tried out extensively. Attempts made by the Bureau of Public Roads to calibrate the model have proved to be totally unsatisfactory. An ardent need was felt to develop suitable calibration procedures. As the Bureau observed,

... research is required to develop calibration procedures for the competing opportunities model. ... 34/

2.3.3 Linear Programming Approach

The Linear Programming approach rests on the assumption that trip makers select origin and destination pairs such that they collectively minimize the total amount of travel time spent on the transport system.

The model is formulated as,

minimize:

$$Z = \sum_i \sum_j C_{ij} T_{ij}$$

subject to:

$$\sum_j T_{ij} = O_i$$

$$\sum_i T_{ij} = D_j$$

34 Heanue, K.E. and Pyres, C.E. A Comparative Evaluation of Trip Distribution Procedures. Highway Research Board, Record No. 114 (1966).

and

$$T_{ij} > 0$$

where,

C_{ij} = cost of making the trip, e.g., distance between zones 'i' and 'j'.

Blunden (Hutchinson, 1974)³⁵ used this approach for simulating home based work trips in Sydney.

The basic hypothesis on which the model is based does not appear to be authentic. Trip makers with diverse socio-economic characteristics may not act collectively to minimize the total travel time.

2.3.4 Multiple Linear Regression Analysis

This method involves identification of important socio-economic and land use variables which are likely to affect trip interchanges between zones. Mathematically, an equation of the following form is developed for each zone,

$$T_{ij} = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n$$

x_1, x_2, \dots, x_n = present day values for independent variables

a_0, a_1, \dots, a_n = coefficients determined by the method of least squares.

For forecasting horizon year trip interchanges, it is assumed that the coefficients remain unchanged. Therefore, horizon year estimates of independent variables are obtained and trip interchanges are estimated by

³⁵ Hutchinson, B.G. Principles of Urban Transport Systems Planning, (1974).

$$T_{ij}^h = a_0 + a_1 X_1^h + a_2 X_2^h + \dots + a_n X_n^h$$

where,

$X_1^h \dots X_n^h$ = horizon year estimates of the independent variables.

This approach was first used by Sam Osofsky (Bruton, 1985) in California. The regression equation developed may be illustrated.

$$T_{ij} = a_1 \cdot \frac{P^2}{D^{1.5}} + a_2 \cdot \frac{E^2}{D^{1.5}} + a_3 \cdot \frac{V}{D^{1.5}} + a_4 \cdot \frac{L}{D^{1.5}} + a_0$$

where,

- P = Population of the destination zone
- E = Employed persons in the destination zone
- V = Vehicle ownership in the destination zone
- L = Land use index for the destination zone
- D = Distance.

The principal advantage of this method is that a number of variables which are considered to have an effect on trip distribution may be taken into account. However, the assumption that coefficients (a_0, a_1, \dots, a_n) remain unchanged may not be realistic.

Of all the trip distribution techniques, the gravity model has been most widely used. Growth factor techniques have been found to produce satisfactory results for making short term estimates. The intervening and competing opportunities model, though sound theoretically, have not been found to be efficient devices, operationally. The linear programming and regression approaches are based on stringent assumptions and have therefore not been used extensively.

2.4 Modal Split

The basis on which people choose among various means of transportation available in different parts of an urban area is of utmost importance to the transport planner. ... With ever increasing cost of operation and construction, the selection of a location and determination of adequate capacity of a new traffic facility requires a reliable framework of references necessary to forecast the probable usage of such a traffic facility. ... 36/

Modal split models attempt to estimate the choice of mode by trip makers between specific origins and destinations and for specific purposes.

There has been some controversy regarding the stage that is most appropriate for conducting modal split analysis. Basically, three approaches have emerged on this point. While the first emphasizes the need to conduct modal split analysis immediately after the trip generation stage, the second approach regards this as being unrealistic since it does not adequately reflect the actual behaviour of the trip maker, in general. A trip maker would, by and large, tend to decide on the mode of travel only after the trip, its purpose and destination have been finalized. Consequently, the need to carry out modal split analysis only after the trip distribution stage is emphasized in order to reflect the behaviour of the trip maker as closely as possible. The third approach emerged out of attempts to refine the second one. While

36 Hill, D. and Voncube, H. Development of a Model for Forecasting Travel Mode Choice in Urban Areas. Highway Research Board, Record No. 38 (1963).

retaining the essential arguments of the second, this view indicates the need to distinguish between those who have access to a variety of modes (choice riders) and those who do not (captive riders) before allocating trip makers to various available modes. Accordingly, modal split analysis is conducted in two stages. First, trips generated by captive and choice riders are identified after the trip generation stage and trip distribution analysis is then conducted separately for the two groups of trip makers. The second stage occurs after the trip distribution stage where choice transit riders are allocated to the available modes.

These three approaches form the basis of modal split models that have been developed. Since the second³⁷ and third approaches³⁸ appear to depict trip making behaviour more realistically, models based on these will be reviewed, namely, (i) trip-interchange modal split models based on the second approach; and (ii) two stage modal split models based on the third approach.

Before going into details of these models, it will be useful to point out some of the factors affecting modal choice. Empirical studies, in general, indicate that three factors can be identified as having considerable influence on the choice of mode by the trip maker, namely, economic status of the trip maker, purpose and length of the trip,

37 Ibid.

38 Hutchinson, B.G., (1974).

characteristics of the available modes of travel. In the modal split stage of the aggregate sequential modelling exercise, attempts are made to build up relationships between modal choice and factors enumerated above using base year data. Given the validity of these relationships, they are utilized to forecast modal choice for the horizon year.

2.4.1 Trip Interchange Modal Split Models

Trip interchange modal split models are based on the approach that a tripper tends to take decisions about the mode of travel only after the trip, its purpose and destination have been fixed. Therefore, modal split analysis is undertaken only after the trip distribution stage. Specifically, the aggregate sequential modelling process would have the sequence of stages as illustrated in the flow chart given in Figure 6.

The Traffic Research Corporation (Hill and Voncube, 1963), New York, used a trip interchange modal split model to conduct modal split analysis in Washington D.C., Toronto and Philadelphia metropolitan areas. Essential aspects of this study will be examined below.

On the basis of multiple regression analysis, five factors were identified as having considerable effect on people's propensity to use public transit. These may be enumerated as:

- a) Economic status of the trip maker (EC),
- b) Relative travel time (TTR) via public transit and private automobile expressed by the ratio

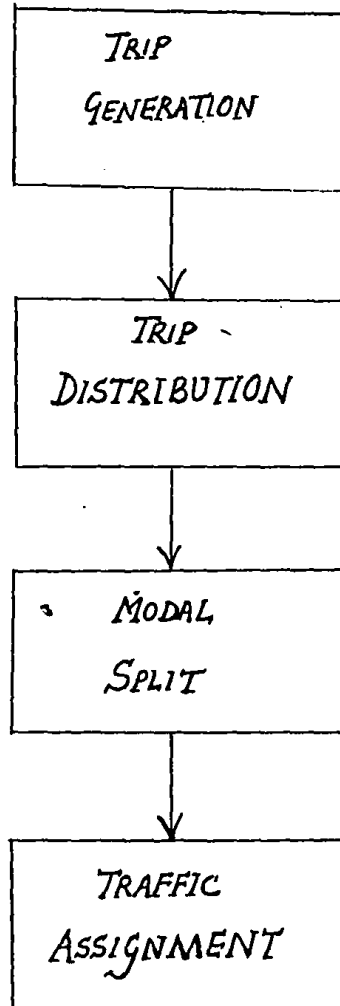


Figure 6 : Trip Interchange Modal Split Analysis:
Sequence of Stages

of door to door travel time by public transit and private automobile.

Symbolically,

$$TTR = \frac{X_1 + [X_2 + X_3 + X_4 + X_5]}{X_6 + [X_7 + X_8]}$$

where,

X_1 = time spent in the transit vehicle

X_2 = walking time to transit vehicle

X_3 = time spent waiting for transit vehicle

X_4 = transfer time between transit vehicles

X_5 = walking time from transit vehicle

$X_2 + X_3 + X_4 + X_5$ = excess travel time by transit

X_6 = car driving time

X_7 = parking delay at destination

X_8 = walking time from parking place to destination

$X_7 + X_8$ = excess travel time by car.

c) Relative travel cost (CR) via public transit and private automobile defined as the ratio of out-of-pocket travel costs per tripper by public transit and private automobile.

Symbolically,

$$CR = \frac{X_9}{[X_{10} + X_{11} + 0.5 X_{12}]/X_{13}} = \frac{X_9}{X_{14}}$$

where,

X_9 = transit fare per tripper

X_{10} = cost of gasoline

X_{11} = cost of oil changes and lubrications

$0.5 X_{12}$ = one way parking costs

X_{13} = average car occupancy

X_{14} = automobile costs per tripper.

- d) Relative travel service (L) via public transit and private automobile given by the ratio of excess travel times by car and public transit as,

$$L = \frac{X_2 + X_3 + X_4 + X_5}{X_7 + X_8}$$

These variables have been defined earlier. Other factors such as comfort, convenience, ease of changing from one mode to another, etc., were excluded from the above ratio since it was not possible to quantify these factors meaningfully.

- e) Trip purpose would tend to influence the modal split relationships based on the four determinant factors described above. For instance, in the case of school trips, transit is the only choice. Again, the automobile would be preferred in the case of non-work trips.

Having identified the principal factors affecting choice of mode, modal split relationships were determined. Mean zonal values were used for all the variables.

Base year data (O-D surveys, parking surveys, published mass transit route schedules outlining headways and fares, and censuses) was used for acquiring information on the five factors mentioned above as well as observed percentage transit usage. Next, cost ratios, service ratios and economic status were stratified into categories. Cost ratios were divided into four categories:

$CR_1 = 0.0$ to 0.5

$CR_2 = 0.5$ to 1.0

$CR_3 = 1.0$ to 1.5

$CR_4 = 1.5$ and over.

Service ratios were also divided into four categories:

$L_1 = 0.0$ to 1.5

$L_2 = 1.5$ to 3.5

$L_3 = 3.5$ to 5.5

$L_4 = 5.5$ and over.

While, economic status was divided into 5 categories:

$EC_1 = \$ 0$ to $\$ 3,100$ per annum

$EC_2 = \$ 3,100$ to $\$ 4,700$ per annum

$EC_3 = \$ 4,700$ to $\$ 6,200$ per annum

$EC_4 = \$ 6,200$ to $\$ 7,500$ per annum

$EC_5 = \$ 7,500$ per annum and over.

Relationship between percentage transit usage and travel time ratio was developed for each of the resultant eighty categories. For this purpose, interzonal and intrazonal trips were classified into these categories. Each category was considered in turn, O-D observations that fell within a particular travel time ratio class grouped together and corresponding observed percentage transit usage for each of these were noted. Weighted average percentage transit usage was then calculated for all travel time ratio classes, weights being assigned according to the total trip interchange volume. Thus, for each of the eighty categories, a schedule consisting of travel time ratios and corresponding

average percentage transit usage was obtained. These schedules were plotted on graph paper and best fit curves were drawn through the plotted points. Each curve known as a 'diversion curve' depicts the relationship between percentage transit usage and travel time ratio for a particular category of relative cost ratio, relative service ratio and economic status. These curves are illustrated in Figure 7.

In general, it is observed that for all categories, percentage transit usage varies inversely with travel time and service ratios. Moreover, for each income group percentage transit usage varies inversely with the cost ratio for all service ratio and travel time ratio classes. These results reflect the decline in demand for transit with fall in its competitiveness vis-a-vis private automobile. However, the effect of fall in competitiveness of transit is not uniform for all the income groups. The higher income groups respond more sharply to this change than lower income groups. This is revealed by the increasing steepness of the curves as we proceed from lower income to higher income groups. Lastly, transit usage is quite high in the case of lower income groups even where the automobile can be considered to be a superior mode in all respects (where $TTR \geq 1$; $SR \geq 1$ and $CR \geq 1$). What seems strange is that this is true, though to a lesser extent, even in the case of the highest income group.

These diversion curves were used to predict choice of

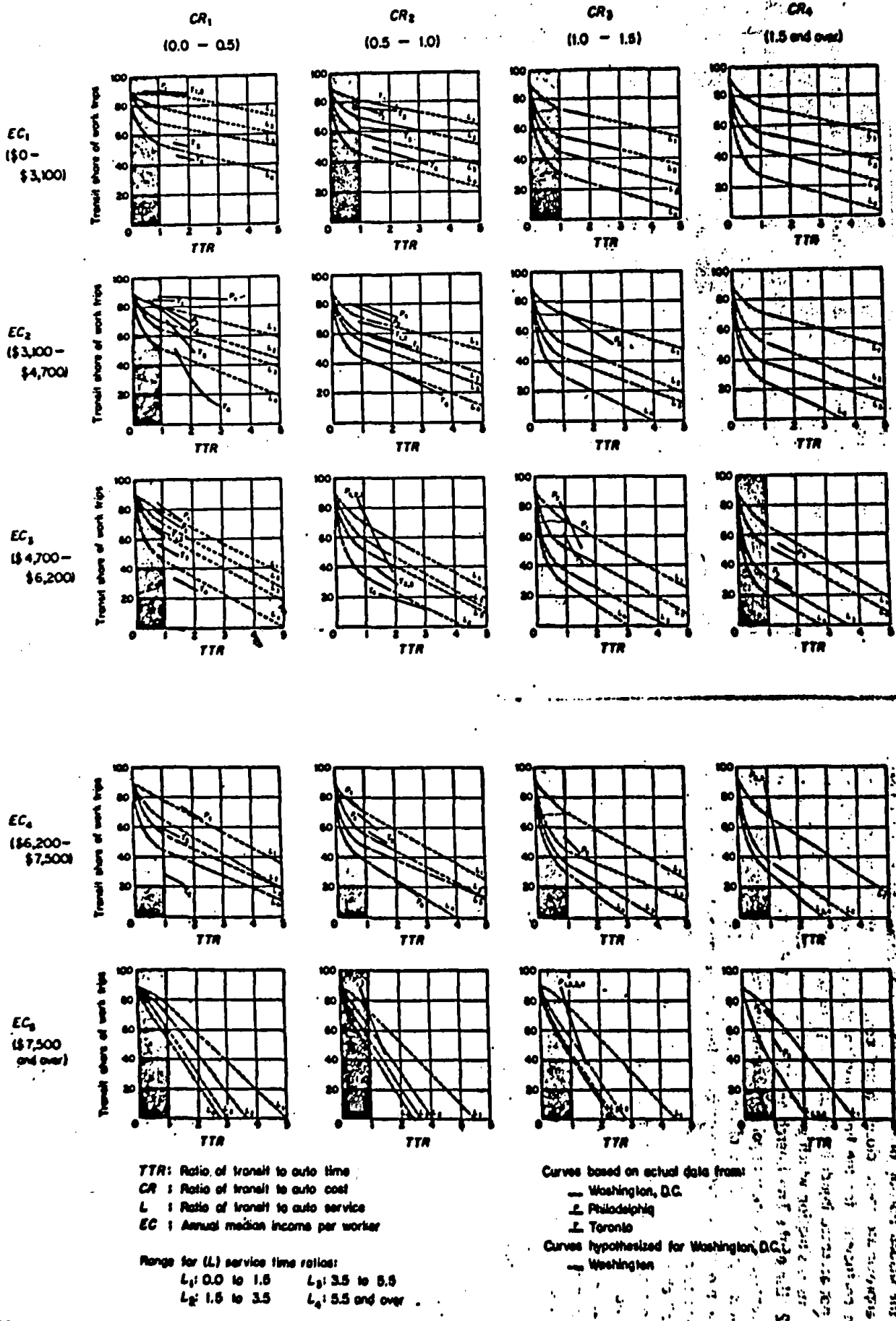


Figure 7 : Diversion Curves for the Traffic Research Corporation Study
 Source: Dickey, J.W. Metropolitan Transportation Planning, (1975).

mode on the assumption that the relationships would hold good for the horizon year. Horizon year forecasts of CR, TTR, L and income distribution were used along with these diversion curves to yield percentage transit usage for the horizon year. Total person trip interchanges between origin destination pairs derived in the trip distribution stage were then multiplied by the corresponding percentage transit usage estimated to yield horizon year transit trips. The remaining trip interchanges were car person trips. These were divided by the average car occupancy rate to obtain the number of car trips between each pair of zones.

Though the model is quite simple the assumption that modal split relations developed using base year data will remain stable over time may not produce accurate forecasts where rapid change in the environment is expected. It may not be easy to forecast TTR, CR, L for the horizon year, especially if a new mode is introduced that did not exist in the base year. Since zonal averages are used for the analysis, differences in trip making behaviour of individuals which may be of significance, tend to get obscured. The Traffic Research Corporation study dealt with a single trip purpose, namely work trips. The assumption was that,

... The conclusions reached concerning the three city work trip relationships generally should apply in the case of non-work trips except school trips. ...39/

This may not be true in the case of other study areas. Moreover, only two modes were considered.

... it is believed at this state of development work, that the division of these travel modes into two main types, public transit and private automobile is sufficient to account for the basic differences in the properties of the main types. ... 40/

However, trip makers may not be indifferent to all the modes that fall within the public and private categories. Lastly, captive and choice riders have not been identified and represented separately in the model.

In spite of these shortcomings, this model,

... is undoubtedly the best available for predicting travel within urban areas for aggregated groups of zones, and it is based on reasonable hypothesis of behaviour. ... 41/

2.4.2 Two Stage Modal Split Models

Unlike the trip interchange modal split models, two stage modal split models explicitly recognize the existence of both captive and choice transit riders. Captive riders are those who have access to public transit only while choice riders have access to both public transit as well as cars or private automobiles.

In these models, modal split analysis is conducted in two stages. In the first stage, (known as captive modal split analysis) trip ends estimated in the trip generation stage are apportioned between captive and choice transit

40 Ibid.

41 Quarmby, D.A. "Choice of travel mode for journey to work," Journal of Transport Economics and Policy (1967).

riders. Trip distribution analysis is then conducted separately for the two groups. In the second stage of modal split analysis (known as choice modal split analysis) the probable split of choice transit riders between public transport and car travel is estimated. Thus the aggregate sequential modelling process takes the modified form as given in the flow chart in Figure 8.

In general, division of trip makers into choice and captive riders, at the captive modal split analysis stage, seems to be influenced by the socio-economic characteristics of the tripper, while attributes of existing modes appears to be the principal factor for determining selection of mode by choice riders, at the choice modal split analysis stage.

Vandertol, Shortreed and Hutchinson (Hutchinson, 1974) have attempted to develop a two stage modal split model for work trips. The first step was to obtain trip-end estimates for captive and choice transit riders. To estimate work trip productions for the two categories, the following relationship was used:

$$p_i^q = h_i \cdot [t_p^q]$$

p_i^q = work trips produced in zone 'i' by type 'q' trip makers

q = 1 = captive transit riders

q = 2 = choice transit riders

h_i = number of households in zone 'i'

t_p^q = work trips per household (or trip production rate) for trip makers of type 'q'.

