UNIVERSITY OF MANITOBA

MODELS OF RESIDENTIAL LOCATION DISTRIBUTION AND LAND DEVELOPMENT PROPOSALS

by

SATISH CHANDRA SHARMA

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MODELS OF RESIDENTIAL LOCATION DISTRIBUTION AND LAND DEVELOPMENT PROPOSALS

BY

SATISH CHANDRA SHARMA

A dissertation submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

DOCTOR OF PHILOSOPHY

For my wife,

Maya Sharma

ABSTRACT

Three different types of models, viz., the competing opportunities model, the intervening opportunities model, and the gravity model, are developed and tested with a view to predicting the residential location distribution of workers in relation to their places of work within the framework of a specific community. Even though, for the purpose of this study, communities in the City of Winnipeg are investigated, the approaches advanced for the models can be used to predict residential location distribution, leading to an assessment of the traffic generated from various land development proposals in other urban areas.

An important feature of the study is that it includes socioeconomic factors, such as income and occupational status of the workers, for the analysis of their choice of a residential location in the city. The parameters of the models developed in this thesis clearly indicate that, in general, workers with high socioeconomic status tend to live farther away from jobs as compared to workers with low socioeconomic status. This may occur because the distance or travel time to work is less of a constraint in their choice of household location for the workers of high socioeconomic status. Another feature of the study is that the models make use of standard census data to predict the behavioural choice of residential location, instead of expensive and time-consuming data collection procedures (such as origin-destination surveys).

The analysis carried out for this study demonstrates that the existing calibration procedure for the competing opportunities model may not adequately simulate trip making or the behavioural choice of residential location in urban areas. A new calibration procedure, as introduced

in this study, can considerably enhance the predictive ability of the competing opportunities model. The new procedure includes an additional step for improving the accuracy of prediction of the dependent variable for the study zones within the first time band. In this step, the total number of residential locations (or trips) predicted for the first time band are redistributed among the residential districts (or destination zones) within the first time band by applying the competing opportunities model. The repeated application of the concept of competing opportunities model confined only to the residential districts within the first time band of the previous stage of application of the model is termed a 'nested model' for redistribution of residential locations.

This thesis also contributes to a better understanding of the intervening opportunities model of spatial distribution. It is evident from the results of this study and several other studies in the past that this model, with a constant (or single) probability parameter, usually known as the L-value, cannot, in most cases, accurately reproduce actual trip (or residential location) distribution. An improvement in the predictive ability results when a variable L-value, instead of a constant one, is utilized in the model. The variation of L appears to depend on the hypothesis that the probability of a destination being accepted, if it is considered, is a function of the number of destinations which have already been considered. This probability is assumed constant in the hypothesis of the original model, independent of the order in which destinations are considered.

The gravity model, using the inverse power distribution function can successfully simulate the residential location preferences of differ-

ent socioeconomic groups of workers in the City of Winnipeg. It is also believed that simple distribution functions, such as the inverse power and the negative exponential, can provide satisfactory results for other medium and small urban areas.

The findings of this study, together with the future research as suggested in this thesis, will contribute to the better understanding of the spatial distribution of different activities in the urban areas. Such an understanding will not only help in the selection of sites for new land development proposals in the existing infrastructure of an urban area, but also assist in decision making in the context of regional planning around urban areas.

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a,b,c	Parameters of variable probability function of the intervening opportunities model
α,β	Parameters of gravity model distribution function
β^v,μ^v	Calibration parameters for employees of income group v in Wilson's model
A_f	$\equiv 1-\exp(-L\Sigma D_j)$ Adjustment factor
A_i,B_j	Normalization factors in gravity model
B	Budget constraint
C	$\equiv \sum_i C_i T_i$, total resources (cost spent in transportation within the system)
C_i	Travel cost between residential district i and the employment centre
C_{ij},F_{ij}	Journey-to-work cost between zones i and j
C'_{ij}	That component of the generalized journey-to-work cost which is the actual money paid
CHS	Members of population participating in both subpopulations H and S
COM	Competing opportunities model
CNRY	Canadian National Railway Yard
d	Parameter in the Golding and Davidson Model of intervening opportunities
d_i	Number of suitable housing opportunities for a type of workers in residential district i

D	Number of Opportunities considered
D_{j-1}	Trip (or residential) destinations considered before reaching opportunity band j
D_j	D_{j-1} + Residential (or trip) destinations in opportunity band j
$\bar{D}$	A vector containing the number of trip attractions in each destination zone
$D_., D_m$	Total study area destinations
$f(D)$	Cumulative Probability function of Golding and Davidson model
F	Function which expresses the effect that spatial separation exerts upon trip interchange
$F(t_i)$	Distribution function; travel time factor function; Impedence function
FGIP	Fort Garry Industrial Park
G	Lagrangian function
H, S	Subpopulations of a universe of population N
IIP	Inkster Industrial Park
k	Type of house
K	Factor incorporating the effect of socioeconomic status of trip makers on the travel patterns
L	Constant probability parameter of intervening opportunities model
L_d	Variable probability parameter of intervening opportunities model
m	Total number of opportunity bands in the study area

MC_i	$\equiv \frac{dC_i}{dt_i}$ Marginal perceived cost of travel between residential district i and the employment centre
n	Total number of residential districts in the study area
N	A universe of population
NEST	Nested competing opportunities model
O, O_i	Total number of trip origins (or residential locations to be distributed) at the zone of origin under consideration
$\bar{O}$	A vector containing the number of trip generations in each origin zone
p_i	Preference function, a function expressing the intrinsic preference of residential location seekers in district i
p(r)	Price per unit of housing service as a function of distance, r of its location from CBD
P_j	Probability of a household destination being accepted in residential district (or opportunity band) j
P'_i	Conditional probability of residential district R_i being accepted for a household location
P(D)	Probability that a trip will terminate by the time D possible destinations are considered
q	Quantity of housing services purchased
q_p	Percentage of income (after the deduction of transport costs) that an employee spends on housing
r	Distance of a household's location from CBD
R_i	Residential district i

R^2	Coefficient of determination
S	The deviation between the observed and predicted residential locations
t_i	Travel time between residential district i and the employment centre
T	The household's expenditure on transportation
T_i	Number of workers who reside in district i
T_j	Predicted number of destinations that will be sought in opportunity band j
(T)	A matrix containing the number of trips from each origin zone to each destination zone
$\hat{T}_i$ or $\hat{T}_j$	Observed number of destinations in residential district i or opportunity band j, respectively
T_{ij}	Trip (or home-work) interation between zones i and j
U	Utility function
W	Uniform width of time bands of competing opportunities model, minutes
W_1	First time-band width of competing opportunities model, minutes
v	Income level of residential location seeker
w	Uniform width of time subbands of nested model, minutes
w_1	First time-subband width of nested model, minutes
x	Household's expenditure on all other commodities except transportation
X	Fraction of the opportunities already considered for a suitable destination
y	Income of household

CHAPTER I

INTRODUCTION

1.1 Prologue

Land is used intensively in urban areas for a variety of activities. The people of the city house themselves in structures ranging from apartments to large single-family homes; they work in places ranging from small office structures to factory lofts to large suburban industrial parks. Transportation facilities in the city, including highways and streets, provide links not only between the residential and employment activities but also between schools, shopping centres, recreational parks and other socioeconomic activities. If an urban system is to function efficiently, its transportation system must be capable of moving people and goods from place to place in a socially acceptable and economically feasible manner.

During the past two decades a substantial amount of work has been done towards the development of an understanding of the relationship between various kinds of land development in the urban areas and the demands for movement which they generate. To forecast future traffic volumes, the earliest urban transportation studies simply multiplied existing traffic volumes by a growth factor. The inadequacy of such a technique soon became clear, mainly from observation of the wide variations in growth rates within the metropolitan areas, and transportation planners began to search for improved methods. The planners thought of directly relating urban traffic to land use. They recognized that the number of trips originating in, or destined for, each part of the region depended on the amount and kind of activity (land use) located there. This concept became the basis of the land use and transportation planning method that has been employed in all recent studies being conducted with an overall view to developing the most efficient arrangement of city services for the citizens.

Kashuba (1974) writes on the importance of residential models:

> Obviously, if the planner could accurately predict residential preferences, he could go on to determine the most efficient arrangement of city services for such a population.

The author supports the belief that urban residential location distribution models are a vital aspect of land use and transportation planning.

1.2 The Research Problem

Travel Demand of the New Development

From time to time, in urban areas, there are proposals to develop available vacant land for nonresidential purposes, such as industrial parks, hospitals, shopping centres and recreational parks. Such developments in any urban region are bound to generate new traffic and affect the existing commuter travel pattern. In particular, the establishment of a large activity centre in medium or small urban areas can cause severe imbalances in the supply and demand relationship of the existing transportation system. In situations of this nature, alterations in the existing transportation facilities might be required to accommodate the new travel demand. The extent of changes required in the facilities, or in other words, the social cost to the environs (or to the city) will depend on the location of the development, because the transportation system is not utilized uniformly throughout the urban regions. An optimum location of the development will obviously be the one corresponding to the minimum social cost to the environs. A transportation planner requires a procedure which he can use to predict the extra travel demand on the network associated with the new development which may lead to an assessment of the social cost to the community.

A Critique of the Conventional Transportation Planning Approach

The conventional urban transportation planning process begins with analysis of the present transportation system. A most probable pattern of land development is predicted for the horizon year (usually 15-20 years ahead) and transport demands created by that land use are estimated. A set of alternative transport plans is generated to accommodate the projected demand for the horizon year.

There are numerous shortcomings associated with the conventional approach of urban transportation planning. These shortcomings are exhaustively reported by Domencich and McFadden (1975), Brand (1972), Stopher and Lisco (1970). Therefore, no attempt is made to enumerate and discuss them at full length here. Instead the discussion that follows includes only those shortcomings which relate to the central theme of the thesis.

Land use forecasting of the urban region in a typical transportation planning study depends on the judgment of planning experts who are supposedly well versed in the economic, social, and political characteristics of the region. Forecasts with such judgmental input often lack in reproducibility by other planning or research teams. Since the forecasts cannot easily take into account the multitude of possible combinations of land use and transportation alternatives, the selected transportation system must necessarily be generated based on a limited number of possible land use plans. This, together with the lack of reproducibility of plans by different planners, may create situations where a specific land development proposal is not included in the land use plan or is not even contemplated at the time of study. For urban areas for which a land use/transportation plan exists, or for areas with no such formal plan, a suitable approach is required to deal with a new development proposal.

It is conceded that area-wide land use studies with a large time scale (usually 15-20 years) utilizing the computerized models, such as the Lowry model (Lowry, 1964) are relevant. It is also desirable to focus on specific locations in a short-to-medium time scale. In the words of Bayliss (1977):

> Ideally transportation planners want models which can, at the very extreme, be operated in a rapid and coarse fashion for sketch planning purposes yet are capable of being increased in resolving power and comprehension to deal with a particular area or aspect of policy. Similarly it is desirable to be able to portray intermediate periods between the base year and the +20-year horizon. There are no major theoretical obstacles to the solution of these problems yet little has been done in this area.

It can also be stated that the linear four-stage modelling procedure of generation and attraction/distribution/modal split/assignment is inadequate for analyzing the impact of a new land development proposal that was not contemplated at the time of land use forecasting. If we consider an example of a new industrial park, the traffic generated from it will be in the form of work trips. The trip distribution model as developed in the four-stage modelling procedure is not adequate to distribute the work trips or residential locations of workers in reference to the industrial park, because the trip distribution model is a part of the simulation package of urban transportation study in which the study area is divided into small traffic zones, with each zone being considered as an imaginary traveller whose trips are generated, attracted and distributed according to some mathematical relationship. When such a simulation model is calibrated, it is the aggregate behaviour of the simulated trip that is brought close to the actual aggregate travel behaviour. The associated trip length frequency distributions are assumed to be constant for each zone of the study area. Researchers have shown that this assumption is not valid and that significant variations occur throughout the urban areas (Edens, 1970).

Another weakness of the approach is that the monetary and time costs associated with the home-interview surveys for the comprehensive urban transportation studies are so high that they often cannot be economically justified for many medium and small urban areas (Hajj, 1971; Zaryouni and Kennel, 1976). Also, the level of accuracy of such surveys is frequently so low that the interzonal trip forecasts based upon them may not be reliable (Lang, 1974). This is why planning analysts now seek to model travel demands by using other data sources, such as standard census statistics.

The preceding arguments suggest that more effort is needed to investigate the interaction between the land use and transportation systems of the urban region while incorporating the use of data sources such as standard statistics. The central theme of this research is to develop partial and disaggregated models which may be used to assess the impact of the land use changes on the transportation network of an urban system.

Boundaries of Research

This study focuses on the effect of the location of a proposed industrial park on its workers' residential distribution within an urban area. The study assumes an urban area with an established distribution of workers' residences and work places. It further assumes that there is no excessive increase or decrease in the number of workers due to high in or out migration, either before or after the proposed site is established as a planned unit,* that the industrial park consists of numerous firms, most of which have been relocated from other areas of the city, with a few relocating from outside the city limits, as well as a few newly established industries. The introduction of this industrial park is bound to affect the existing commuter travel pattern and probably cause an imbalance in the supply and demand relationship of transportation facilities of the urban system. The questions generated are: What could happen to the system in terms of workers' residential distribution? Will workers whose jobs are directly affected by the new industrial park move to enhance accessibility to the new job or will they remain at their present address and choose to travel the extra distance? Will they choose to seek a new job near at hand? Will the location decisions be affected by the socioeconomic characteristics of the workers? The most important question is: Can the residential location distribution of the workers be predicted using the available spatial distribution models, and if not,

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* The term "planned unit" implies a single large firm or a large number of smaller, scattered firms. The restriction placed on scattered firms is that they must all be established within a few years of one another and all must be located in a relatively compact area of the city, so that a common centroid can be used in the road network to denote a focal point of traffic generation.

what improvements can be made in these models to make them more suitable for the purpose of workers' residential location distribution? Which is the best model for the prediction of residential location choice behaviour? If a model is adequate for predicting the residential pattern of those working at a particular industrial park, is it also adequate for any similar park or employment centre? These are the questions which serve as a guide in establishing boundaries for the structuring of this thesis.

In particular, this study concentrates on developing and testing three different types of models, viz., the competing opportunities model, the intervening opportunities model, and the gravity model, with a view to predicting the residential location distribution of workers in relation to their place of work. The residential location models to be developed here differ mainly in two ways from the usual application of the above models for the trip distribution in urban areas. Firstly, the residential models of this study reverse the frame of reference, in that they still seek to distribute the trips, but from an employment centre towards the residential districts with their socioeconomic characteristics. Secondly, instead of including numerous origins and destinations, only one employment centre is considered as the trip generator, with residential districts as its numerous destinations. The trips are generated from the employment centre in the form of work trips. It is assumed in this study that the distribution of work trips is the same as the distribution of residential locations of workers in relation to their workplace. A further assumption is that the distribution will be helpful in predicting the extra travel demand due to the new development proposal. Indeed, a direction is indicated in Chapter VII as to how this residential distribution could be used towards this purpose.

The residential models of this study are disaggregated by socio-economic status of workers. Also, these models are partial because they focus only on a specific location, the proposed site of an employment centre.

The residential models are made a function of access to the work-place. The importance of the work trip for locating the household was first hypothesized by Kain (1961). The Lowry model (Lowry, 1964) perhaps the most popular land use model, utilizes access to workplace as a determinant of residential location. The proposed location of an employment centre is considered to have an organizing effect on the choice of residential location by its workers similar to the Lowry model, in which the residential pattern is made a function of the basic employment in the urban region.

Even though, for the purpose of this study, communities in the City of Winnipeg are investigated, the approaches advanced for the models can be used to predict the residential location distribution, leading to an assessment of the traffic generated from various land development proposals in other urban areas.

Research Objectives

The following are the specific objectives of this research project:

1. to investigate the possibility of using census data sources for the estimation of traffic generated from the new land development proposals in the form of residential distribution.

2. to develop and test the partial and disaggregated models of residential location distribution using the approaches of (i) the competing opportunities model, (ii) the intervening opportunities model, and (iii) the gravity model, in the following steps:
   a) to test the adequacy of the existing model for the purpose of modelling the residential distribution of workers in relation to their employment centre,
   b) to refine the basic hypothesis or its calibration procedure if the existing model is not particularly adequate for the residential distribution,
   c) to test the refined models using samples of other industrial parks,
3. to investigate the effect of socioeconomic status of workers on their residential location choice,
4. to make a comparative evaluation of the above three modelling approaches.

CHAPTER II

REVIEW OF LITERATURE

2.1 Introduction

During the past two decades, a wealth of literature has developed relating to the theory and models to describe, explain or predict the patterns of land use and transportation in urban areas. Models are simplified representations of real processes, and mostly focus on illuminating a relatively narrow spectrum of interrelated events. Due to the multiplicity of interrelated events in urban areas, a variety of transportation models is reflected in the literature. It is not attempted in this review to give an exhaustive description of existing land use and transportation planning models. Instead, attention is focused on the models of residential location in urban areas, which are directly related to the central theme of this thesis.

2.2 The Origin and an Overview of Residential Models

The pioneer developments in land use modelling for the purpose of more systematic planning and better forecasting came almost exclusively from the United States. Increasing car ownership during the 1940s and early 1950s led to the growing realization that cities with their traditional physical form could not simply cope with the new mobility. Planners and engineers started to seek the understanding and solution of traffic congestion and, by the late 1950s, the rudiments of the transportation planning process had been established. The early transportation studies did not encompass land use forecasting. The interrelationship between traffic and land use was a subject of much practical and academic debate during these years and the pioneering work of Mitchell and Rapkin (1954) in their book Urban Traffic: A Function of Land Use did much to convince engineers and planners of the need for integrated land use and transportation planning.

The immediate success in operational and academic areas of transportation planning and modelling led those concerned to begin to think about the possibility of building land use models, and by 1960 several land use models were in use. These earliest models were used mainly for the prediction of population (households or families) distribution. The CATS (Chicago Area Transportation Study) density-saturation gradient model was felt to embody some of the most advanced techniques available during that period. Naive, Stouffer's intervening opportunities, and accessibility models are other examples of the earliest land use models. A good description of all these models is given by Kashuba (1974). As a sample, however, the CATS density-saturation gradient model is discussed briefly in the following section of this chapter.

Another tradition apart from transportation planning had an effect upon land use (or residential) modelling in the 1960's research activity in urban and location economics. A series of theoretical models of urban structure were developed at this time. The intra-urban location model designed by Wingo (1961), and a similar but slightly more theoretically oriented economic model proposed by Alonso (1960) established an economic theory for urban systems, comparable to existing theories of economic location in regional systems. Muth (1968) used the general structure of Alonso's and Wingo's theory and developed a model of urban residential land and housing markets. Another attempt by economists (Herbert and Stevens, 1969) was "A Model for the distribution of residential activity in urban areas". The Muth and Herbert-Stevens models are briefly discussed in the sample description of residential models in Section 2.3.

A landmark analysis of the relationships of the journey to work and housing consumption and location by Kain (1961) had a profound influence on the development of residential models in the early 1960s. Kain persistently aimed for direct empirical testing and modelling of the theories of urban housing markets using information on the behaviour of individual households and his work led to the design of the NBER (National Bureau of Economic Research, New York) urban simulation model. A more detailed description of Kain's work is included below.

Conventional and well-established linear statistical techniques were also used as a basis for several residential models, in particular the Multiple Regression Model of the Traffic Research Corporation (Kashuba, 1974), and the Empiric model of the Boston Region (Hill, 1965). Both of these models are well explained by Kashuba (1974) and are therefore not described at length in this chapter.

"A Model of Metropolis" by Lowry (1964), perhaps the most successful of all land use models, particularly the large scale models, was originally calibrated for Pittsburgh. Its great popularity resulted in many extensions to the model and its successors have embellished its structure substantially. The Lowry model and its successors use journey-to-work as a criterion and employ the gravity modelling approach. A more detailed description of the Lowry family of models is given at a later stage in this chapter.

When one first encounters the land use models, their similarity to trip distribution is striking. It was due to this similarity that Lathrop and Hamburg (1965) presented Schneider's formulation of trip distribution (Schneider, 1960) as an opportunity-accessibility model for allocating population growth. Since the intervening opportunities approach is of main interest in this study, the Schneider model and its revised forms due to Golding and Davidson (1970) are presented in considerable detail at a later stage of this thesis. Another trip distribution formulation which has been tried for the purpose of residential location is the competing opportunities model proposed by Tomazinis (1962). This model is also of main interest in this study and therefore is dealt with in considerable detail.

2.3 A Sample Review of Residential Models

"It is only a slight exaggeration to claim that most existing land use models are no more than models of residential location or population distribution" (Brown et al., 1972). The author has concentrated only on those models and ideas which provide good insight for modelling the residential-choice behaviour of individuals in the urban market. There are some excellent sources of information on land use models and particular reference may be made to Batty (1976), Kain (1975), Franklin (1974), Lee (1973), Brown et al. (1972), Kashuba (1974), Harris (1968), and Lowry (1968), who have provided useful summaries and interpretations of the most important facets of the North American and European experience.

As indicated in Section 2.2, an appropriate sample of residential (or land use) models for this review would appear to consist of the following models:

1. The CATS land use model;
2. Muth's model of "urban residential land and housing markets";
3. Herbert-Stevens model for the "distribution of residential activity in urban areas";
4. "The journey to work as a determinant of residential location", the analysis of Kain;
5. The Lowry model and its extensions;
6. The NBER urban simulation model;
7. The Schneider model of intervening opportunities;
8. The Tomazinis model of competing opportunities.

Certain points need to be made before describing the above models. Firstly, some of the above listed models are described at a greater length than the others simply on the basis of their relative importance to this study. Secondly, Kain's empirical work on journey to work has been reinforced by some other models of commuting. Finally, Schneider's intervening opportunities model and Tomazinis's competing opportunities model are not included under this section. Instead, the models are appropriately reviewed in Chapters 4 and 5, respectively, at the point of the development and testing of these models for the purpose of residential distribution of workers of large employment centres in Winnipeg, the sample city of this study.

The CATS Land Use Model

The Chicago Area Transportation Study used the "density-saturation gradient" model for forecasting 1980 land use in that study area, (Hamburg and Creighton, 1959). Of the models included in this sample review, it is the earliest known. It had a less formal structure than its successors, and ad hoc judgments were introduced at many points in the forecasting process.

In simple terms, urban structure and growth in this model were viewed in the following way (Kashuba, 1974).

(1) The more accessible a site, the higher its cost per unit of area.

(2) The site will be built on as intensely as necessary to offset the high per unit area cost.

(3) Assuming no physical barriers the CBD (Central Business District) is the most accessible place in an urban area.

(4) Competing forces exist of need to be accessible and ability to pay that result in regular and gradual declines in intensity of use about the CBD.

(5) As more land becomes increasingly accessible, the supply more nearly equals demand, resulting in a decrease in initial site cost; which, in turn, reduces the need to develop the site intensely.

(6) Developed sites resist change in accessibility and sometimes they may even force new means of transportation to serve them, even at high cost, in order to maintain this accessibility and, hence, value.

The observed patterns of population and worker (employment) densities provided evidence for the above theory for the Chicago area. There was a systematic decline in the densities as distance from the CBD increased (Figs. 2.1 and 2.2). These observed regular declines in densities for 1956 served as the base for the estimation of population density and worker density for 1980.

The model was built around a strong system of land use accounting for small areas (or zones) of the study area. For each such zone in turn, the future estimates of land uses were extrapolated from the initial

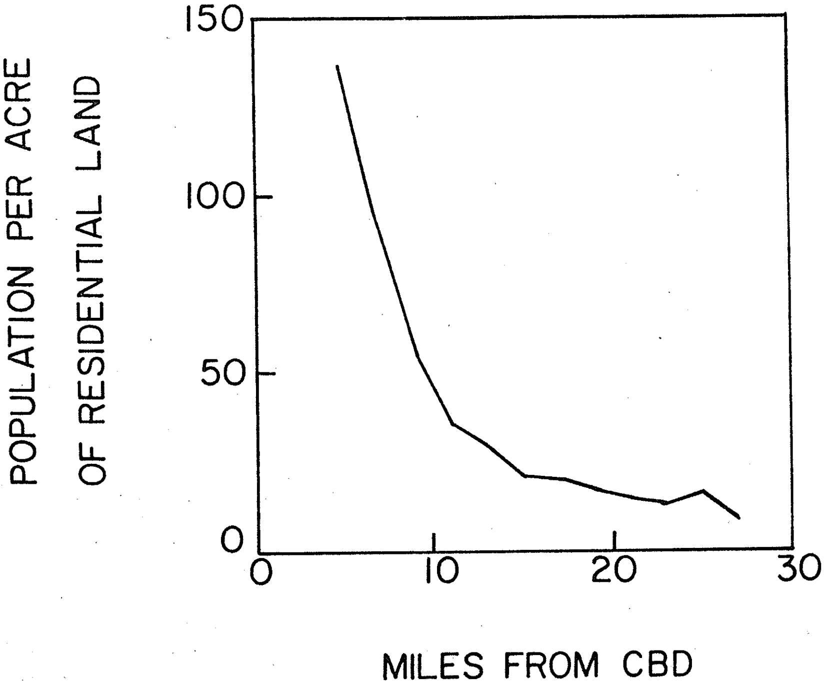

Fig.2.1 Population Densities by Distance From the CBD, Chicago Area, 1956.(Hamburg and Creighton, 1959)

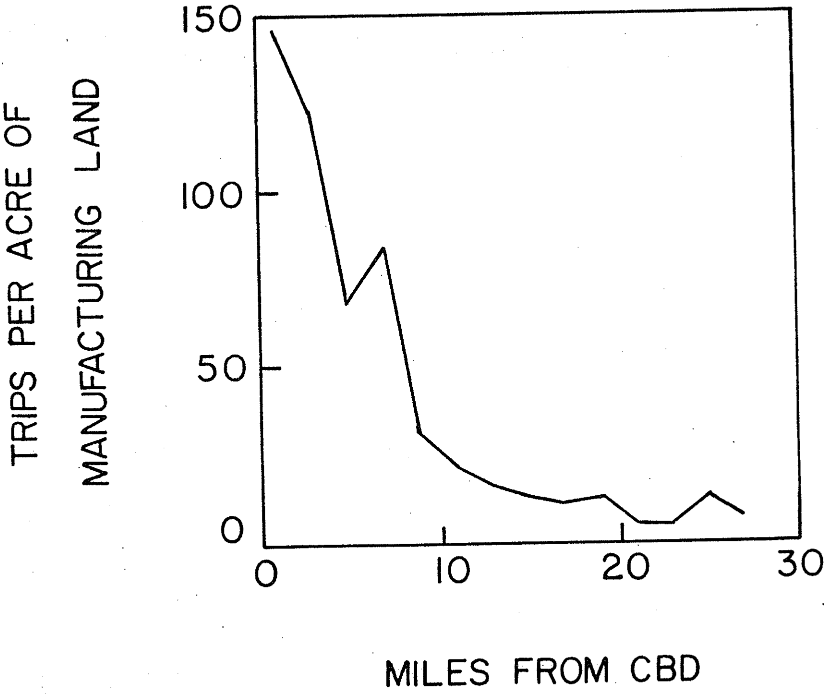

Fig. 2.2 Manufacturing Worker Densities by Distance From CBD, Chicago Area,1956.(Hamburg and Creighton,1959)

patterns according to norms (modified by judgment) specific to a kind of use. Different types of land use were recognized: residential, commercial, manufacturing, transportation, public buildings, public open space, etc. Vacant land was classified as residential, commercial, or industrial, according to its status under local zoning ordinances.

The procedure of land use forecasting for the 1980s as carried out by the CATS may be summarized in the following simple steps (Lowry, 1968):

1. Specific parcels of land in some zones were designated for conversion to public open space and transportation uses (e.g., a new airport). The designations were based primarily on existing plans of public agencies for such developments.