Income and average number of employees per household (zonal

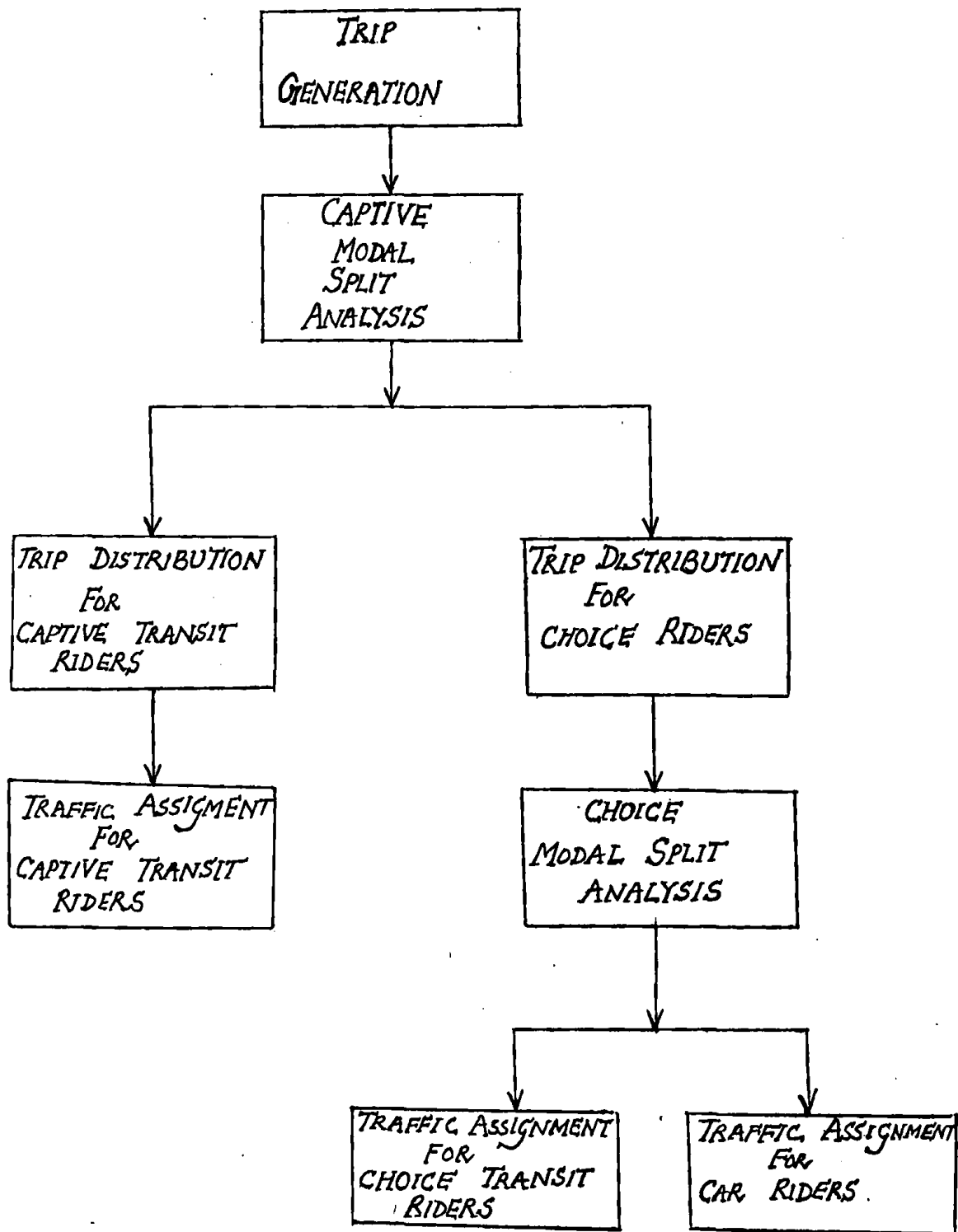


Figure 8 : Sequence of Stages for Two Stage Modal Split Models

averages were used) were identified as crucial influences on trip production rates. Income was stratified into three categories based on data obtained from the cities of Hamilton and Ottawa (Ontario, Canada). These categories are summarized in the Table 2.2.

Table 2.2 : Characteristic Income Distributions

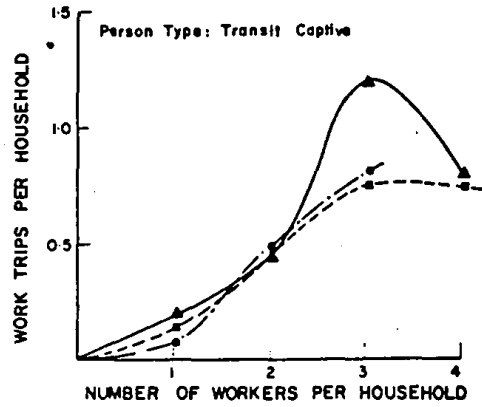
Income range	(Per cent)		
	Income level classification of zone		
	Low	Medium	High
< \$ 3000	60-35	30-10	20-0
\$ 3000-6000	40-50	50-60	40-30
> \$ 6000	0-15	20-30	40-70

Source : Hutchinson, B.G. Principles of Urban Transport Systems Planning, (1974).

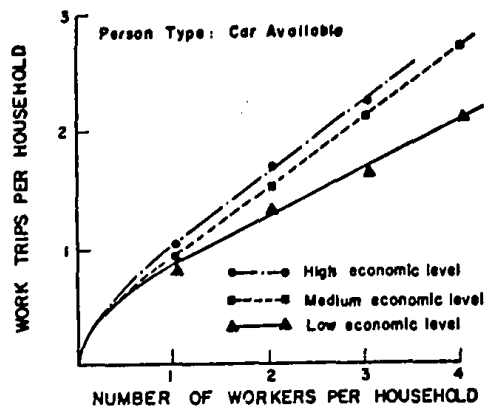
For instance, if 60-35 per cent of the trip makers in a zone had incomes less than \$ 3,000, 40-50 per cent had incomes between \$ 3,000 and \$ 6,000 and 0-15 per cent had incomes above \$ 6,000, then the zone was classified as low. Work trip production rates corresponding to number of workers per household was obtained empirically for each of the three income categories. These relationships for captive and choice riders are depicted in Figures 9(i) and (ii).

Work trip attractions for choice and captive riders was obtained using the following relationship:

$$a_j^q = [Pr(q)^c]_{1xc} \cdot [Pr(c)^t]_{cxt} \cdot [e_{tj}]_{txj}$$



(i) CAPTIVE TRANSIT RIDERS



(ii) CHOICE RIDERS

Figure 9 : Trip Production Rates for Captive and Choice Transit Riders
(Study by Vandertol, Shortreed and Hutchinson)

Source: Hutchinson, B.G. Principles of Urban Transport Systems Planning, (1974).

where,

a_j^q = the number of work trips of type 'q'
tripmaker attracted to zone 'j'

e_{tj} = number of jobs within industry of type⁴² 't'
in zone 'j' (t x j matrix)

$Pr(q)^c$ = Probability of a trip maker of type 'q' being
in occupation category⁴³ 'c' (a row vector 1 x c)

trip makers of type 'a' belonging to
occupation category 'c'
= $\frac{\text{trip makers of all types belonging to category 'c'}}{\text{trip makers of all types belonging to category 'c'}}$

$Pr(c)^t$ = probability of an occupation category 'c'
being within an industry type 't' (c x t
matrix)

numbers in category 'c' belonging
to type 't'
= $\frac{\text{total numbers in type 't'}}{\text{total numbers in type 't'}}$

Having estimated trip ends for captive and choice transit riders, trip distribution analysis was conducted separately for each of the two groups.

In the next step, choice modal split analysis was conducted. Trip interchanges for choice riders whose destination was the central business district (CBD) were allocated to public transport and motor cars using diversion curves. Choice riders whose destination was not the CBD were assumed to use cars for their journey.

42 Five industry types were used in the model: Primary, manufacturing, service, commercial (retail), and others.

43 Four occupation categories were used in this model: Primary, professional-managerial, clerical sales, labour service.

Relationships established using base year data were used along with forecasts of independent variables to derive modal split for the horizon year.

The greatest advantage of the two stage modal split analysis lies in the explicit recognition of captive and choice riders. This is useful since the effect of change in the competitiveness between modes can be analysed by concentrating on choice transit riders alone. This can be of great significance to policy makers if the magnitude of choice and captive transit riders differs significantly. However, in the model examined above, certain shortcomings of the trip interchange modal split models persist. Only two modes are considered. Again, zonal averages are used. It may not be easy to obtain future forecasts of factors affecting modal split analysis at both the stages.

From the above discussion it appears that it would be more appropriate to treat trip makers separately as choice and captive transit riders in estimating modal split. Hence, two stage modal split models are to be preferred. Further, it may be possible to improve results if analysis is conducted at the individual level incorporating all the available modes.

2.5 Traffic Assignment

Assignment is the most powerful device of transport studies for testing designs for the improvement of the means of circulation and for suggesting where improvements are needed. It can be used to forecast traffic volumes on the existing network at some future time and to forecast the effect of improvements

in the network so that the operational efficiency of the present system or proposed systems, can be evaluated. ...44/

This is the final stage of the aggregate sequential modelling process which deals with the assignment of inter-zonal, modal trips to alternative routes between zones.

Since the fifties, attempts have been made to develop assignment techniques with a view to achieving the following purposes:

- a) Assigning existing trips to the existing network to test the ability of the model in simulating existing travel patterns. The underlying implication is that, if the model can successfully reproduce current trip patterns, then it could prove to be useful in forecasting future travel patterns as well.
- b) Assignment of estimated future trips to the existing network in order to detect deficiencies in the existing network and thereby provide a framework for the development of future additions and improvements to this network.
- c) Assignment of estimated future trips to proposed future networks in order to decipher efficacy of these networks and therefore indicate where changes may be necessary.

Before analysing the techniques developed for route assignment analysis, it will be useful to consider in general

44 O'Sullivan, P., Holtzclaw, G.D., Barber, G., (1979).

the factors that affect choice of routes by trip makers. A trip maker would normally tend to prefer that route which has the least 'travel resistance' between his origin and destination. Travel time, speed, comfort and levels of service on a route are indices of 'travel resistance'. Thus, in trying to select a route, the trip maker consciously or subconsciously evaluates these characteristics of the routes available and decides to choose one that has the least travel resistance.

In this section, an attempt will be made to review some of the widely used assignment techniques. These may be categorized under:

- i) Two path traffic assignment or diversion curve techniques
- ii) Single path network assignment methods.

2.5.1 Two Path Traffic Assignment or Diversion Curve Techniques

The diversion curve technique is based on the assumption that at least two alternative routes exist between each pair of zones and that it is possible to obtain a measure of travel resistance on each of these routes.

The procedure involves collection of data on travel resistance and the corresponding route usage for the base year. This data is then used to construct diversion curves that reflect the relationship between travel resistance and route usage. This relationship depicted by the diversion curve is assumed to remain the same for the horizon year. Thus, the diversion curve is used in conjunction with horizon

year forecasts of travel resistance to obtain future assignment of trips to alternative routes between each pair of zones. Similarly, traffic volumes on a new route and an existing route or a pair of new routes could be obtained.

Two types of diversion curves have been developed. The Bureau of Public Roads (Bruton, 1985) has developed diversion curves based on a single measure of travel resistance namely travel time. Percentage usage of a route between two zones is a function of the ratio of travel time on the route under consideration to travel time on an alternative route. Thus, as the travel time ratio (TTR) increases, it seems intuitively clear that percentage usage of the route as compared to the alternative one must progressively decline. The following diversion curve was constructed using base year data on travel time ratio and corresponding percentage transit usage (Figure 10).

This curve depicts the inverse relationship between route usage and travel time ratio. It must be noted that percentage motorway usage does not fall to zero even where $1 < \text{TTR} < 1.50$. This may be because factors other than travel time prevent the trip maker from using the motorway. There are two shortcomings associated with this method. Firstly, only a single measure of travel resistance has been incorporated. This approach is quite common since travel time is easy to quantify, whereas it may not be possible to meaningfully measure other indices of travel resistance such as comfort and convenience on the route. Associated with

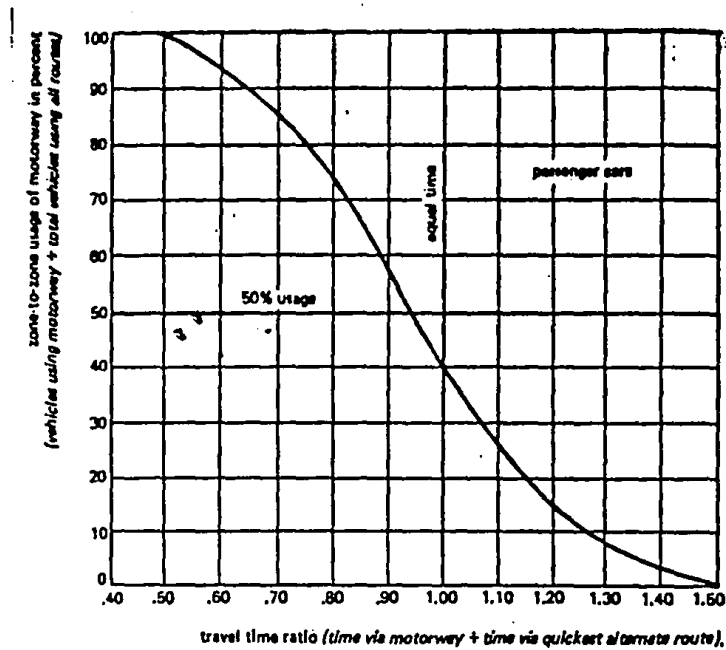


Figure 10 : Bureau of Public Roads Diversion Curves

Note : Motorway is the route under consideration. More specifically these are links of a primary network envisaged to carry sufficient traffic to justify their being reserved for motor traffic only.

Source: Bruton, M. Introduction to Transport Planning, (1985).

the first problem arises the second. Regardless of the length, trips with the same travel time ratio are given the same diversion rate. This may not be true.

Two variable travel resistance diversion curves have been developed by the California Division of Highways and the Detroit Area Traffic Study Team (Bruton, 1985). The Californian curves alternatively known as 'travel time and distance saved curves' incorporate two measures of travel resistance, namely, travel time saved and distance saved.⁴⁵ The assumption is that,

Factors other than time and distance cannot be measured explicitly, nor forecasted and can therefore be ignored. ... 46/

From the curves in Figure 11 it is observed that greater the travel time saved, greater the route usage and greater the distance saved, greater the route usage. This approach takes into account the influence of both travel time and distance and is therefore an improvement over the curves developed by the Bureau of Public Roads. The Detroit curves (Bruton, 1985) also known as 'speed distance ratio curves' rest on the premise, that

... although time, distance and speed are the principal factors affecting a

45 Travel time saved = (Travel time via alternative route) - (Travel time via route under consideration)
 Distance saved = (Distance via alternative route) - (Distance via route under consideration)

46 Bruton, M., (1985).

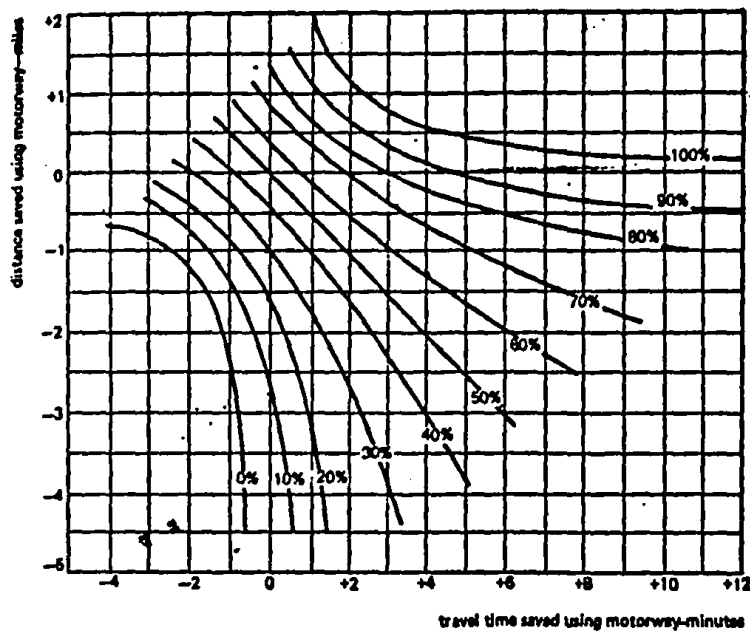


Figure 11 : Travel Time and Distance Saved Diversion Curves, Developed by California Division of Highways

Source : Bruton, M. Introduction to Transport Planning, (1985).

driver's choice of route, because they are interrelated it is only necessary to define two of them. ...

Route usage is related to speed ratio and distance ratio.⁴⁷ For a given speed ratio and varying distance ratio the relationship between route usage and travel time ratio⁴⁸ can be implicitly obtained. Similarly, for a given distance ratio and varying speed ratio the relationship between travel time and route usage can be determined. The curves obtained are illustrated in Figure 12.

Diversion curves have been widely used for assigning traffic flows. One weakness of this technique is that comparison can be made only between two routes of the network, at a time. In a rapidly changing environment where changes in attitudes of trip makers towards factors affecting travel resistance are important, one can question the validity of the hypothesis that the relationship between route usage and travel resistance will remain the same over time. Thus, diversion curves need to be used with caution. This method could produce successful results to determine traffic volumes over short periods of time only where minor extensions to the network are proposed.

47 Speed ratio = $\frac{\text{Average speed on route under consideration}}{\text{Average speed on alternative route}}$

Distance ratio = $\frac{\text{Distance on motorway under consideration}}{\text{Distance on alternative route}}$

48 Travel time ratio = $\frac{\text{Distance ratio}}{\text{Speed ratio}}$

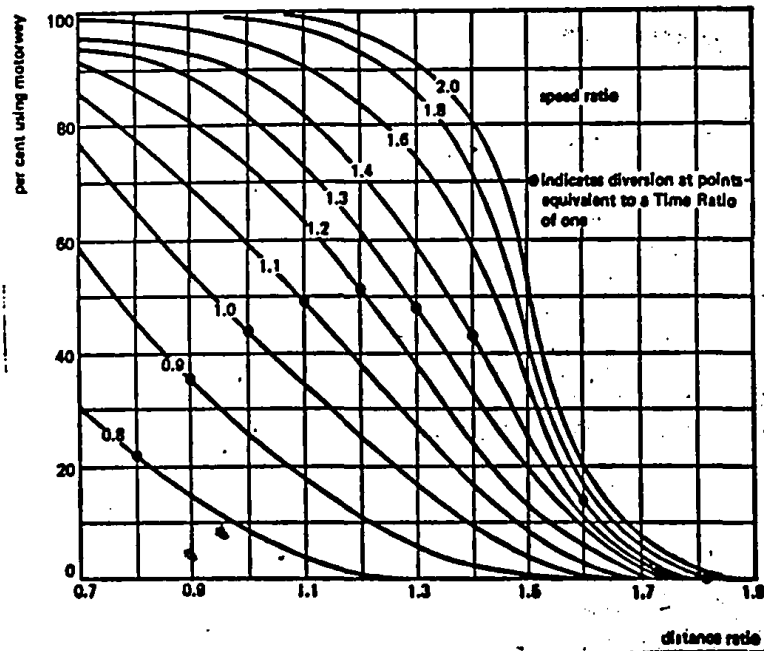


Figure 12 : Distance and Speed Ratio Diversion Curves
Developed by the Detroit Metropolitan
Traffic Study Team

Source : Bruton, M. Introduction to Transport Planning, (1985).

2.5.2 Single Path Network Assignment Methods

Single path network assignment methods were developed, in an attempt to overcome disadvantages of the diversion curve technique. Unlike the latter which considers only two routes (between each origin-destination pair) of the network at a time, single path assignment techniques take the entire network into account while assigning flows. However, there is one restriction that there is a single preferred path between each pair of zones. Single path techniques, in general, consist of three phases as illustrated in the flow chart given in Figure 13.

In the first phase, driver's route selection criteria must be identified. Most single path techniques emphasize travel time as the sole measure of travel resistance. Wardrop (Hutchinson, 1974) has suggested two criteria for describing trip makers attitude to route choice. At one extreme, it is proposed that each trip maker, oblivious of the other, acts selfishly.

... they consider only own individual travel times in making route choice decisions. ...

Whereas, the second criteria suggests that,

... Drivers are thought of as though they are aware of the way in which their route choices influence the travel time of all drivers using the network. ...

Most assignment techniques assume that Wardrop's first criterion governs route choices of trippers. Therefore, each trip maker is likely to select that route which has the minimum travel time between his origin and destination.

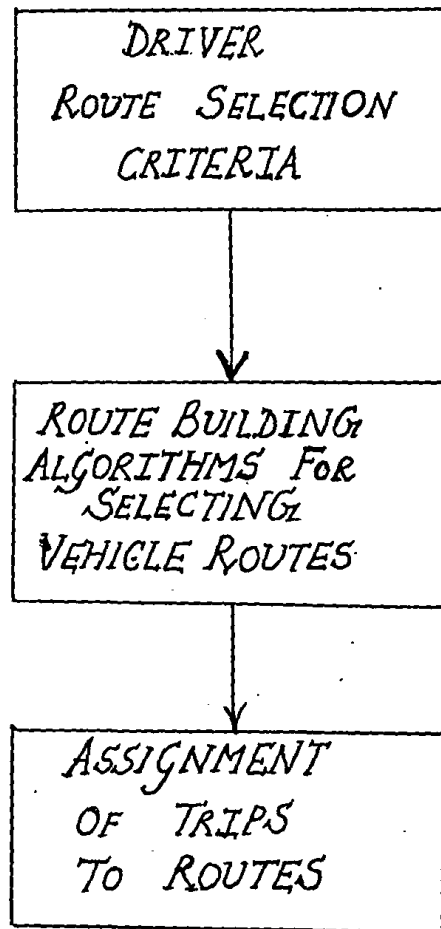


Figure 13 : Phases of the Single-Path Assignment Technique

The second phase is concerned with the development of route building algorithms which are based on the driver's route selection criteria that has been hypothesized in phase one. Route building algorithms based on Wardrop's first criterion seek to determine minimum travel time routes between each pair of zones. All other routes are eliminated.

Moore's algorithm (Hutchinson, 1974) was amongst the first of the route building algorithms to be developed. This algorithm will be explained with the help of a simple example. Consider the following hypothetical street network given in Figure 14. The above network consists of a zone centroid (15), eight nodes, (10, 11, 12, 13, 14, 16, 17) and eleven links.⁴⁹ The aim is to determine minimum time paths from zone centroid 15 to all other nodes. The following steps are involved.

Step 1:

Start at zone centroid 15 and consider travel times between 15 and the nodes nearest to 15. These may be enumerated as:

$$T_{15 - 16} = 1$$

$$T_{15 - 12} = 3$$

-
- 49 Link : A link is defined as the one way path of the route between two intersections.
- Nodes : These are representations of the intersections between the links of the street system.
- Centroids : Centroids are those nodes that represent points of trip production and trip attraction for the traffic analysis zones.

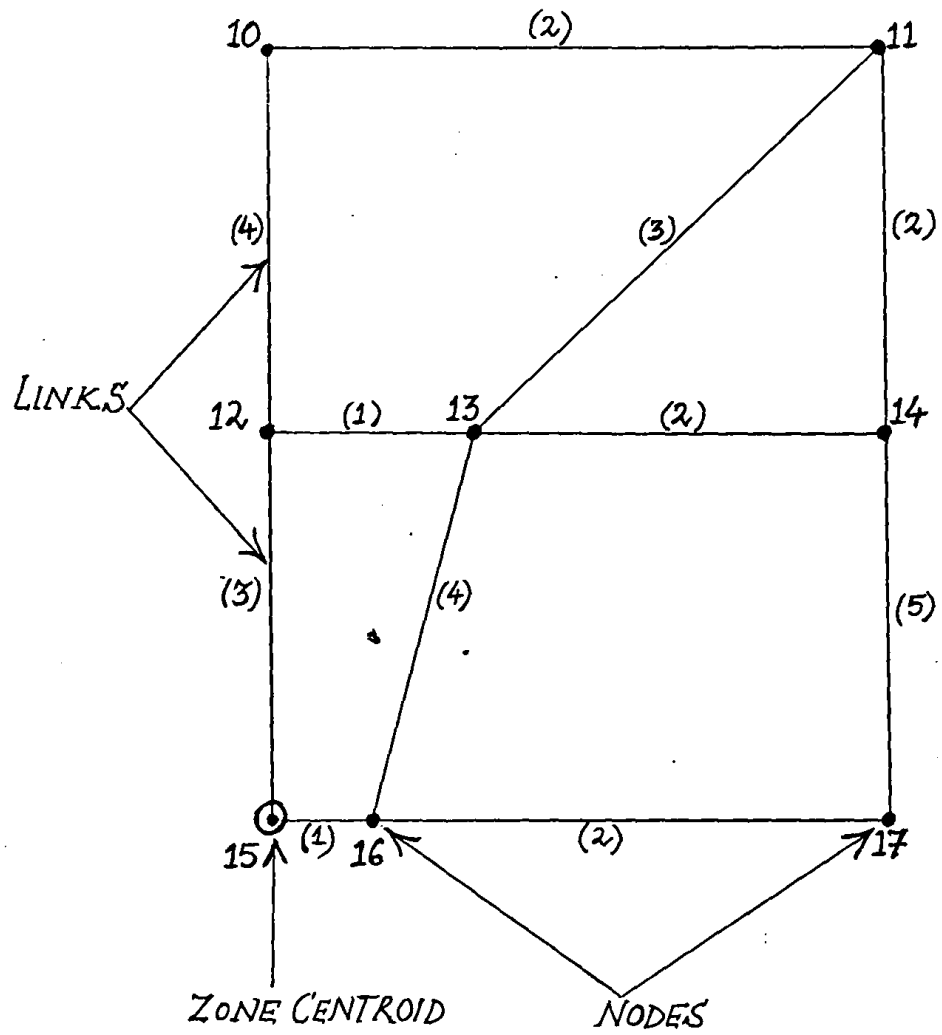


Figure 14 : Hypothetical Street Network

Note : Figures in brackets indicate link travel times.

where, T_{15-16} = travel time between nodes 15 and 16.

similarly T_{15-12} .

Step 2 :

Now, select that node which has the least travel time from 15 (here, 16) and enumerate travel times between 15 and those nodes nearest to this node (here, 17 and 13).

$$T_{15-16-17} = 1 + 2 = 3$$

$$T_{15-16-13} = 1 + 4 = 5$$

Next, consider the node which has the next highest travel time from 15 (here, 12) and consider travel times between 15 and the nodes closest to this node (here, 10, 13).

$$T_{15-12-10} = 3 + 4 = 7$$

$$T_{15-12-13} = 3 + 1 = 4$$

Since $T_{15-16-13} > T_{15-12-13}$, the route 15-16-13 is eliminated.

Step 3:

We must now begin with node '17' which is closest to node '16' and consider travel times between '15' and those nodes closest to node '17' (here, 14). In a similar manner we consider travel times between node '15' and those nodes closest to node '13' and '10', we get the following results:

$$T_{15-16-17-14} = 3 + 5 = 8 \text{ (eliminate)}$$

$$T_{15-12-13-14} = 4 + 2 = 6$$

$$T_{15-12-13-11} = 4 + 3 = 7$$

$$T_{15-12-10-11} = 7 + 2 = 9 \text{ (eliminate)}$$

$T_{15-16-17-14} > T_{15-12-13-14}$. Therefore, the route 15 - 16 - 17 - 14 is eliminated $T_{15-12-10-11} >$

$T_{15-12-13-11}$. Therefore the route 15-12-10-11 is eliminated.

Step 4:

$$T_{15-12-13-14-11} = 6 + 2 = 8$$

But from step 3 it is clear that $T_{15-12-13-14-11} >$

$T_{15-12-13-11}$ (=7). Therefore, the route 15-12-13-14-11 is eliminated.

In this manner, we have built the minimum path tree for zone centroid 15. This is depicted in the Figure 15 with the results summarized in Table 2.3.

Table 2.3 : Minimum Path Tree for Zone Centroid 15

Route	Links	Minimum Travel Time (in minutes)
15 - 10	15 - 12 - 10	7
15 - 11	15 - 12 - 13 - 11	7
15 - 12	15 - 12	3
15 - 13	15 - 12 - 13	4
15 - 14	15 - 12 - 13 - 14	6
15 - 15	-	0
15 - 16	15 - 16	1
15 - 17	15 - 16 - 17	3

In the last phase of the single path assignment techniques trips are assigned to the minimum tree path developed in phase two for each of the centroids. Two such methods will be reviewed, namely, the all or nothing assignment and capacity restrained assignment techniques.

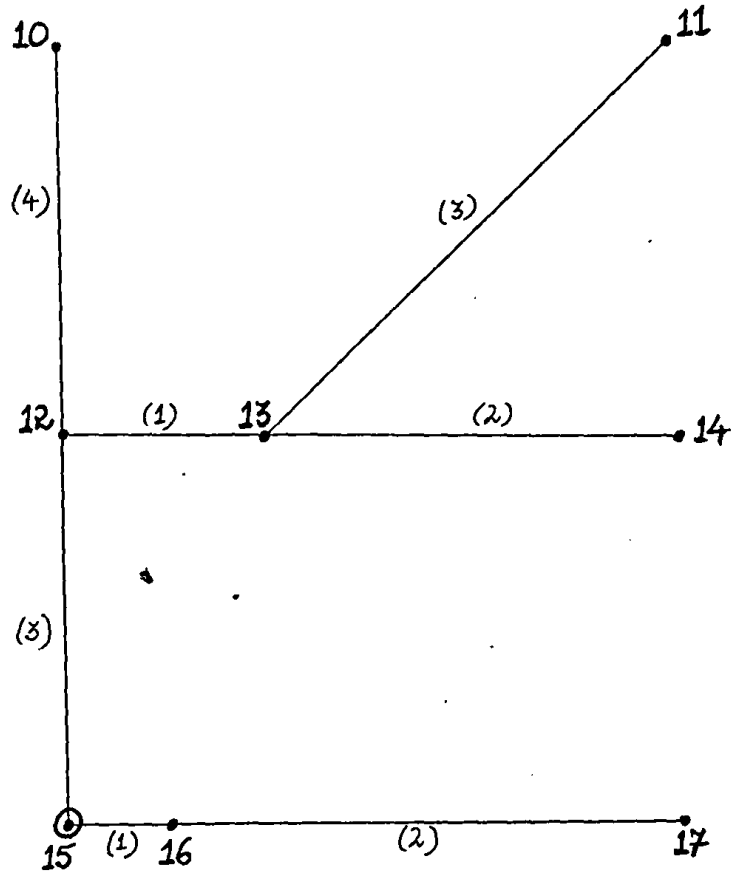


Figure 15 : Minimum Time Path for Hypothetical Street Network Depicted in Figure 14

In the 'all or nothing' assignment method, trip interchange volumes are assigned to the minimum path trees, independently of traffic capacities on the links. To illustrate using our example (Figure 14). Suppose the trip interchange matrix is that given below:

		DESTINATION						
		10	11	12	13	14	16	17
ORIGIN	15	100	200	200	300	100	500	300

These are assigned to the network as illustrated in Figure 16. Thus, the all or nothing link volumes assigned may be summarized in the following Table 2.4.

Link	All or Nothing Assigned Volumes
15 - 16	$500 + 300 = 800$
15 - 12	$100 + 200 + 200 + 300 + 100 = 900$
12 - 10	100
12 - 13	$200 + 300 + 100 = 600$
16 - 17	300
13 - 11	200
13 - 14	100

The capacity restrained assignment method recognizes the relationship between traffic flows and travel times on links. Basically, the procedure is to assign traffic volumes to minimum path trees using the all or nothing assignment technique and the assigned volumes are compared

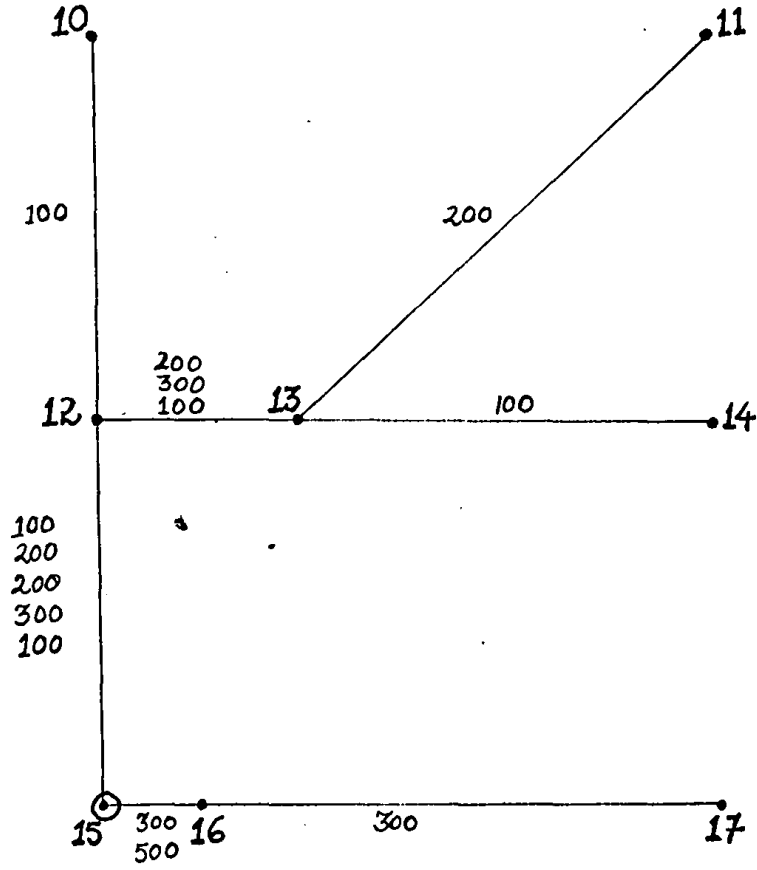


Figure 16 : 'All-or-Nothing' Assignment on Hypothetical Street Network Depicted in Figure 14

with capacity volumes on links. Where actual volumes exceed capacity volumes, travel times are revised upwards and where actual volumes fall short of capacity volumes, travel times are revised downwards. These revised travel times are incorporated into the network and minimum path trees built once again for each zone centroid. All or nothing assignments are made to these links and once again actual and capacity volumes compared. This procedure is repeated until discrepancy between actual and capacity flows is removed or settles at some pre-determined level. Thus, the effect of congestion on travel times which influence selection of routes, is effectively incorporated.

The Wayne State arterial assignment method was one of the earliest capacity restrained assignment techniques to be developed. The sequence of steps involved may be briefly examined.⁵⁰

Step 1

Travel times on each link was determined by dividing the length of the link by the 'typical speed' on that link. 'Typical speeds' derived empirically constituted the average speed on a link over a specified period of time. This first set of travel times were denoted by V_1 .

Step 2

Minimum path trees were constructed for all zone centroids on the basis of V_1 .

⁵⁰ Smock, R. "An Iterative Assignment Approach to Capacity Restraint on Arterial Networks," Highway Research Board, Record No. 347, (1962).

Step 3

Traffic volumes were assigned on an all-or-nothing basis to these trees and link volumes designated by X_1 .

Step 4

The ratio of actual assigned volumes to capacity volumes⁵¹ on each link was determined and designated as R_1 .

Step 5

Link travel times V_1 were modified on the basis of R_1 by using the following relationship:

$$V_2 = [e^{(R_1 - 1)}] \cdot V_1 \quad \dots (21)$$

where, V_2 = modified travel times

If $R_1 = 1$ then $V_2 = V_1$

If $R_1 = 0$ then $V_2 = (e^{-1}) \cdot V_1$

If $R_1 < 1$ then $V_2 < V_1$

If $R_1 > 1$ then $V_2 > V_1$

Step 6

Steps 1 to 3 were repeated using new link travel times V_2 , to obtain volumes X_2 on the new trees constructed. An average volume $\frac{X_1 + X_2}{2} = A_2$ on all links was computed. The ratio R_2 was arrived at by dividing this average (A_2) by capacity flows on each link. A new set of travel times V_3 was obtained by using R_2 in (21) above.

⁵¹ Capacity volumes are the number of vehicles that can traverse a link in twenty four hours under 'typical' urban conditions. A link's capacity is estimated by averaging the capacities of the intersections at its ends.

This procedure was repeated until a pre-determined balance between actual and capacity flows was reached on each link.

It is quite obvious from the above steps that the model tends to generate capacity flows on links rather than simulating existing flows. Consequently, deficiencies in the existing network cannot be detected since estimated traffic volumes neither exceed nor fall short of capacities.

The capacity restrained assignment technique developed by the Traffic Research Corporation (TRC)⁵² incorporates relationship between traffic flow and travel times on links. Greater the congestion on a route, greater will be the travel time on this route and trip makers will tend to seek alternative, less congested routes to reach their destination.

... It is well known that delay caused by congestion will cause travelers to seek other less congested routes ... conversely, it is known that the existence of an uncrowded direct route between two areas will quickly draw traffic from other more crowded routes and will even create new trip demand between the two areas. ... 53/

This relationship between the level of congestion, travel time and consequent selection of route by trip makers governs the assignment technique developed by the T.R.C.

The steps involved in this technique, may be summarized in the flow chart given in Figure 17.

52 Irwin, N.A., Dodd, N., Voncube, H.G. "Capacity Restraint in Assignment Programs," Highway Research Board Bulletin No. 297 (1961).

53 Ibid.

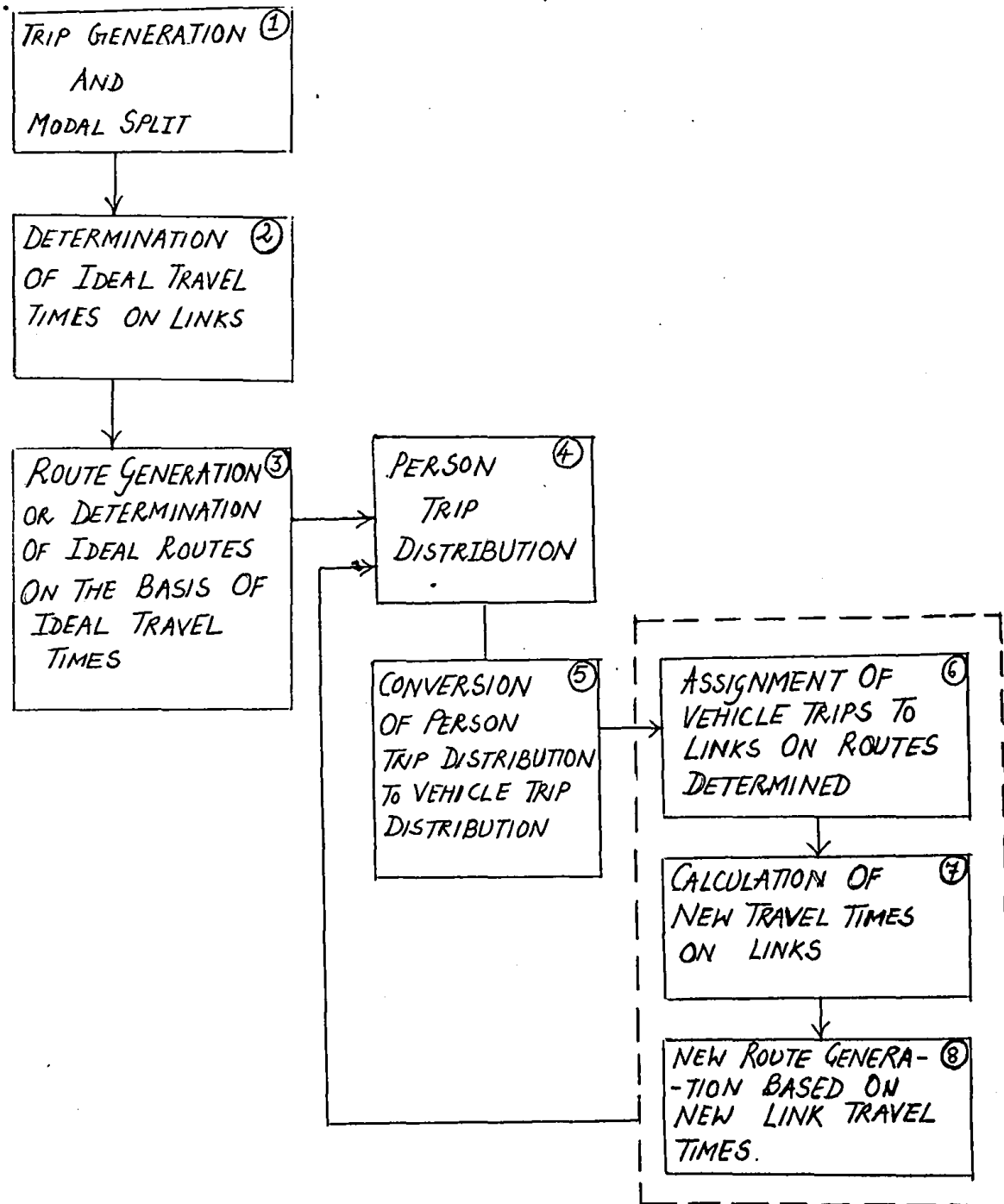


Figure 17 : Sequence of Stages in the Traffic Research Corporation Capacity Restraint Assignment Technique

As is evident from Figure 17 the sequence differs from the conventional aggregate sequential modelling process. Trip generation and modal split analysis once completed, are not conducted again (Step 1). However, the trip distribution stage (Steps (4) and (5)) needs to be repeated once new interzonal travel times have been incorporated into the network, after which these traffic volumes are assigned. This will be clear as we examine the steps involved in greater detail (refer to Figure 17).