2. Commercially zoned vacant land in some zones was designated for shopping centres and heavy commercial uses. These designations were based on announced private plans and staff judgements.

3. Residentially zoned vacant land was designated for residential use. The amount of such a designation depended on the location of the zone and its residential holding capacity at existing or slightly modified net densities. The percentage of a zone's capacity to be filled by 1980 was defined as a function of distance from the CBD, with sectoral and local modifications based on staff judgments.

4. For residentially oriented uses, per capita norms were applied to the estimated 1980 population of each zone as determined in the third step. Thus space for street's, local commercial facilities, public buildings, and recreation was set aside in each zone.

5. Industrially zoned vacant land was designated for manufacturing use. The amount so designated in each zone depended on the location of the district and its manufacturing holding capacity. Trends in net employment density in manufacturing establishments, both over time and by distance from the CBD, served as the basis for 1980 forecasts of such employment density for each zone; this projected

> density, in conjunction with the amount of industrially zoned space, determined the zone's holding capacity. The percentage of this capacity to be filled by 1980 was defined as a function of distance from the CBD, with sector and local modifications based on staff judgments.

The CATS approach of land use forecasting has been criticized for several reasons. First, the procedure is not objective and it is necessary to use subjective judgments. Second, the process is not completely amenable to machine processing; every time a subjective evaluation is required, the machine is useless until the evaluation is made. Third, the model theory places too much emphasis on the import of accessibility and ignores factors such as skills and services that may be responsible for a district's value. Another criticism of the model is that it avoids systematic comparisons of zones with respect to their merits as locations for establishments belonging to a given activity group; such comparisons are either highly generalized (distance from CBD) or else embedded in undocumented staff judgments.

Muth's Model of "Urban Residential Land and Housing Markets"

The general structure of Muth's model is similar to the models of residential location choice created by Alonso (1964) and Wingo (1961). What primarily distinguishes Muth's model is the completeness with which it is developed using the utility-maximizing approach. As a preliminary step to a description of the salient features of this model, it is worthwhile to dwell briefly on the utility-maximizing approach.

Consider a household with utility function $U = U(x,q)$, where q is the quantity of housing services purchased, and x is its expenditure on all other commodities except transportation. The household is subject to the budget constraints.

$$B = x + p(r)q + T(r,y) - y \leq 0 \tag{2.1}$$

where p, the price per unit of housing service, and T, the household's expenditure on transportation, are functions of the distance, r, of its location from the CBD. T is assumed to include the value of time spent in travel and therefore is made a function of money income, y. T is defined to include the money value of travel and leisure time. Differentiating the Lagrangian function $G = U - \psi (B)$, where ψ is the undetermined multiplier, with respect to x and q, yields the following well-known proposition (Muth, 1968): to maximize its utility, the household consumes housing and all other commodities in such proportions that the marginal utility per dollar spent is the same for both. Differentiating with respect to r, one finds:

$$\frac{dp}{dr} q = - \frac{dT}{dr} \quad \text{or} \quad \left(\frac{-dp/dr}{p}\right) = \left(\frac{dT/dr}{pq}\right) \tag{2.2}$$

The first form of Eq. 2.2 states that at its equilibrium location the marginal cost of purchasing space at r is equal to the marginal savings in transportation cost. Figure 2.3 illustrates the condition stated in Eq. 2.2.

The city depicted in Muth's model is a theoretical city in which all jobs are located in a sort of CBD. Households within this city choose a residential location and a quantity of housing services which maximize their utility in a manner described earlier. There are several important implications of the model for metropolitan structure. First, due to a positive marginal transport expenditure with respect to distance, Eq. 2.2 implies that the price per unit of housing services must decline with distance. Second, under reasonable assumptions, Muth's model implies that more wealthy households will choose to live at greater distances from the centre of the city. Savings in housing expenditures depend not only on reductions in the price per unit of housing services, but also on the quantity of housing the household desires to consume. More wealthy households consume greater quantities of housing than do poorer ones, so that the potential savings on housing resulting from unit price difference are greater for wealthy households. This effect is partially offset by the fact that transportation cost will be greater for

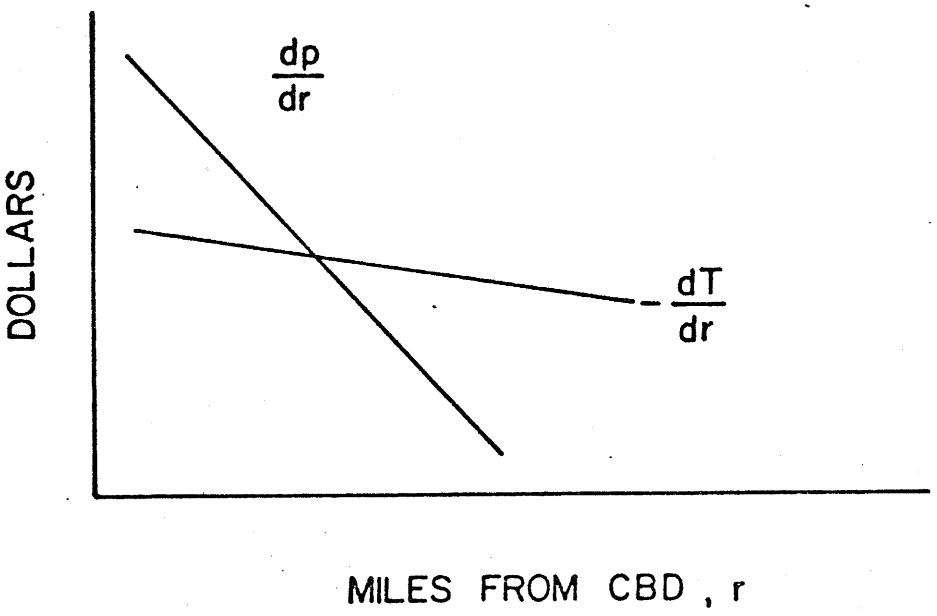

Fig. 2.3 Functions of Marginal Costs of Space and Marginal Cost of Transportation.

wealthy households to commute for increased distances, but according to Muth, reasonable empirical estimates of the relationships of income and housing expenditure and travel costs suggest that the former should be more powerful. On the basis of a decrease in housing price with distance, Muth demonstrates that the density of residential land use should diminish with distance from the CBD.

Another important feature of the model is that "by specifying the relationships controlling the supply of urban land, the housing production function, transport costs, and a number of other aspects of urban areas, Muth is able to account for the origin of slums, the likely effects of housing allowance schemes on urban housing and land prices, the likely impact of secular improvements in urban transportation systems on aggregate land rents and urban density, and a wide range of other facets of urban housing markets" (Franklin, 1974).

The assumptions of monocentricity and uniformity of utility between individuals are the main limitations of Muth's model (as well as other theoretical models). Such assumptions will have to be relaxed for designing realistic residential location models. Although there have been empirical tests concerning the form of the density and rent functions on strongly monocentric cities such as Chicago, the models based on classical approaches can never be operational in the sense in which discrete urban models are operational. Indeed, it can be argued that the purpose of the classical approach is to provide insight into certain basic conditions which must be represented in any operational model if it is to be at all relevant (Batty, 1976).

The Herbert-Stevens Model

Herbert and Stevens (1960) proposed "A Model for the Distribution of Residential Activity in Urban Areas" originally to simulate the locational behaviour of different household types in the Penn-Jersey Transportation study. The model did not succeed in its role and was therefore abandoned by the study. However, the failure of this model was considered as instructive since its success might have been mainly because it demonstrated the potential usefulness of linear programming for the analysis of locational activities.

The Herbert-Stevens model of residential location was based on the economic theory that individual households tend to maximize their local advantage, and at the same time land was allocated to that group of households which could pay the highest price for it. The equilibrium location of households based on maximization of satisfaction was generated within the constraints posed by their budgets. Linear programming techniques were used to translate this process into an operational form.

Though this model was proved difficult to calibrate and is probably one of the models that requires the greatest amount of data, there is little doubt that the model builders gained good insight into the mechanisms of the urban development (Reif, 1973).

"The Journey to Work as a Determinant of Residential Location"; The Analysis by Kain

In the year 1961, John F. Kain completed his Ph.D. dissertation entitled "The Journey to Work as a Determinant of Residential Location". Kain's analysis (Kain, 1961) focused on the residential location choices of a sample of working persons in the Detroit region in 1953. He divided the region into six concentric distance rings around the central business district. Each individual in the sample was identified by the workplace ring of the person, the residence ring of the person and by race, sex, family size, income, occupation and the type of housing structure the person inhabited. The work-trip patterns of different types of workers employed in the same ring, and of similar workers employed in different rings were compared.

The central hypothesis as suggested by Kain's analysis was that "households substitute journey-to-work expenditures for site expenditures and this substitution depends primarily on household preferences for low density as opposed to high density residential services". The term site expenditures in the hypothesis refers to the transportation cost of obtaining residentially oriented services within the immediate residential area, i.e., groceries, elementary school, etc., and of obtaining other services available only outside the residential area.

Kain postulated that residential land rents, and thus housing costs, decline with distance from the CBD, but at a decreasing rate: i.e., the rent curve becomes flatter at greater distances from the CBD. Such an assumption implies that the dominant work-trip patterns should be from centrally located work-place rings to more peripheral zones, and that the strength of this dominance should diminish as the work-place becomes more distant from the city centre. In addition, the assumption implies that greater consumption of housing and residential space farther away from the CBD enhances the absolute savings in housing expenditure which accrue to a household as a result of variation in the price per unit of housing and space. So long as transportation costs do not in-

increase commensurately, greater housing consumption means longer work-trips for centrally employed households; this implies that a greater proportion of workers with high incomes, large families, or large housing preferences will choose to live in peripheral zones.

Kain presented evidence for each of the above implications. Fig. 2.4 is taken from his analysis to show the proportion of high-, medium-, and low-income CBD (Detroit) workers residing in each residential ring. Clearly low-income workers have the least dispersed residential pattern; the high-income workers, the most dispersed.

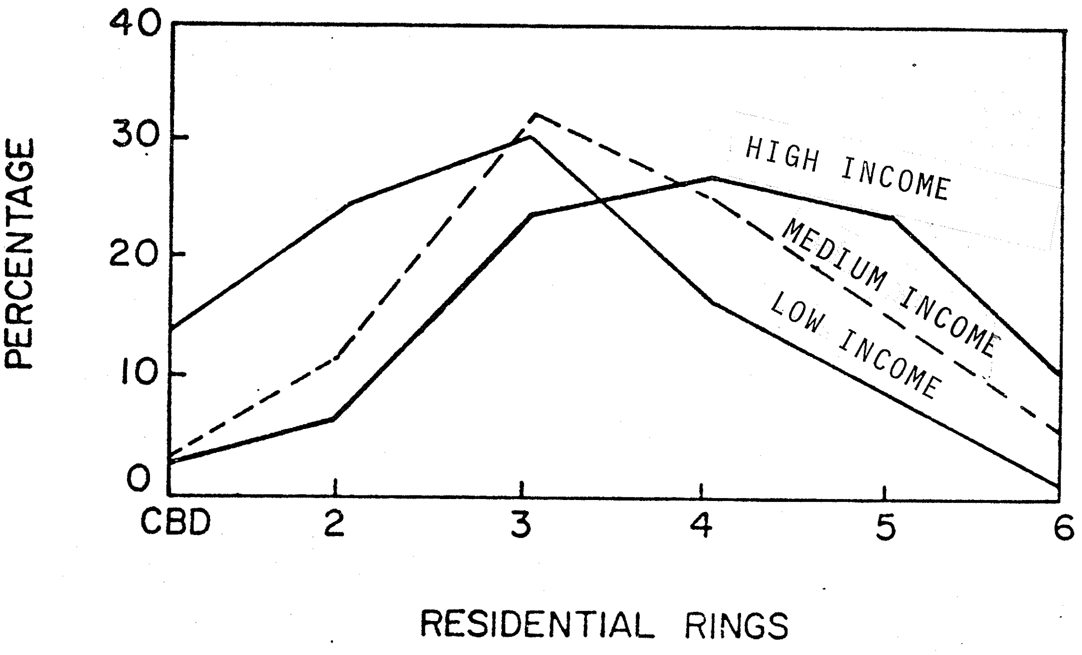

Fig.2.4 Proportion of CBD's Low, Medium, and High Income Workers Residing in Each Residential Ring. (Kain, 1961)

Kain also found that the work-trip patterns of

> ...nonwhites, who because of housing market segregation are unable to compete freely in the market for residential space as we have defined, are exactly the opposite. The longest trips by Detroit nonwhites are made by those employed in outer rings and the shortest by those employed in inner rings.

The findings of Kain's study support the importance of the journey to work for residential location. It is therefore useful to include a description of past studies which relate to the separation of home and work-places. The following is a presentation of some of the main studies on this subject.

Models of Commuting

There have been many studies on the subject of separation of home and work-place in urban areas. A detailed description of these studies would appear to be beyond the scope of this thesis. Therefore, it is intended here to highlight only some of the more important studies which have generated the hypotheses regarding the separation of home and work.

The object of early studies on the subject was to minimize the distance between home and work in order to reduce the consumption of transportation resources, such as tires, metals, gasoline, and construction materials which were in critical shortages because of the second world war (Mouchahoir, 1970). However, the results of some of these studies were used later by several people for planning purposes.

Carroll (1949) used data from a survey of war production plants in Massachusetts in his doctoral dissertation about the journey between home and work-place. This thesis was considered as the first major study to approach the problem from a broad view. In his findings, Carroll hypothesized that the separation of home and work-place was the key to understanding the physical structure and form of urban regions. He found that families tended to locate their homes as close as possible to the work-place of the head of the household. The reason for this tendency was sought in the general behaviour theory of human activities, which holds that people try to minimize work or effort wherever possible. Carroll also showed that the distance between home and work-place was directly related to the population of urban areas.

Beyer (1951) studied the effects of social and economic variables on the separation of home and work-place. He noted that the families which lived far from their place of work had higher incomes and were younger than those which lived nearer to their place of work. Beyer also mentioned that those who lived farther had better education and their homes had larger lots.

Voorhees (1961) found in his investigation that the work-trip length was proportionally related to changes in the population of metropolitan areas and was a direct function of family income. Voorhees also showed that there was a certain amount of statistical nonrandomness in home and work separation which could be simulated.

Catanese (1969), for his doctoral dissertation, studied in detail the separation of home and work-place. He stated that

> Family income dominates as a socioeconomic force. Such other variables as education, age, occupation, status and race are more related to income than to home-work distance.... The knowledge of family income associations provides sufficient and necessary conditions for explanation and prediction. This becomes quite meaningful, in a cost reduction sense, for analysis. In fact, through analytical study, it is possible to use family income to

> generate other socioeconomic variables. This would substantially reduce the costs of data collection and processing.

The Lowry Model and Its Extensions

The Lowry model was developed by Ira S. Lowry in 1962-63 as part of a modelling system to generate alternatives and decision-making in the Pittsburgh Comprehensive Renewal Program (CRP). The object of this model, as stated by Lowry (1964) was:

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

The model has a very well-defined structure. Batty (1970) referring to this model remarks:

> The Lowry Model is the most complete for it is extremely well documented and it is one of the simplest models to construct in terms of its data requirements.

The urban spatial structure in the model is seen as comprising three broad sectors of activities; (i) a basic employment sector which includes those industries whose locations are assumed to be unconstrained by local circumstances of population distribution, market areas, etc., (ii) employment in population-serving industries, which covers all those activities dependent directly on local resident population and purchasing power, and (iii) the household or population sector, which consists of the resident population, on which sector (ii) depends and which itself depends on the total employment level (both (i) and (ii)) available.

The interactions between the three major sectors that take place in the Lowry model system can be considered to be of the following three types:

(1) Between employees and residences;

(2) Between households and services;

(3) Between employees and services.

With the Lowry model, the spatial distribution and level of the basic employment activity is supposed to be known. The model derives the number of dwelling units and the level of services required which are allocated to zones of the system; that is, the model allocates households and population-serving employment. The allocations are subject to constraints on the maximum number of households and the minimum population-serving employment for each zone in the study area.

The Residential Allocation Function

The conceptual elements of the model and its mathematical structure are very well documented by the originator (Lowry, 1964) of the model itself and many others (Batty, 1976; Hutchinson, 1974). Therefore, a formal presentation of the model structure is not given here. Only the residential distribution element of the model, which is directly related to the theme of this thesis, is described.

The distribution of residential location is considered to be influenced by the location of employment opportunities and the journey to work is a criterion of locational choice. The model makes use of the following mathematical relationship for the purpose of arranging population around work-places:

$$T_{ij} = \frac{O_i \; D_j \; F_{ij}}{\sum_j D_j \; F_{ij}} \qquad (2.3)$$

where T_{ij} = the number of zone i employees who live in zone j

O_i = the total number of employees who work in zone i

D_j = a measure of the attractivity of zone j for household location

F_{ij} = the travel-cost factor between zones i and j which reflects the manner in which the spatial separation of zones influences the residential location choices of employees

Eq. 2.3 is a gravity-type interaction model. The factor F_{ij} has several alternative functional forms, some of which are described at a latter stage in the thesis.

The distribution of population-serving employment is dependent upon the population distribution and is carried out by using the gravity-type approach analogous to the residential distribution. The coupling of two submodels (i.e., the residential and the service employment) together through different calibration procedures is exemplified in the literature (Batty, 1976; Hutchinson, 1974).

The original Lowry model and even some of its successors (such as the Garin-Lowry model) assume in their analysis that the spatial distribution of activities in the horizon year has reached an equilibrium condition. In other words, these models have no time dimension, and they generate what is called as "an instant metropolis". Several researchers in the past have suggested a number of dynamic extensions of the Lowry model. Crecine (1964, 1968, 1969) has attempted to develop Time-Oriented Metropolitan Model (TOMM) to turn the simple static Lowry model into a more complex dynamic model by specific consideration of system behaviour. The first version of TOMM attempted to model changes in the stock of activity over five-year time intervals using the same mechanisms as in the Lowry model. In the second version, TOMM II, a more realistic formulation of the measure of locational attraction, incorporating site rent, amenity and transport costs, was provided, although the simulation procedure remained similar to that used in the Lowry model. TOMM III, which is still under development (Batty, 1976) concentrates on questions of dynamics and mover behaviour in the model. A time interval of two years is now being used in the model.

Rogers (1966), and Echenique (1969) have also contributed towards the dimension of time in the Lowry model. Hutchinson (1974) presents a convenient formulation of the model based largely on Echenique's work.

With regard to the operationality of TOMM (first version), Lee (1968) reports that "a trickle of resources have gone into the model in the past few years, but not enough to make the model usable". A similar criticism will perhaps hold good to TOMM II, TOMM III, and the Echenique formulation.

Wilson's Disaggregated Residential Location Model

The original Lowry model incorporated very little behavioural content on the part of the household. The behavioural (or microeconomic) component in residential location choice based on spatial interaction was introduced by Alan G. Wilson of the Centre for Environmental Studies in London. In a remarkable paper, Wilson (1969) proposed a residential location model in which the focus was upon distributing persons earning income v to housing type k, rather than allocating persons to housing in a particular zone. Using his own entropy-maximizing approach (Wilson, 1967), Wilson derived a residential allocation model of the following type (Hutchinson, 1974):

$$T_{ij}^{kv} = A_i^k B_j^v O_i^k D_j^v \exp(-\beta^v C_{ij}) \exp\{-\mu^v [p_i^k - q_p^v (v - c'_{ij})]^2\} \qquad (2.4)$$

where

T_{ij}^{kv} = the number of workers who live in zone i in house type k and who work in zone j earning wage v

O_i^k = the number of houses of type k in zone i

D_j^v = number of jobs in zone j offering wage v

β^v, μ^v = model calibration parameters for employees of income group v

C_{ij} = journey-to-work cost between zones i and j

P_i^k = the price of type k houses in zone i

q_p^v = the average percentage of income (after the deduction of transport costs) that an employee of income group v spends on housing

c'_{ij} = that component of the generalized journey-to-work cost c_{ij} which is the actual money paid

$$A_i^k = \frac{1}{\sum\limits_{j}\sum\limits_{v} B_j^v E_j^v \exp(-\beta^v c_{ij}) \exp\{-\mu^v [p_i^k - q_p^v (v - c'_{ij})]^2\}} \qquad (2.5)$$

$$B_j^v = \frac{1}{\sum\limits_{i}\sum\limits_{v} A_i^k H_i^k \exp(-\beta^v c_{ij}) \exp\{-\mu^v [p_i^k - q_p^v (v - c'_{ij})]^2\}} \qquad (2.6)$$

The distribution of residential location in Eq. 2.4 is influenced by what Wilson calls the "budget term": $\exp\{-\mu^{v}[p_{i}^{k}-q_{p}^{v}(v-c'_{ij})]^{2}\}$. This term suggests that the average person balances his budget with regard to what is available to him as his income and how much he spends for housing, transportation, and a composite of all other goods, but that there are individuals who expend more or less than their available resources (Batty, 1976). The distribution around this average is assumed to be normal with a mean value of zero.

Another type of disaggregation of residential location models by Wilson (1974) relates to partitioning the residential locations on the basis of four contrasting behavioural patterns. These reflect the behaviour of workers who are:

(1) locationally unconstrained, seeking both work-place and residence;
(2) constrained to fixed residences, seeking work-place only;
(3) constrained to fixed jobs, seeking residence only;
(4) constrained to fixed residences and fixed jobs, seeking neither residence nor job.

Wilson's formulation of the residential location model (Eq. 2.4-2.6) and an inclusion of disaggregation of workers on the basis of the above four contrasting behavioural patterns has obviously a tremendous appetite for data. Wilson has himself noted: "The data problems associated with calibrating a model of this type are clearly immense. However, they are not intractable: on the one hand, the development of this type of model should encourage the collection of the appropriate data; on the other hand, even in the short run, proxy variables can be constructed for indices such as house type".

There is no doubt that Wilson's work on disaggregation has added enormously to the elegance, comprehensiveness, and sophisitication of the Lowry model. Unfortunately most of this work has been theoretical in nature without much practical implementation. The main problem is perhaps the additional requirement for data with any increase in the sophistication of the model. Despite this, the model is becoming more and more popular among other available large scale land use models. It may also be noted here that this model has been more popular in countries outside the United States, the country of its origin (Hutchinson, 1974). Some applications of the model are being made in Canada (Hutchinson, 1976), as well.

The NBER Urban Simulation Model

Two major approaches to representing patterns of urban spatial development and residential location had emerged by the late 1960s. First, a number of analytical models of urban structure arrived which tended to be deeply rooted in the microeconomic theory and usually their formulation was highly abstract and exceedingly elegant. Such theoretical models were very much lacking from the operational point of view. Second, numerous simulation models emerged which were usually formulated as computer algorithms, representing a particular city, and had little or no theoretical content. The NBER (National Bureau of Economic Research, New York), initiated the development of an urban simulation model incorporating the theoretical approach of traditional analytical models of residential location and urban spatial structure into a framework with more realistic and less restrictive assumptions (Ingram and Kain, 1974).

The structure of the NBER model can be considered a direct outgrowth of the analysis by Herbert and Stevens (1960) of the usefulness of linear programming for the determination of land rent surfaces within urban areas, and empirical analysis discussed earlier by Kain and others of the relationships of the work-trip and housing consumption and location (Franklin, 1974). The NBER model is believed to be innovative in several respects. First, the NBER model relaxes the monocentric assumption of the analytical models and explicitly incorporates multiple work-places. Second, the NBER model represents the standing stock of physical capital and the processes of adjustment of the supply side and thus abandons the long-run equilibrium framework used in the analytical models. A third important characteristic of the model is the representation of interactions among decision-makers in the housing market. The model includes the consideration of neighbourhood quality as a dimension of the housing bundle.

The NBER model like others, is not free from criticisms. A more famous critique is from Lee (1973) who asserts that the NBER model represents "more of the same", in the sense that the model is very complex, has an enormous appetite for data, and its internal complexity makes its comprehension and criticism difficult.

2.4 Summary and Comments

It is obvious from the review of residential models that an extensive variety of approaches have been utilized involving a diverse selection of techniques ranging from linear regression and gravity modelling to mathematical programming. Emphasis on theory has ranged from the pragmatic to pure.

Although a great deal has been learned from the modelling experience in the past, there have been many disappointments with previous land use models. Reactions to the relative failure of these models differ quite widely. For example, Lee (1973) considers the experience to have been a salutary warning of the dangers of technocracy whereas Ingram, Kain, and Ginn (1972) regard the modelling attempts as vindicating the view that modelling is a large complex affair, which requires far more resources than have been available in the past or are even now available. Whether such reactions are true or not, it is worthwhile to identify the main shortcomings of land use models of the past.

In 1974, Bouchard, reporting to a conference of the United States Highway Research Board, identified six shortcomings of the existing techniques for the prediction of travel demand.

(1) The models are too time-consuming and too expensive to operate.

(2) The models fail, in many ways, to examine all relevant points in decision-making process.

(3) Too much thought is given to the models and too little to the things which are really important in the selection of planning strategies.

(4) The models are geared too much to the 1990, or 20-year situation, when in fact transportation problems are now and projects are now.

(5) The technicians themselves do not always understand the models.

(6) The models are too data-hungry.

All these criticisms were undoubtedly just for the land use models which existed at the time of the conference. In this author's view, the situation in more recent years has not improved significantly. Nevertheless, there is growing concern at present to build models in the light of the above shortcomings of the traditional models.

There has recently been a spate of literature suggesting disaggregate, behavioural demand models as a direction of great potential (Richards and Ben-Akiva, 1975). The current research priorities appear to go even beyond the inclusion of disaggregation and behavioural content in the models. Bayliss (1977) indicates a "need of very careful in-depth analysis of travel behaviour of different types of people, in different circumstances". Reporting on the "urban transport research priorities" in the area of land use/transport models Bayliss thinks that

> research in this area must move on from the classic works of the regional scientist to deal with the situations where land development and use are subject to planning controls; most change will be in the occupation of existing sites rather than the development of open sites. This will require a fine analysis of land usage, finer than represented in currently disaggregated versions of Lowry-type models.

Arguing about the need to develop simple, and small scale (or partial) models, Bayliss further suggests that, while area-wide studies are relevant and still carried out, decision-making should be focused increasingly on specific locations, such as the CBD, industrial parks and other large employment centres, and particular corridors. Such a change in scale of interest can take into account the increasing public concern, which is naturally more specific than that of provincial (or regional) governments, and of greater interest in the foreseeable future, in which local, rather than area-wide change is feasible.

The residential models developed in this study are partial and disaggregated. The models are partial in the sense that they are developed for predicting residential distribution of the workers of specific large employment centres in the context of the City of Winnipeg. These models are socioeconomically disaggregated.

Three main approaches of trip distribution models, namely the competing opportunities model, the intervening opportunities model, and the gravity model, are utilized for the purpose of residential distribution. At first, it appears that use of these rather well-known trip distribution models for distributing residential locations (the term "residential locations" may also be replaced by work-trip distribution) is likely to be very easy and may not produce significant contribution to the existing art of modelling. The analysis carried out in this thesis indicate clearly that this is not true. Indeed, the partial and disaggregated approach of this study helps significantly in the better understanding of the trip distribution models. An improved procedure of calibrating the competing opportunities model and a new form of the intervening opportunities model have been developed and tested in this study.

CHAPTER III

METHOD OF STUDY

3.1 Introduction

For the purpose of this study it was necessary to obtain data for a specific community. The City of Winnipeg provided the data base. Before describing the procedure and sources of data collection for this study, a brief discussion of the type of data required for the development of any spatial distribution model is introduced. A spatial distribution model provides a description or forecast of human interaction between concentrations of population. When the human interaction is in the form of passenger trips and the concentrations of population are the zones of an urbanized area, the spatial model is known as a general trip distribution model which can be represented in the following mathematical function:

$$(T) = f(\bar{O},\bar{D},F,K) \tag{3.1}$$

where

(T) = a matrix containing the number of trips from each origin zone to each destination zone,

$\bar{O}$ = a vector containing the number of trip generations in each origin zone,

$\bar{D}$ = a vector containing the number of trip attractions in each destination zone,

F = a function which expresses the effect that spatial separation exerts upon trip interchange between zones,

K = a factor incorporating the effect of socioeconomic status of trip makers on the travel patterns.