Step 1

Trip generation and modal split analysis was conducted. Once completed this block was not repeated.

Step 2

Ideal travel times on links were determined. Ideal travel times are travel times on links when the flow of traffic on these links is zero. Mean speed at zero volume on each link was first obtained (empirically). Then, the length of the link was divided by this mean speed at zero volume to obtain the ideal travel time on the link. Thus, ideal travel time = $\frac{\text{length of the link}}{\text{mean speed at zero volume}}$.

Step 3

On the basis of ideal travel times, shortest routes between each pair of zones in the study area was determined using a slightly modified version of Moore's algorithm. Since route generation was based on 'ideal travel times', the outcome of this exercise was referred to as 'ideal routes'.

Step 4

The gravity modal formulation was used to distribute trip ends by mode between each pair of zones.

Step 5

Person trip interchanges were converted into vehicle trip interchanges using average occupancy rates (derived empirically). An iterative procedure involving steps 6, 7 and 8 was then undertaken. (Refer to Figure 17.)

Step 6

For the first iteration, vehicle trips were assigned to ideal routes on an all-or-nothing basis.

Step 7

A new set of travel times was calculated using the following 'capacity function'

$$tt = [tt_c + d \frac{(V_a - V_c)}{V_c}] \cdot l$$

where,

V_c = critical link volume above which flow becomes unstable and travel time rises rapidly

V_a = volume of traffic assigned to links in Step 6

tt_c = link travel time per mile at critical volume

l = link length (miles)

d = delay parameter (minutes per mile)

$d = 0.5$ for $V_a < V_c$

$d = 10$ for $V_a > V_c$

Ten capacity functions showing relationship between travel time and traffic flows were constructed using empirical data. Each function was based on a unique combination

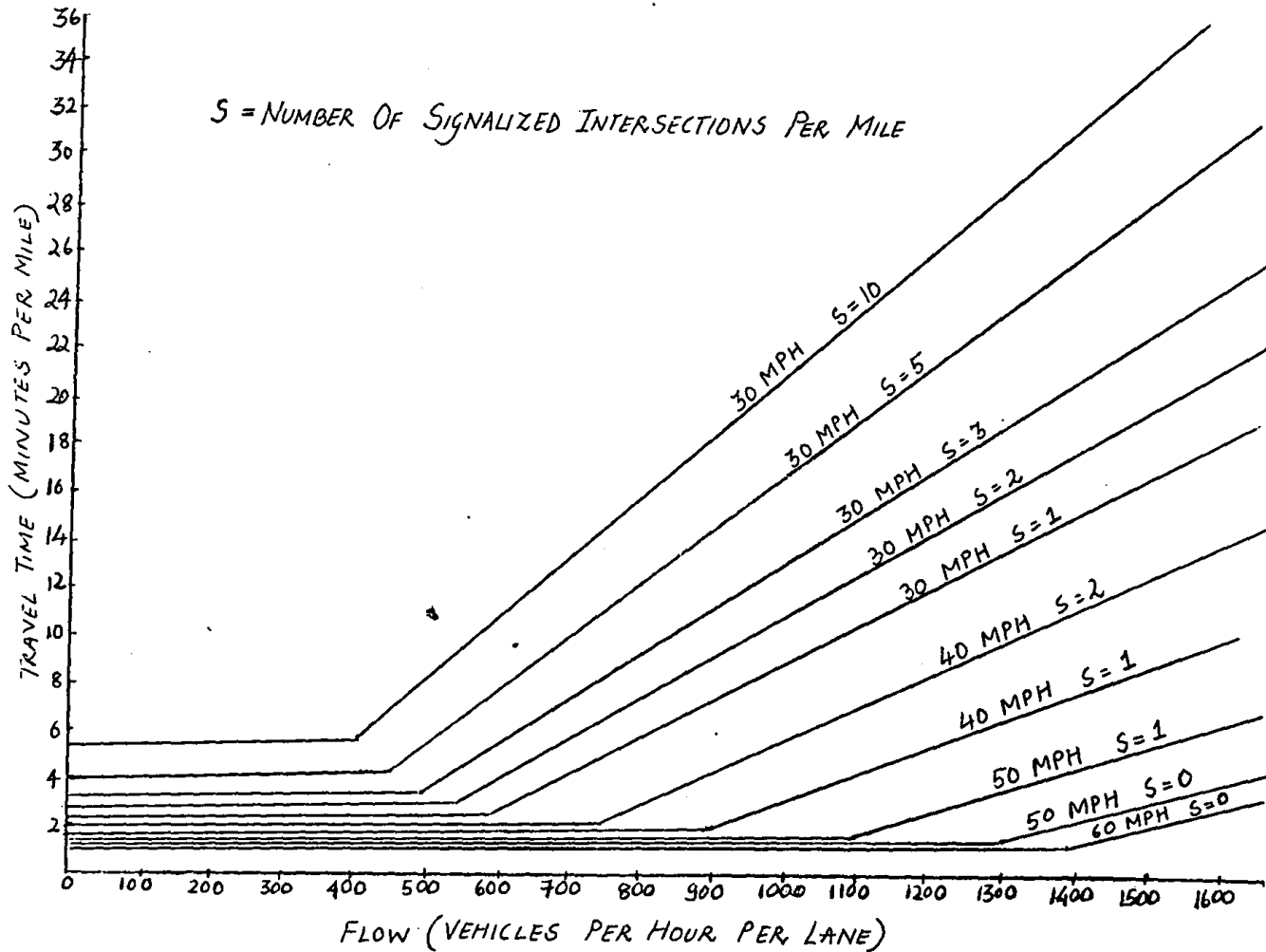


Figure 18 : Capacity Function Curves Developed by the Traffic Research Corporation

Source : Irwin, N.A., Dodd, N. and Voncuba, H.G.
 "Capacity Restraint in Assignment Programs,"
 Highway Research Board, Bulletin No. 297, (1961).

of signalized intersections per mile and speed limit on a link. These functions that were used are illustrated in the Figure 18.

Step 8

New minimum time path routes were generated on the basis of travel times computed in Step 7. For the next iteration, Step 6 was repeated with one difference that traffic volumes were assigned to all routes between each pair of zones that were developed so far. For instance, for this iteration, trips between two zones would be assigned to routes generated in Step 3 and Step 8 above. For this purpose the following expression was used.

$$T_{rij} = T_{ij} \cdot \left[\frac{1/tt_{rij}}{\sum_{r=1}^n (1/tt_{rij})} \right]$$

where,

T_{rij} = proportion of trips T_{ij} assigned to route 'r' linking 'i' and 'j'

tt_{rij} = travel time between 'i' and 'j' on route 'r'

r = routes determined so far.

Steps 7 and 8 were repeated once again. This iterative procedure involving Steps 6, 7 and 8 were repeated until changes in link volumes from one iteration to the next remained less than a pre-determined value.

After this was achieved, a new set of travel times, 'average travel times' were determined by a weighted average of all the link travel times generated by each iteration.

The weights were the corresponding traffic volumes assigned to these routes.

Symbolically, (say after 'n' iterations)

$$\overline{tt}_{ij} = \frac{\sum_{r=1}^n T_{rij} \cdot tt_{rij}}{\sum_{r=1}^n tt_{rij}}$$

where,

\overline{tt}_{ij} = average travel time between zones i and j

tt_{rij} = travel time on route 'r' between zones i and j

These average travel times were incorporated into the network to yield new minimum time paths. The trip distribution stages (Steps 4 and 5) were repeated once again on the basis of these minimum time paths. The iterative procedure involving Steps 6, 7 and 8 were carried out, till changes in link volumes were insignificant from iteration to iteration.

The distinguishing feature of the T.R.C. method is that assignment is not restricted to a single route between zonal pairs. This may be a more accurate representation of reality. What is more important, the repercussions of congestion are incorporated into the system and modifications made right from the trip distribution stage.

In this section attempts have been made to review some of the more widely used assignment techniques. Although, fairly complex traffic assignment models have been developed, few have been resorted to in travel forecasting studies

because collection of sufficient data on the choice of routes can be quite expensive. In any case, there seems to be a feeling among transport planners that the traffic assignment phase of the travel forecasting process is only of marginal use in resolving strategic transport planning issues.

APPENDIX 2.1

CONSTRUCTION OF BASE YEAR TRIP LENGTH FREQUENCY DISTRIBUTION

The base year trip length frequency distribution serves as a measure for detecting how well the calibrated model simulates base year travel patterns. It will be worthwhile to briefly describe the construction of the base year trip length frequency distribution.

To begin with, origin destination survey¹ data on number of trip origins O_i^b , number of trip destinations D_j^b , trip interchanges between each pair of zones T_{ij}^b is obtained for the base year. Interzonal and intrazonal travel times are then derived.² In the study conducted by the U.S. Bureau of Public Roads³ for Washington D.C., interzonal in-vehicle

1 A succinct account of survey methods can be obtained from: Lane, R., Powell, T.J. and Smith, P.P. Analytical Transport Planning (1971), Chapter 2.

2 Travel time = In-vehicle travel time + excess travel time. In-vehicle travel time is the actual driving time while excess travel time is time spent outside the vehicle in order to reach the destination. For example, excess travel time in the case of public transit would include: transfer time between transit vehicles, time spent waiting for transit vehicles, walking time to transit vehicle, walking time from transit vehicle. For cars the excess time component would include: parking delay at destination, walking time from parking place to destination.

3 Bouchard, R.J. and Pyres, C.E. "Use of Gravity Model for Describing Urban Travel," Highway Research Board, Record No. 88 (1965).

travel times were estimated using 'minimum path tree building algorithms', while intrazonal in-vehicle travel times were estimated on the basis of interzonal in-vehicle travel times to adjacent zones. Excess travel times were calculated by taking into account zonal differences in congestion and available parking facilities.

Trip length frequency distribution of the base year is then obtained by 1 minute travel time intervals. To illustrate, consider 5 minutes as the intercentroid travel time. Then, trip interchanges between all pairs of zones, whose intercentroid travel time is 5 minutes would be summed up to denote frequency for this travel time category. Similarly, frequencies for other intercentroid travel time categories, 6 minutes, 7 minutes, etc., could be obtained. A hypothetical trip length frequency distribution is illustrated in the Figure 19.

The mean trip length for the base year is estimated in the following manner:

$$\overline{T.L.} = \frac{\sum z \cdot (T_{ij})_z}{T^0}$$

where,

- $\overline{T.L.}$ = mean trip length in minutes
- z = a particular intercentroid travel time category
- $(T_{ij})_z$ = all trip interchanges that fall within category 'z'.

The summation is over all intercentroid travel time categories.

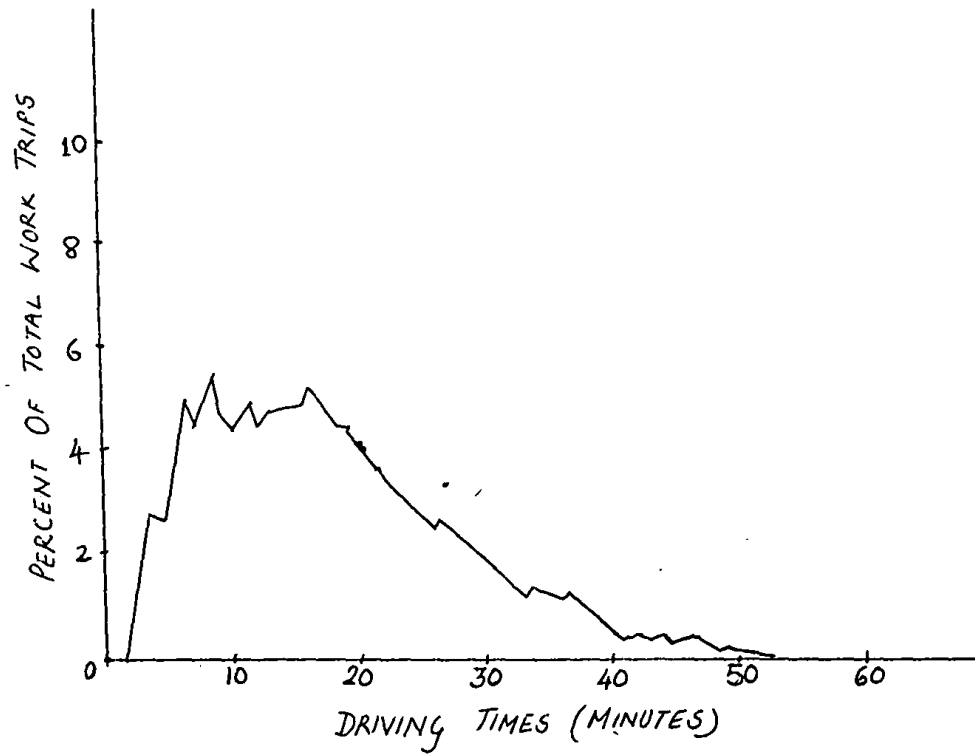


Figure 19 : Trip Length Frequency Curve

Note : In the above figure, percentage of total trips rather than total number of trips denotes frequency corresponding to intercentroid travel time categories.

THEORETICAL BASE OF THE GRAVITY MODEL

Wilson (1967)¹ has attempted to provide a sound theoretical base to the gravity model by using a probability maximizing method.

This method assumes a single trip purpose and only one mode of travel. The aim is to arrive at an origin-destination matrix $[T_{ij}]$ which satisfies the following constraints:

$$\begin{aligned} \sum_j T_{ij} &= O_i && \dots \text{ I} \\ \sum_i T_{ij} &= D_j && \dots \text{ II} \\ \sum_i \sum_j T_{ij} C_{ij} &= C && \dots \text{ III} \end{aligned}$$

where, C_{ij} is the impedance, or generalized cost, of traveling between 'i' and 'j'. Constraint III, then implies that the total amount spent on trips in the region, is a fixed amount 'C'.

Now, there can be a number of trip distribution matrices $[T_{ij}]$ which satisfy the above three constraints. Therefore, the aim is to choose that trip distribution matrix, among all these possible matrices, which has the highest probability of occurrence.

¹ Wilson, A.G. "A statistical theory of spatial distribution models," *Transportation Research*, Vol. 1 (1967).

If 'x' denotes a particular trip distribution matrix $[T_{ij}]$, then the probability of the occurrence of this distribution, is given by the multinomial distribution,² expressed as:

$$\begin{aligned}
 P(x) &= [W_x (T_{ij})] \cdot [P_{11}^{T_{11}} \cdot P_{12}^{T_{12}} \cdot \dots \cdot P_{nn}^{T_{nn}}]_x \\
 &= [W_x (T_{ij})] \cdot [p_{i,j}^{T_{ij}}]_x \quad \dots (1)
 \end{aligned}$$

where,

$P(x)$ = probability of occurrence of any particular trip distribution matrix 'x'

$W_x(T_{ij})$ = number of distinct arrangements of the elements of a particular trip distribution matrix $[T_{ij}]_x$ which is given by

$$\left[\frac{T!}{\prod_{i,j} T_{ij}!} \right]_x$$

P_{ij} = the probability of occurrence of a single trip between 'i' and 'j'

$p_{ij}^{T_{ij}}$ = the probability of occurrence of all the trips (T_{ij}) between zones 'i' and 'j'.

Now a probability maximizing technique may be applied.

Or, maximizing $P(x)$, would generate a trip distribution matrix that has the highest probability of occurrence. The basic assumption of the probability maximizing approach, is that the probability of occurrence of a trip distribution

² Hoel, P.J. Introduction to Mathematical Statistics, pp. 163, 164 and 13.

matrix $[T_{ij}]$ is proportional to $W_x \cdot [T_{ij}]$, which gives rise to this distribution, or,

$$P(x) \propto W_x (T_{ij}) \quad \dots (2)$$

Therefore, maximizing $W_x (T_{ij})$ subject to the three constraints, would generate that trip distribution matrix which is overwhelmingly the most probable distribution. This maximizing procedure can be outlined as follows:

Using the Lagrangian expression:

$$M = \log W + \sum_i \lambda_i^{(1)} (O_i - \sum_j T_{ij}) + \sum_j \lambda_j^{(2)} (D_j - \sum_i T_{ij}) + \beta (C - \sum_i \sum_j T_{ij} C_{ij}) \quad \dots (3)$$

$\lambda_i^{(1)}$, $\lambda_j^{(2)}$ and β are Lagrangian multipliers. It is more convenient to maximize $\log W$ than 'W'.

T_{ij} s which maximize 'M' are solutions of :

$$\frac{\partial M}{\partial T_{ij}} = 0$$

$$\text{Now, } \frac{\partial M}{\partial T_{ij}} = \frac{\partial [\log W]}{\partial T_{ij}} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta C_{ij} \quad \dots (4)$$

$$= \frac{\partial [\log T! / \pi_{i,j} T_{ij}!]}{\partial T_{ij}} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta C_{ij} \quad \dots (5)$$

$$= \frac{\partial [\log T! - \log(\pi_{i,j} T_{ij}!)]}{\partial T_{ij}} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta C_{ij} \quad \dots (6)$$

$$= \frac{\partial [\log T! - (\sum_{i,j} \log T_{ij}!)]}{\partial T_{ij}} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta C_{ij} \quad \dots (7)$$

Sterling's approximation can now be used, where,

$$\log N! = N \log N - N$$

$$\log T! = T \log T - T, \text{ which is a constant} \quad \dots (8)$$

$$\therefore \frac{\partial \log T!}{\partial T_{ij}} = 0 \quad \dots (9)$$

Further using Sterlings' approximation

$$\frac{\partial \log N!}{\partial N} = \log N$$

$$\therefore \frac{\partial \log T_{ij}!}{\partial T_{ij}} = \log T_{ij} \quad \dots (10)$$

expanding (7) above we get

$$\frac{\partial M}{\partial T_{ij}} = \frac{\partial \log T!}{\partial T_{ij}} - \frac{\partial (\sum_{i,j} \log T_{ij}!)}{\partial T_{ij}} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij} \quad \dots (11)$$

Using, (9) and (10) in (11) we get

$$\frac{\partial M}{\partial T_{ij}} = - \log T_{ij} - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij} \quad \dots (12)$$

Now $\frac{\partial M}{\partial T_{ij}} = 0$ yields,

$$\log T_{ij} = - \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij}$$

$$\text{or } T_{ij} = \exp [- \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij}] \quad \dots (13)$$

Now, $\sum_j T_{ij} = O_i$ and $\sum_i T_{ij} = D_j$

Substituting for T_{ij} in (13) we get

$$O_i = \sum_j \exp [- \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij}]$$

$$D_j = \sum_i \exp [- \lambda_i^{(1)} - \lambda_j^{(2)} - \beta c_{ij}] \quad \dots (14)$$

$$\therefore \exp [- \lambda_i^{(1)}] = O_i / \sum_j \exp [- \lambda_j^{(2)} - \beta c_{ij}]$$

$$\exp [- \lambda_j^{(2)}] = D_j / \sum_i \exp [- \lambda_i^{(1)} - \beta c_{ij}] \quad \dots (15)$$

$$\text{Let } A_i = \exp [-\lambda_i^{(1)}] / O_i$$

$$\text{Let } B_j = \exp [-\lambda_j^{(2)}] / D_j \quad \dots (16)$$

$$\therefore A_i O_i = \exp [-\lambda_i^{(1)}]$$

$$B_j D_j = \exp [-\lambda_j^{(2)}] \quad \dots (17)$$

Substituting (17) in (13) we get,

$$T_{ij} = A_i B_j O_i D_j \cdot \exp [-\beta C_{ij}] \quad \dots (18)$$

This formulation can be used to obtain the most probable trip distribution matrix. Values for A_i and B_j are solved iteratively. Thus the most probable distribution of trips, (18) is the same as the gravity model distribution. This statistical derivation constitutes a new theoretical base to the gravity model.

Niederhorn and Bechdolt (1969)³ have developed an economic derivation of the gravity model, within the framework of utility theory.

The aim is to study trip making behaviour of an individual 'k' at origin 'i' to all other destinations 'j'. Then, this individual's utility of trip making from origin 'i' to destination 'j' is,

$$k^{U_{ij}^*} = f(k T_{ij}) \quad \dots (19)$$

where,

³ Niederhorn, J. and Bechdolt, B. Jr. "An economic derivation of the 'gravity law' of spatial interaction," *Journal of Regional Science*, Vol. 9, No. 2, (1969).

- $k^{U_{ij}^*}$ = net utility of individual 'k' at origin 'i' of interacting with persons or things at destination 'j' per unit of time
- $k^{T_{ij}}$ = number of trips taken by individual 'k' from origin 'i' to destination 'j' per unit of time.

Therefore, an individual's total utility of interaction with all destinations is,

$$k^{U_i^*} = \sum_{j=1}^n f(k^{T_{ij}}) \quad \dots (20)$$

where,

- $k^{U_i^*}$ = total net utility of individual 'k' at origin 'i' of interacting with persons and things at all destinations, per unit of time.

In reality, there are likely to be more than one person or thing at each destination to interact with. The number of such persons is assumed to be proportional to the population of the destination zone. Therefore, (20) becomes,

$$k^{U_i} = a \cdot \sum_{j=1}^n P_j \cdot f(k^{T_{ij}}) \quad \dots (21)$$

- P_j = population of destination zone 'j'
- a = constant of proportionality.

Two constraints operate so that the individual cannot make an unlimited number of trips:

$$I) \quad k^{M_i} \geq r \cdot \sum_{j=1}^n d_{ij} \cdot k^{T_{ij}}$$

where,

k^M_i = total amount of money individual 'k' at 'i' is willing to spend on travel

r = cost per mile of distance travelled

d_{ij} = distance between origin 'i' and destination 'j'

i.e. constraint (I) indicates that money spent on travel must be less than or equal to the amount available for this purpose, (k^M_i).

$$\text{II) } k^H_i \leq \frac{1}{S} \sum_j d_{ij} \cdot T_{ij}$$

k^H_i = total amount of time individual 'k' located at 'i' is willing to allocate for travel

S = average speed at which people in the region travel.

i.e. constraint II indicates that the amount of time spent on time is restricted by the amount allocated for the same, (k^H_i).

The total net utility of individual 'k' for interacting with persons or things at all destinations when constrained by money is obtained by maximizing,

$$k^U_i = a \sum_{j=1}^n P_j \cdot f(k^T_{ij}) - \lambda (r \sum d_{ij} \cdot k^T_{ij} - k^M_i) \quad \dots (22)$$

where λ = Lagrangian multiplier. The utility maximizing values of k^T_{ij} for all j , which emerge by this process, are found to be similar to versions of the gravity model developed earlier.

CHAPTER III

TRANSPORT RELATED LAND USE MODELS

3.1 Introduction

Land use is an important explanatory variable in comprehending the nature of travel patterns. Around the early sixties, an ardent need for the development of land use models arose in order to enable planners gain an insight into the theory of urban spatial structures. This was necessary for the provision of amenities (such as transport) on a long-term, planned basis rather than relying on ad-hoc means to tackle problems of rapidly expanding areas.

The principal objective of each of these land use models is to determine the spatial distribution of activities within an urban area, namely, the determination of the level and location of households as well as employment in the area.

Lowry¹ was the first to develop a land use model in 1964. The purpose of this model, which forms the basis of most land use models developed till now, was to estimate land use patterns as input to the transport models. However, R.A. Garin² improved upon the Lowry model, illustrating how land

1 Lowry, I.S. Model of Metropolis. Rand Corporation, Santa Monica (1964).

2 Garin, R.A. "Formulation of the Lowry Model for Intrametropolitan Activity Allocation," Journal of the American Institute of Planners (January 1966).

use allocation and related travel demand could be derived simultaneously. This model has been often referred to as the 'Garin-Lowry Model'. The basic justification for this approach was that since land use and travel demand are closely interlinked, it would seem most appropriate to tackle these problems in a single model.

This chapter is mainly devoted to an examination of the Garin-Lowry model which is an adaptation of the Lowry model. However, essential aspects of the original Lowry model will be emphasized wherever necessary.

3.2 Garin-Lowry Model

The original Lowry model was developed as part of an economic study of the Pittsburg region. The objective of this study was,

... the development of an analytical model capable of assigning urban activities to sub-areas of a bounded region in accordance with those principles of locational interdependence that could be reduced to quantitative form. ...3/

Thus, the model could be used as a tool for predicting changes in metropolitan form over time.

The metropolitan spatial structure is thought of as comprising of basic, retail and household sectors. The basic sector manufactures goods consumed outside the region. The location of this sector is independent of the population and service employment distribution of that region. Thus the

3 Lowry, I.S. (1964).

level and spatial distribution of basic employment is determined exogenously to the model. The retail sector is dependent on local clients. Hence, site-selection is assumed to be powerfully constrained by problems of access to local residents while employment levels are closely tied to local growth of population. Residential site-selection for the household sector is influenced by residents place of work, while the number of resident households depends on the number of basic and retail jobs available. The locations and levels of employment of establishments in the retail sector as well as the number and location of households are determined within the model. The structure of this model is illustrated in the Figure 20.

Given the level and location of basic employment, the model performs two functions. The level of residential population and retail employment is determined. Residential population is then allocated to residential zones and retail employees to retail centres, on the basis of a simple gravity model formulation.

The sub-models used to derive and allocate residential population and retail employment are explained below, in the sequence illustrated in Figure 20.

The sub-model for allocating employees to residential zones is developed in the following manner. The interaction sub-model based on the gravity law forms the essence of this allocation model. This is given below as,

$$I_{ij}^{wh} = K \left[\frac{N_j}{d_{ij}^{\alpha}} \right] \dots (1)$$

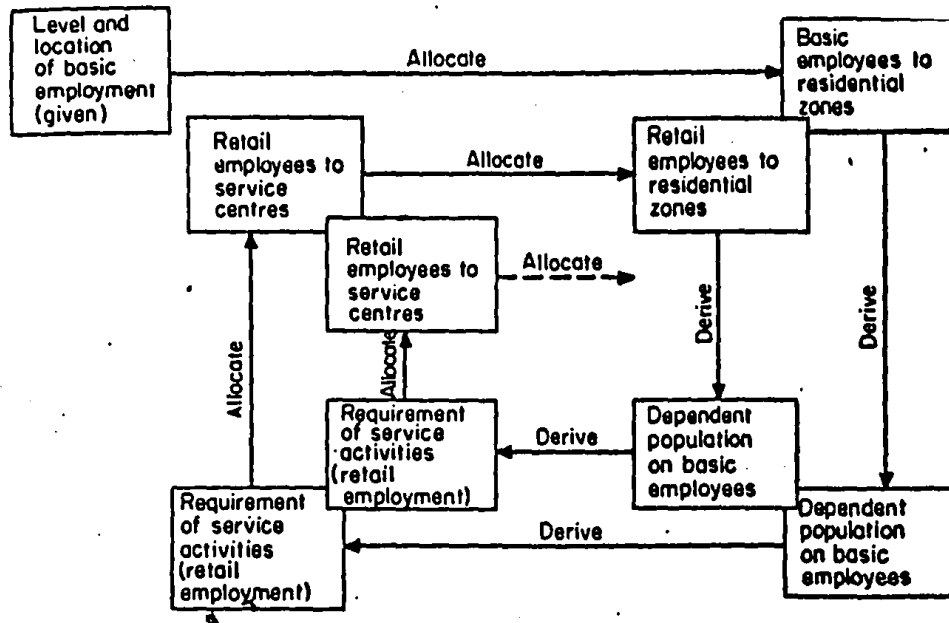


Figure 20 : Structure of the Garin-Lowry Model

Source : Reif, B. Models in Urban and Regional Planning, (1973).

where,

I_{ij}^{wh} = work to home trips between zones 'i' and 'j'

N_j = population in zone 'j' (measure of attractiveness of zone 'j')

d_{ij} = distance between zones 'i' and 'j'
(deterrence factor between zones 'i' and 'j')

α = a parameter

K = scaling factor.

Now, the probability that an employee working in zone 'i' lives in zone 'j', is,

$$P_{ij}^{wh} = \frac{\text{number of trips from zone 'i' to 'j'}}{\text{number of trips from zone 'i' to all zones}}$$

Symbolically,

$$P_{ij}^{wh} = \frac{[N_j/d_{ij}^\alpha]}{\sum_j [N_j/d_{ij}^\alpha]} = \frac{I_{ij}^{wh}}{\sum_j I_{ij}^{wh}} \quad \dots (2)$$

If ' E_i ' i.e. employment in zone 'i' is a proxy for the total number of trips generated in zone 'i', then,

$$I_{ij}^{wh} = E_i \cdot [P_{ij}^{wh}] \quad \dots (3)$$

The total number of employees living in zone 'j', ' L_j ' can be determined by the total number of work to home trips originating at all zones 'i' to destination zone 'j', or,

$$L_j = \sum_i I_{ij}^{wh} \quad \dots (4)$$

If 'z' denotes a particular iteration, then the total number of employees living in zone 'j' is arrived at by summing over all 'z' iterations:

$$L_j = \sum_z L_j^{(z)} \quad \dots (5)$$

Residential population depends on the total employment and is derived by the following relationship:

$$N = f.E \quad \dots (6)$$

where,

- N = total population
- E = total employment in the study area
(Basic + Retail)
- f = inverse of the labour participation rate
(= N/E) i.e., the households dependent
on each employee.

The level of retail employment depends on the total number of households in the study area.

$$\dots E^R = a.N \quad \dots (7)$$

where,

- E^R = total retail employment
- a = service employment ratio (= E^R/N) i.e.
service employees needed to service a
single household.

The interaction model which forms the basis of the sub-model to allocate retail employment to retail centres is given by a gravity model formulation, as:

$$I_{ij}^{hs} = K \left[\frac{E_i^R}{d_{ij}^\lambda} \right] \quad \dots (8)$$

- I_{ij}^{hs} = home to shop trips between zones 'i' and 'j'
- E_i^R = retail employment in zone 'i' (Measure of
attractiveness of zone 'i')
- d_{ij} = distance between zones 'i' and 'j' (deterrence
factor between origin and destination zones)
- λ = a parameter
- K = scaling factor

Now, probability that a person living at 'j' will go for shopping at zone 'i', is,

$$P_{ij}^{hs} = \frac{\text{number of trips from zone 'j' to zone 'i'}}{\text{number of trips from zone 'j' to all zones}}$$

Symbolically,

$$P_{ij}^{hs} = \frac{[E_i^R/d_{ij}^\lambda]}{\sum_i [E_i^R/d_{ij}^\lambda]} \quad \dots (9)$$

From equation (6) we know that

$$N_j = f.L_j$$

where, N_j = population in zone 'j'.

From (7) it is clear that

$$D_j = a.N_j$$

where, D_j = retail employees needed to service households in zone 'j'.

Now,

$$E_{ij}^R = D_j \cdot P_{ij}^{hs} \quad \dots (10)$$

where, E_{ij}^R = total retail employees in zone 'i' servicing households in zone 'j'.

Therefore, the total number of employees in zone 'i' servicing households in all zones 'j' is,

$$E_i^R = \sum_j E_{ij}^R \quad \dots (11)$$

If 'z' denotes a particular iteration, then,

$$E_i^R = \sum_z \sum_j E_{ij}^R(z) \quad \dots (12)$$

The associated travel demands can be arrived at from

equation (3) which gives the work to home trips and equation (10) which gives the home to shop trips.

The final outputs emerging from the model are best understood by examining the steps involved in the solution method. These are given below:

Input data to the model include distance ' d_{ij} ' between all pairs of zones; level and location of basic employment, retail employment and population for the current year; parameters ' α ' and ' λ '.

Step 1:

The inverse of the labour participation rate ' f ' and the population servicing ratio ' a ' is determined using current year data:

$$f = \frac{N}{E} \quad \text{and} \quad a = \frac{E^R}{N}$$

Step 2:

The probability distribution of residential location (P_{ij}^{wh}) and service centre location (P_{ij}^{hs}) is obtained using current year data.

$$P_{ij}^{wh} = \frac{[N_j/d_{ij}^\alpha]}{\sum_j [N_j/d_{ij}^\alpha]} \quad \text{and} \quad P_{ij}^{hs} = \frac{[E_i^R/d_{ij}^\lambda]}{\sum_i [E_i^R/d_{ij}^\lambda]}$$

Step 3:

The total employment and the total retail employment is computed by the short-cut method.⁴

⁴ Refer to Appendix 3.1 for derivation of these results.

$$E^* = E^B(1 - af)^{-1}$$

$$E^{R*} = E^* - E^B$$

These are to serve as measures towards which the iterative process must converge.

Step 4:

The iterative process can now commence. (Refer to Figure 20.)

i) z = iteration number

Set $z = 1$

Land Use

ii) Employees allocated to residential zones

$$L_j(z) = \sum_i E_i(z) \cdot P_{ij}^{wh} = \sum_i I_{ij}^{wh}(z)$$

$$\text{or } L_j(1) = \sum_i E_i(1) \cdot P_{ij}^{wh} = \sum_i I_{ij}^{wh}(1)$$

$$E_i(1) = E_i^B \text{ for the first iteration.}$$

iii) Number of households dependent on employees in zone 'j' = $N_j(1) = f \cdot L_j(1)$

iv) Retail employees needed to service households in zone 'j' =

$$D_j(1) = a \cdot N_j(1)$$

v) Retail employees at 'i' needed to service households at 'j' =

$$E_{ij}^R(1) = D_j(1) \cdot P_{ij}^{hs}$$

vi) Total retail employees in zone 'i' =

$$E_i^R(1) = \sum_j E_{ij}^R(1)$$

Associated Travel Demand

- i) $I_{ij}^{wh}(1)$ gives the associated work to home trips .
 ii) $E_{ij}^R(1)$ gives the associated home to shop trips.

For the second iteration, $z = 2$ and $E_i(2)$ in (ii) of Step 4 is set to $E_i^R(1)$ and Steps (ii) to (iv) for land use and (i) and (ii) for travel demand are repeated. This iterative process is continued until changes in level and location of population, retail employment and associated travel demand are insignificant from iteration to iteration, or, the total retail employment converges to E^{R*} and total employment to E^* (calculated in Step 3).

The end results after say, 'm' iterations are as follows:

LAND USE:

$$\sum_{z=1}^m E_i^R(z) = E_i^R, \text{ i.e., total retail employment at 'i'.$$

$$\sum_{z=1}^m N_j(z) = N_j, \text{ i.e., households in zone 'j'.$$

$$E = \sum_i E_i^B + \sum_i E_i^R \text{ i.e., total employment}$$

$$N = \sum_j N_j \text{ i.e., total population.}$$

ASSOCIATED TRAVEL DEMAND

$$\sum_{z=1}^m I_{ij}^{wh}(z) = I_{ij}^{wh} \text{ i.e., total work to home trips.}$$

$$\sum_{z=1}^m E_{ij}^R(z) = E_{ij}^R \text{ i.e. total home to shop trips.}$$

What distinguishes the Garin-Lowry model from the original Lowry model is that both land use allocation and associated travel demand are simultaneously determined. Further, it explicitly incorporates spatial sub-models into the framework. Garin has also attempted to express the fundamental Lowry algorithm in vector and matrix format.⁵ However, the Garin-Lowry model though conceptually more satisfying, excludes the constraints⁶ which Lowry imposed in the original formulation. These constraints may be crucial to prevent lopsided growth of activities in a rapidly

5 Refer to Appendix 3.2 for a matrix formulation of the Lowry algorithm

6 In the original Lowry model, three constraints have been laid down.

$$i) N_j \leq Z_j^H \cdot A_j^H$$

where, N_j = population in zone j ; Z_j^H = households permitted per 1000 sq.ft. of residential space; and A_j^H = land used for residential activities in zone j .

This constraint prevents generation of excess population densities in locations with high accessibility indices or major employment centres.

$$ii) E_j^K \geq Z^K$$

where, E_j^K = retail employment of type 'K' in zone j ; and Z^K = establishment of minimum efficient size for retail activity of type 'K'. This constraint limits dispersion of retail activity which may cause inconvenience to consumers.

$$iii) A_j^R \leq A_j - A_j^U - A_j^B$$

where, A_j = land available in zone 'j'; A_j^U = unusable land in zone 'j'; A_j^B = land available for basic sector; and A_j^R = land available for retail sector in zone 'j'. This constraint ensures that land set aside for retail establishments must not exceed the amount of land available.

expanding metropolitan environment. These constraints need to be incorporated in the Garin-Lowry formulation in order to enhance its use as a policy-oriented model.

3.3 Derivatives of the Lowry Model⁷

Many other land use models have been developed as derivatives to the original Lowry model.

Prominent among the Lowry model derivatives that emerged in the U.S. around the mid-sixties were: the Time Oriented Metropolitan Model (TOMM); the Projective Land Use Model (PLUM); and the Disaggregated Residential Allocation Model (DRAM). Essentially these derivatives were developed in order to bring about refinements in certain aspects of the original Lowry model. For instance, a variety of allocation functions have been experimented with. Further, analysis is conducted at a much more disaggregated level for a closer depiction of reality. However, these models lacked an adequate theoretical foundation and they were considered to be too data-hungry.

A new group of land use models started emerging around the end sixties. These were the Eichenique group of models and the National Bureau of Economic Research (NBER) urban simulation model. These models were developed essentially, to overcome the main weakness of the Lowry model and some of its derivatives, namely, non-existence of a theoretical basis.

⁷ An extensive review of these models is available from the following reference: Rakesh, Mohan. Urban Economic and Planning Models. World Bank Staff Occasional Papers, No.25, Chapter 3, p. 74.

The Eichenique models which were developed for South American cities are essentially Lowry model derivatives wherein Wilson's⁸ entropy maximizing concept is used to give a better theoretical basis to the gravity models used in distribution and allocation. However, these models lack adequate behavioural underpinnings and it is not very clear whether these can be used as effective predictive devices. The main objective of the NBER simulation model was to predict land use that could be used only as input to the transport planning process and not for simultaneously determining land use patterns and associated travel demands. The distinguishing feature of this model is its behavioural structure based on micro-economic theory. However, it has been found to be unwieldy to operate and its data requirements are heavy.

The main objective of the land use models, reviewed in this chapter, is to distribute activities spatially within an urban area. Only the Garin-Lowry model explicitly determines travel demands that emerge with this spatial distribution of activities.

The Lowry model and its adaptation, the Garin-Lowry model, have been criticized on grounds that these simulate rather than explain land use patterns and associated travel demands. Again, problems of modal split and route assignment are not considered. Although attempts were made to refine the Lowry model, specifically to equip it with a sound theoretical base, the results have not been very satisfactory.

⁸ Ibid., pp. 87-93.