The value of factor F, for the particular pair of origin-destination zones depends upon some measure of spatial separation such as travel distances, travel time or travel cost between the zones.

The models of residential location distribution as developed in the following chapters of the thesis are basically of the same form as the general trip distribution (Eq. 3.1). The location of an employment centre may be considered as the zone of origin for the purpose of distributing residential location of its workers. Then, residential districts in the region are the destination zones in which the workers would seek their residences. In a problem where the objective is to predict how people decide on their possible residential location, obviously there is a multitude of reasons why one destination would be chosen over another. The spatial location of a potential residential district with respect to the employment centre and the quality of housing, together with other neighbourhood services are among the most important criteria.

It is obvious from the preceding discussion that the following data are essential for the development of a residential location distribution model:

(1) The quality and number of housing opportunities which are available in various residential zones of the urban region for a particular socioeconomic group of people working at the employment centre,

(2) A measure of spatial separation between the employment centre and the residential zones,

(3) Socioeconomic status of workers of the employment centre and their corresponding places or zones of residence. These data are the actual or observed residential distributions which are used along with information items (1) and (2) to develop the model, and to test its predictive ability.

Recently, some researchers (Schafer, 1974) have suggested the use of "gross price", the sum of housing price and household transport cost, to make a prediction of residential choice more realistic. The present study, however, does not include housing price as a variable in simulating residential location choice behaviour. This is partly because a study (Carvalho et al., 1974) conducted in Winnipeg, the sample city of the present study, indicated that the prices of similar types of housing did not vary significantly with respect to distance from the CBD. The authors point out that the decentralized nature of employment in the city was perhaps the main reason for such a uniformity of housing price. It is useful to note here that these authors did not consider the effect of the location of other major employment centres on the housing price in the city. The household transport cost of the term 'gross price' generally includes the cost of journey to work, and of obtaining residentially oriented services, such as groceries and school. This author's contention is that for the majority of urban households the sum of transportation costs to points other than work is small and the journey to work cost, by way of contrast, is large and significant. For the sake of simplicity, then, the models in this study use travel time (for household transport costs) as a measure of spatial separation between home and the work place.

Income, which was recognized in the literature (Catanese, 1969), as the most dominant socioeconomic variable, is included in the analysis for this thesis. The models of workers' residential location are disaggregated by income groups of the workers. The occupational status of workers is also considered, to a lesser extent.

3.2 Data Acquisition

The development and testing of residential location distribution models requires socioeconomically stratified samples of workers from numerous employment centres located in the suburbs of the Greater Winnipeg Area. As indicated earlier, the study also looks to data sources such as census statistics to eliminate, in part, the requirement of expensive surveys.

The Greater Winnipeg Area has six distinct industrial districts or parks within its boundaries, excluding the Central Business District (Winnipeg Economic Development Board, 1975). These are: (i) Fort Garry Industrial Park, (ii) Canadian National Railway Yard and Transcona Industrial Park, (iii) Inkster Industrial Park, (iv) St. James Industrial Park, (v) East Kildonan Industrial Park, and (vi) North Kildonan Industrial Park. Table 3.1 provides statistics of employment in Winnipeg's industrial areas. East Kildonan Industrial Park and North Kildonan Industrial Park were considered too small to be included in the investigation. From the remaining areas, Fort Garry Industrial Park (FGIP), Inkster Industrial Park (IIP), and Canadian National Railway Yard were selected to be included in the analysis. St. James Industrial Park (SJIP) was excluded from the analysis for the simple reason of limiting the effort of data collection. The exclusion of SJIP also appeared justified because it is close to the IIP for which the work-place/residential location data were already available from Saccomanno's (1972) study. Assuming that SJIP workers may exhibit a residential location pattern of its employees similar to that of IIP, other areas such as FGIP and CNRY, located in different parts of the city, were chosen for the study in an attempt to cover the entire metropolitan area of Winnipeg.

Table 3.1 Estimated Employment* in Winnipeg's Industrial Areas (Winnipeg Economic Development Board, 1975)

	Name of Industrial Area	Total Number of Employees
(i)	Fort Garry Industrial Park	6,550
(ii)	Canadian National Railway Yard and Transcona Park	4,170
(iii)	Inkster Industrial Park	5,350
(iv)	St. James Industrial Park	11,360
(v)	East Kildonan Industrial Park	690
(vi)	North Kildonan Industrial Park	580

* Includes manufacturing, warehousing, commercial and service sectors

In the fall of 1974 a survey of FGIP in the Greater Winnipeg Area was undertaken to acquire data for the development of the residential location distribution models. All the firms of FGIP which were contacted for data acquisition were established at the industrial site at least five years prior to the survey date. The period of five years was assumed to be sufficient for the equilibrium of residential locations of workers with respect to the industrial park. For a total of 1,560 workers employed permanently in FGIP, the information about their occupation, income, and places of residences was obtained. Workers who lived in rural areas, who accounted for approximately five per cent of the total, were omitted from the study.

The development of various residential location distribution models in the following chapters of the thesis uses the socioeconomically stratified samples of FGIP workers. The testing of these models is carried out using samples from CNRY (and also from IIP as obtained by Saccomanno, 1972). The socioeconomically stratified data for CNRY employment centre were obtained in early 1975. The sample of CNRY contained a total of 2,169 workers.

Census tracts as adopted by Statistics Canada (1971) are used as the districts of residential opportunities in this investigation. Census tracts are defined as "permanent census statistical areas which are as homogeneous as possible in terms of economic status and living conditions ... Data available from these statistical units are of value in comparisons of social and economic factors within an urban community" (Statistics Canada, 1971). Since census tracts are defined uniformly across Canada, using these units may facilitate the expansion of the study to include other urban areas in the country.

As stated earlier, while searching for a suitable housing location in a residential district a worker is concerned about the quality of housing, together with other neighbourhood services. Based on the assumption of a significantly large correlation of these housing and neighbourhood variables with the income of the housing location seeker, the census tract statistics of population distribution by income (Statistics Canada,

1971) have been used as housing attraction estimates. This assumption is fairly reasonable because a recent study (Kennel, 1973) concluded that the income variable is strongly interrelated with several socioeconomic variables, such as automobile ownership, quality of housing and occupational status.

Data on income distribution by census tracts for all the workers in the City of Winnipeg were derived from the 1971 census (Statistics Canada, 1971). The adoption of three groups was necessitated in order to match the census income data with the income data obtained for FGIP and CNRY employment centres. These income groups are: high, more than \$12,000 per year; medium, \$9,000 to \$12,000; and low, less than \$9,000. All these income figures refer to the 1974 dollars. The breakdown of the workers of various income groups at FGIP and CNRY is given in Table 3.2. The occupational distribution by census tracts was not chosen for the analysis due to the apparent difficulty of matching census occupational data with the occupational data obtained for the employment centres.

Table 3.2 Breakdown of the Workers of Various Income Groups at FGIP and CNRY

Employment Centre	Number of Workers of Various Income		
	Low	Medium	High
FGIP	778	471	237
CNRY	520	1,509	140

Travel time is used as a measure of the cost of transportation between a residential district and the employment centre. The travel times from all census districts in the City of Winnipeg to the district containing the employment centre were determined by the 'floating car' technique during the morning peak hours. In this technique an automobile is driven over a predetermined course of streets attempting at all times to 'float' with the traffic stream, while, at the same time, an observer in the automobile records the travel times at preselected check points.

The employment centres included in this study are located in the suburbs of the Greater Winnipeg area (Fig. 3.1). There are no specific public transportation services available for commuting to these centres. As a result, most of the workers use private automobiles for commuting to their work places. For this reason, only automobile trips have been included in the analysis used for this thesis.

As pointed out earlier in this chapter, Saccomanno's (1972) data of IIP (located in the Winnipeg area) are also used to test the models of this study. Although acquired and classified in a slightly different manner than the author's data for FGIP and CNRY, Saccomanno's samples of IIP workers provide additional validation of the findings of this thesis.

In his work on "A Predictive Model of the Residential Distribution Pattern of Industrial Occupation Groups' for a Master's thesis, Saccomanno collected the information about the occupation of IIP workers, and their corresponding places of residences. For the purpose of studying group behaviour with respect to residential/work-place location as it is affected by socioeconomic conditions, he divided the workers into three

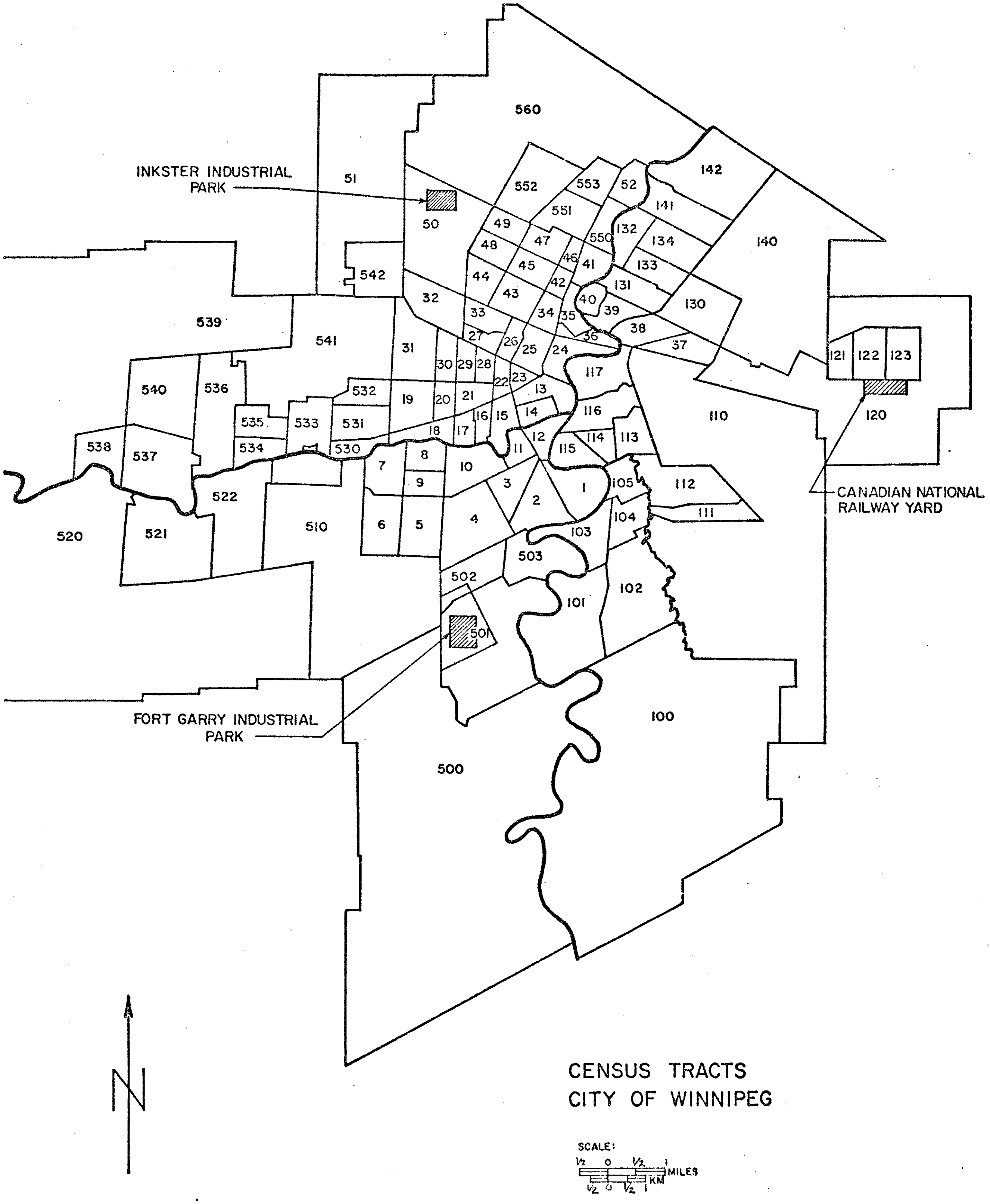

Fig. 3.1 Location of Sample Employment Centres in Winnipeg

broad occupational groups: managerial, clerical, and labour. Census tracts were adopted as districts of work trip origin. Saccomanno derived the data of occupational distribution by census tract from the 1961 Census (Statistics Canada, 1961). Although the 1961 Census divided labour statistics into nine distinct classifications, the adoption of the three categories, managerial, clerical, and labour, was necessitated by the nature of sample data from the case study and other socioeconomic factors associated with these three groups. For the more detailed discussion of the reasons behind the adoption of the three groups and their components, a reference may be made to Saccomanno (1972).

All the data acquired for this study are tabulated in Appendix A.

3.3 Approach to the Analysis and Development of Models

The development and analysis of the competing opportunities model, the intervening opportunities model and the gravity model are described in Chapters IV, V and VI, respectively, of this thesis. The development and analysis of all the models are generally described in three stages. The first stage presents the theoretical derivation of the model. The second stage presents application of the model to a specific employment centre and recognizes the shortcomings of its existing application procedures. This stage then proposes some changes which improve the predictive ability of the model. The third stage tests the model using samples from other employment centres to confirm the validity of the model incorporating the proposed changes.

CHAPTER IV

COMPETING OPPORTUNITIES MODEL OF RESIDENTIAL LOCATION DISTRIBUTION

4.1 Introduction

The competing opportunities model for trip distribution was developed by Tomazinis (1962). The model involves the direct application of probability theory already introduced to the trip distribution problem by Schneider (1959) of the Chicago Area Transportation Study.

As its name implies, the model is based on the concept that individuals compete for opportunities up to a destination, within equal travel time, travel distance and/or travel cost bands as measured from the place of origin. Within a given band, every opportunity has an equal probability of acceptance.

The basic formula of the trip distribution procedure is

$$T_{i-j} = O_i \times P_j \tag{4.1}$$

where

T_{i-j} = number of one-way trips from zone i to zone j,

O_i = total number of trips originating in zone i,

P_j = probability of stopping at destination j.

The theoretical derivation of this model and its application to trip distribution are fully explained by Tomazinis (1962). However, in order to present the model in reference to the problem of residential location distribution, the model is derived in the following parts of this chapter.

4.2 Theory

Fig. 4.1 shows a universe of population N. There are two subpopulations, H and S, within the universe. It is given that part of subpopulation H is also part of subpopulation S, and vice versa. The probability of randomly selecting from the population N a member of the subpopulation H is

$$P(H) = \frac{H}{N}$$

Similarly, $P(S) = \frac{S}{N}$

The probability that the choice is a member of both subpopulations S and H is

$$P(HS) = \frac{CHS}{N}$$

where CHS represents the members which are common in both subpopulations H and S. By definition, the conditional probability that H is chosen given that S has already been chosen is:

$$P(H/S) = \frac{P(HS)}{P(S)} = \frac{CHS/N}{S/N} = \frac{CHS}{S}$$

This concept of conditional probability, which is treated sufficiently in most textbooks of probability theory, can now be adapted to the problem of residential location distribution as follows.

4.3 Adaptation to the Problem and Derivation

The competing opportunities model derived by Tomazinis deals with general-purpose trip distribution in the overall urban area. The model derived here reverses the base of references, in that it seeks to collect trips rather than to distribute them. Instead of having numerous destination points, only one point is considered (i.e., employment centre) to

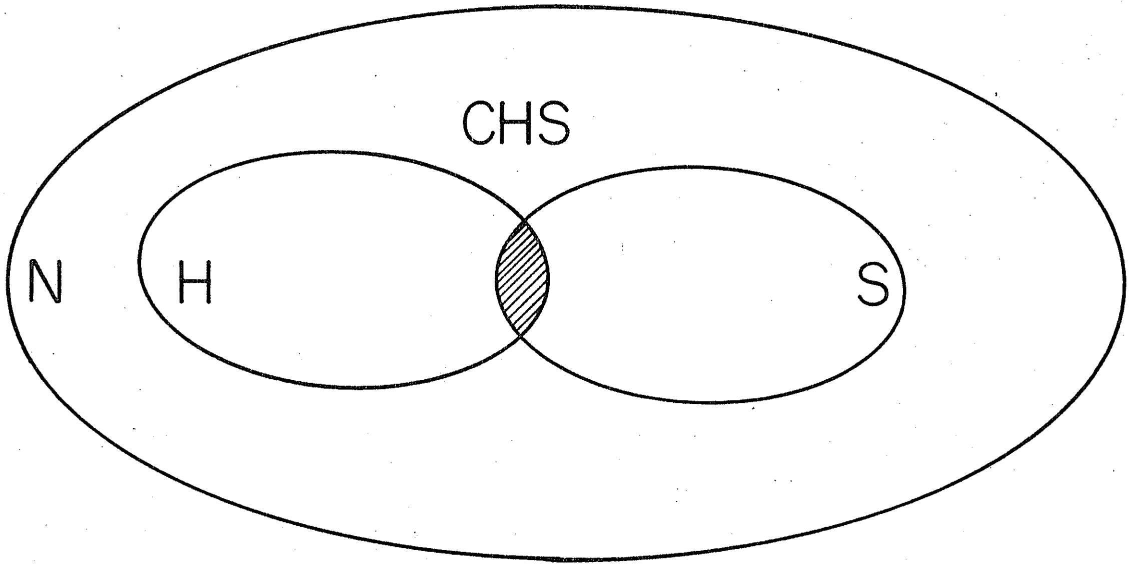

Fig. 4.1 Population Diagram (CHS = H∩S)

receive work trips from numerous points of origin (i.e., residential districts). Trip makers in this analysis are the individual workers employed at a particular centre, who are categorized by their socioeconomic characteristics. The type and number of these categories will depend on the availability of an estimate, or projection, of suitable housing opportunities for the workers of those particular categories within each residential district of the urban area.

Fig. 4.2 illustrates the structure which underlies the derivation of the competing opportunities model of residential distribution. The employment centre A is shown as a focus for n residential districts in the entire urban area. The centre is a source of employment providing different kinds of jobs to the residents of the urban area according to their skills and backgrounds. The residential districts which are located at various distances from A are suppliers of suitable housing opportunities to the workers of various socioeconomic groups.

Let the terms used in the model derivation be defined as:

O = number of workers of a socioeconomic group employed at A,

d_i = number of suitable housing opportunities for the group available in district i,

$D\cdot$ = total number of suitable housing opportunities for the group in the entire urban area,

= $\sum_{i=1}^{n} d_i$, where n is the total number of residential districts in the area,

t_i = travel time between centre A and residential districts i, in minutes.

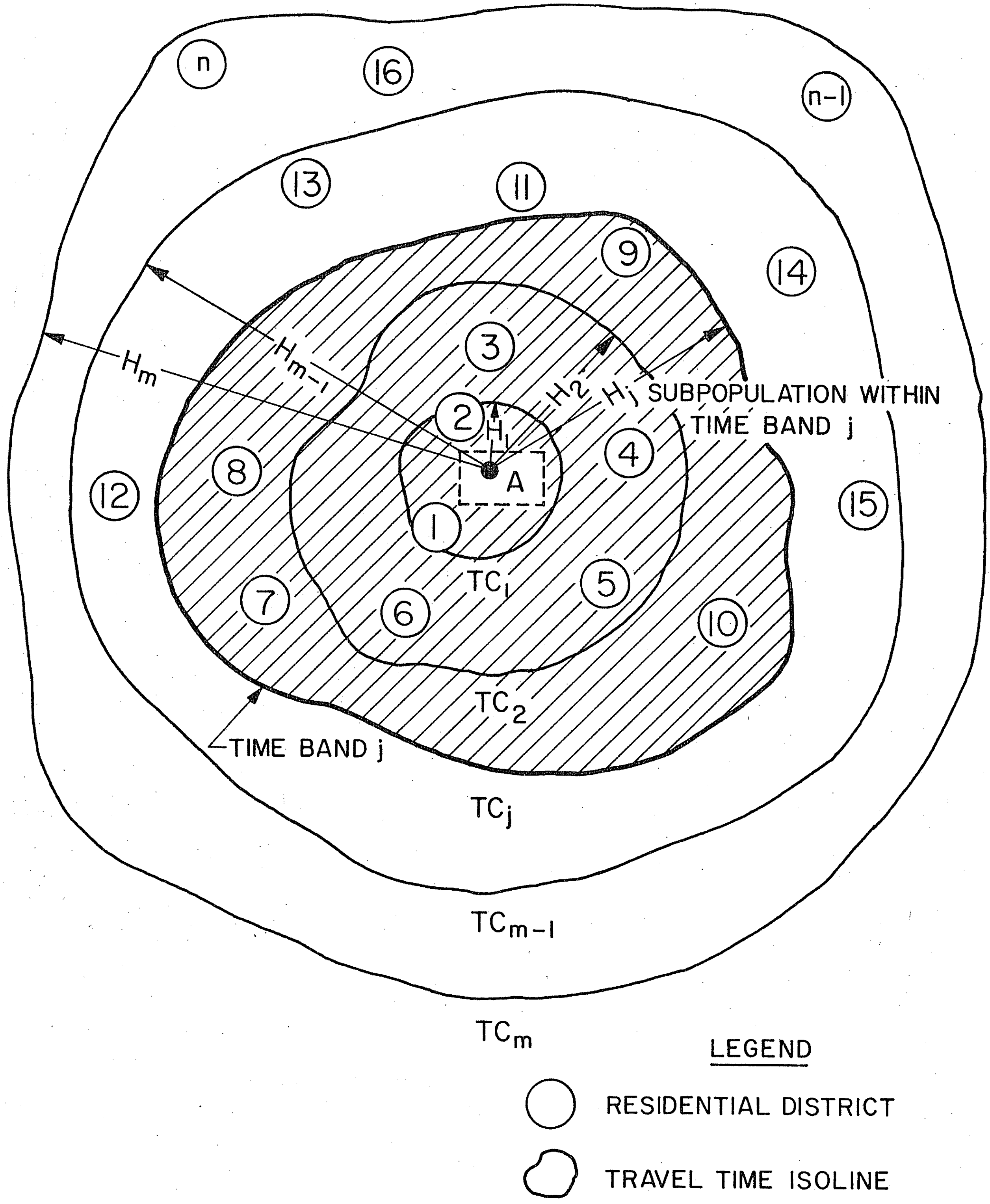

Fig. 4.2 Schematic Diagram Showing Employment Centre A as a Focus for Residential Districts in the Region

The terms H_1, H_2, etc., designate all housing opportunities for the group available in the area bounded by the travel times TC_1, TC_2, etc., respectively, between the centre A and the residential districts. The travel times TC_1, TC_2, etc., define the residential area by the proper "time band", or "time code". Each time band can include any agreed-on time interval in minutes. The H subpopulation is the total of the cumulative housing opportunities in all time bands until the time band of the residential district of the destination is reached. The cumulative nature of the subpopulation can best be understood by the following expressions for H_1, H_2, H_3, etc. With reference to Fig. 4.2.

$$H_1 = d_1 + d_2 \tag{4.2a}$$

$$\begin{aligned} H_2 &= d_1 + d_2 + d_3 + d_4 + d_5 + d_6 \\ &= H_1 + d_3 + d_4 + d_5 + d_6 \end{aligned} \tag{4.2b}$$

Similarly,

$$H_3 = H_2 + d_7 + d_8 + d_9 + d_{10} \tag{4.2c}$$

$$H_4 = H_3 + d_{11} + d_{12} + d_{13} + d_{14} + d_{15} \tag{4.2d}$$

in general,

$$H_j = H_{j-1} + \text{sum of opportunities in jth band.} \tag{4.2e}$$

Given that the centre A employs O number of workers of a particular group, then choosing at random a worker of that group, the probability that the chosen worker is a member of subpopulation H_1 is:

$$P(H_1) = \frac{H_1}{D\cdot}$$

The probability that the chosen worker is also a resident of residential district 1 (say R_1) which is a part of H_1 is:

$$P(R_1) = \frac{d_1}{D\cdot}$$

By definition then, conditional probability of district R_1 is:

$$P(R_1/H_1) = \frac{d_1}{H_1} = P'_1 \qquad (4.3a)$$

Similarly,

$$P(R_2/H_1) = \frac{d_2}{H_1} = P'_2 \qquad (4.3b)$$

$$P(R_3/H_2) = \frac{d_3}{H_2} = P'_3 \qquad (4.3c)$$

and so on.

The above expressions for conditional probabilities of various residential districts, P'_1, P'_2, P'_3, etc., imply that the probability of finding a housing location in a residential district is equal to the housing locations available in the district divided by the total housing locations inside the area delineated by the time code of the district in consideration. This concept can be termed "concept of competing opportunities", in which the probability that a worker will find a housing site in a district depends on the ratio of the housing opportunities. It should be noticed here that the equating of opportunities depends on an equal or lesser travel time or travel cost experienced by a worker.

Since the total number of housing locations sought by the competing workers should equal the total number of jobs available at the employment centre, the summation of the probability of each district within the area should be unity; hence:

$$\Sigma P_i = 1$$

where i represents residential districts 1, 2, 3, 4, 5, ...n. Here n is the total number of districts in which residential locations are sought.

To obtain $\Sigma P_i = 1$, the conditional probability of each district (Eqs. 4.3a, 4.3b, 4.3c) is divided by the summation of all conditional probabilities of each district (i.e., $\Sigma P_i'$), giving

$$P_1 = \frac{P_1'}{\Sigma P_i'}$$

$$P_2 = \frac{P_2'}{\Sigma P_i'}$$

$$P_3 = \frac{P_3'}{\Sigma P_i'}$$

and so on for all the remaining districts.

The required summation of conditional probabilities of all districts can be found by using the relationships in Eqs. 4.2 and 4.3. To start with, dividing Eq. 4.2a by H_1, 4.2b by H_2, 4.2c by H_3, etc., results in the following equations:

Eq. 4.2a divided by H_1 gives

$$1 = \frac{d_1}{H_1} + \frac{d_2}{H_1} \qquad (4.4a)$$

Eq. 4.2b divided by H_2 gives

$$1 = \frac{d_1}{H_2} + \frac{d_2}{H_2} + \frac{d_3}{H_2} + \frac{d_4}{H_2} + \frac{d_5}{H_2} + \frac{d_6}{H_2}$$

or (4.4b)

$$1 = \frac{H_1}{H_2} + \frac{d_3}{H_2} + \frac{d_4}{H_2} + \frac{d_5}{H_2} + \frac{d_6}{H_2}$$

(since $d_1 + d_2 = H_1$)

Eq. 4.2c divided by H_3 gives

$$1 = \frac{H_2}{H_3} + \frac{d_7}{H_3} + \frac{d_8}{H_3} + \frac{d_9}{H_3} + \frac{d_{10}}{H_3} \tag{4.4c}$$

Eq. 4.2d divided by H_4 gives

$$1 = \frac{H_3}{H_4} + \frac{d_{11}}{H_4} + \frac{d_{12}}{H_4} + \frac{d_{13}}{H_4} + \frac{d_{14}}{H_4} + \frac{d_{15}}{H_4} \tag{4.4d}$$

and Eq. 4.2e divided by H_j gives, in general,

$$1 = \frac{H_{j-1} + \text{sum of all opportunities in jth band}}{H_j} \tag{4.4e}$$

Adding Eqs. 4.4a, 4.4b, 4.4c, 4.4d, and 4.4e, and also taking m as the total number of bands results in:

$$m = \frac{H_1}{H_2} + \frac{H_2}{H_3} + \frac{H_3}{H_4} + --- + \frac{H_{j-1}}{H_j} --- + \frac{H_{m-1}}{H_m}$$

$$+ \frac{d_1}{H_1} + \frac{d_2}{H_1} + \frac{d_3}{H_2} + \frac{d_4}{H_2} --- + \frac{d_n}{H_m}$$

or

$$m = \frac{H_1}{H_2} + \frac{H_2}{H_3} + \frac{H_3}{H_4} --- + \frac{H_{j-1}}{H_j} --- + \frac{H_{m-1}}{H_m} + \Sigma P_i'$$

or

$$\Sigma P_i' = m - \sum_{j=2}^{m} \frac{H_{j-1}}{H_j} \tag{4.5}$$

The probability of a residential district being chosen as a housing location can be calculated by using the above expression as follows:

$$P_i = \frac{P_i'}{m - \sum_{j=2}^{m} \frac{H_{j-1}}{H_j}} \qquad (4.6)$$

Writing the above expression for a socioeconomic group and multiplying it by the total number of workers of that particular group employed at the employment centre results in the following residential location distribution model:

$$T_i = 0 \times \frac{\frac{d_i}{H_j}}{m - \sum_{j=2}^{m} \frac{H_{j-1}}{H_j}} \qquad (4.7)$$

where T_i = number of workers of the group who reside in district i when employed at A.