APPENDIX 3.1

SHORT CUT METHOD OF OBTAINING EMPLOYMENT
AND POPULATION LEVELS

Now we know that,

$$N = f.E$$

and $E^R = a.N$

∴ For the first iteration:

$$\begin{aligned} N(1) &= f.E(1) \\ &= f.E^B \end{aligned}$$

$$\begin{aligned} E^R(1) &= a.N(1) \\ &= a.f.E^B \end{aligned}$$

where, figures in brackets denotes iteration number.

For the second iteration:

$$\begin{aligned} N(2) &= f.E^R(1) \\ &= a.f^2.E^B \end{aligned}$$

$$\begin{aligned} E^R(2) &= a.N(2) \\ &= a^2.f^2.E^B \end{aligned}$$

∴

∴

For the 'm'th iteration:

$$E^R(m) = a^m.f^m.E^B$$

$$\begin{aligned} \therefore E &= E^B + E^R(1) + E^R(2) + \dots + E^R(m) \\ &= E^B + a.f.E^B + a^2.f^2.E^B + \dots + a^m.f^m.E^B \\ &= E^B(1 + af + a^2.f^2 + \dots + a^m.f^m) \\ &= E^B(1 - af)^{-2} \end{aligned}$$

since $af < 1$ and $m \rightarrow \infty$

$$\begin{aligned} \therefore N &= f.E \\ &= f.E^B(1 - af)^{-2} \end{aligned}$$

APPENDIX 3.2

MATRIX FORMULATION OF THE GARIN-LOWRY MODEL
 (Refer to Figure 20 to follow closely the steps involved)

Given matrix E^B

$$E_{1 \times n}^B = \begin{bmatrix} E_1^B & E_2^B & \dots & E_n^B \end{bmatrix}$$

Labour participation rate diagonal matrix F :

$$F_{n \times n} = \begin{bmatrix} f_1 & 0 & 0 & \dots & 0 \\ 0 & f_2 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ \vdots & \vdots & \vdots & & \vdots \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \dots & f_n \end{bmatrix}$$

Population serving ratio diagonal matrix A:

$$A_{n \times n} = \begin{bmatrix} a_1 & 0 & 0 & \dots & 0 \\ 0 & a_2 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ \vdots & \vdots & \vdots & & \vdots \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \dots & a_n \end{bmatrix}$$

Work to home trip probability distribution matrix p^{wh} :

$$p_{n \times n}^{wh} = \begin{bmatrix} p_{11}^{wh} & p_{12}^{wh} & \dots & p_{1n}^{wh} \\ p_{21}^{wh} & p_{22}^{wh} & \dots & p_{2n}^{wh} \\ \vdots & \vdots & \dots & \vdots \\ \vdots & \vdots & \dots & \vdots \\ p_{n1}^{wh} & p_{n2}^{wh} & \dots & p_{nn}^{wh} \end{bmatrix}$$

Home to shop trip probability distribution matrix P^{hs} :

$$P_{n \times n}^{hs} = \begin{bmatrix} P_{11}^{hs} & P_{12}^{hs} & \dots & P_{1n}^{hs} \\ P_{21}^{hs} & P_{22}^{hs} & \dots & P_{2n}^{hs} \\ \cdot & \cdot & \ddots & \cdot \\ \cdot & \cdot & \dots & \cdot \\ P_{n1}^{hs} & P_{n2}^{hs} & \dots & P_{nn}^{hs} \end{bmatrix}$$

Iteration 1

$$\begin{aligned} & \text{Allocation of retail employees to residential zones} = \\ & E(1) \cdot P^{wh} \\ & = E^B \cdot P^{wh} \end{aligned}$$

Dependent population =

$$\begin{aligned} N(1) &= E(1) \cdot P^{wh} \cdot F \\ &= E^B \cdot P^{wh} \cdot F \end{aligned}$$

Derivation of retail employment =

$$N(1) \cdot A$$

Allocation of retail employment =

$$E(2) = N(1) \cdot A \cdot P^{hs}$$

Substituting for $N(1)$ we get

$$E(2) = E^B \cdot P^{wh} \cdot F \cdot A \cdot P^{hs}$$

Iteration 2

$$\begin{aligned} N(2) &= E(2) \cdot P^{wh} \cdot F \\ &= E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}] \cdot (P^{wh} \cdot F) \end{aligned}$$

$$\begin{aligned} E(3) &= N(2) \cdot A \cdot P^{hs} \\ &= E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}]^2 \end{aligned}$$

Iteration 3

$$\begin{aligned}
 N(3) &= E(3) \cdot P^{wh} \cdot F \\
 &= E^B \cdot (P^{wh} \cdot F \cdot A \cdot P^{hs})^2 \cdot P^{wh} \cdot F \\
 E(4) &= N(3) \cdot A \cdot P^{hs} \\
 &= E^B \cdot (P^{wh} \cdot F \cdot A \cdot P^{hs})^3
 \end{aligned}$$

Iteration m

$$\begin{aligned}
 N(m) &= E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}]^{m-1} \cdot (P^{wh} \cdot F) \\
 E(m) &= E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}]^{m-1} \\
 E &= E^B + E(2) + E(3) + \dots + E(m) \\
 &= E^B + E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}] + E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}]^2 \\
 &\quad + \dots + E^B \cdot [P^{wh} \cdot F \cdot A \cdot P^{hs}]^m \\
 &= E^B \cdot [I + (P^{wh} \cdot F \cdot A \cdot P^{hs}) + (P^{wh} \cdot F \cdot A \cdot P^{hs})^2 + \dots] \\
 &= E^B \cdot [I - (P^{wh} \cdot F \cdot A \cdot P^{hs})]^{-1} \quad \dots (1) \\
 \therefore N &= E^B [I - (P^{wh} \cdot F \cdot A \cdot P^{hs})]^{-1} \cdot P^{wh} \cdot F \quad \dots (2)
 \end{aligned}$$

By solving (1) and (2) we obtain the level and location of employment and population.

CHAPTER IV

ECONOMIC DEMAND MODELS

4.1 Introduction

Since the late sixties, attempts have been made to construct travel demand models which derive their theoretical underpinnings from the micro-economic theory of consumer choice. These economic demand models were developed as alternatives to the aggregate sequential modelling techniques which were proving to be ill-suited and unreliable in providing answers to policy questions facing planners. While possessing a simple structure the traditional models were severely criticized on the ground that they had few, if any, explanatory powers and therefore were correlative rather than causal models.

... The prime test has been how well the base year data set can be duplicated. Such a test, however, does not provide evidence on the consistency of the relationships over time, or that they represent a coherent theory of travel behaviour. 1/

It was emphasized that only by explaining the causal relationships between socio-economic and transport system characteristics, on the one hand, and trip making, on the

1 Goodwin, P.B. and Hensher, D.A. "The transport determinants of travel choice: An overview," in Hensher, D.A. and Dalvi, Q. (ed.). Determinants of Travel Choice (1978).

other, could the model be used to forecast the effects of future changes in the performance of the transportation system. More specifically, it was pointed out that the aggregate sequential models utilize data aggregated to the zonal level thereby concealing differences in individual trip making behaviour which may be of great significance for depicting actual behavioural associations.

Thus travel demand models using data aggregated in any way ... are unlikely fully to explain the behaviour of the individual travellers, and thus they are likely to be poor prediction models. 2/

Further, the recursive structure of these models, consisting of a series of sub-models applied sequentially, has often been considered to be unrealistic. Now, an individual trip maker has certain choices to make. He must decide, for instance, whether to make the trip, the destination to be reached, the route to be taken, the mode to be used and even the time of the day to travel. From the standpoint of the individual trip maker these decisions appear to be so inter-related that together they can best be treated as a single complex joint decision rather than independent separate ones.

... these decisions are so intertwined that they are best treated as being made simultaneously rather than separated. 3/

The original impetus for the development of economic

² Ben-Akiva, M.E. and Richards, M.G. A Disaggregated Travel Demand Model (1975).

³ Domencich, T.A., Kraft, G., Valette, J. "Estimation of urban passenger travel behaviour: An economic demand model," Highway Research Board, Record No. 238, (1968).

demand models centred around two specific travel choice problems, namely, the valuation of time and the choice of travel mode. These models view travel,

... as the result of individual's rational decision-making in an economic context ... the various modes or destinations of travel are regarded as commodities, each with its own price and among which the consumer chooses so as to maximise either implicitly or explicitly some index of satisfaction. 4/

However, it was pointed out that the estimation of travel demand choice had certain unique features associated with it, such that reformulation of the conventional micro-economic theory of consumer choice was essential to account for these. One of the most significant features of travel demand choice is that the alternatives available to the individual trip makers can be best defined in terms of journey attributes. Thus, unlike the conventional consumer demand theory which deals with the question of how much of any commodity the consumer will purchase, travel choice focuses on the problem of selection of an alternative, representing a vector of travel attributes. One of the crucial journey attributes affecting travel choice is the amount of time spent on travel. Conventional demand theory was not designed to incorporate factors such as the value

4. Quandt, R.E. "Introduction to the analysis of travel demand," in Quandt, R.E. (ed.). *The Demand for Travel: Theory and Measurement*, (1970).

of travel time⁵ which can play a significant role in the determination of travel choice of individuals. By and large, these economic models of travel demand are based on an index of generalized cost of travel.

In contrast to a direct specification of the demand function several approaches attempt to specify the consumer's (dis)-utility function of travel or, what is quite similar, attempt to define the cost of travel in a sufficiently generalized manner to account not only for out-of-pocket money costs but for the time cost of travel and perhaps other attributes as well. 6/

The rest of this chapter is devoted to an examination of some of the economic models which can be broadly classified under:

- i) Direct demand models
- ii) Probabilistic models.

4.2 Direct Demand Models

In this category of economic models all elements of travel choice, namely, generation, attraction, distribution between zones and modal choice are determined simultaneously by a single model. However, these models employ

5 The value of travel time represents the marginal rate of substitution of money for travel time, i.e., the amount of money decision-makers are willing to sacrifice for the reduction in the amount of time that they spend in travel. Theoretically, the value of travel time is calculated from a disaggregate demand model based on utility maximization as the ratio of the estimated coefficient for travel time (which is in units of utility per unit of time) to the estimated coefficient for travel cost (which is in utility per dollar). It is common practice in passenger transportation studies to express value of time estimates as a percentage of the wage rate to facilitate various comparisons that can be made.

6 Quandt, R.E., (1970).

aggregate level data. In these models the number of trips between any zonal pair for a given purpose and mode are expressed as a function of the number of individuals or households in the origin zone and their socio-economic characteristics, an appropriate measure of the level of activity and other relevant socio-economic and land use characteristics in the destination zone, together with travel times and costs of a given mode and alternative modes.

Quandt and Baumol⁷ have developed a direct demand model known as the 'abstract mode model'. What forms the essence of this model is that the trip maker is assumed to perceive each alternative in terms of its attributes alone.

... A mode can be thought of in abstract terms if it is characterized only in terms of features such as travel time, cost, departure frequency, other convenience factors, etc. ... at no point is it necessary to identify any of the modes in terms of institutional characteristics. 8/

Besides determining the various aspects of travel simultaneously, the principal advantage of this approach is that a new mode can be introduced into the model simply by specifying its costs, travel time and other major factors. The effect of introducing a new mode on existing modes can therefore be predicted.

7 Quandt, R.E. and Baumol, J. "The demand for abstract modes: Theory and measurement," Journal of Regional Science, Vol. 6, No. 2, (1966).

8 Ibid.

Symbolically, the model may be represented as,

$$T_{kij} = \alpha_0 \cdot P_i^{\alpha_1} \cdot P_j^{\alpha_2} \cdot Y_i^{\alpha_3} \cdot Y_j^{\alpha_4} \cdot M_i^{\alpha_5} \cdot M_j^{\alpha_6} \cdot N_{ij}^{\alpha_7} \cdot f_1(H) \cdot f_2(C) \cdot f_3(D)$$

where,

$$f_1(H) = (H_{ij}^b)^{\beta_0} \cdot (H_{kij}^r)^{\beta_1}$$

$$f_2(C) = (C_{ij}^b)^{\gamma_0} \cdot (C_{kij}^r)^{\gamma_1}$$

$$f_3(D) = (D_{ij}^b)^{\delta_0} \cdot (D_{kij}^r)^{\delta_1}$$

T_{kij} = total number of trips between zones 'i' and 'j' by mode 'k'

P_i, P_j = populations of origin zone 'i' and destination zone 'j' respectively

Y_i, Y_j = mean incomes of origin zone 'i' and destination zone 'j' respectively

M_i, M_j = land use characteristics such as level and type of activity being conducted in zone 'i' and 'j' respectively

H_{ij}^b = best (least) travel times between zones 'i' and 'j'

H_{kij}^r = relative travel time for 'k'th mode between zones 'i' and 'j' ($= H_{kij}/H_{ij}$)

C_{ij}^b = best (least) cost of travel between zones 'i' and 'j'

C_{kij}^r = relative cost of travel by 'k'th mode between zones 'i' and 'j' ($= C_{kij}/C_{ij}$)

D_{ij}^b = best departure frequency between zones 'i' and 'j'

D_{kij}^r = relative departure frequency by mode 'k' between zones 'i' and 'j' ($= D_{kij}/D_{ij}$)

N_{ij} = total number of modes in operation between zones 'i' and 'j'.

This model was tested using data relating to twenty city pairs in California, for the year 1960. Seven regression equations involving different combinations of the explanatory variables were developed. The correlation coefficient (R) varied from 0.9331 to 0.9386. These results are summarized in Table 4.1.

Though the representation of alternatives in terms of attributes is quite appealing, a serious shortcoming of this approach is that while estimating travel demand, the model incorporates the effect of the mode under consideration relative to the "best" available mode alone. As a result, a change in the characteristic of any mode other than the "best" mode is not allowed to affect the demand for the mode being considered. A more useful formulation is one in which the attributes of all competing modes are allowed to affect the demand for each mode. Gronau and Alcaly⁹ have attempted to rectify the Quandt-Baumol model on these lines.

Domencich, Kraft and Valette¹⁰ developed a direct demand model based on the theory of consumer demand in economic literature, while attempting to comprehend urban passenger demand behaviour in the Boston metropolitan area. In this approach, transport is perceived of as a derived demand commodity. Hence the transport demand model is analogous in structure to a derived demand commodity model.

9 Gronau, R. and Alcaly, R.E. "The demand for abstract modes: Some misgivings," *Journal of Regional Science*, Vol.9, No. 1 (1969).

10 Domencich, T.A., Kraft, G. and Valette, J., (1968).

Table 4.1 : Results of Regressions on California Data

Variable	Regression						
	1	2	3	4	5	6	7
Constant	-31.91 (-0.95)	-38.04 (-1.14)	-40.71 (-0.69)	-33.82 (1.45)	-36.57 (-1.62)	-32.56 (-1.37)	-28.73 (-1.25)
log P _i	0.95 (5.88)	0.92 (4.44)	0.94 (3.71)	0.93 (6.99)	0.91 (7.40)	0.95 (7.54)	0.88 (6.95)
log P _j	1.08 (5.14)	1.14 (6.20)	1.14 (6.37)	1.12 (6.38)	1.14 (6.95)	0.99 (6.41)	0.88 (5.47)
log Y _i	1.75 (0.53)	4.59 (1.30)	3.32 (0.33)	2.64 (1.05)			
log Y _j	3.71 (0.99)	3.11 (1.01)	3.02 (0.99)	3.72 (1.43)			
log D _i	0.67 (0.57)						
log D _j	0.17 (0.19)						
log W _i			-0.36 (-0.05)				
log W _j			2.38 (0.76)				
M _i		-0.73 (-0.53)					
M _j		-0.96 (-1.15)					
log($\frac{Y_i + Y_j}{2}$)					6.83 (2.35)		
log C ^b _{ij}	-0.99 (-1.19)	-0.61 (-0.70)	-1.57 (-1.75)	-1.20 (-1.69)	-1.12 (-1.68)	-0.62 (-1.04)	-0.57 (-0.99)
log C ^r _{ki j}	-3.17 (-11.40)	-3.15 (-11.51)	-3.18 (-11.48)	-2.62 (3.59)	-3.17 (11.82)	-3.15 (-11.62)	-2.34 (-4.54)
log H ^b _{ij}	-0.32 (-0.21)	-0.92 (-0.59)	0.59 (0.36)	-0.15 (-0.12)	-0.20 (-0.16)	-1.19 (-1.17)	-1.20 (-1.23)
log H ^r _{ki j}	-2.04 (-5.45)	-2.01 (-5.45)	-2.05 (-5.51)	-1.73 (-3.23)	-2.04 (-5.66)	-2.01 (-5.51)	-1.75 (-4.59)
log F ^r _{ki j}							0.44 (1.83)
log A _{ij}				0.66 (0.81)			
log $\frac{P_i Y_i + P_j Y_j}{P_i + P_j}$						6.33 (2.08)	5.82 (1.96)
R	0.9355	0.9376	0.9360	0.9361	0.9350	0.9331	0.9386
F	25.94	26.91	26.18	29.92	39.70	38.49	36.09

Source : Adapted from: Quandt, R.E. and Baumol, W.J. "The Demand for Abstract Transport Modes: Theory and Measurement," Journal of Regional Science, Vol. 6, No. 2 (1966), p. 24.

Factors affecting demand were identified as prices of the mode under consideration, prices of complementary goods and services, prices of competing modes and income. Prices were conceptualized in terms of two components, namely, travel time and travel cost. Since transport is not desired for its own sake but as a means for satisfying other demands such as shopping, work or personal business, measures of output of these activities were also incorporated into the model. A general expression of the travel demand model was given as,

$$N(i, j, i/M_0, P_0) = f[S(i/P_0), A(j/P_0), T(i, j, i/P_0, M_0), C(i, j, i/P_0, M_0), T(i, j, i/P_0, M_\infty), C(i, j, i/P_0, M_\infty)]$$

where,

- $N(i, j, i/P_0, M_0)$ = the number of round trips between origin 'i' and destination 'j' for purpose 'P₀' by mode 'M₀'
- $S(i/P_0)$ = vector of socio-economic characteristics relevant to purpose 'P₀' for travellers living in zone 'i'
- $A(j/P_0)$ = vector of socio-economic and land use characteristics describing the level of activity relevant to purpose 'P₀' in destination zone 'j'
- $T(i, j, i/M_0, P_0)$ = vector of travel time components for the round trip from 'i' to 'j' for purpose 'P₀' by mode 'M₀'
- $C(i, j, i/M_0, P_0)$ = vector of travel cost components for the round trip from 'i' to 'j' for purpose 'P₀' by mode 'M₀'

$T(i,j,i/M_{\alpha},P_0)$ = vector of travel time components for the round trip from 'i' to 'j' for purpose 'P₀' by each of the alternative modes ' α ' ($\alpha = 1, 2, \dots n$)

$C(i,j,i/M_{\alpha},P_0)$ = vector of travel cost components for the round trip from 'i' to 'j' for purpose 'P₀' by each of the alternative modes ' α ' ($\alpha = 1, 2, \dots n$)

In the Boston study, socio-economic and land use variables consisted of population and population density, personal income, car ownership, employment and employment density for relevant industry groups, etc. It was felt that trip makers react differently to different components of travel time and cost. Consequently, travel time and cost were disaggregated into the following components:

Auto travel time = Auto-in-vehicle time¹¹ + Auto-out-of-vehicle time

11 Auto-in-vehicle time = line haul time from zone centroid to zone centroid + parking time

Auto-out-of vehicle time = walk-to-car time at origin of trip + time spent in walking from parking place to destination.

Transit line-haul time = in-vehicle time spent in the principal transit mode

Transit excess time = travel time spent outside the principal transit mode.

Auto line-haul costs = operating costs of driving an automobile from the zone of origin to the zone of destination

Auto-out-of-pocket costs = toll + parking charges

Transit line-haul costs = fare paid on the principal transit mode

Transit excess costs = money spent travelling to and from the principal transit mode.