Other terms have previously been defined.

4.4 Calibration and Analysis of the Model

Discussion of Existing Calibration Procedure

The competing opportunities model is calibrated by varying the width of the attracting time bands until there is an agreement between the actual and predicted values of the dependent variable. A review of the literature shows that only a limited number of attempts have been made to calibrate and use this model. As a result, no simple procedure is available at present to calibrate the model successfully.

To this date, only two major attempts have been made to use this model, one by Tomazinis (1962) of the Penn-Jersey Transportation Study, and the other by Heanue and Pyers (1966) of the Washington Transportation

Study. Attempts by Bell (1970), and Soliman and Saccomanno (1972) are felt to be important to an understanding of the problem, and some of the controversy surrounding it.

Tomazinis (1962) reported that application of the competing opportunities model provided satisfactory results for most of the samples tested for distributing trips in New Jersey. He indicated, however, that the success of the model depends upon the manner in which opportunity districts are aggregated into time codes. Some guidelines, which underlie the selection of the width of time bands, are well explained by Tomazinis:

> Before the width of time codes can be decided, another thought should be explored. The objective here is to simulate human behavior in choosing the destination of a trip within a complex set of trip destinations of a region. This takes place on the basis of two elements of experience; e.g. experience with the transportation system considered, and the ability and sensitivity to count and utilize time in small increments. What is implied is that one cannot have a first time code of 5 min for a mass transit system where "waiting time" alone may be more than 5 min. It also implies that for auto travel or mass transit travel one should not have time codes of odd increments (of say, 6.25 min) but of blocks of time that are easily conceived and frequently used by people in their everyday activities; e.g., time codes of say 5 or 10 min.
>
> This consideration of simulating human behavior has proven of substantial importance where the best results were achieved with time codes of 5 min driving time in distributing auto trips. In the case of mass transit trips the first time code was 20 min in most of the area and 30 min for the districts at the outskirts of the metropolitan region. The rest of the time codes were of 5 min riding time. This variation of the width of the first time code was in response to the variation of "waiting time" in the system, which ran up to 12 and 18 min, respectively.

> The preceding paragraphs imply a need to introduce a dichotomy between auto trips and mass transit trips. For a small city without major mass transit facilities, this is not an important dichotomy and need not be carried out. However, when such facilities exist in a large scale, then there is a substantial distortion of reality if the various districts would be arranged from a given point of origin on the basis of a single minimum path used on highway facilities. This is true because "combined" (all modes) minimum paths are difficult to estimate objectively. Thus, it became evident that suitable time codes by auto and mass transit should be established in each case on the basis of the pertinent minimum time paths.

The competing opportunities model proved to be very difficult to calibrate when applied to 1948 Washington survey data by Heanue and Pyers (1966). Since it was only the second major attempt to use this model, no systematic calibration procedure was available, and therefore, the researchers tried many alternative approaches for obtaining a simulated trip distribution with the same trip length characteristics as the survey data. Initially, uniform time bands were tried with little success. Next, varying-width time bands were utilized and the results became somewhat more meaningful. Two such attempts were: (1) a 24-minute initial time band followed by uniform 2-minute time bands and (2) a 40-minute initial time band followed by uniform 2-minute bands. Even with this approach, however, it was not possible to obtain a trip-length frequency distribution approaching the survey trip length. A comparison of these results with those of the present study is included later in this chapter.

A study was undertaken by Bell (1970) with the objective of calibrating the COM.* He reported that the method was able to simulate trip

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* Competing Opportunities Model

making behaviour in Sydney, Australia, reasonably well. Due to some discrepancies, however, Bell concluded that some kind of attraction trip-end balancing procedure would have improved its accuracy of simulation.

Soliman and Saccomanno (1972) used the COM to predict and simulate patterns of commuter travel generated by the introduction of a proposed industrial site. Their application of the model to an industrial park in the City of Winnipeg, Canada, has proved to be successful within reasonable limits. However, the authors have called for a more extensive testing and refinement of the model. A more detailed discussion of the results of the study by Soliman and Saccomanno is presented in the latter part of this chapter.

Development of an Improved Calibration Procedure

The foregoing review of the literature dealing with the COM shows that only a few attempts have been made to calibrate and use the model. Consequently, no systematic calibration procedure is available. It is evident, however, from the work of Tomazinis (1962), Heanue and Pyers (1966), and Bell (1970) and the experience of this author's preliminary work with the COM that any attempt at model calibration must comprise three distinct steps:

i) selection of a suitable uniform width of time bands for the study area,

ii) determination of the width of first time band to achieve the best possible results,

iii) improvement in the accuracy of prediction of the dependent variable for the districts within the first time band.

A calibration procedure, which integrates all the above steps developed in this study, is described in full detail in the following sections of the thesis.

Uniform Width of Time Bands

Some guidelines which underlie the selection of width of time bands were cited in the preceding section. Based on these guidelines, and taking into account the experience of other researchers with this model, several uniform time-band widths were tested using the COM (Eq. 4.7) and the data from FGIP for various income groups of workers. A uniform time width of 5 minutes was selected for further development of the model from among various possible widths for two specific reasons: 1) because travel time is commonly weighted in multiples of 5 minutes, and ii) in a medium sized city like Winnipeg, 5-minute bands give an appropriate level of aggregation of housing opportunities.

For the initial attempt using 5-minute uniform time bands, the number of predicted and actual residential locations (for various group) are shown in Fig. 4.3. Clearly the predicted numbers of residential locations in most of the time bands are not close to the actual number for any income group of workers. However, a definite pattern of discrepancy exists for all the groups. For the first few bands, the model shows a high positive deviation from the actual results in each case. The remaining time bands, as a result, have moderate to high negative deviations. The results obtained for any other uniform width of time bands (e.g., 2, 3, 4, 6, 7, 8 minutes, used in the study) were similar in nature to the results of 5-minute uniform width. Therefore, it was decided to continue the calibration of the model using 5-minute bands for the reasons

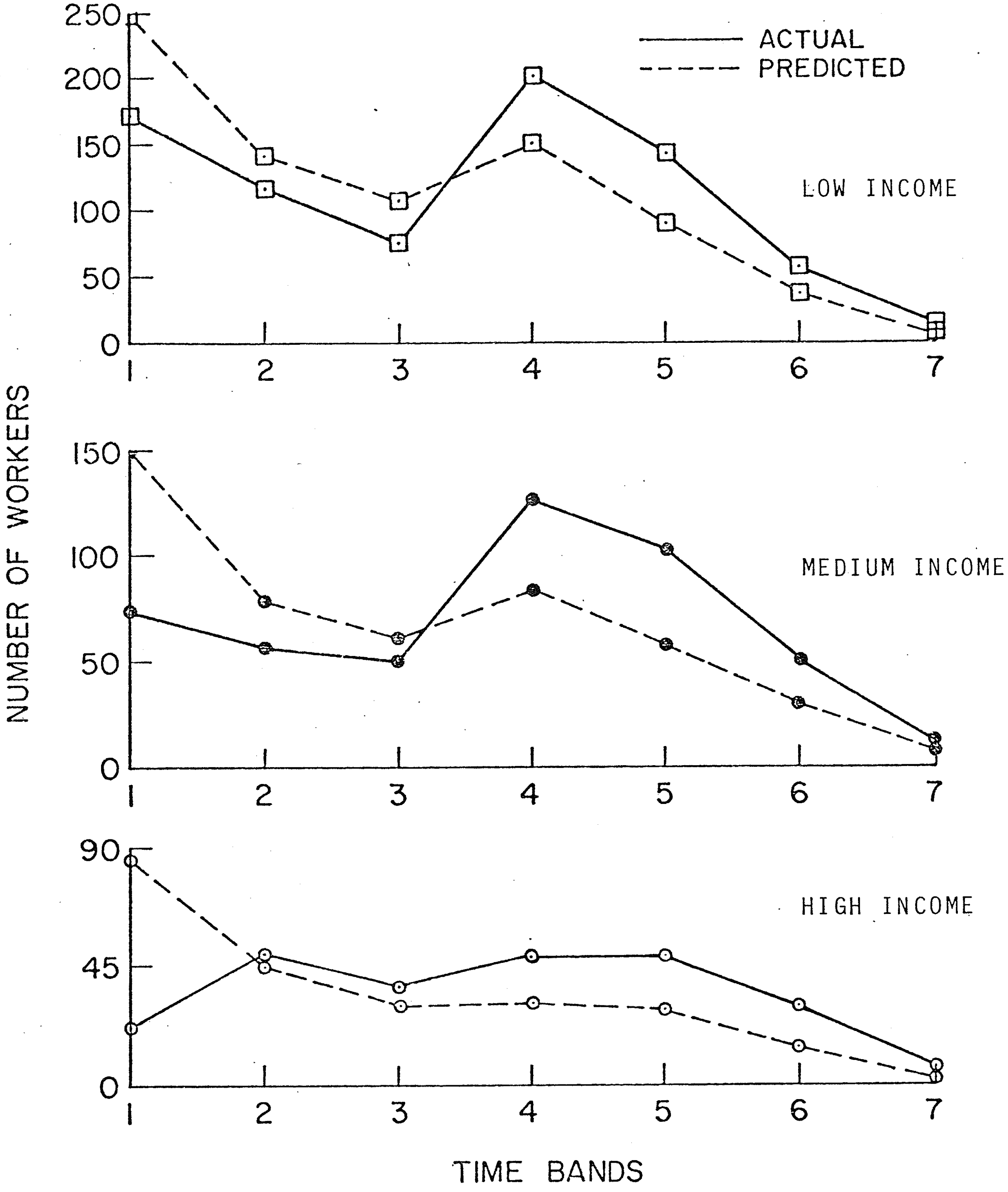

Fig. 4.3 Actual and Predicted Residential Location Distribution of the Workers of Various Income Groups by Time Bands of Uniform Width.

stated in the preceding paragraph.

The results of this study, using uniform width of time bands, are also similar to the results of other researchers in the past. Soliman and Saccomanno (1972), who classified the work force of Inkster Industrial Park in Winnipeg into three broad groups - managerial, clerical, and labour - for the purpose of studying their behaviour with respect to residential/work-place location, encountered the same kind of discrepancy using uniform 5-minute time bands. Fig. 4.4 and 4.5 show their calculated and observed residential locations for the labour and clerical groups, respectively. Fig. 4.6 is a comparison of trip-length distribution - actual vs. COM with uniform time bands as obtained by Heanue and Pyers (1966).

The discrepancy in COM prediction using 5-minute uniform time bands requires some explanation at this point. The high positive deviations for the first few time bands (Fig. 4.3) and the resulting negative deviations for the remaining time bands are essentially due to the basic objective of the "theory of competing opportunities", which is the configuration of a function expressing a rate of diminishing probability of residential choice at increasing travel time from the given employment centre. The model assigns overly high probabilities to the residential districts in the first few time bands. It is obvious that this situation is due to an excessive overlap in competition for residential locations with these time bands.

Width of the First Time Band

The failure of the model using uniform time bands necessitated further trial and adjustment in the prediction procedure. From the over-

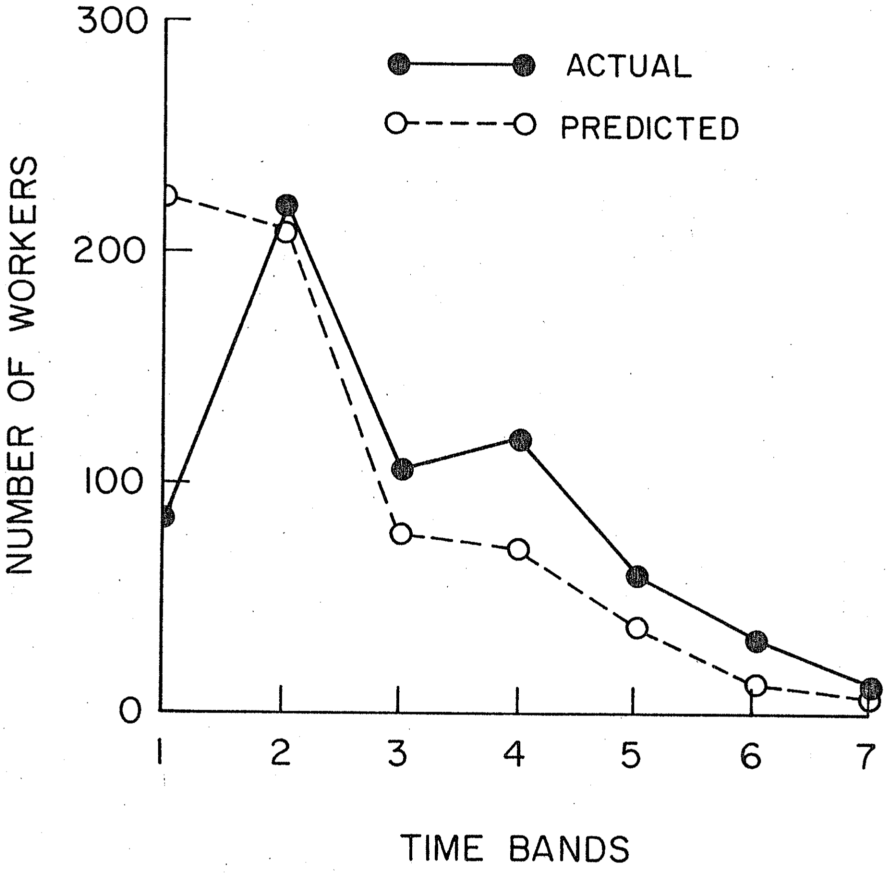

Fig. 4.4 Actual and Predicted Residential Location Distribution for the Labour Group by Time Bands of Uniform Width (Source: Soliman and Saccomanno, 1972)

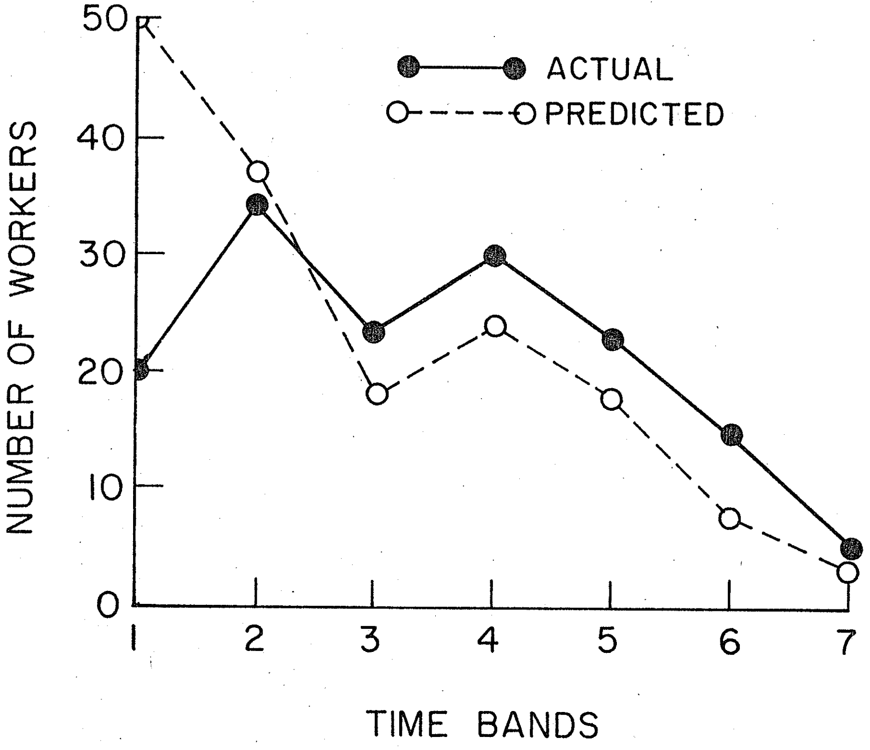

Fig. 4.5 Actual and Predicted Residential Location Distribution for the Clerical Group by Time Bands of Uniform Width (Source: Soliman and Saccomanno, 1972)

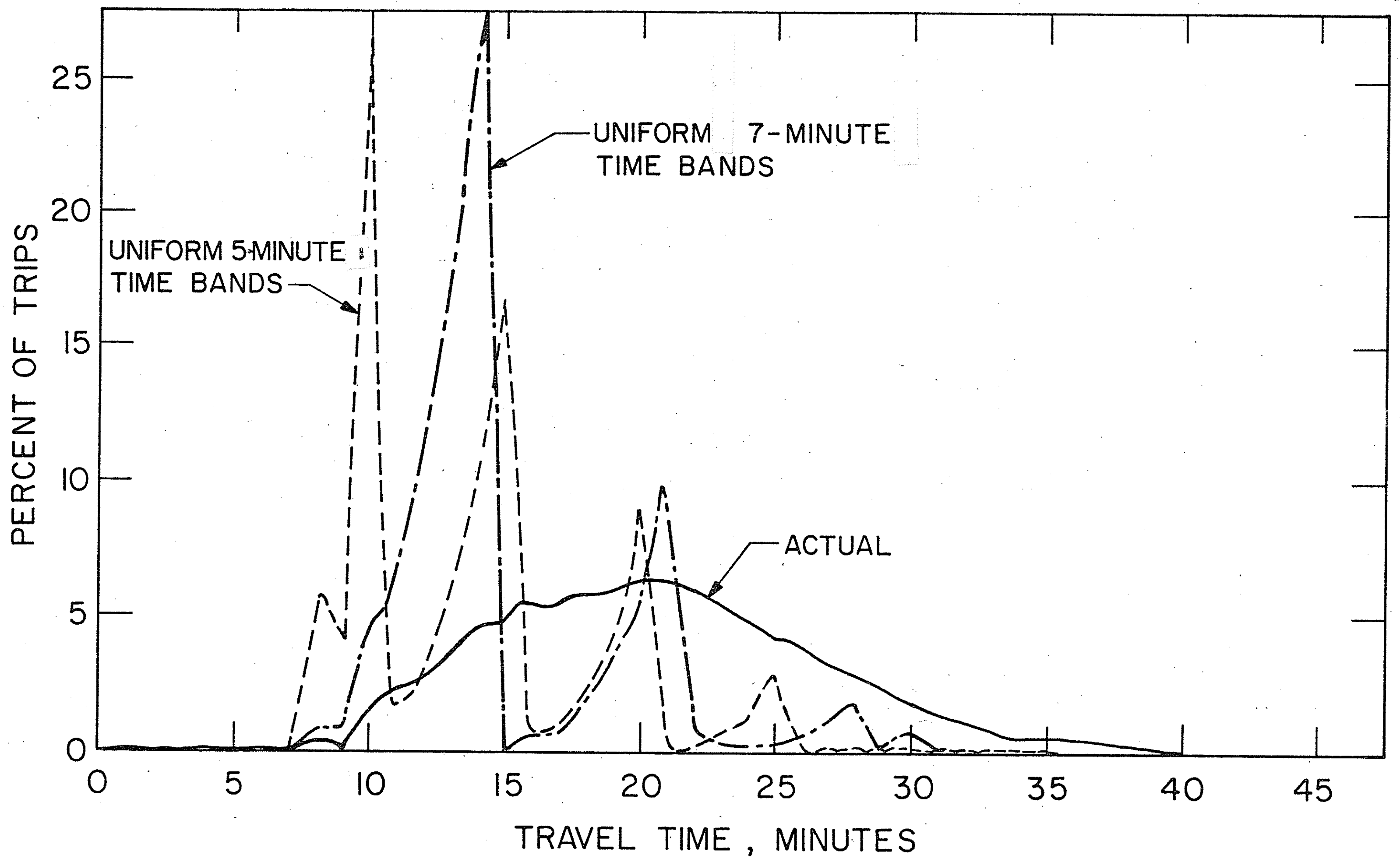

Fig. 4.6 Comparison of Trip-Length Distribution-Actual vs Competing Opportunities Model with Uniform Time Bands (Source, Heanue and Pyers, 1966)

prediction of residential locations in the first few time bands, it was obvious that the probabilities assigned by the model to residential districts in these bands were higher than the actual probabilities. Experimentation involving variation in the width of time bands made it clear that the probability function (Eq. 4.6) is significantly affected by increasing the width of the first time band. Fig. 4.7, for example, shows the effect of increasing the width of first time band, W_1 on the cumulative probability function of residential locations for the low income group. As W_1 increases, the probability assigned to the residential districts close to the employment centre decreases. This decrease in probability values is due to the fact that when W_1 increases, more and more residential districts lying in first band share the advantage of competitiveness of opportunities over residential districts in remaining time bands.

The width of the first time band, W_1, was varied from 5 to 25 minutes, followed by a uniform width, W, of 5 minutes for all the groups of workers. The attempts at varying W_1 resulted in a better agreement between the actual and the model values in all time bands for each socio-economic group. The first time band widths are: 10 to 15 minutes for low, 15 to 20 for medium, and 20 to 25 for high income group. Fig. 4.8 shows the comparison of actual and predicted residential location distribution using W_1 of 15 minutes for low, 20 minutes for medium, and 25 minutes for high income workers. All the first time band widths in the figure are followed by the uniform widths of 5 minutes.

The calibration results of this study are in agreement with the results of Heanue and Pyers (1966). These authors were more successful

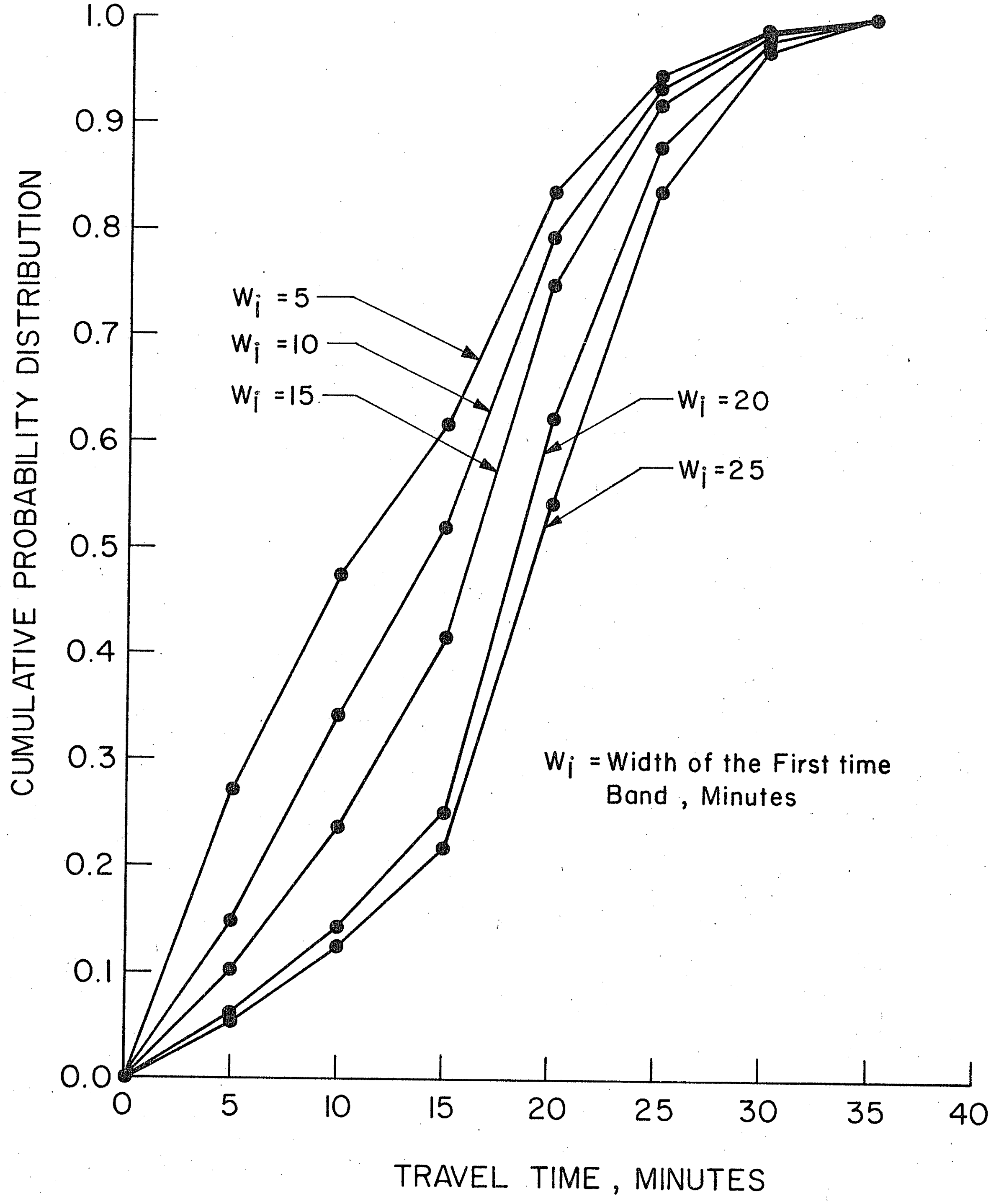

Fig. 4.7 Effect of the Width of First Time Band on the Probability Function of Residential Location Distribution

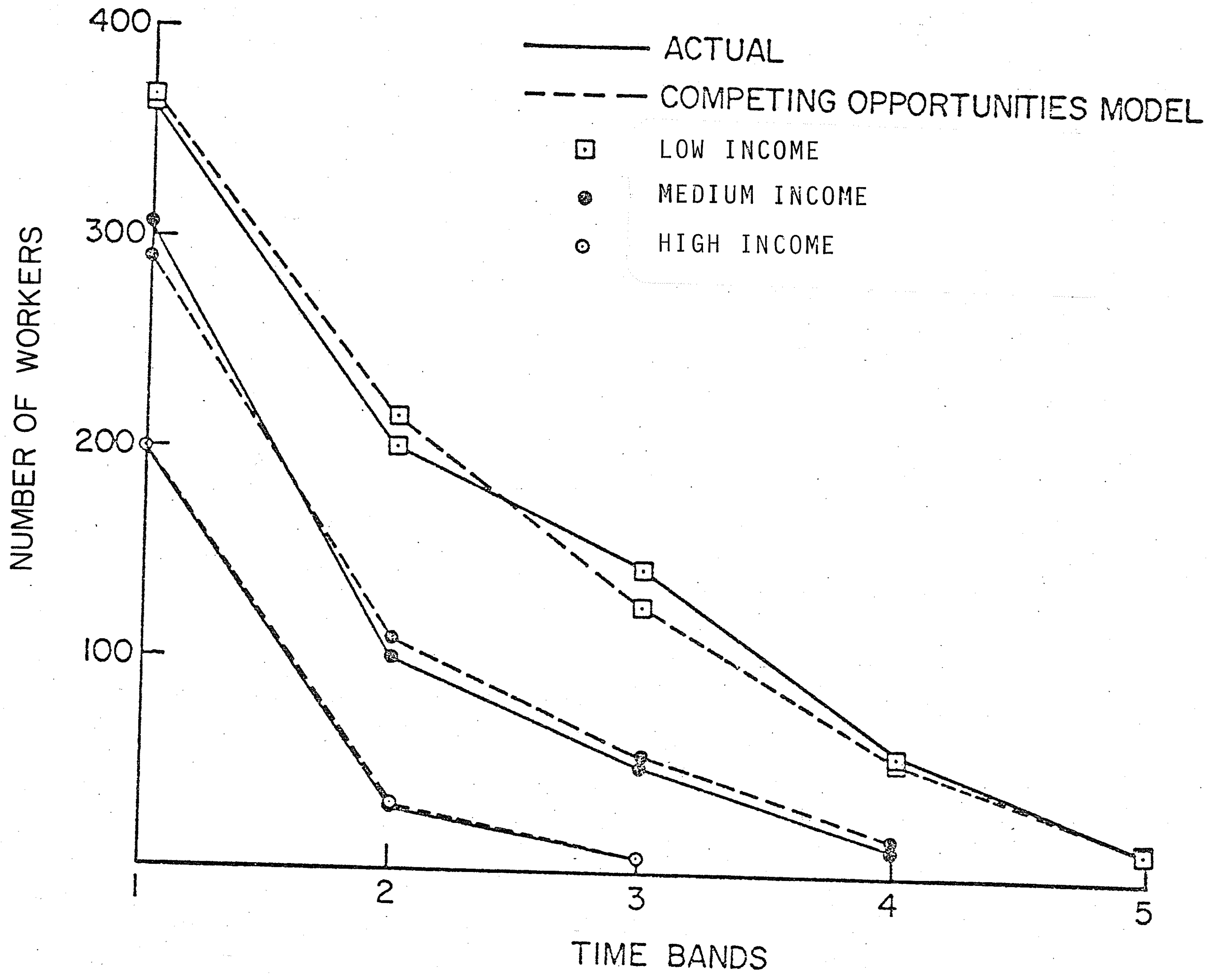

Fig. 4.8 Actual and Predicted Residential Location Distribution of the Workers of Various Income Groups by Time Bands of Nonuniform Width.

in finding an adequate solution with a 24-minute first time band followed by uniform 2-minute time bands than with any other combination of time bands they used.

Adjustment in Prediction Within the First Time Band Using a 'Nested Model'

In the previous analysis of COM calibration we were concerned with the performance of the model with respect to the time bands. It was noticed that a model with the first time band wider than other bands could provide adequate prediction for most of the time bands. A wider first time band, required to achieve satisfactory prediction, may cause a problem of high aggregation of opportunities, especially in medium and small urban areas. For example, a first time band width equal to 25 minutes for the high income group of FGIP in Winnipeg results only in 3 time bands; first, from 0 to 25 minutes; second, from 26 to 30 minutes; and third, from 31 to 35 minutes. Most of the housing opportunities in such a case fall in the first time band. Any comparison of actual and predicted values at such high aggregation does not provide any clue about the adequacy of the model, especially for the residential districts within the first time band. The model, when applied in this manner, becomes less useful for planning or prediction purposes. The following analysis, which was carried out to make the model more useful for prediction (by reducing the degree of aggregation), is based on travel time comparisons instead of time band comparisons of actual and predicted numbers of residential locations.

It is evident from Fig. 4.8 that the predicted residential locations in most time bands are reasonably close to the actual values. However, when the residential locations are plotted against travel time, as shown in Fig. 4.9, discrepancy between the actual and predicted distribution is clearly noticeable for travel time less than W_1 minutes (width of the first time band). For the low income group, for example, the COM with a first time band width of 15 minutes followed by 5-minute uniform bands (say COM/15/5 model*) underpredicts for a travel time interval of 0 to 5 minutes, and overpredicts for a travel time interval of 11 to 15 minutes. The results for a 6-to 10-minute time interval are in better agreement. This type of disagreement for time intervals falling within the first time band occurs because the COM/15/5 model does not provide any competitive preference to the residential districts which are located closer to the employment centre (0 to 5 minutes) over the other districts farther from the centre (6 to 10, and 11 to 15 minutes). A similar discrepancy may be noticed for the medium group. The high income group, however, does not exhibit any large systematic disagreement (Fig. 4.9).

To improve the accuracy of prediction, the total numbers of residential locations predicted for the first time bands of all the income groups were redistributed among the residential districts within these first time bands by applying the competing opportunities model. The repeated application of the concept of competing opportunities, confined only to the residential districts within the first time band of the previous stage of the application of the model, could be termed a 'nested

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* COM/15/5 model specifies a competing opportunities model with a first time band of 15 minutes followed by 5-minute uniform bands.

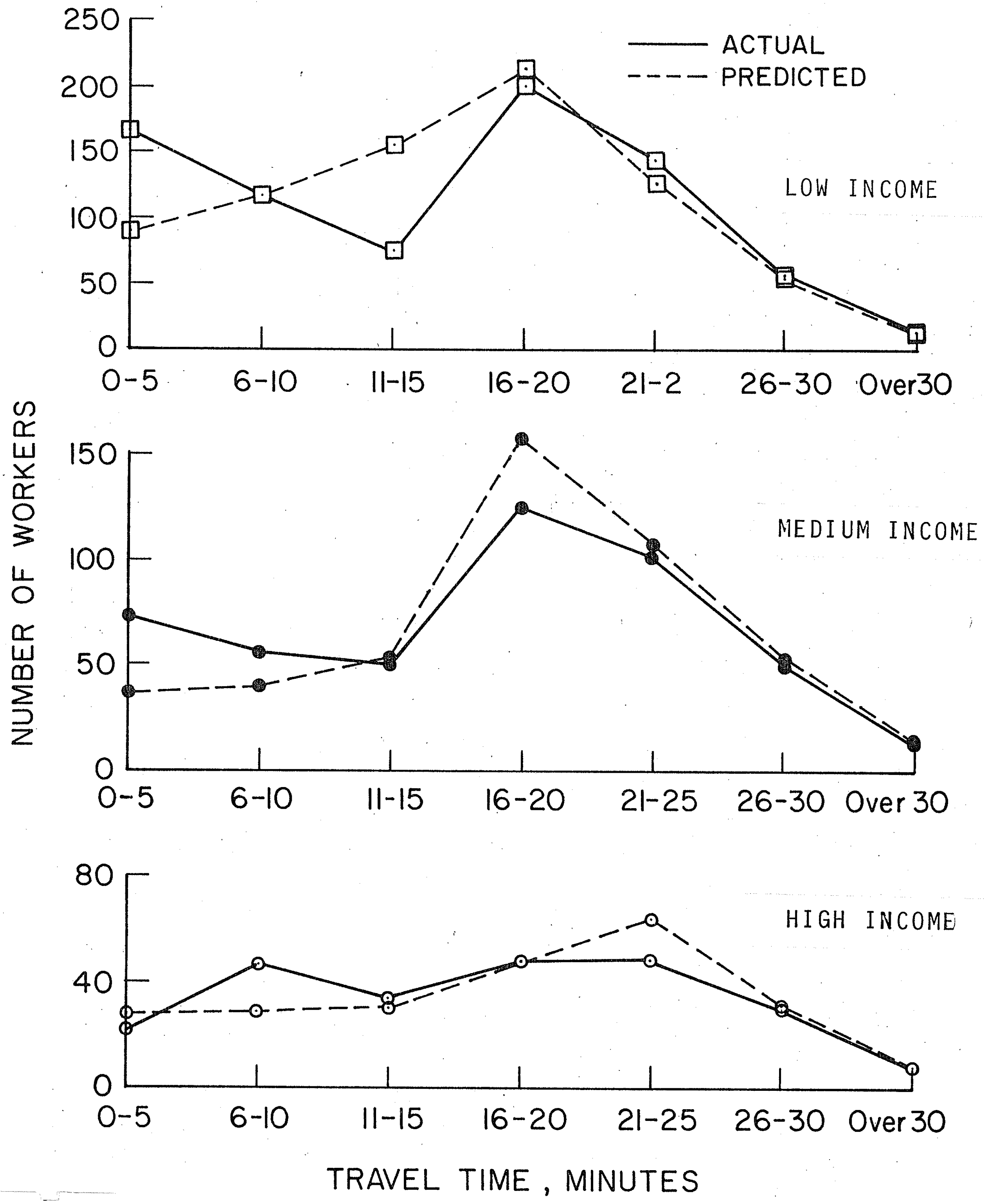

Fig. 4.9 Actual and Predicted Residential Location Distribution of the Workers of Various Income Groups by Travel Time.

model' for redistribution of residential locations. Time sub-band* widths of a nested model for various groups of workers were determined by utilizing the same procedure as described previously under the titles "Uniform Width of Time Bands", and "Width of the First Time Band". The nested model, with a first time sub-band width of 5 minutes followed by 5-minute uniform sub-bands (say NEST/5/5 model), produced reasonable results for the low income group. For the medium income group, NEST/10/5 model and NEST/15/5 model were found to be appropriate for prediction within the first time bands of COM/15/5 and COM/20/5 models, respectively. In the case of the high income group, appropriate models were NEST/15/5 and NEST/20/5, corresponding to COM/20/5 and COM/25/5 models, respectively. Fig. 4.10 demonstrates the improvement in accuracy of prediction (as compared to Fig. 4.9) for travel time less than W_1 minutes, achieved by a nested model using first time sub-band widths of 5 minutes for the low, 15 minutes for the medium, and 20 minutes for the high income group. It is clear from the figure that a nested model improves the predictions for the low and medium groups. No further improvement is clearly exhibited by its application to the high income group.

In general, the predicted results, after introducing the nested model, are close to the actual results for all the groups of workers. The remaining variation between the actual and the predicted values can be attributed to various factors, such as the error in samples, the lack of precision in the values of independent variables, and some variables not included in the analysis.

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[*] The term 'sub-band' refers to time band of a nested model.

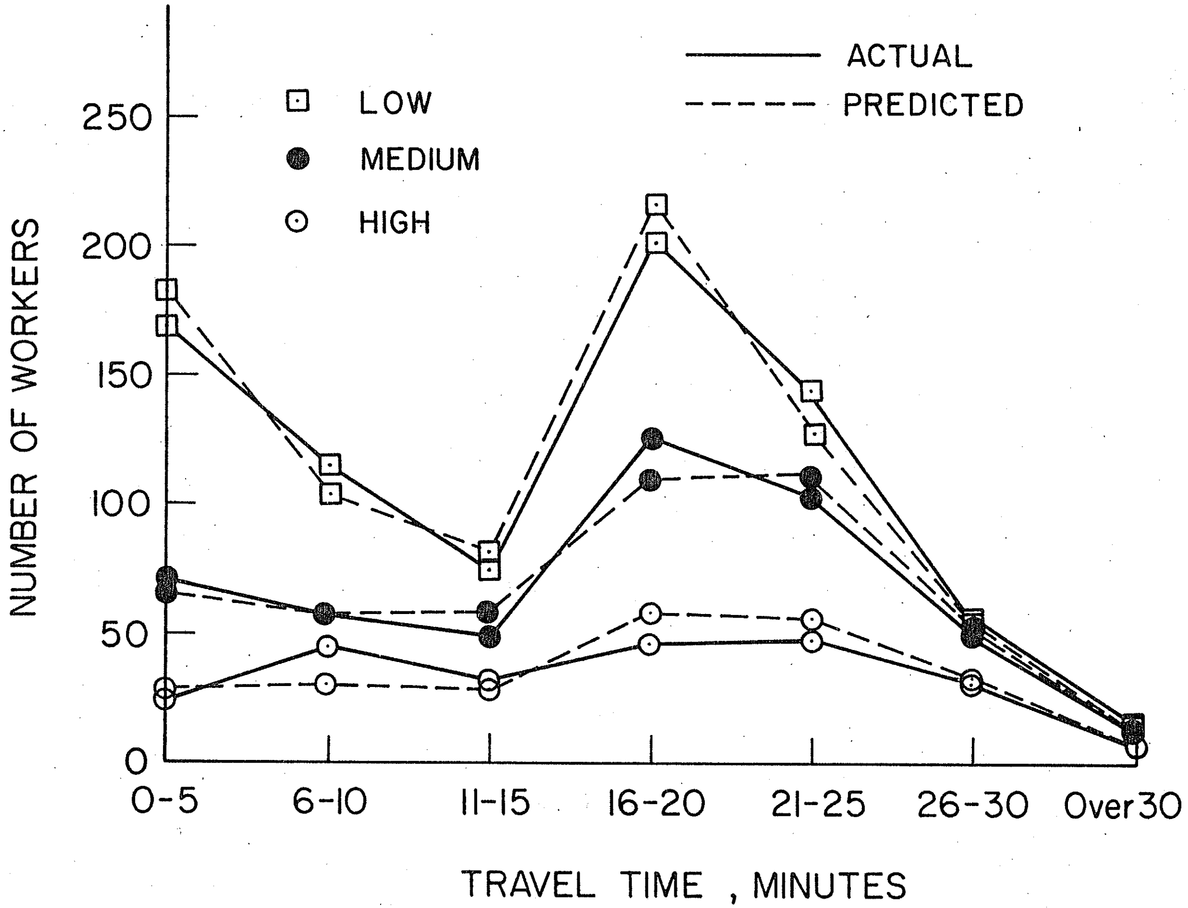

Fig. 4.10 Comparison of Residential Location Distribution of the Workers of Various Income Groups - Actual vs Competing Opportunities Model Utilizing the Improved Calibration Procedure.

The model of Heanue and Pyers (1966), with a 24-minute first time band followed by 2-minute uniform bands, also produced results within the first time band which show a resemblance in nature to the results of this study. Fig. 4.11 displays an underprediction in short trips and an overprediction in long trips within the first time band of 24 minutes. The predicted results for the remaining time bands, however, are in good agreement with the actual results. It appears that the technique of applying the nested model for this case as well should bring the actual and predicted trip distribution into closer agreement.

4.5 Testing of the Model

Table 4.1 summarizes the results obtained during the calibration process using data for FGIP in Winnipeg. It is necessary, after having developed a residential location distribution model using data from a specific employment centre in an urban area, to confirm its validity, before it can be used for prediction purposes. The model (Table 4.1) developed in this study was tested for (i) Canadian National Railway Yard (CNRY) and, (ii) Inkster Industrial Park (IIP). Both of these industrial parks are located in suburbs of the City of Winnipeg.

As mentioned in Chapter 3, data were collected from CNRY to test the developed model. The workers of CNRY were classified into high, medium, and low income groups as defined for FGIP while developing the model. The sample of CNRY contained 140 high, 1,509 medium and 520 low income workers. The actual and predicted residential location distribution for all the income groups of workers at CNRY is shown in Fig. 4.12. This figure utilizes the first time band widths of COM as 10, 15, and 20 minutes for low, medium, and high income groups, respectively. The adjust-

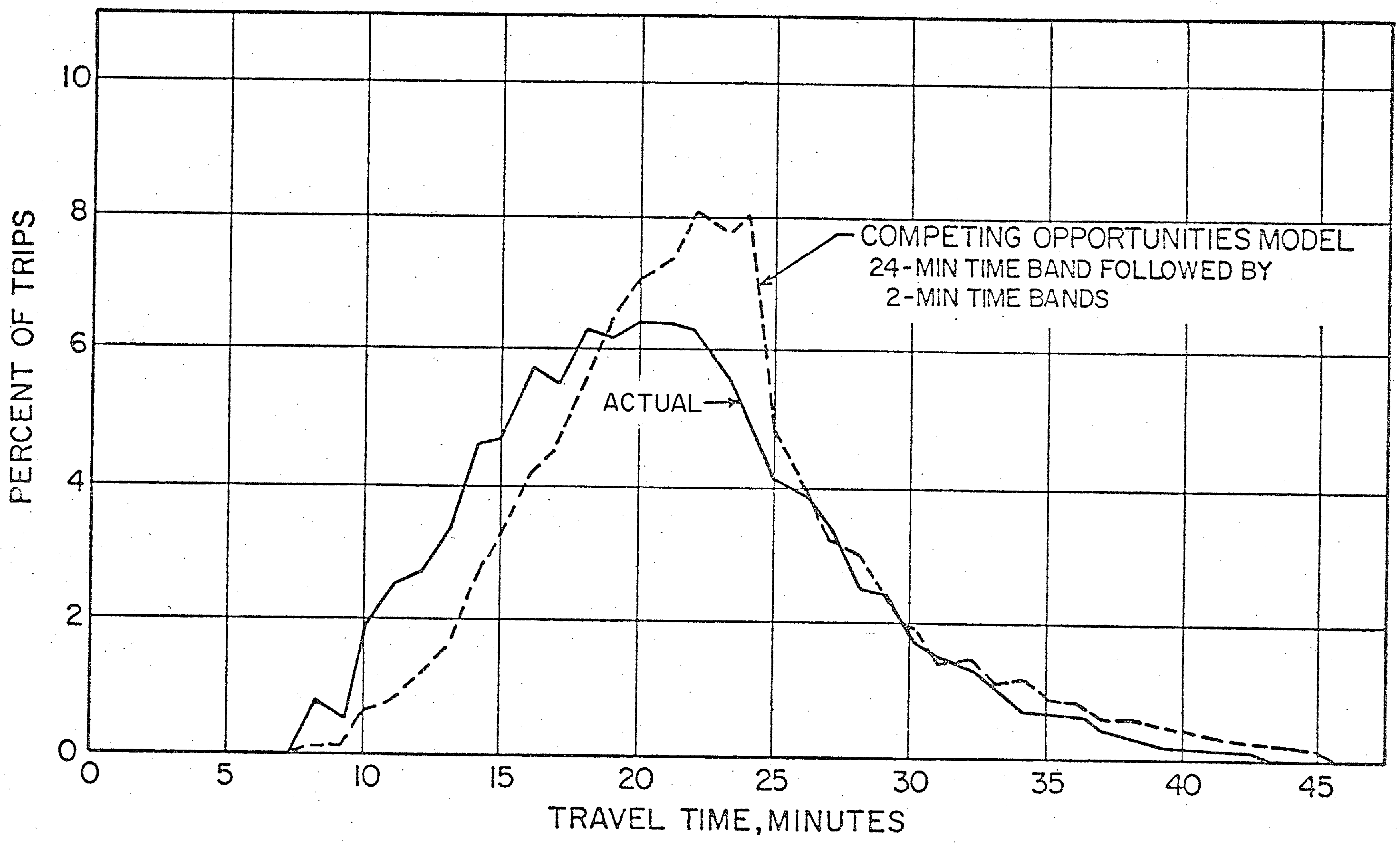

Fig. 4.11 Comparison of Trip-Length Distribution - Actual vs Competing Opportunities Model with Variable Time Bands (Source: Heanue and Pyers, 1966).

Table 4.1 Summary of Model Calibration and Analysis of Results

INCOME	COM/W_1/W*MODEL PARAMETERS		NEST/w_1/w**MODEL PARAMETERS	
	W_1, in Minutes	W, in Minutes	w_1, in Minutes	w, in Minutes
LOW	10	5	5	5
	15	5	5	5
MEDIUM	15	5	10	5
	20	5	15	5
HIGH	20	5	15	5
	25	5	20	5

*COM/W_1/W	specifies a competing opportunities model with first time band width of W_1 minutes followed by uniform bands of W minutes.
**NEST/w_1/w	specifies a competing opportunities model (called a nested model), applied only to the residential districts within the first time band of COM/W_1/W, with first time sub-band of w_1 minutes followed by uniform sub-bands of w minutes.

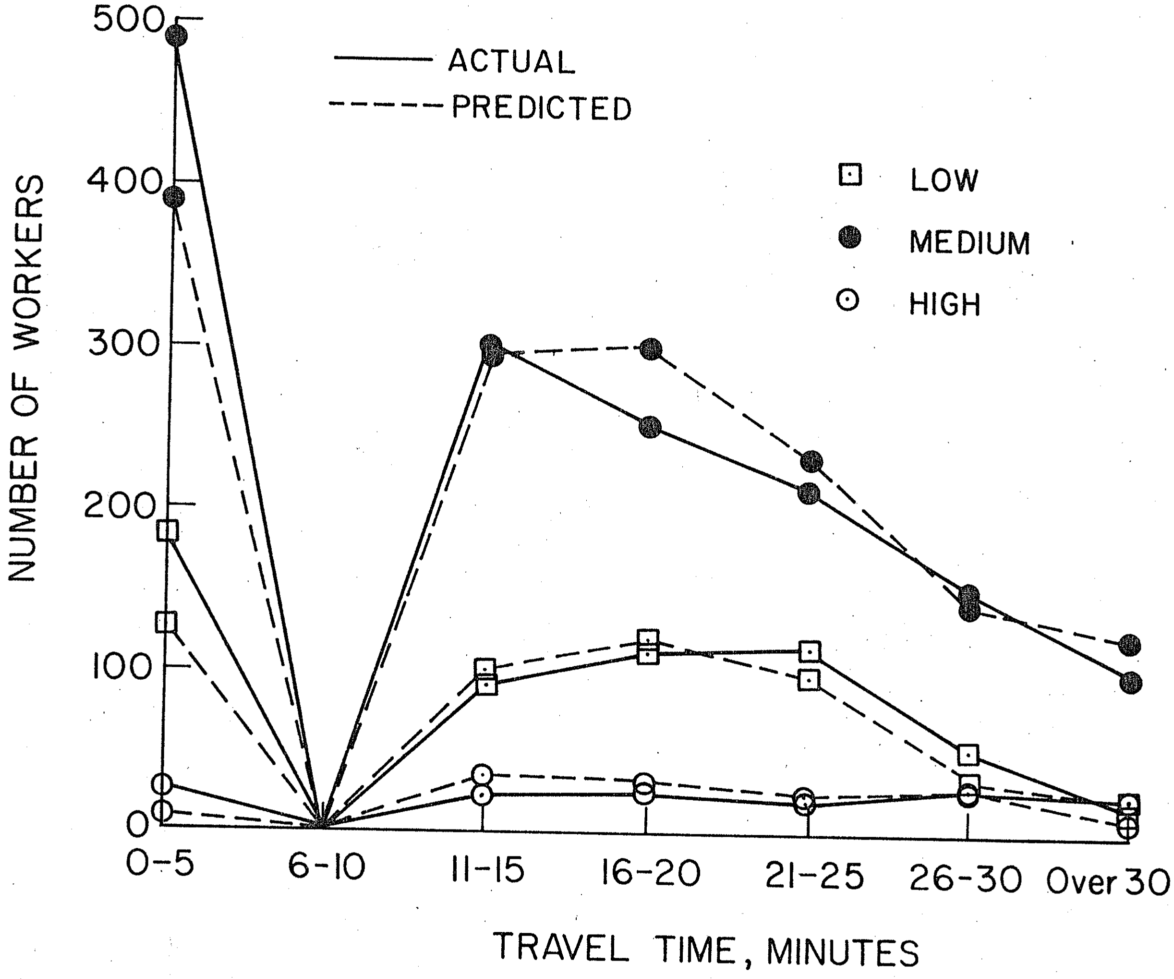

Fig. 4.12 Actual and Predicted Residential Location Distribution of CNRY Workers of Various Income Groups.

ent in prediction within the first time band of the COM is carried out by using the nested model with the first time sub-band widths of 5 minutes for low, 10 minutes for medium, and 15 minutes for high income groups of workers. The predicted results of residential location distribution are in fairly close agreement with the observed results for all the groups of CNRY workers. It is worth noting, however, that the model which was developed using only FGIP data underpredicts the residential locations in 0-5 minute interval. It may be surmised that such deviations are quite understandable, considering that we are trying to simulate human behaviour by mathematical relationships.

The procedure of calibration and analysis of the COM was also tested using the data obtained by Saccomanno (1972) for IIP for his study, "A Predictive Model of the Residential Locational Distribution Pattern of Industrial Occupation Groups". Saccomanno's classification of industrial workers is different from the classifications in this study. As mentioned earlier, he considered three occupational groups - labour, clerical, and managerial. Assuming that these occupational groups might correspond to the low, medium, and high income groups, respectively, the model was applied to the data of Saccomanno. Fig. 4.13 compares the actual and the predicted residential locations using the first time band width of the COM as 15 and 20 minutes for labour and clerical groups, respectively. The adjustment in prediction within the first time band of the COM is carried out by using the nested model with the first time sub-band widths of 5 minutes for labourers and 15 minutes for clerical workers. These model parameters correspond to the low income group (for labour), and medium income group (for clerical) in Table 4.1. The closeness of the

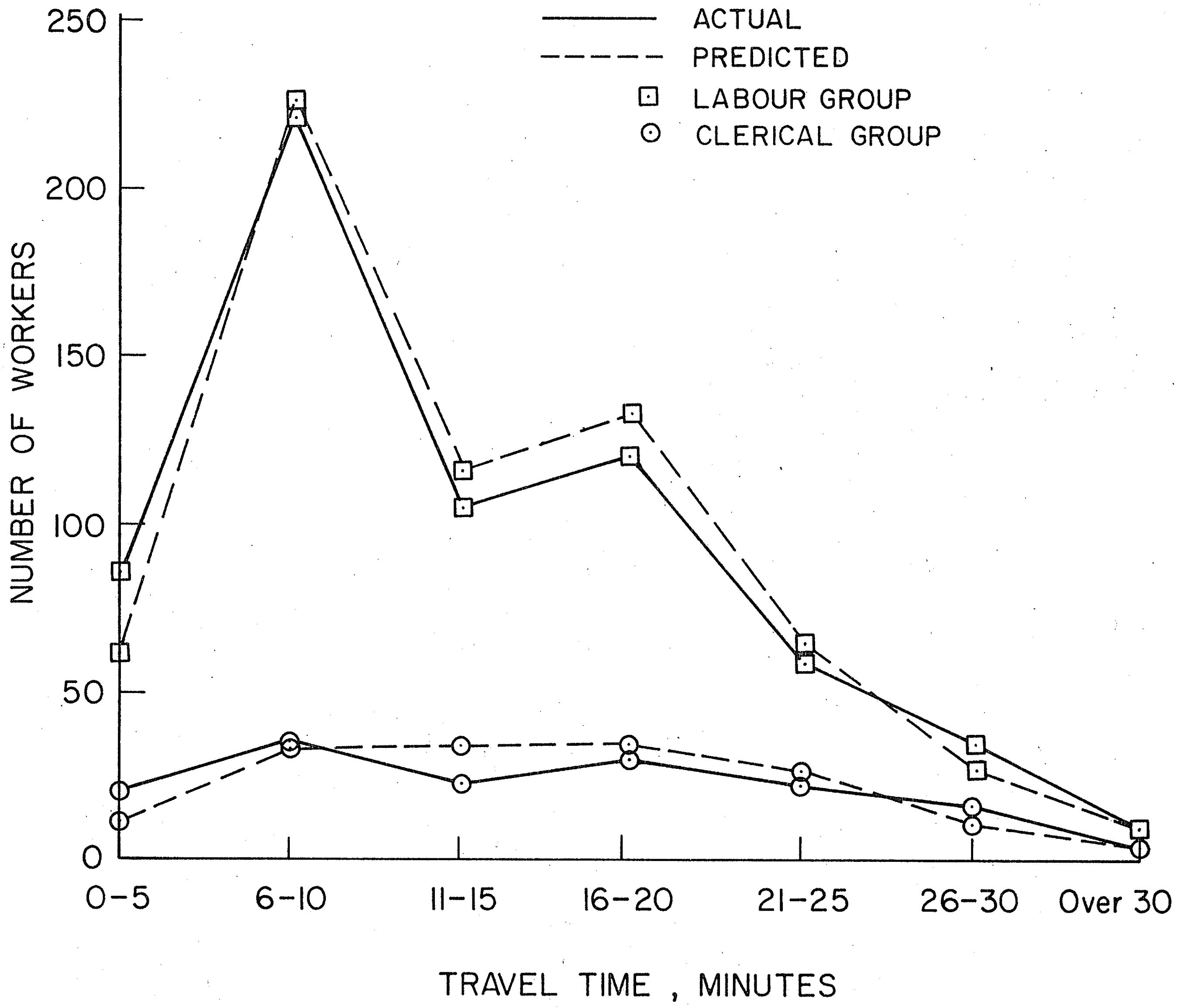

Fig. 4.13 Actual and Predicted Residential Location Distribution of IIP Workers (Source: Soliman and Saccomanno, 1972)

actual and predicted results in the figure demonstrates the success of the model in predicting the residential location of workers of various socioeconomic status in Winnipeg. The managerial group could not be included in testing the model since the sample size of 52 managers was considered too small to indicate a pattern (Soliman and Saccomanno, 1972).