Transit travel time = Transit line-haul time + Transit excess time

Auto costs = Auto line-haul cost + Out-of-pocket costs

Transit costs = Transit line-haul costs + Transit excess cost

A mixed log-linear form was selected to express the demand model so that effects of both relative and absolute changes in the explanatory variables could be measured. The parameters of this model were estimated by means of constrained multiple regression analysis. The constraints included assignment of appropriate signs to the parameters on the basis of standard postulates of economic demand theory.

In order to examine the responsiveness of travel demand to changes in any one of the explanatory variables, the concept of demand elasticity was employed:

$$\eta_x = \frac{\partial N/N}{\partial X/X}$$

where,

N = travel demand

X = a particular explanatory variable

η_x = elasticity of travel demand with respect to variable 'x'.

Empirically derived elasticities for work and shopping trips with respect to time and costs are summarized in Tables 4.2 and 4.3. The direct elasticities derived reveal that shopping trips are more sensitive to changes in travel time and cost than work trips. Further, trip making behaviour is quite

Table 4.2 : Elasticities of Passenger Travel Demand with Respect to Components of Travel Time

		Auto trips			
Trip Purpose	R ²	Direct Elasticities		Cross Elasticities	
		Auto In-vehicle	Auto Out-of-vehicle	Transit Line-haul	Transit Excess
Work	0.41	-0.82	-1.437	0	0.373
Shopping	0.55	-1.02	-1.440	0.0950	0
		Transit Trips			
Trip Purpose	R ²	Direct Elasticities		Cross Elasticities	
		Transit Line-haul	Transit Excess	Auto In-vehicle	Auto Out-of-vehicle
Work	0.35	-0.39	-0.709	0	0
Shopping	0.63		-0.593 ^a	0	0

^a The available shopping transit trip sample was unsuitable for estimating elasticities for the disaggregated time components.

different in response to different components of travel time and cost. For instance, trip makers seem to be more sensitive to out-of-pocket costs than line-haul costs and out-of-vehicle times appear to be more onerous than in-vehicle times. This is especially pronounced in the case of shopping trips. Lastly, the most significant observation that can be made is that socio-economic characteristics rather than

Table 4.3 : Elasticities of Passenger Travel Demand with Respect to the Components of Travel Cost

Auto trips				
Trip Purpose	Direct Elasticities		Cross Elasticities	
	Auto Line-haul	Auto Out-of-pocket	Transit Line-haul	Transit Excess

Work	-0.494	-0.071	0.138	0
Shopping	-0.878	-1.65	0	0

Transit Trips				
Trip Purpose	Direct Elasticities		Cross Elasticities	
	Transit Line-haul	Transit Excess	Auto Line-haul	Auto Out-of-pocket

Work	-0.09	-0.100	0	0
Shopping		-0.323 ^b	0	0

^b The available shopping transit trip sample was unsuitable for estimating elasticities for the disaggregated cost components.

Source : Domencich, T.A., Kraft, G. and Valette, J.P.
 "Estimation of Urban Passenger Travel Behaviour:
 An Economic Demand Model," Highway Research Board,
 Record No. 238, (1968).

transport systems characteristics appear to be major determinants of travel choice. This is evident from the fact that cross-elasticities with respect to alternative mode costs and travel times are either insignificant or close to

zero. These results have important implications for policy issues. For instance, the elasticities of demand with respect to costs for transit trips are highly inelastic and no cross-elasticities appear. This indicates that a decrease in transit fares would not substantially increase ridership and would only add to transit revenue difficulties. On the other hand, it implies that a fare increase would increase revenues because it would cause a less than proportionate drop in ridership.

It must be noted that the data available for this study was not adequate for meeting model requirements. For instance, transit trips represented all non-auto trips since data on commuter rail, subway or bus trips was not available. R^2 values ranged from 0.35 to 0.63 which may be considered to be quite low. However it must be stressed that the concept of elasticity of demand used for interpreting results was quite novel.

4.3 Probabilistic Models

This group consists of studies which attempt to model the probability of making a transportation choice. It is hypothesized that the tripper selects that alternative which maximizes his utility, given his resource constraints usually time and money. Initially, the basic aim of research undertaken in this field was to measure the value of time or to derive tools for analysing consumer's decision about choice of mode. Thereafter, such models have been diversified to take account of all elements of travel choice wherein the

main thrust is to arrive at a more precise definition of utilities of alternatives available to the trip maker. These models are often referred to as choice-theoretic models.

Quarmby¹² developed a probabilistic model to explain the choice of mode by car owners. The model is expressed in terms of the disutility of alternative modes of travel. It is assumed that the decision to travel and the destination of the trip have already been made. There are a number of 'dimensions' of travel such as travel cost, travel time, etc., which yield disutility to the trip maker. Suppose there are 'k' such dimensions, 'h' modes and 'n' individuals. Let 'dp_{ij}' denote the measure of dimension 'p' (1 to k) for mode 'i' (1 to h) for person 'j' (1 to n). Let the contribution of this dimension to utility be given by 'λ_{p_{ij}}'. Then the disutility of the 'p'th dimension of mode 'i' to person 'j' is 'λ_{p_{ij}}.dp_{ij}' and the disutility of travel by mode 'i' for person 'j' is,

$$D_{ij} = \sum_{p=1}^k \lambda_{p_{ij}} \cdot dp_{ij}$$

The hypothesis is that the trip maker will choose that mode which has the minimum disutility. If we can reduce the choice to two modes, it may be better to compare relative disutilities rather than absolute disutilities because

12 Quarmby, D.A. "Choice of travel mode for journey to work," Journal of Transport Economics and Policy, Vol. 1 (1967).

people tend to perceive characteristics of modes, relative to one another. Therefore, for two modes relative disutility can be expressed as:

$$R_j = \sum_p \lambda_{p1j} \cdot fp(dp_{1j}, dp_{2j})$$

where 'fp' is some function of the dimensions of mode 1 and mode 2 that yield disutility to individual 'j'. A threshold level of relative disutility is then postulated, say ' R_j^T '. If $R_j < R_j^T$ then mode 1 will be chosen and if $R_j > R_j^T$ then mode 2 will be chosen. The model is calibrated using the technique of discriminant analysis in order to determine that set of weighting coefficients, ' λ 's that categorize ' R_j 's above and below ' R_j^T ' most accurately. Given relevant information on the dimensions for the horizon year, this set of ' λ 's could be used for predicting relative disutilities and the resulting modal split.

In this study, data relating to the city of Leeds was used for calibrating the model. Only two modes, private auto and public transport were considered. Overall travel time difference, cost difference, excess travel time difference and the possibility of using the car at work were found to be important in influencing modal choice. The following disutility function was estimated:

Related disutility of bus travel (= Z) =
 + 0.0556 (overall travel time difference in minutes)
 + 0.0966 (excess travel time difference in minutes)
 + 0.0911 (cost difference with 2 d a mile car cost)

- 0.535 (income in £ p.a. divided by 1000)
- 0.333 (car demand ratio = $\frac{\text{driving licences in the household}}{\text{number of cars in the household}}$)
- + 0.620 (use of car for work, either 3 or 0)
- + 0.323 (ownership of car by firm either 1 or 0)
- + 0.461 (constant term)

$$R = 53.2\%$$

Quarmby's approach throws light on the importance of conducting analysis at the disaggregate household level. However, it is restricted to the extent that only the modal choice stage is considered.

Choice-theoretic models¹³ of travel are concerned with the definition of the comparative utilities of alternatives as a basis for specifying the resulting choice. In this approach decision making by the individual is modelled by the use of probabilities of choice where these probabilities must conform to the following:

$$0 \leq p_k^i \leq 1 \text{ for all 'i' and 'k'}$$

and

$$\sum_{k=1}^{n_i} p_k^i = 1 \text{ for all 'i'.$$

where,

p_k^i = probability of individual 'i' choosing alternative 'k'

n_i = set of alternatives available to individual 'i'.

13 Adapted from Dalvi, Q. "Economic theories of travel choice," in Hensher, D.A. and Dalvi, Q. (ed.). *Determinants of Travel Choice* (1978).

Probabilities are assigned to alternatives on the basis of consideration by the trip maker of the travel environment modified by relevant characteristics of the individual.

Early attempts to develop choice-theoretic models were based on the assumption that alternatives available to a trip maker have an exact measurable utility, (strict utility model). However, the individual is uncertain about his choice even after assessing these utilities. The structure of the model is based on Luce's Axiom of Irrelevant Alternatives. This axiom essentially states that the probability of choosing an alternative 'a' over another alternative 'b', for an individual 'i' is independent of the absence or presence of other alternatives. Or,

$$\frac{p^i(a/a, b)}{p^i(b/a, b)} = \frac{p^i(a/a, b, c \dots)}{p^i(b/a, b, c \dots)}$$

where,

$p^i(a/a, b), p^i(b/a, b)$ = probability of choosing alternative 'a' and 'b' respectively, by individual 'i' given that the set of alternatives consists only of 'a' and 'b'

$p^i(a/a, b, c \dots),$
 $p^i(b/a, b, c \dots)$ = probability of choosing alternative 'a' or 'b' respectively, by individual 'i' given that the set of alternatives consists of a, b, c ...

Now, the ratio of probabilities is equal to the ratio of the utilities of the two alternatives. Or,

$$\frac{p^i(a/a, b)}{p^i(b/a, b)} = \frac{U(S_1, X_a)}{U(S_1, X_b)} \dots (1)$$

where,

S_i = attributes of individual 'i'

X_a, X_b = attributes of alternatives 'a' and 'b' respectively.

If a specific functional form is assumed for the utility function, such as,

$$U(S_i, X_a) = \exp[V(S_i, X_a)]$$

then (1) may be written as,

$$\frac{p^i(a/a, b)}{p^i(b/a, b)} = \frac{p_a^i}{p_b^i} = \frac{\exp[V(S_i, X_a)]}{\exp[V(S_i, X_b)]}$$

If 'a' and 'b' are the only alternatives available then,

$$p_a^i = \frac{\exp[V(S_i, X_a)]}{\exp[V(S_i, X_a)] + \exp[V(S_i, X_b)]}$$

$$p_b^i = \frac{\exp[V(S_i, X_b)]}{\exp[V(S_i, X_a)] + \exp[V(S_i, X_b)]}$$

If 'm' alternatives are available then the probability of choosing alternative 'j' from set 'm' is,

$$p_j^i = \frac{\exp[V(S_i, X_j)]}{\sum_{k=1}^m \exp[V(S_i, X_k)]}$$

Thus the choice-theoretic model takes the form of the familiar multinomial logit model.

Recent advances in choice-theoretic models tend to view utilities of alternatives differently. Termed as the 'random utility model', this approach postulates that the utility of an alternative to the individual consists of two parts: an observed component $U(S_i, X_j)$ and an unobserved component $E(S_i, X_j)$. The latter part includes the unobserved

tastes of the decision maker and other unobserved influences. Thus ' U_{ij} ' the utility of alternative ' j ' to individual ' i ' can be expressed as,

$$U_{ij} = U(S_i, X_j) + E(S_i, X_j) \quad \dots (2)$$

Since only part of these utilities are measurable, the utilities of alternatives are not certain but are random variables determined by a specific distribution. Thus the choice probability of alternative ' j ' is given as,

$$p_j^i = \text{Prob}[U_{ij} \geq U_{ik}] \quad \begin{array}{l} k = 1, 2, \dots, m \\ j \neq k \end{array} \quad \dots (3)$$

This expression basically means that the probability of choosing one alternative out of the complete set of possible alternatives equals the probability of the utility of that alternative being greater or equal to the utility of any of the other alternatives in the full range of alternatives. Substituting (2) in (3) we get,

$$p_j^i = \text{Prob}[U(S_i, X_j) + E(S_i, X_j) \geq U(S_i, X_k) + E(S_i, X_k)]$$

Rearranging the terms we get,

$$p_j^i = \text{Prob}[E(S_i, X_k) - E(S_i, X_j) \leq U(S_i, X_j) - U(S_i, X_k)]$$

This expression implies that the mathematical form of the choice model is determined from the assumption about the joint distribution of the random elements. If we assume that

$$U(S_i, X_j) = \exp[V(S_i, X_j)]$$

and the random elements, $E(S_i, X_k)$ are distributed according to a Weibull distribution, then the multinomial logit model

results.¹⁴

Ben-Akiva and Richards (1975) used a multinomial logit model based on the random utility approach for the estimation of travel demand in the Eindhoven area, Netherlands. In this study both a simple disaggregate conditional model, the mode choice model for work trips and a disaggregate simultaneous model, the shopping destination and mode-choice model were developed. Coefficients of the multinomial logit model were estimated by the maximum likelihood method.

Data relating to the year 1970 was used for the purpose of calibrating the model. The model appeared to simulate base year (1970) travel patterns quite satisfactorily.

The most significant results of this study may be summarized. Mode choice for work trips and for shopping trips seemed to be unaffected by travel costs. This implies that increase in fuel or parking costs, or increases or decreases in public transport fares, will have little impact on modal split. Car availability seemed to explain most of the choice of car as a mode and this seemed to increase in importance with the length of the trip. Further, terminal times, i.e. the time taken walking to or from a car, bus, train, etc., were found to be more burdensome to trip makers than in-vehicle travel times. An important conclusion reached was that the characteristics of the transport system or the

14 This is shown by McFadden in McFadden, D. "Conditional logit analysis of quantitative choice behaviour," in Zsarembka, P. (ed.). *Frontiers of Econometrics*. Academic Press (1973).

level of service variable is more important in the choice of destination and mode for shopping trips than it is in the choice of mode for work trips. This study is concluded by an important comment which may be quoted:

If meaningful predictions of travel demand are to be prepared, then much more attention must be given to the forecasting of socio-economic structure of communities. ...

McFadden and Domencich¹⁵ considered two models (within the choice theoretic framework) the work modal split model and the complete shopping demand model (choice of mode, time of the day of travel, shopping destination and frequency of travel) for the analysis of travel in the city of Pittsburg.

The basic data source were the home interview and network information available from the files of the South Western Pennsylvania Regional Planning Commission (SPRPC). Fieldwork was restricted to checking the existing SPRPC data and developing limited supplementary information, where needed.

Both linear probability models, estimated by ordinary least squares regression analysis and logit models estimated by maximum likelihood, were explored in the statistical estimation. Typically, the approach was to use regression analysis, because of its much lower computational costs, in the initial stages to explore alternative measures of a variable or

15 McFadden, D. and Domencich, T.A. Urban Travel Demand, A Behavioural Analysis. Charles River Associates (1975).

numerous alternative specifications of the model. Then, after reducing options by this explanatory analysis, the logit model was estimated for the important alternative specifications.

In spite of certain limitations of the data set the statistical results appeared to be quite encouraging.

The work modal choice models and the complete shopping demand model were of the form:

$$\log Q_i = \sum_{k=1}^k \beta_k \cdot Z^{ki}$$

where,

$\beta_1, \beta_2, \dots, \beta_k$ = unknown parameters

$Z^{1i}, Z^{2i}, \dots, Z^{ki}$ = socio-economic characteristics of individual 'i' and attributes of alternative under consideration

where,

$Q_i = P_i / (1 - P_i)$ = odds that Mr. 'i' will choose auto, and P_i is the probability of Mr. 'i' choosing auto.

Best results were obtained using logit models. Among the various alternatives that were tested, the following were found to be most satisfactory:

(i) The work modal choice model:

$$\begin{aligned} \log Q = & -4.76 + 0.147 \text{ TW} - 0.0411(\text{AIV} - \text{TSS}) - 2.24(\text{AC} - \text{F}) \\ & + 3.78 \text{ A/W} \end{aligned}$$

where,

TW = transit walk time (in minutes)

AIV = auto in-vehicle time, equals auto line-haul plus park and unpark time (in minutes)

TSS = transit station-to-station time, equals
transit line-haul plus wait and transfer
time (in minutes)

AC = auto parking charges plus vehicle operating
costs (in dollars)

F = transit fare (in dollars)

A/W = autos per worker in the household.

(ii) The shopping modal choice model:

$$\begin{aligned} \text{Log } Q = & -6.78 + 0.374 \text{ TW} - 0.0654(\text{AIV} - \text{TSS}) - 4.11(\text{AC} - \text{F}) \\ & + 2.24 \text{ A/W} \end{aligned}$$

The study emphasizes the need for a more sensitive characterization of the size, composition and socio-economic characteristics of the household which would go a long way in improving the results.

The choice-theoretic models discussed above are based on data at the disaggregate level and are hence not subject to the problems encountered by the aggregate models. However, data required by these models may not be easily available. Further, the method of estimation, namely, the maximum likelihood technique, is complicated and time consuming and hence costly to utilize. Again, the specific assumption about the distribution of random elements, $E(S_1, X_k)$ is quite restrictive.

Heggie¹⁶ claims that

¹⁶ Heggie, I.G. "Behavioural Dimensions of travel choice," in Hensher, D.A. and Dalvi, Q. (1978).

... There is no demonstration that the models are necessarily behaviourally sound, or that they are policy relevant. ... They merely characterize certain aspects of behaviour which are modelled as if it were a true and exhaustive statement of the relevant behaviour being modelled. ...

Recent advances in travel demand modelling based on economic theory have been highlighted in this chapter. It is pointed out that there is considerable scope for further research in this field especially regarding form of the demand function, creation of a reliable and highly disaggregated data base and development of the notion of dynamic transport demand models.

CHAPTER V

APPLICATION OF TRAVEL DEMAND MODELS IN THE INDIAN CONTEXT

5.1 Introduction

Rapid urbanisation and increased personalized transport vehicles are the root causes for the problems of urban transportation in the Indian cities. Added to this, the inadequate provision of road space and lack of road sense among the users complicated the problems. ... To solve and overcome problems like delays, accidents and provide safe, efficient and effective movements, a systematic action plan is an absolute must which requires comprehensive travel demand estimation. ... 1

Since the inception of planning in 1951, transport has been viewed as an important catalyst in furthering India's developmental efforts. Increasing amount of resources have been devoted to the transport sector for the fulfilment of this role. Public sector outlay on transport has increased from Rs. 434 crores in the First Plan to Rs. 22,971 crores in the Seventh Plan.

Despite these enormous outlays, the transport sector has been afflicted by a host of maladies. Bottlenecks and capacity shortages have resulted in all spheres. These

1 Raghavachari, S., Chandrasekhar, B.P. and Anjayenyulu, M.V.L.R. "Experiences in the calibration of trip distribution model for HUDA area," in Workshop papers, Workshop on Transportation Research, Indian Institute of Management, Ahmedabad (1987).

problems are even more apparent when we consider the urban areas. Spectacular growth of personalized vehicles, inefficient functioning of the public transport system, inadequate expansion of the road network in relation to growth of vehicular population, poor quality of roads and unplanned growth of activities over the area in general, has led to ever-growing congestion, steep increase in accident rates and pollution of all sorts.

Inability to overcome congestion and to remove obstacles to mobility threaten to make big cities economic liabilities rather than assets... it will raise the question whether the nation born in farms is destined to die in cities. ... 2/

One reason for this chaotic state of affairs is that few attempts have been made to formulate comprehensive plans on the basis of systematic forecasts of transport demand. For instance, the methodology used by the Planning Commission³ for this purpose, even today, is based on intuition and vague macro-economic analysis, resulting in forecasts at an aggregate level. No consideration is given to the spatial allocation of national supplies and demands which ought to form the basis of any meaningful transport planning. Further this exercise is restricted to the estimation of railway freight traffic demand alone.

² Patankar, P.G. Urban Mobility in Developing Countries, (1978).

³ Dalvi, M.Q. Transport planning model for India. UNDP, Transport Policy Planning Project, Planning Commission, (1982).

However, in the recent years, use of sophisticated techniques for travel demand forecasting, especially in the context of urban areas, is growing. We provide below a brief review of some of these studies.

5.2 Review of Transport Planning Studies in India

In the past two decades studies have been undertaken to examine the traffic and transportation scene in the urban areas.⁴ The ultimate aim of studies that have been undertaken to examine the traffic and transportation scene in the urban areas was to formulate long term plans on the basis of demand forecasts for solving ever-increasing problems of movement. In these studies forecasts have been made using aggregate sequential modelling techniques. For the purpose of trip generation analysis, trip ends have been estimated separately for home-based and non-home-based trips. While internal trips have been estimated using linear regression tools, intercity trip ends have been obtained on the basis of growth factor techniques. Trip distribution analysis has been mostly based on a simplified version of the gravity model for internal trips and growth factor techniques for intercity trip interchanges. In all the studies modal split analysis was carried out after the trip distribution stage. However, the diversion curve

⁴ Mahajan, B.M. has presented a fairly exhaustive review of eight urban transport planning studies in India, in a paper presented at National Symposium on Transportation Studies, Indian Institute of Technology, New Delhi, (1981).

technique was used only in one study and a regression based modal split model in another while in the others, either modal split for the base year was assumed to be invariant over the plan period or the method was not elaborated. At the traffic assignment stage, traffic flows were assigned to minimum travel time paths on an 'all-or-nothing' basis. It is felt that these studies would have been more realistic if analysis was pursued at the household level and the concept of 'generalized cost' was incorporated in the deterrence function. Further, results could have been improved by using better calibration techniques while estimating zonal trip interchanges using the gravity model.

Gangopadhyay et al (1986)⁵ carried out a study of taxi travel characteristics in Greater Bombay. Because of the growing magnitude of taxi travel in Bombay, the main objective of the study was to assess the load of taxis on the existing road network and to determine the future taxi travel demand for the year 2001 through suitable mathematical models.

The study area was restricted to Bombay island and suburbs. Trip ends were estimated on the basis of regression techniques. It was observed that taxi trips per person decrease as distance from CBD increases. Accordingly, the following relationship was estimated by the least square method:

5 Gangopadhyay, S., Khemchand, Mukhopadhyay, D., and Sarna, A.C. "Taxi Travel Characteristics - A Study for Greater Bombay," Journal, Indian Roads Congress, Vol. 47, No. 3 (1986).

$$Y = (1.259)X^{-1.80}$$

where,

$$Y = \text{trips per person} \left(= \frac{\text{Trip ends (zone)}}{\text{Population (zone)}} \right)$$

X = travel time of the zone from the CBD.

Trip ends were distributed on the basis of a doubly constrained gravity model given by:

$$T_{ij} = R_i \cdot C_j \cdot P_i \cdot A_j \cdot F_{ij}$$

where,

$$F_{ij} = \exp[-A(t.t.)_{ij}] \cdot (t.t.)_{ij}^{-B}$$

where,

$(t.t.)_{ij}$ = travel time between zones 'i' and 'j'.

The values of 'A' and 'B' were calibrated through an iterative procedure until base year observed and synthesized trip length frequency curves closely approximated one another. These curves are presented in Figure 21.

Future trip ends were estimated by obtaining future population levels from the local authorities and by assuming that existing travel times between the CBD and the zones will be reduced by half in the horizon year. Future trip ends were distributed by the gravity model calibrated using base year data.

Raghavachari et al (1987)⁶ developed and calibrated a doubly constrained gravity model for estimating trip interchanges in the Hyderabad Urban Development Authority

⁶ Raghavachari, S., Chandrashekhar, B.P. and Anjayenyulu, M.V.L.R. (1987).

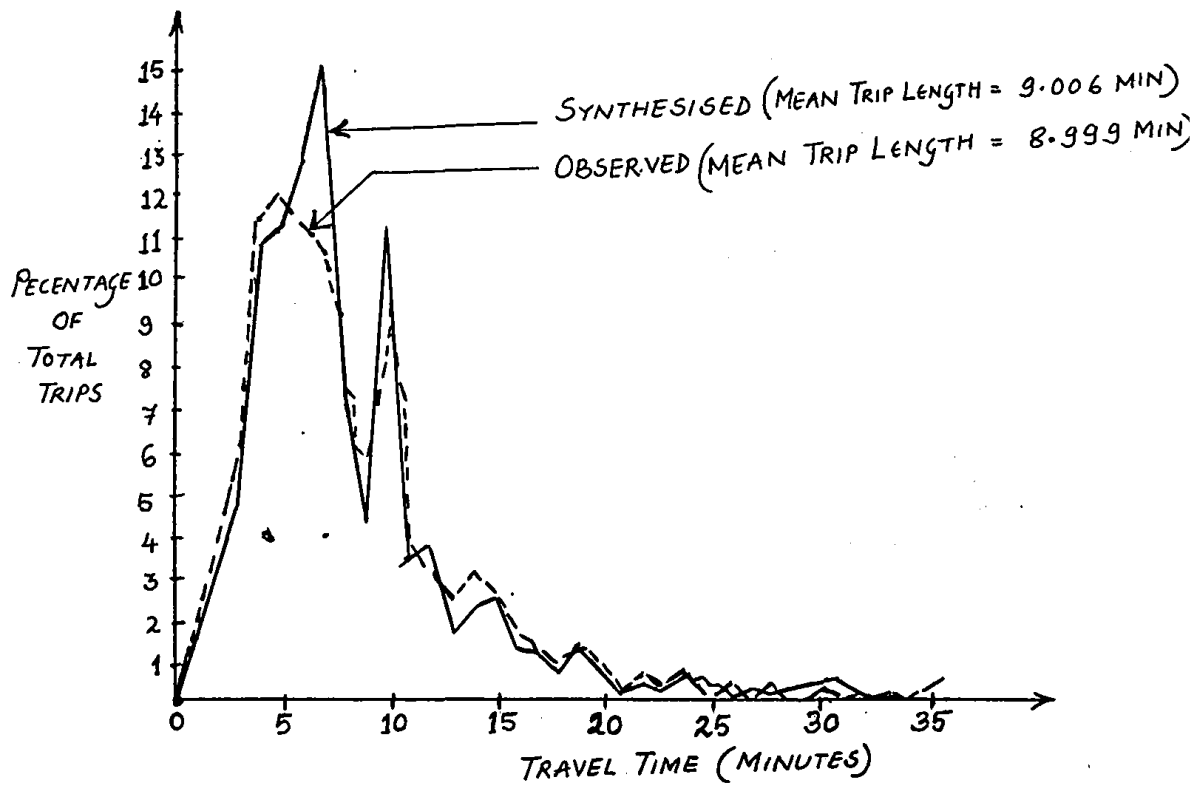


Figure 21 : Taxi Travel Characteristics: Greater Bombay, Trip Length Frequency Distribution

Source : Gangopadhyay, S., Khemchand, Mukhopadhyay, D. and Sarna, A.C. "Taxi Travel Characteristics - A Study for Greater Bombay," Journal, Indian Roads Congress, Vol. 47, No. 3, (1986).

area. For the purpose of data collection, a home interview survey was conducted in addition to information obtained from Hyderabad Area Transportation Study Progress Reports.

The gravity model used may be illustrated as:

$$T_{ij} = R_i \cdot C_j \cdot P_i \cdot A_j \cdot F_{ij} \cdot K_{ij}$$

The calibration procedure involved trying out five travel time factor functions such that base year trip length frequency distribution could be approximated as closely as possible. The following travel time factor functions were selected as the best for each of the trip purposes:

i) Home-based work trips:

$$F_{ij} = \left[\frac{81.8}{(t.t.)_{ij}} \right] \cdot \exp[-0.039 \cdot (t.t.)_{ij}]$$

ii) Home-based education trips:

$$F_{ij} = \left[\frac{36.0}{(t.t.)_{ij}} \right] \cdot \exp[-0.028 \cdot (t.t.)_{ij}]$$

iii) Home-based other trips:

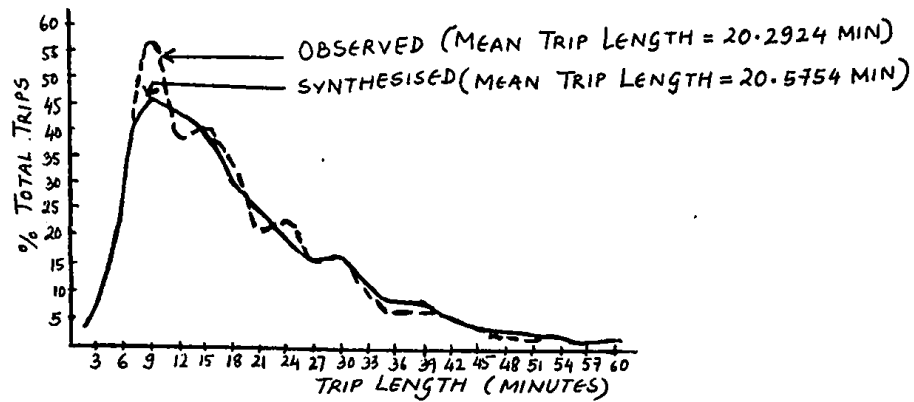
$$F_{ij} = (C_{ij}^{0.00008}) \cdot \exp[-0.107 \cdot (CC_{ij})]$$

where,⁷

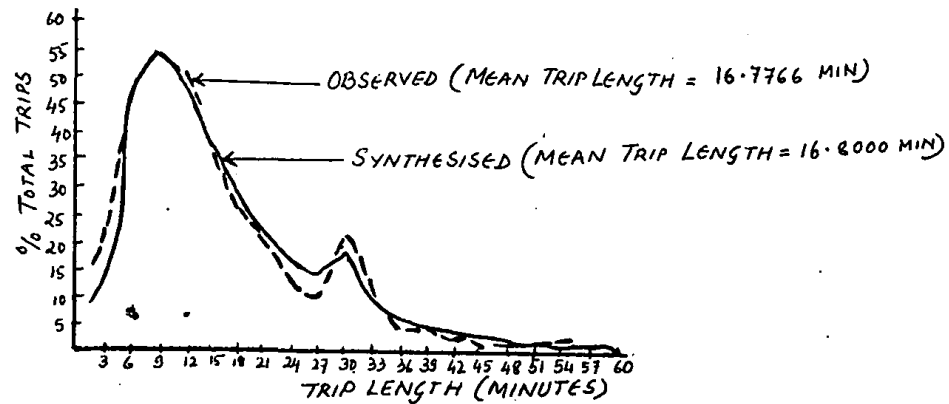
$$\begin{aligned} C_{ij} &= (t.t.)_{ij} + 3 && \text{for } (t.t.)_{ij} \leq 12 \\ &= (t.t.)_{ij} && \text{for } (t.t.)_{ij} > 12 \\ CC_{ij} &= (t.t.)_{ij} - 5 && \text{for } (t.t.)_{ij} \leq 12 \\ &= (t.t.)_{ij} && \text{for } (t.t.)_{ij} > 12 \end{aligned}$$

The trip length frequency distribution based on observed and

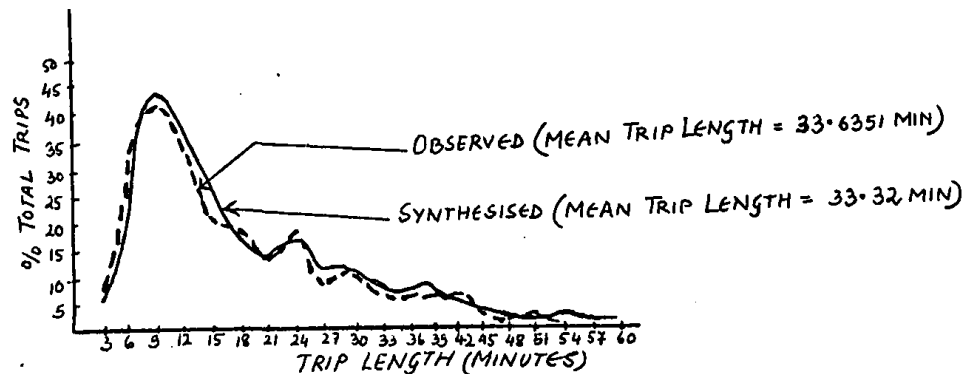
⁷ In the case of home-based other trips modelling is done by stratifying travel time into intervals viz. 1-12 and 12-160 minutes as this gave good reproduction of trip length frequencies.



HOME-BASED WORK TRIPS



HOME-BASED EDUCATION TRIPS



HOME-BASED OTHER TRIPS

Figure 22 : Trip Length Frequency Distribution (by Purpose) for HUDA Study Area

Source : Raghavachari, S., Chandrashekar, B.P. and Anjayenyulu, M.V.L.R. "Experiences in the Calibration of Trip Distribution Model for HUDA Area," in Workshop Papers, Workshop on Transport Research, Indian Institute of Management, Ahmedabad (1987).

synthesized trip interchanges for each trip purpose is given in Figure 22.

An interregional transportation study for the Bombay metropolitan region was carried out by Sarna et al (1986)⁸ to determine present and future passenger traffic flow by road and rail between different parts of Bombay on the one hand and adjacent areas on the other. This study was of special significance since the spill-over growth of industries in peripheral areas of Bombay Metropolitan Region like Tarapur and Roha, apart from Vapi, Surat, Baroda, Pune and Nasik, was likely to have a cascading effect on interregional travel.

Forecast^s were obtained by using growth factors incorporating past trends and prospective possibilities in future. For instance, a growth rate of 7.5 per cent per annum was assumed for road based interregional passenger trips and 5 per cent per annum for railway passenger trips. This study indicated that road based passenger trips are likely to increase by 4.9 times and that of rail by 2.9 times in 2001.

Another intercity trip generation model was developed by Thamizharasan and Rengaraju (1986)⁹ for conducting bus-

⁸ Sarna, A.C., Shetty, P.S., Bhatia, N.L. and Mukherjee, D. "Interregional passenger transportation study in Bombay Metropolitan Region," in Satsangi, P.S. and Agarwal, A.L. (ed.) Transportation Systems Analysis and Policy Studies, (1986).

⁹ Thamizharasan, V. and Rengaraju, V.R. "A methodology of approach for intercity travel demand modelling," Indian Roads Congress, Vol. 14, No. 12 (1986).

passenger travel demand analysis for the city of Madras. A model for average daily bus-passenger trips originating at Madras urban area and finding their destination at different cities and towns in Tamil Nadu State was developed based on demographic, socio-economic factors and travel resistance between city pairs. Linear models were formulated using stepwise regression analysis and the most appropriate one was selected on the basis of statistical significance. Data for the base year (1985) was obtained from the census records and by conducting traffic surveys. The final form of the model may be given:

$$T_{Mj} = 837.86 + 0.01052 X_{1j} - 0.03463 X_{2j} - 1.806 X_{3j}$$

where,

T_{Mj} = number of bus passenger trips per day from Madras (M) to urban centre 'j'

X_{1j} = number of households in urban centre 'j'

X_{2j} = agricultural population of urban centre 'j'

X_{3j} = distance of urban centre 'j' from Madras.

The signs for X_{1j} and X_{3j} were found to be logical. While, the negative sign for X_{2j} was explained by indicating that the agricultural population in Tamil Nadu consists of small farmers whose economic condition is quite poor. Thus, the agricultural population of any part of the State is an index of poor economic condition tending to reduce total intercity travel.

Kumar and Khanna (1986)¹⁰ have used a multinomial logit model for analysing mode choice behaviour of trip makers in two urban city pairs, namely, Deoband-Saharanpur and Hardwar-Saharanpur areas (Uttar Pradesh).

In this study only two modes rail and road were considered. Door-to-door travel times and out-of-pocket costs were considered to be the only relevant variables affecting mode choice. The general form of the logit model used is given as:

$$P_{ij} = \frac{e^{V_{ij}}}{\sum_j e^{V_{ij}}}$$

$$V_{ij} = a_0 + \sum_p a_p \cdot x_{ijp}$$

where,

- P_{ij} = probability that i th traveller will select mode ' j '
- V_{ij} = utility (disutility) or choice function. This is the generalized cost of mode ' j ' as perceived by i th traveller.
- x_{ijp} = values of p th attribute of mode ' j ' as perceived by i th traveller
- a_0 = constant term
- a_p = vector of generic parameters associated with system attributes.

The final form of the choice function was:

¹⁰ Kumar, V. and Khanna, S.K. "Integrated Inter-Urban Travel Demand Estimation with Policy Implications," in Satsangi, P.S. and Agarwal, A.L. (ed.). Transportation Systems Analysis and Policy Studies (1986).

$$V_{ij} = a_1 x_{ijt} + a_2 x_{ijc}$$

where,

x_{ijc} = total out-of-pocket costs for individual 'i' by mode 'j'

x_{ijt} = total travel time for individual 'i' by mode 'j'

a_1, a_2 = parameters.

The model was calibrated using the maximum likelihood technique.

Banerjee and Satsangi (1986)¹¹ have discussed the possibility of using an integrated land use-transport model for forecasting transportation demand. This model is based on the Leontief-Strout framework of input-output economics. Data relating to the city of Delhi, for the year 1969, has been resorted to for calibrating the model parameters.

This chapter gives a general idea of the trend of transport demand forecasting studies being pursued in India. It appears that, by and large, these models are based on simple techniques such as regression or growth factor methods. It is useful to note that the Planning Commission is attempting to formulate a comprehensive national transport plan based on more advanced techniques incorporating the spatial aspect into the exercise.¹² However the lack of an adequate

11 Banerjee, D. and Satsangi, P.S. "Integrated Land Use-Transport Forecasting Models: A Case Study of Delhi Urban Area," in Satsangi, P.S. and Agarwal, A.L. (ed.). *Transportation Systems Analysis and Policy Studies*, (1986).

12 Dalvi, M.Q., (1982).

data base is proving to be a major obstacle in these attempts. It is only to be expected that the nature of this problem is all the more formidable in the case of individual researchers pursuing work in this area.

CHAPTER VI

CONCLUSION

It is widely recognized that model building and forecasting are crucial phases of the transport planning process, since an ex ante assessment of the quantum and pattern of movement is extremely important for minimizing misallocation of valuable resources. It is against this background that an attempt has been made, in this thesis, to review some of the important travel demand models, that have been developed in the past few decades with a view to highlighting the more desirable aspects of these models as well as their weaknesses.

To begin with, the analytical transport planning process was conceptualized as a series of models, namely, trip generation, trip distribution, modal split and traffic assignment. These models have been severely criticized for lacking the requisite theoretical framework and for being unrealistic in depicting the tripper's decision-making process when confronted with innumerable travel alternatives. However, despite these shortcomings, these models have much to offer in practice and are widely used, even today, for making forecasts for a period of 15-20 years.

Transport related land use models were developed to examine the interrelationship between land use patterns and the associated travel demands within an integrated framework.

However, these models have been found to be insufficient in the sense that these have merely provided inputs to the sequential modelling exercise. Attempts to incorporate the simultaneity involved in the relationship between land use patterns and the transport network have been far too theoretical and ambitious to form the basis for any concrete plan.

Economic demand models were the outcome of attempts to provide a sound behavioural grounding to travel demand models. These have been tested only in a limited way mainly due to the non-availability of the requisite data and partly due to complexities in estimation. Moreover, critics have questioned the very purpose for which these models were developed.⁴ It is pointed out that the theoretical framework of these models is behaviourally naive and that the mathematical equations do not satisfactorily describe the characteristics of travel behaviour.

Though developments in the sphere of travel demand forecasting have been remarkable, further work needs to be undertaken in a number of crucial areas. More attention needs to be given to the form of the demand function. Specifically, it would be useful to examine in greater detail the manner in which attribute variables enter the model as well as the socio-economic theory that underlies the generation of travel. Further, creation of a reliable and highly disaggregated data base preferably with information at the household level could go a long way in improving model results especially in the context of economic demand models.

This is of special significance for our country, wherein scanty data resources has been a recurring problem. It is also apparent that,

... Future developments may have to turn aside from the usual scientific paradigm and move in the direction of using actual individuals, or groups of them, as a substitute for the normal optimisation rules that are held to capture the essential ingredients of human behaviour ... may thus have to become less mathematical and more human if they are to give realistic insights into the manner in which individuals arrange their various activities in both time and space. ... 1/

¹ Stopher, P., Meyburg, A.H. and Borg, W., in Bruton, M. (1985).

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