4.6 Discussion of Results

Table 4.1 summarizes the results obtained during the calibration process. The width of the first time band, W_1, in the case of various income groups, may be considered as a demarcation line which splits the entire study region into two areas of competition for residential opportunities: (i) the area within W_1 minutes time of the employment centre, as the low competition area, and (ii) the area beyond W_1 minutes time, as the high competition area. Due to the existence of a range of W_1 for each group, no clear distinction can be made between these areas. It is evident from the values of W_1 obtained for different groups that, as the income of the worker increases, the line of demarcation of low and high competition areas (i.e., W_1) moves outward from the employment centre. For example, it is obvious from the values of W_1 that the high income workers compete for housing location more discerningly beyond 20 to 25 minutes of travel time from their job place as compared to 10 to 15 minutes for the low income group.

Inclusion of the first time sub-band width of the nested model into the discussion suggests the existence of a very low competition area within the low competition area for each income group. These very low competition areas for housing opportunities are: 0 to 5 minutes for the low income group, 0 to 15 minutes for the medium income group, and 0 to 20 for the high income group of workers.

The magnitudes of the first time band width of the competing opportunities model and the first time sub-band width of the nested model derived in this study for various groups indicate that, in general, the workers of the high income group live farther from their place of employment than do the workers of the low income group. The desire of the low income group to live closer may be linked with their concern for the fact that the farther they live from their place of work the greater the share of their income that is spent on commuting and less is available for other expenses.

Since the predicted number of residential locations agreed with the actual numbers for the labour and clerical group of workers at IIP (Fig. 4.13) using different values of the width of the first time band, W_1, of the COM, and first time sub-band width of the accompanying nested model, w_1, the above discussion of travel time sensitivity may also be applied to the occupational status of the workers. It appears that the workers of low occupational status are more sensitive to the travel time, and thus the travel distance (or expense), as compared to the workers of higher occupational status.

CHAPTER V

INTERVENING OPPORTUNITIES MODEL OF RESIDENTIAL LOCATION DISTRIBUTION

5.1 Introduction

The intervening opportunities model is the name given to the mathematical procedure developed by Morton Schneider (1960) to distribute, over all possible destinations, the actual destinations of all trips having a stated origin. The distinguishing feature of the model is its unique independent variable, intervening opportunities. Although new to the urban transportation field when proposed by Schneider, this variable had been used earlier for population migration and intercity travel studies (Stouffer, 1940). The model has been used successfully in several urban transportation studies in recent years.

5.2 Model Theory

The hypotheses and mathematics underlying the intervening opportunities model are given briefly as a prelude to the discussion of interpretations of the model and its parameters. The intervening opportunities model of trip distribution (which the existing problem of residential location distribution resembles in nature) is based on the following hypotheses (Ruiter, 1967):

1. Total travel time (or distance) from a point is minimized, subject to the condition that every destination point has a stated probability of being accepted if it is considered.
2. The probability of a destination being accepted, if it is

considered, is a constant, independent of the order in which destinations are considered.

It can be shown that the above hypotheses lead to the following mathematical formulations, in terms of limitingly small quantities (Fisk, 1974):

$$dP = L[1-P(D)]dD \tag{5.1}$$

where

dP = the probability that a trip will terminate when considering dD possible destinations,

$P(D)$ = the probability that a trip will terminate by the time D possible destinations are considered,

D = possible destinations already considered, or subtended volume of destinations, and

L = the constant probability of a possible destination being accepted if it is considered.

Assuming L to be constant, the solution of Eq. 5.1 gives:

$$P(D) = 1 - \exp(-LD) \tag{5.2}$$

Thus the probability, P_j, that a trip will terminate in opportunity band j (or volume of destination that falls into j^{th} travel time or distance ranking), for a given origin zone, is:

$$\begin{aligned} P_j &= P(D_j) - p(D_{j-1}) \\ &= \exp(-LD_{j-1}) - \exp(-LD_j) \end{aligned}$$

where

D_{j-1} = trip destinations considered before reaching opportunities band j,

$$D_j \;=\; D_{j-1} + \text{trip destinations in opportunities band } j.$$

The expected number of trip interchanges, T_j, between opportunity band j and the origin zone equals the number of trip origins at the origin zone multiplied by the probability of a trip terminating in j, i.e.,

$$T_j \;=\; O \times P_j$$

or

$$T_j \;=\; O \times [\exp(-LD_{j-1}) - \exp(-LD_j)] \tag{5.3}$$

where

O = the total number of trip origins at the original zone under consideration.

Interpretation of the L-Value

Eq. 5.2 can be changed to a linear form by rearranging and taking logarithm of both sides. This procedure results in the following:

$$-LD \;=\; \mathrm{Ln}[1-P(D)] \tag{5.4}$$

Observed values of D and Ln(1-P(D)] for a given origin zone, when plotted on a semilog graph paper, will theoretically result in a straight line. Then the parameter L can be viewed simply as the slope of the straight line which best fits this set of empirical D and Ln[1-P(D)] data.

Mathematically, the L-value can be expressed as:

$$L \;=\; \frac{-\mathrm{Ln}[1-P(D)]}{D} \tag{5.5}$$

P(D) is always smaller than unity so that L is always positive and has units of 1/opportunities. Experience in past studies indicates that L is always very small, usually of the order of 10^{-5}, and always much smaller than one.

The above characteristics support the interpretation of the L-value as a modified probability quantity. Just as for other probability quantities, L lies between zero and one. Unlike more common probabilities, L is not unitless. It can be thought of as the probability, per individual opportunity or trip end, of destination acceptance (Ruiter, 1967).

Calibration of the Model

Calibration of the intervening opportunities model involves determination of the L-value such that its use in Eq. 5.3 generates a trip interchange pattern similar to the actual interchange obtained from the survey. A number of calibration procedures have been utilized by researchers (Catanese, 1974) in the past, depending on the nature of the trip distribution problem. Out of these existing procedures, the single-L-value method is appropriate to the existing problem.

The single-L-value calibration method involves the use of some initial value of parameter L and then adjustment through an iterative process to bring the estimated trip exchange frequency as close as possible to the survey data. More specifically, in the first step, an initial estimate of L is used to calculate the estimates of trip interchanges which are then compared with the actual interchanges. In the second step the value of L is changed by a certain increment and the dependent variable is re-estimated, and compared with the actual trip interchange again. This latter step is repeated until a most satisfactory value of L is found which results in as close an agreement as possible between the predicted and the observed results.

To ensure that all the trips available at the origin zone are distributed among the destination zones, the summation of the probability of all opportunities bands within the area should be unity, hence:

$$\Sigma P_j = 1$$

The formula for the intervening opportunities model (Eq. 5.3) lacks a built-in process to ensure that all the trips will be distributed (Pyers, 1965). For a given set of trip destinations in a study area, any particular L-value used in the formula will determine the number of trips sent from any zone or origin. The percentage of trips that will actually be sent from a particular zone with a given L and number of trip destinations can be calculated by solving Eq. 5.3. By summing both sides for all opportunities bands or destination zones j, we have:

$$\Sigma T_j = O \times \Sigma[\exp(-LD_{j-1}) - \exp(-LD_j)] \qquad (5.6)$$

Dividing the above equation by O gives

$$\Sigma T_j/O = \Sigma[\exp(-LD_{j-1}) - \exp(-LD_j)] \qquad (5.7)$$

The quantity on the left of this equation is the ratio of the trips actually distributed from the origin zone and those available to be sent. The quantity on the right side may be expanded as follows:

$$\Sigma[\exp(-LD_{j-1}) - \exp(-LD_j)] = [\exp(-LD_o) - \exp(-LD_1)]$$
$$+ [\exp(-LD_1) - \exp(-LD_2)] + [\exp(-LD_2) - \exp(-LD_3)] + \dots$$
$$+ [\exp(-LD_{m-1}) - \exp(-LD_m)] = 1-\exp(-LD_m)$$

where

$D_m = \sum_{j=1}^{m} D_j$, the total study area destinations which are known.

Thus Eq. 5.7 may be written as:

$$\Sigma T_j/O = 1-\exp(L\Sigma D_j) \tag{5.8}$$

It appears that by setting $\Sigma(T_j/O)$ or fraction of trips sent at 0.95 or any desired level, the required L can be calculated using the above equation. However, an L-value so calculated to assure sending the correct number of trips may not provide a satisfactory trip distribution. To overcome this problem, the U.S. Bureau of Public Roads suggests that an L-value should be sought which would give a satisfactory trip-length distribution after each of the probability terms, i.e., $[\exp(-LD_{j-1}) - \exp(-LD_j)]$ in Eq. 5.3, is adjusted so that the summation of the probability terms becomes unity (Pyers, 1965). The adjustment in the probability terms can be carried out by dividing each term by $[1-\exp(-L\Sigma D_j)]$, resulting in the following modified intervening opportunities model:

$$T_j = O \times [\exp(-LD_{j-1}) - \exp(-LD_j)]/A_f \tag{5.9}$$

where

$$A_f = \text{adjustment factor}$$

$$= 1-\exp(-L\Sigma D_j)$$

The Golding-Davidson Extension to the Model

Golding and Davidson (1970) have provided an interesting extension of Schneider's intervening opportunities model. The main purpose of their extension was to overcome the shortcomings of the Schneider model, to be discussed later in this chapter, associated with the assumption of a constant L magnitude. The Golding and Davidson model is based on the hypothesis that the desirability of a destination declines uniformly with increase in the opportunities considered. The model is expressed as:

$$T_j = O \times \left[\left(\frac{D_m - D_{j-1}}{D_m} \right)^d - \left(\frac{D_m - D_j}{D_m} \right)^d \right] \qquad (5.10)$$

where

D_m = total area destinations

d = calibration parameter

This model can also be calibrated using the iteration approach as described earlier for the Schneider Model.

5.3 Application of the Existing IOM* to FGIP

This section describes the inadequacy of the IOM, in its existing state of art, for the modelling of residential location distribution of FGIP workers in Winnipeg. Examples from several other studies (Bell, 1970; Ruiter, 1967) are cited to exhibit the limitation of the model for distributing spatial activities in urban areas. A comparison of the Schneider model and the Golding and Davidson model is also made in terms of their practical ability for prediction purposes.

Application to the Schneider Model

In the context of determination of residential location distribution of workers of any socioeconomic group around their place of employment the variables of the intervening opportunities model (Eq. 5.9) can

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* Intervening Opportunities Model

be redefined as follows:

T_j = number of workers who reside in housing opportunities band j,

O = total number of workers who seek residences in the urban area under study,

D_{j-1} = housing opportunities considered before reaching opportunities band j,

D_j = D_{j-1}+ housing opportunities available in band j,

L = the constant probability of a possible housing location being accepted if it is considered.

As mentioned earlier, an iterative procedure of the single L-value calibration was employed in this investigation to develop the model for various groups of workers at the FGIP. The algorithm on this procedure began with the determination of an initial value of parameter L to provide a basis for the iteration process. This was done by arbitrarily setting $\Sigma(T_j/O) = 0.9$, and substituting the total number of housing opportunities in Eq. 5.8. In the case of the low income group of workers, for example, an initial value of L was obtained as follows:

$$0.90 = 1-\exp(-L \text{X} 109{,}945)$$

$$(\Sigma D_j = 109{,}945 \text{ from the data})$$

or

$$-L\text{X}109{,}945 = \text{Ln}(.10)$$

or

$$L = \frac{2.30258}{109{,}945}$$

or

$$L \approx 2 \text{ x } 10^{-5}$$

The use of this initial value of L in the intervening opportunities model (Eq. 5.9) provided estimates of residential locations, which were then compared with the actual values from the survey. The principal measure used as the criterion for the predictive ability of the model was the relative deviation S, defined as:

$$S = \sum_j (T_j - \hat{T}_j)^2 \qquad (5.11)$$

where

T_j = predicted number of residential locations in opportunity band j,

$\hat{T}_j$ = actual number of residential locations in opportunity band j.

The next step of the algorithm was to change the value by adding (or subtracting) a constant value of 1×10^{-5}, re-estimate the dependent variable, and calculate a new value of S. This step was repeated until S failed to decrease. The magnitude of L corresponding to the lowest S-value was considered the best fitting model parameter.

The above procedure was used to determine the best fitting values of constant probability parameter L of the model (Eq. 5.9) for various income groups of workers. These are 2×10^{-5} for the low, 4×10^{-5} for the medium, and 2×10^{-5} for the high income group of workers. Since the magnitude of L for a group is dependent on the number of destinations available for that group in the region (Eq. 5.5), the best fitting L-values cannot be used as such to conclude any pattern of variation in the behaviour of different income groups relating to their residential location distribution. This aspect of behavioural difference in the choice of residential location is discussed at a later stage in the chapter.

Because there is no guarantee that the IOM using the best fitting L-value would necessarily provide adequate simulation results, model evaluation was carried out by comparing the predicted and surveyed residential location frequency distribution for each group. It was noticed from the comparisons that the model with a single value of parameter L could not accurately reproduce actual residential location distribution. Fig. 5.1 emphasizes the inadequacy of prediction for the low income group with the use of a single value of L in the IOM. Since spatial separation for the IOM is measured in terms of the number of intervening opportunities or destinations, the actual and predicted number of workers seeking residences are plotted as a function of opportunity bands. For convenience in following the distribution patterns, the entire study area is divided into 10 opportunity bands. Band 1 includes all the possible destinations which fall into the 0-10 percent range of cumulative (by travel time sequence) housing opportunities from the employment centre. Similarly, bands 2, 3, 4, ... 10 include destinations into 11-20, 21-30, 31-40, ... 91-100 percent ranges of cumulative opportunities.

It can be seen from the Fig. 5.1 that the actual and predicted residential distributions are not in close agreement throughout the region when only a single value of L is used in the model. For example, the use of $L = 2 \times 10^{-5}$ (the best fitting value for the low income group) results in underprediction for band 1 and overprediction for band 2 and 3, followed by moderate predictions for some bands and underpredictions for the remaining bands. It is also evident from the figure that as the value of L is increased, more residential locations are assigned to the destinations close to the employment centre.

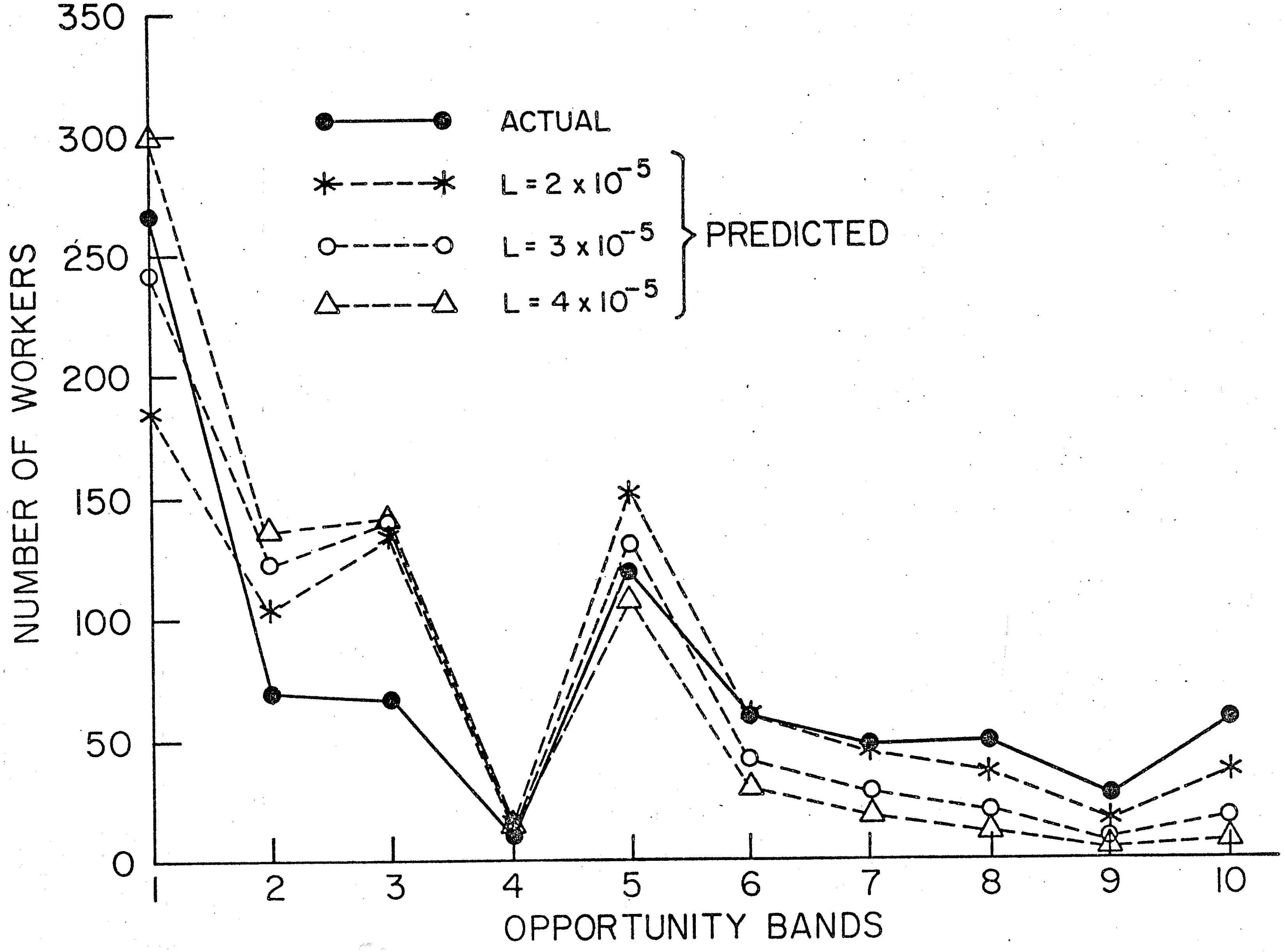

Fig. 5.1 Actual and Predicted Residential Location Distribution Using the IOM with Constant L Parameter.

The above examination of Fig. 5.1 indicates the presence of a systematic error in prediction with a single value of the probability parameter of the IOM. The nature of such an error is further clarified from Fig. 5.2, in which error factors for the different opportunity bands are plotted for different values of the parameter L. The error factor in the figure is defined as the ratio of the actual and the predicted number of workers who seek residence in a particular opportunity band. It is obvious that the errors in prediction are not random but are related to the opportunity bands or the intervening housing opportunities. Similar error patterns were observed for the medium and the high income groups of workers when a single value of L was used for the analysis.

The inadequacy of the IOM using a constant probability parameter L can be more clearly understood by plotting the percentage of total residential locations which are sought at or beyond a specified destination (plotted on a logarithmic scale) against the percentage of all housing opportunities in the intervening space up to that destination. As stated earlier, such a semilog relationship should be of linear form if the intervening opportunities relationship is to prove valid for the data of any study. Fig. 5.3 shows the distribution of residential location of the various groups of workers and the intervening residential opportunities about the FGIP in Winnipeg. It can be observed from the figure that the distribution of workers' residences cannot be very well explained by the 'straight line, semilogarithmic rule' for any of the income groups.

Several other studies of the IOM also observed the nonlinear nature of the semilog relationship between the remaining percentage of

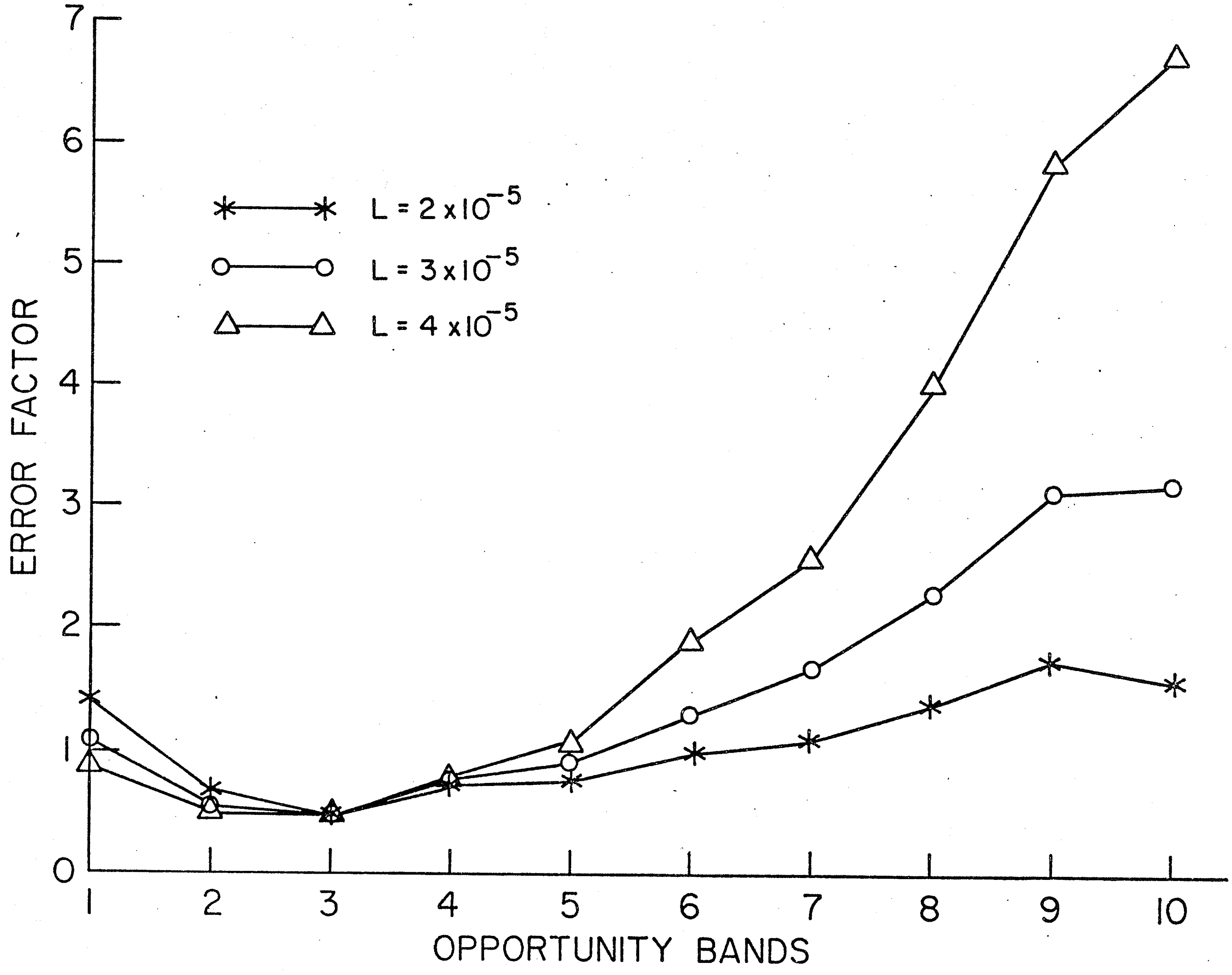

Fig. 5.2 Analysis of Error in Prediction Using the IOM With Constant L Parameter.

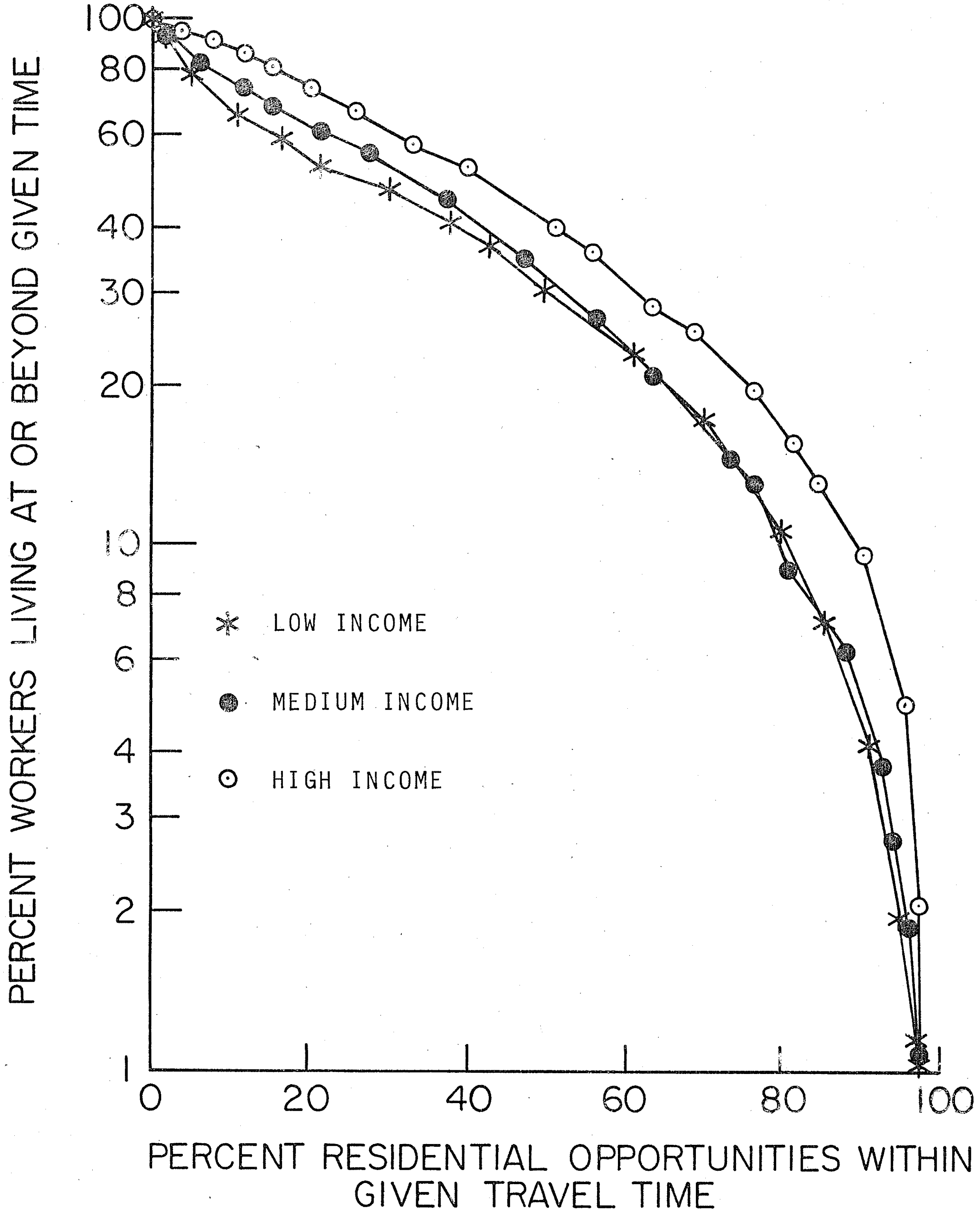

Fig. 5.3 Intervening Opportunities Analysis of Residential Location Distribution of FGIP Workers by Income.

trips vs. the percentage of intervening opportunities. The work of Ruiter (1967) and Bell (1970) may be taken as evidence of this fact. Ruiter cites the example of CATS zone 487 to demonstrate the nature of the semilog relationship for total trips. It is clear from Fig. 5.4 that a straight line (single L-value) would be a poor fit to the relationship. Fig. 5.4 also includes a plot of the relationship for the distribution of trips from a sample employment area of Bell's study. Again, the relationship is of a nonlinear nature which cannot be approximated by a straight line.

Application to the Golding and Davidson Model

The Golding and Davidson model was calibrated using an iteration approach similar to that used for Schneider's model. The value of parameter d in the model (Eq. 5.10) was varied in order to obtain a predicted residential location pattern as close as possible to the actual pattern. The best fitting value of d was chosen on the basis of minimum deviation S as given in Eq. 5.11. When the model evaluation was carried out by plotting the predicted and the actual residential location distribution, the Golding and Davidson model was found inappropriate for all the income groups of workers at the FGIP. Fig. 5.5 clarifies the inadequacy of prediction for the low income group. The figure uses several values of calibration parameter d, including its best fitting value of 1.5, to show the nature of error in prediction. The model with $d = 1.5$ results in a very large underprediction for opportunity band 1, and mostly overpredictions for remaining bands. It is evident from the figure that, as d increases, more residential locations are assigned to the destinations

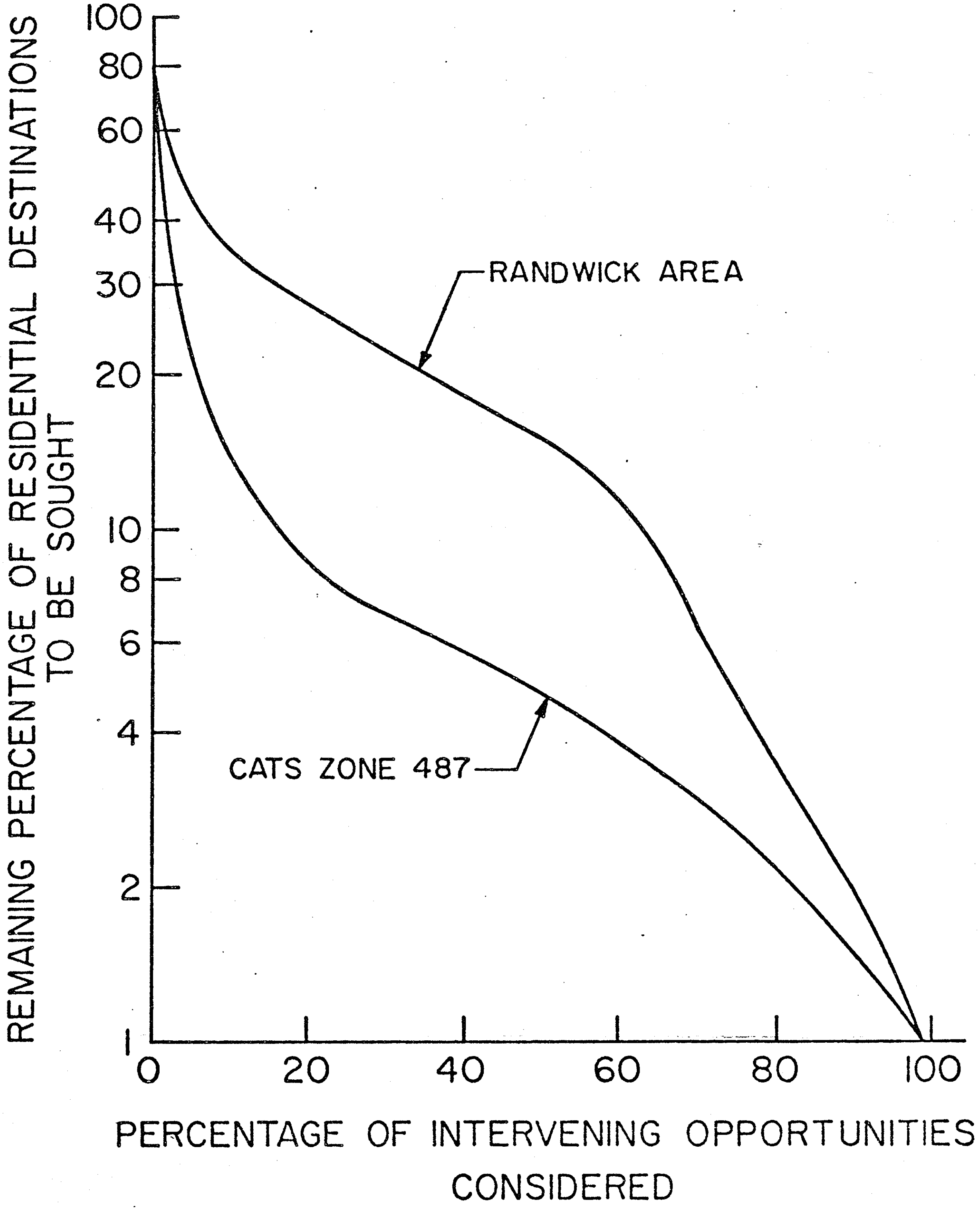

Fig. 5.4 Some Examples of Intervening Opportunities Analysis from Past Studies (Bell, 1970; Ruiter, 1967).

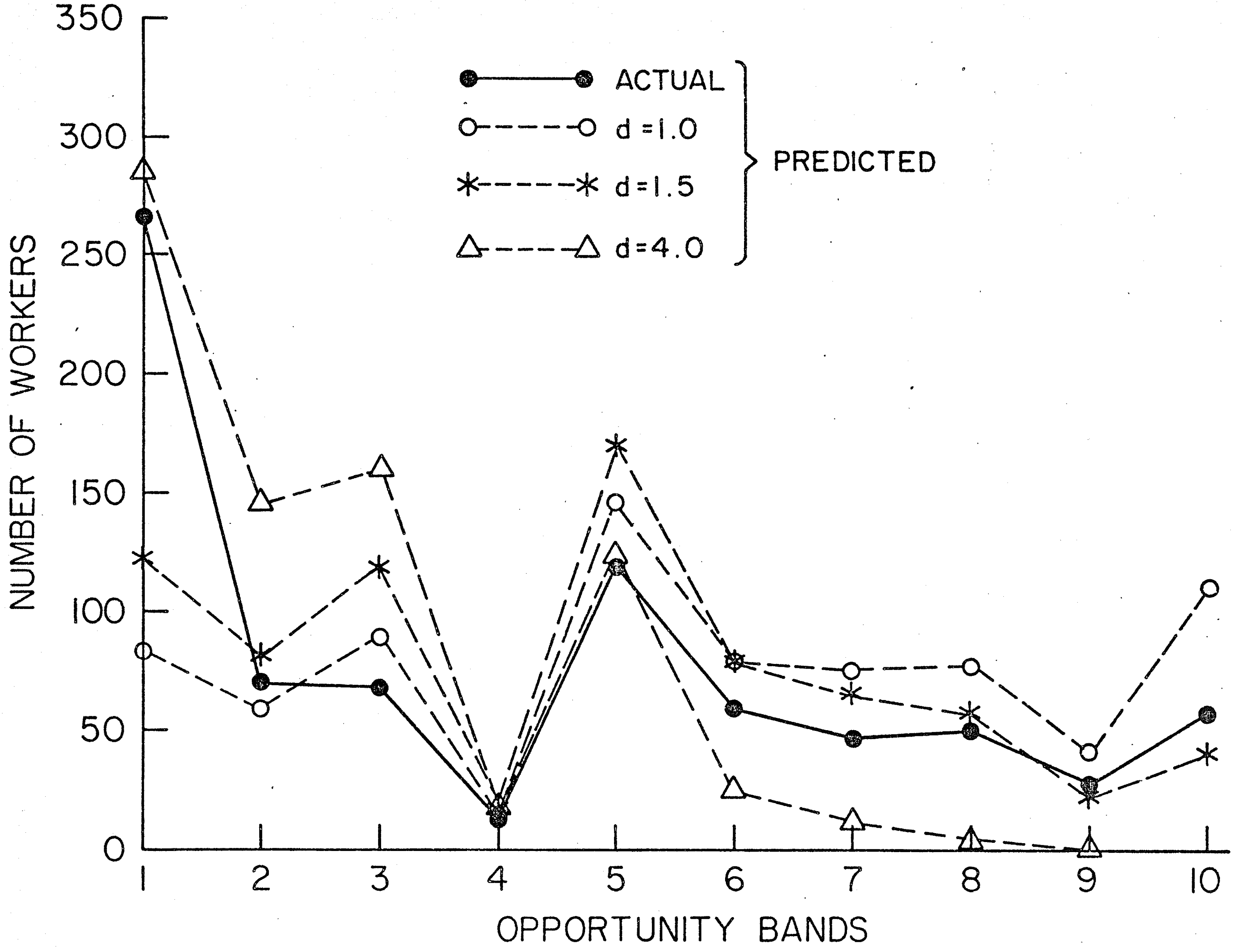

Fig. 5.5 Actual and Predicted Residential Location Distribution Using the Golding and Davidson Model.

close to the employment centre. The value of d = 4 is required in order to bring predicted results close to the actual results in case of band 1. But such a value of d results in large discrepancies for the remaining bands.

The inadequacy of the model of Golding and Davidson can also be demonstrated for the examples of CATS zone 487, Randwick Area, and even for their own study sample of Ipswich City. Fig. 5.6 shows a comparison of the observed probability distribution for CATS zone 487, and Randwick Area (Fig. 5.4) with the theoretical probability distribution as provided by the model. The model distribution of probability is defined in the figure as:

$$f(D) = 1 - \left[\frac{D_m - D}{D_m}\right]^d$$

or

$$f(D) = 1 - (1-X)^d \tag{5.12}$$

where

$f(D)$ = the probability that a suitable destination has been found by the time D opportunities are considered,

D_m = total area destinations,

D = number of opportunities considered,

X = D/D_m, the fraction of opportunities already considered,

d = model parameter.

It is apparent from the pattern of probability distribution curves in the figure (each curve corresponding to a particular value of parameter d) that the model cannot produce results similar to the observed results for CATS zone 487 and the Randwick Area. The inadequacy of the Golding and Davidson model for their own study sample of Ipswich City is shown

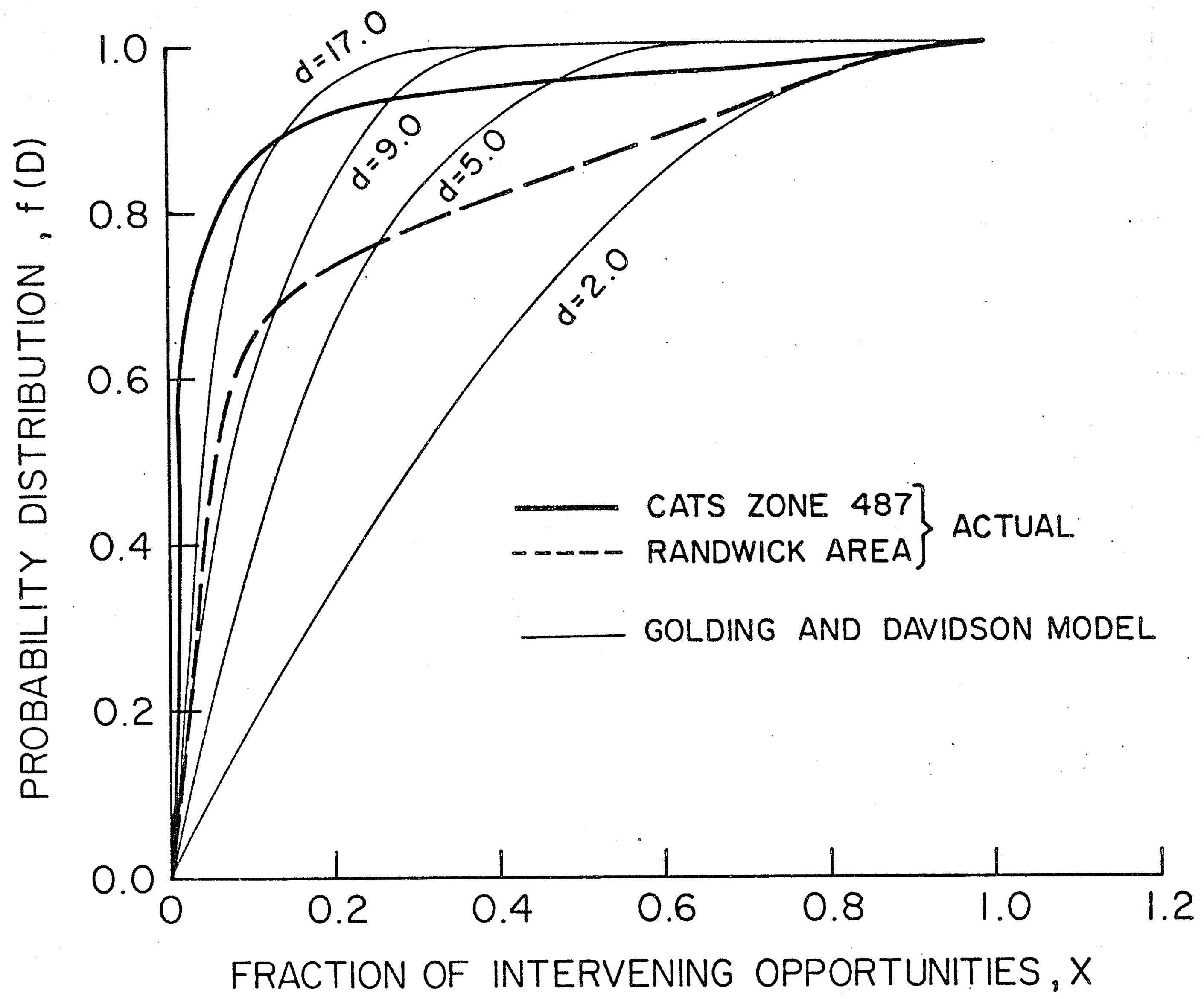

Fig. 5.6 Comparison of Actual and the Golding and Davidson Model Probability Distribution for the Examples of Bell (1970). and Ruiter (1967).

in a later part (Fig. 5.14) of this chapter. It is worthwhile to make the following points in context of the model failure:

(1) In the derivation of their model, Golding and Davidson assume that the desirability of residential location (or any other activity allocation) declines uniformly with increase in the opportunities considered. While such an assumption may hold true for a very limited number of cases in urban activities allocation, it will be difficult to justify that it is general in nature. The author's study of the FGIP, CNRY, and IIP (which is included in a later part of this chapter), the work of Ruiter (1967) and Bell (1970), and all those studies in which the IOM with a constant L-value was found appropriate may be cited as examples to show its lack of general applicability.

(2) It may appear that the Golding and Davidson model has simulation capability better than the Schneider model with a constant L-parameter since the former utilizes a variable probability concept in the intervening opportunities model. Because of the fact that both models involve only one parameter in their probability functions they should have approximately the same predictive ability. The probability functions of these models are: e^{-LD} for the Schneider model, and $[(D_m-D)/D_m]^d$ for the Golding and Davidson model.

The failure of the existing IOM to adequately simulate the residential or trip distribution justifies a further investigation of the subject. The following section describes the development of the IOM with a new probability function which is believed to be a definite improvement over the existing models.

5.4 Development of the IOM with a New Probability Function

The new IOM, as proposed below,is an extension of the Schneider model. Instead of the constant L-value, the proposed model utilizes a variable L-value (say L_d), which is a function of the number of destinations which have already been considered. The idea of using a variable probability originated from the residential or trip distribution curves of Fig. 5.3 and Fig. 5.4. Each of these distribution curves generated discernable L-value curves when the L-values, as calculated by using Eq. 5.5 corresponding to a particular point on the distribution curve, were plotted against the intervening opportunities or destinations. These discernable patterns of L-value curves clearly indicated the possibility of finding a relationship between the probability parameter L and the number of destinations already considered. Incorporating the use of variable probability parameter, L_d in the Schneider model, we get the following distribution model:

$$T_j = O \times [\exp(-L_d D_{j-1}) - \exp(-L_d D_j)]/\{1-\exp(-L_d \Sigma d_j)\} \qquad (5.13)$$

where L_d is a function of D, the number of destinations which have already been considered. The other terms of this equation have been defined previously.

Calibration of the New Model

The calibration of the new model largely consists of curve fitting using data similar to those in Fig. 5.3 and 5.4, and determining methods of predicting the parameter needed to relate the variable L_d value to D, the number of destinations which have already been considered.

The least squares procedure of curve fitting which was utilized in this study can be explained in the following manner:

First data points L_d and D for fitting an appropriate curve were obtained from Fig. 5.3 using Eq. 5.5. It may be noted that the distribution curves of Fig. 5.3 (and 5.4) are the plots of remaining percentage of destinations to be sought or 100[1-P(D)], vs. percentage of intervening opportunities considered or $100(D/D_m)$. Corresponding to a particular point on the plot of the figure, the value of L_d was determined as follows:

$$L_d = \frac{-\mathrm{Ln}[1-P(D)]}{D}$$

Secondly, these data points were plotted on a graph paper to identify the type of equation that would fit this data. It appeared from such a plot that a relationship of the following form (known as Hoerl's special function) would fit the data (for all groups of workers),

$$L_d = aD^b e^{cD} \tag{5.14}$$

The next step was to find constants a, b, and c in the above relationship. This was accomplished by using the least squares technique after Eq. 5.14 was changed to a linear form by taking the logarithm of both sides as:

$$\mathrm{Ln}L_d = \mathrm{Ln}a + b\mathrm{Ln}D + cD$$

For the different groups of workers, the least squares technique resulted in the following L_d models:

(i) Low Income Group

$$L_d = 0.5827 \times 10^{-5} X^{-0.6717} e^{1.7277X} \quad (5.15)$$

[coefficient of determination, $R^2 = .9222$]

(ii) Medium Income Group

$$L_d = 1.5520 \times 10^{-5} X^{-0.4582} e^{1.6736X} \quad (5.16)$$

($R^2 = .9401$)

(iii) High Income Group

$$L_d = 2.9578 \times 10^{-5} e^{1.1536X} \quad (5.17)$$

($R^2 = .9149$)

where X is a fraction of the opportunities already considered for a suitable destination, i.e. X = D/total opportunities in the region.

5.5 Behavioural Interpretation of the New Model

The R^2 values for Eq. 5.15, 5.16 and 5.17 indicate that the form of Eq. 5.14 provides a good fit for the variable probability parameter L_d and X, in all income groups of this study. Also, it is worth noting that the structure of this model appears to express an understandable relationship between the variables involved. Let us consider the components X^b and e^{cX} in the expression to make a behavioural interpretation of the model. Since b is less than or equal to zero in any of the above models (Eq. 5.15, 5.16, or 5.17) the component X^b tends to decrease the value of L_d as X increases. The e^{cX} component tends to increase L_d with an increase in X because of the positive magnitude of the constant c in all the cases. It is clear from the curves of Fig. 5.3, and Fig. 5.4 that a decrease in L_d-value has a lessening effect on the rate of accepting a destination when it is considered. The component X^b may therefore be considered as a factor which diminishes the rate of accepting a destination as X increases. On the other hand, e^{cX} may be interpreted as a factor which increases the rate of accepting a destination. The structure of the variable probability parameter model resulting from the multiplication of X^b and e^{cX} components can be viewed then as a relationship describing the behaviour of people in terms of two independent objectives that they are trying to satisfy simultaneously. One objective is concerned with a desire for the proximity of a destination, mainly in order to keep their transportation costs in line with their income. The other objective may be concerned with an abhorrence of proximity. Without regard to the level of income, or even the type of employment (as illustrated from other studies), certain people seemingly choose to live a long way away from the place of work. This may perhaps be related to childhood training, experience and cultivated life style, and other psychological variables determining the taste of the individual. The values of constants a, b, and c in the probability model will depend upon trip makers of a specific type and for a specific purpose, and may vary from one type of origin zone location to the other type of location in any urban region.

A comparison of the models of L_d-parameter for various income groups is made in Fig. 5.7. The plots of cumulative probability of residential location distribution in the figure utilizes Eq. 5.15, 5.16, and 5.17 corresponding to the low, medium, and high income groups, respectively. It is clear for the community under investigation that the workers of the low income group live closer to their places of employment as compared to the workers of the high income group. This fact is also

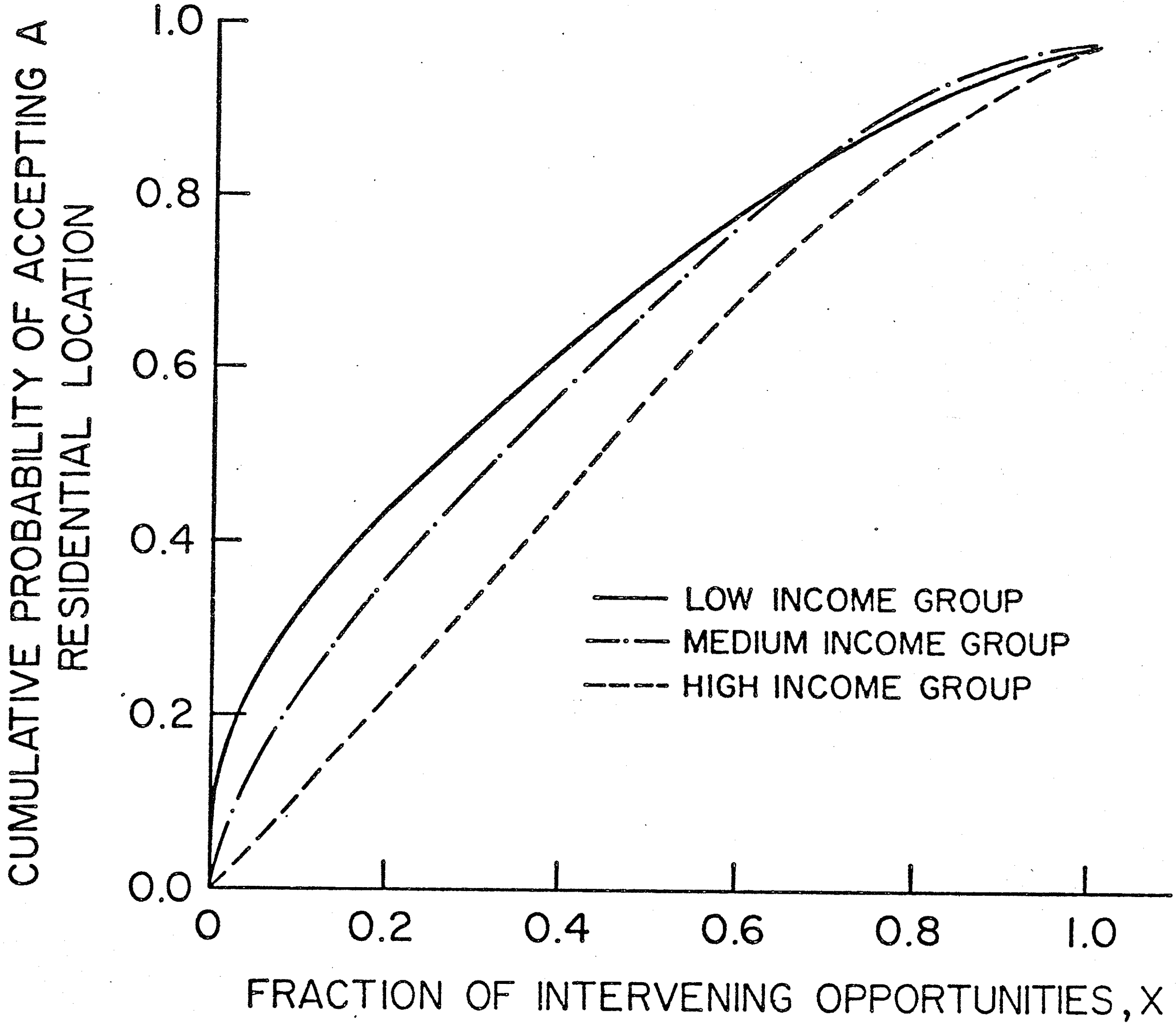

Fig. 5.7 Comparison of Residential Location Choice Behaviour of Various Income Groups at FGIP.

corroborated in the application of the model for CNRY and IIP data which is discussed later in the chapter. The low income group may choose to live closer to the place of employment depending upon neighbourhood affiliation, land use infrastructure, type of housing, or merely because the part of the income spent on commuting seems disproportionately large. The medium income group would appear comparatively less susceptible to the influence of the cost of transportation in choosing a residential location; the high income group perhaps may be considered completely unaffected in this respect.

Fig. 5.8 and 5.9 are included to show the adequacy of the IOM prediction results using the variable L_d-value for various income groups of workers of FGIP.

5.6 Testing of the Model

As was done for the competing opportunities model, the intervening opportunities model as developed using the data from FGIP was also tested for other employment centres located in the City of Winnipeg. Fig. 5.10 exhibits a comparison of the actual residential distribution of CNRY workers with the predicted results employing the IOM developed using specific data from FGIP. It is obvious that the model does not provide a very close agreement with the surveyed residential distribution for workers of CNRY. Specifically, the observed number of residential locations in the first opportunities band is considerably greater than can be predicted by the model for any of the income groups. For most other bands, as a result, the observed number is lower than the predicted number of residences. Such a discrepancy between the actual and the model

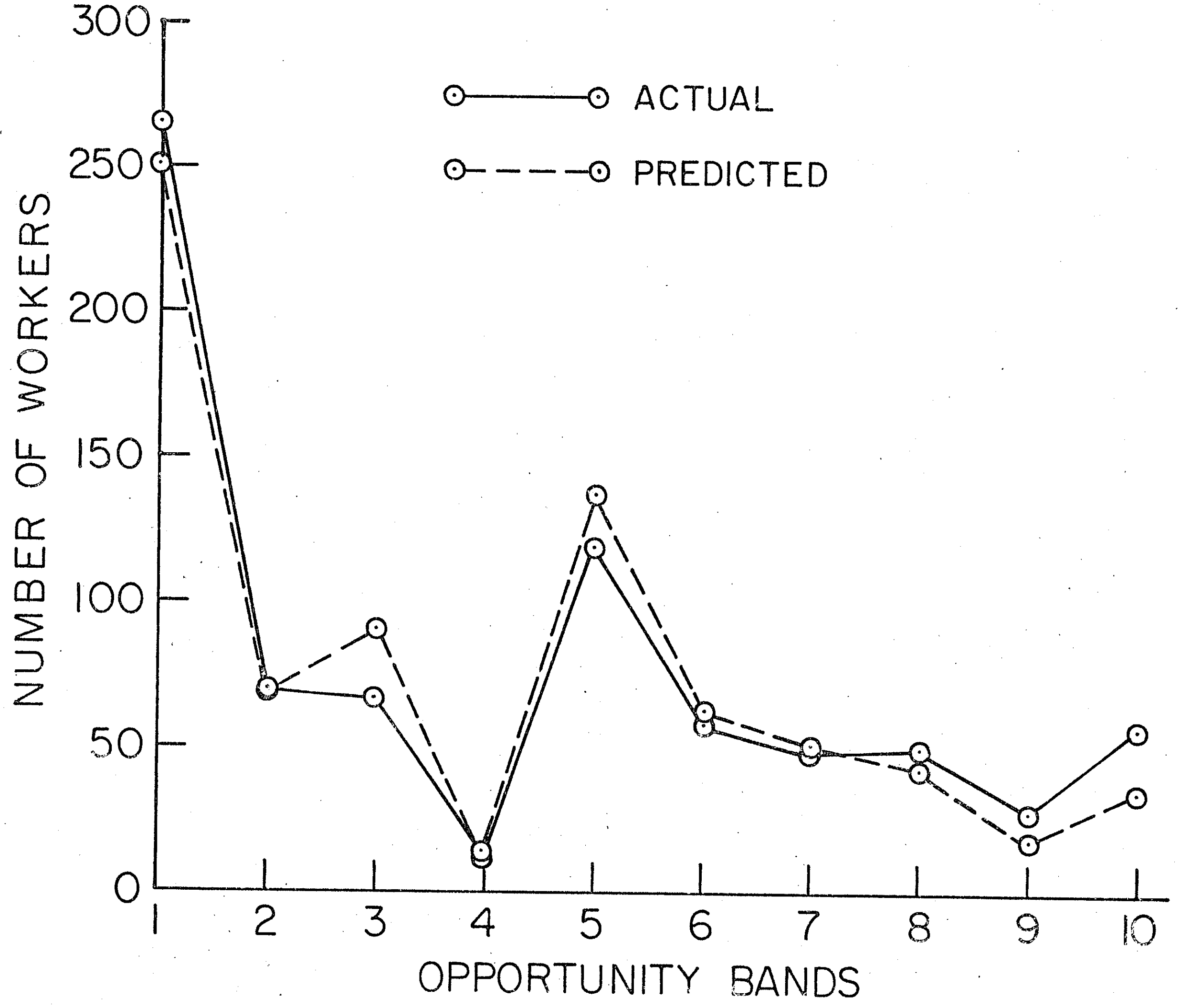

Fig. 5.8 Actual and Predicted Residential Location Distribution Using the IOM With Variable L_d Parameter for the Low Income Group at FGIP.

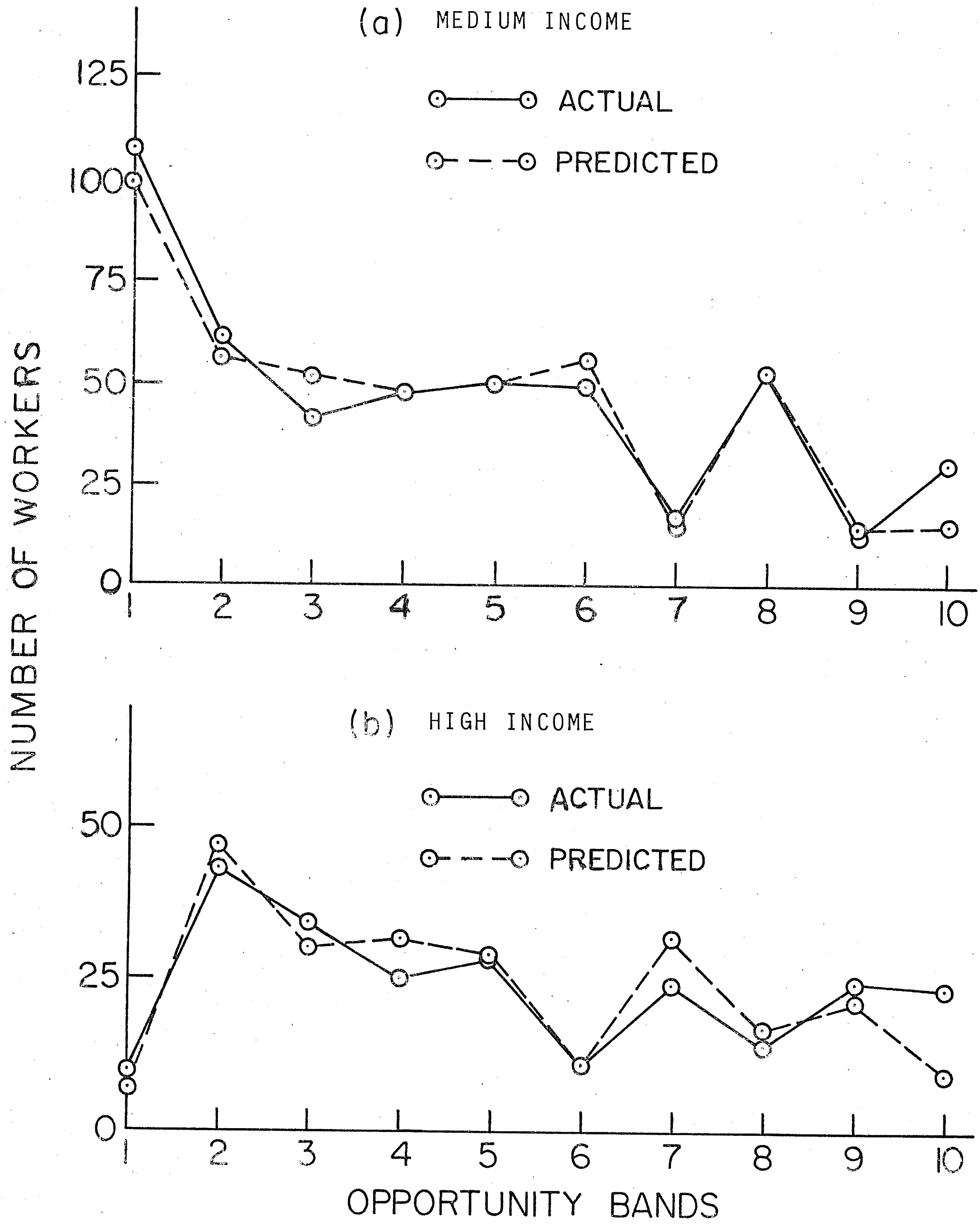

Fig. 5.9 Actual and Predicted Residential Location Distribution Using the IOM With Variable L_d Parameter for the Medium and the High Income Groups at FGIP.

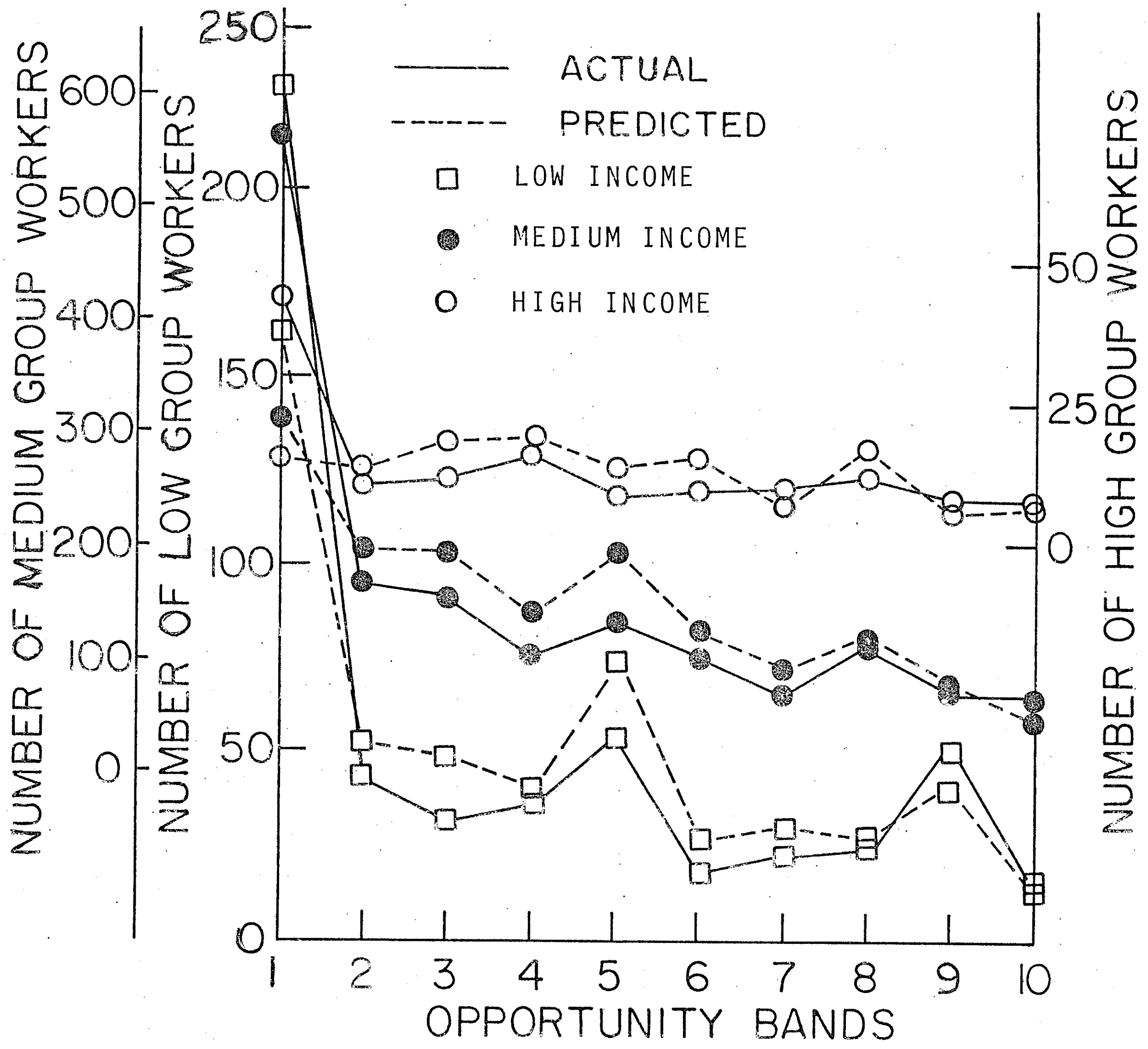

Fig. 5.10 Actual and Predicted Residential Location Distribution Using the IOM With Variable L_d Parameter for Workers at CNRY.

distribution can perhaps be attributed to the location of CNRY employment centre in the City of Winnipeg. There is an apparent discontinuity in the residential development between Transcona community (where the CNRY is located) and other nearby communities such as East Kildonan, and St. Boniface. This discontinuity of residential development probably forces some additional workers to choose their residences in Transcona because otherwise they would have to choose from other communities which mignt be located too far for their consideration.

In testing of the COM for IIP it was noticed that the residential location distribution models developed for low and medium income groups of workers at FGIP were also found adequate for labour and clerical groups of workers*, respectively at IIP. Therefore the low group IOM was tested for labour and the medium group IOM was tested for clerical workers of IIP. However, a correction in the IOM developed for FGIP, was required before testing for IIP data collected by Saccomanno (1972). From Eq. 5.5 it is clear that magnitude of the probability parameter is inversely proportional to the available opportunities in a zone and since the housing opportunities for low and medium income groups are classified in a different manner than Saccomanno's classification (Chapter III), the L_d-values for the two classification can be brought into relation as follows:

$$L_{d2} = \frac{D_1}{D_2} \times L_{d1} \qquad (5.18)$$

where

---

* The managerial group of workers is not included in the testing since its sample of 52 was considered too small to show any pattern.

L_{d1}, L_{d2} = parameter values for classification 1 and 2, respectively

D_1, D_2 = number of classified opportunities according to classification 1 and 2, respectively.

Employing the above relationship and Eq. 5.15 and 5.16 (corresponding to low and medium groups, respectively) residential locations of labour and clerical groups were predicted and compared with the observed locations as shown in Fig. 5.11. The predicted values appear to be fairly close to the actual values with the exception of fairly large overprediction in the first opportunities band for labour group. The disagreement may be due to the different nature of Saccomanno's classification, the location of IIP in the study region, or other variables not included in the model. A further interpretation of the disagreement between the actual and the predicted distribution for CNRY and IIP is included in Chapter VII.

It may be appropriate at this stage to compare the semilogarithmic residential distribution of CNRY and IIP workers with FGIP distribution as shown in Fig. 5.3. It is noticable from Fig. 5.12 that a higher percentage of CNRY workers than FGIP workers lives in residential areas nearest to the employment centre. On the other hand, Fig. 5.13 shows that a lower percentage of IIP labour workers than FGIP low-income workers live in the residential areas nearest to the centre. It may be said that workers at curves for CNRY and IIP are otherwise, in general, quite comparable to that of FGIP.

It is worthwhile now to comment briefly on the general applicability of the model proposed in this chapter. The IOM with variable probability parameter can also adequately simulate the trip making be-

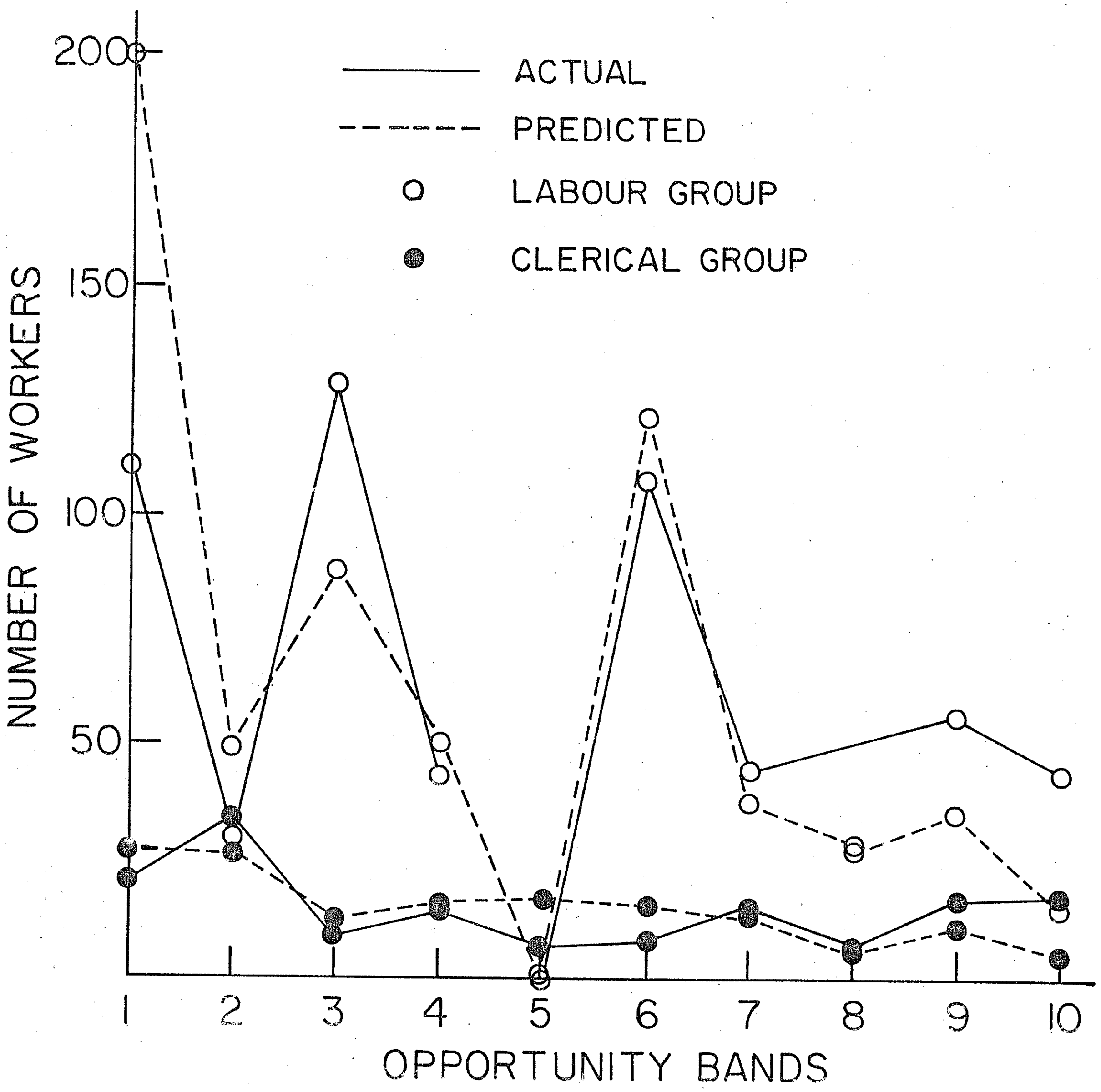

Fig. 5.11 Actual and Predicted Residential Location Distribution Using the IOM with Variable L_d Parameter for Workers at IIP.

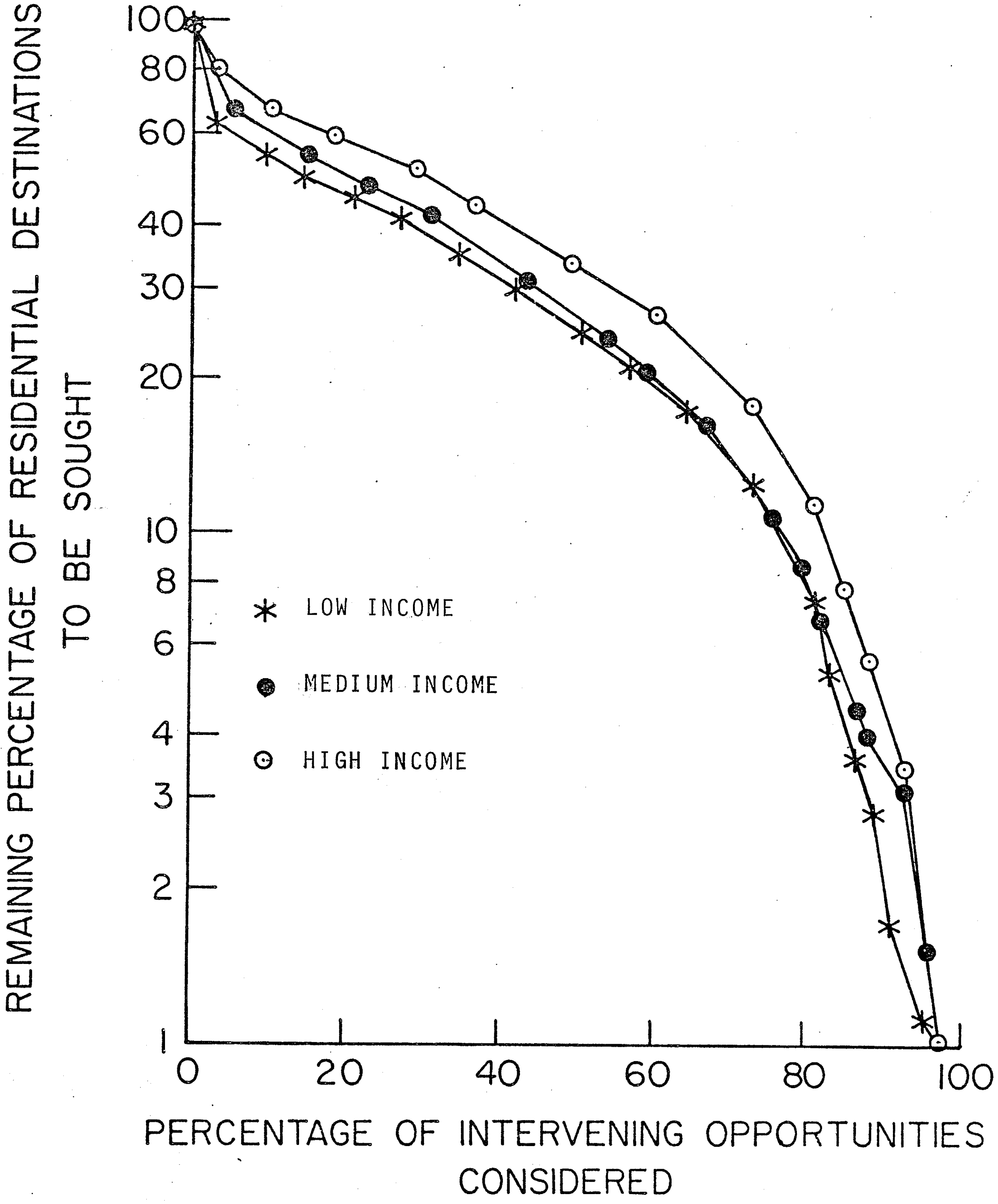

Fig. 5.12 Intervening Opportunities Analysis of Residential Location Distribution of CNRY Workers of various Income Groups.

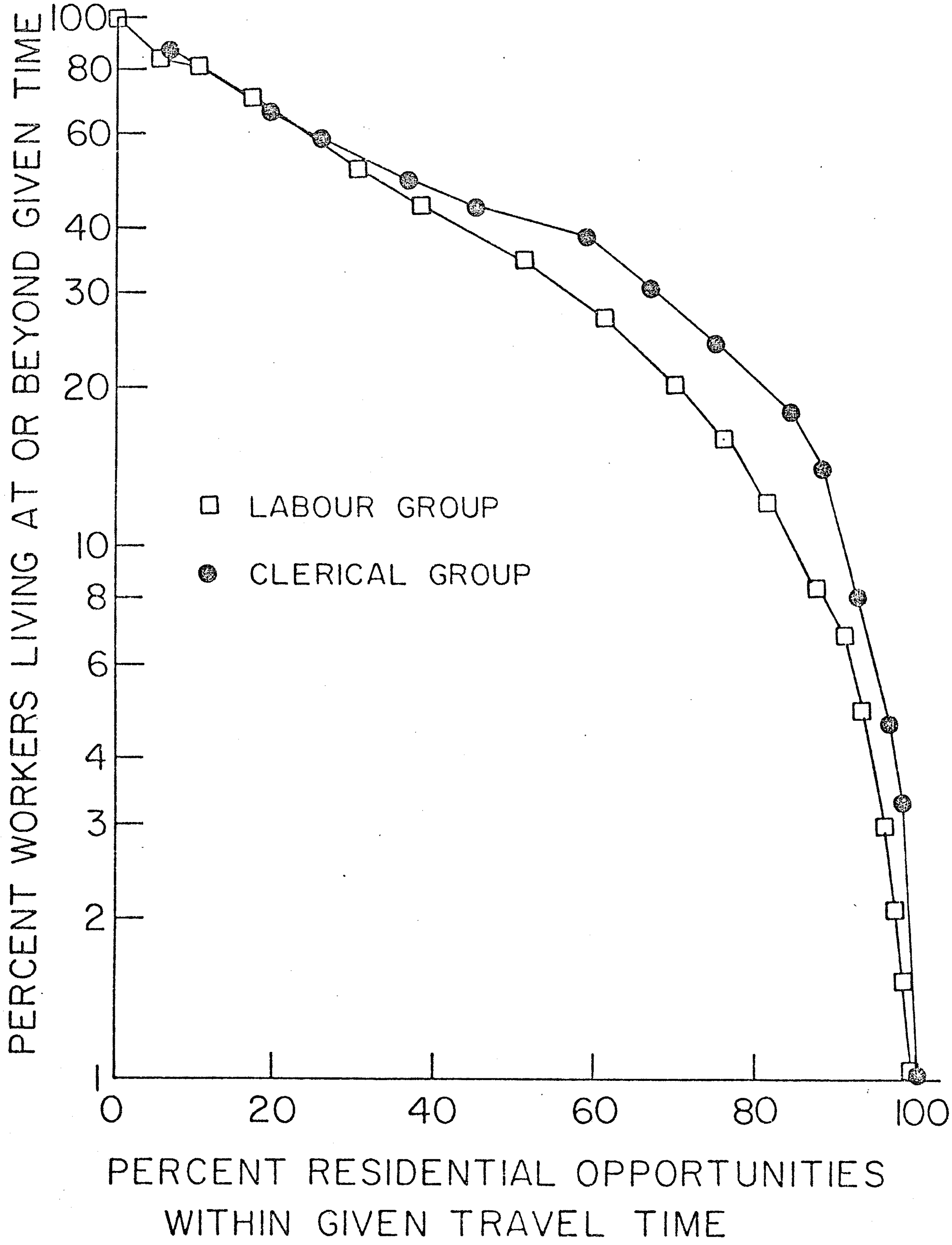

Fig. 5.13 Intervening Opportunities Analysis of Residential Location Distribution of IIP Workers.

haviour as observed in the cases of CATS zone 487, and Randwick Area. The use of a total number of destination opportunities in the area, D_m = 100,000 resulted in the following L_d models for these two cases:

(i) <u>CATS zone 487</u>

$$L_d = 6.07 \times 10^{-6} X^{-2.0456} e^{3.5603X} \qquad (5.19)$$

$$(R^2 = .9943)$$

(ii) <u>Randwick Area</u>

$$L_d = 3.344 \times 10^{-9} X^{-7.5401} e^{13.0234X} \qquad (5.20$$

$$(R^2 = .9979)$$

The R^2-values for Eq. 5.19 and 5.20 indicate that the form of probability parameter L_d, as suggested in this study, can explain very well the variation in the probability parameter as a function of the fraction (or number) of opportunities considered before reaching a destination for the two examples. The predictive ability of the new model and its superiority over the existing models is further exemplified in Fig. 5.14. It is obvious from the figure that, when applied to the Ipswich City data of Golding and Davidson, the new model produces much better results than the Schneider model and the Golding and Davidson model.

The validity of the new model can be further highlighted by considering yet another example. Fig. 5.15 is a comparison of actual and predicted distribution of work trips using the Schneider model for Washington, D.C. The comparison which was performed by Pyers (1965) shows that the use of a constant value of L (2.85×10^{-6}) does not provide a close agreement between the actual and the predicted distribution. However, it is apparent from the figure that a systematic error exists

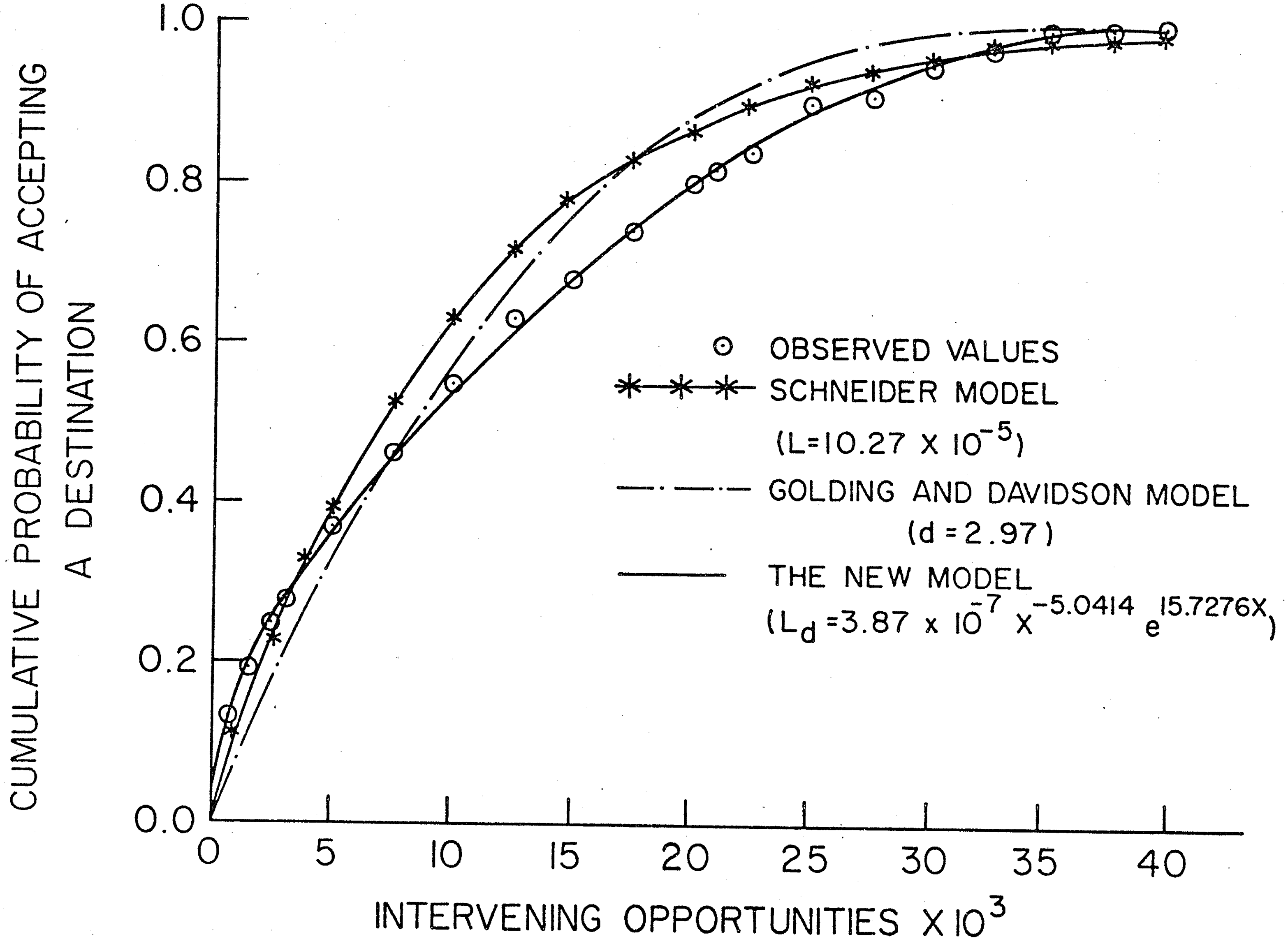

Fig. 5.14 An Application of Various Intervening Opportunities Models to the Ipswich City Data of Golding and Davidson (1970).

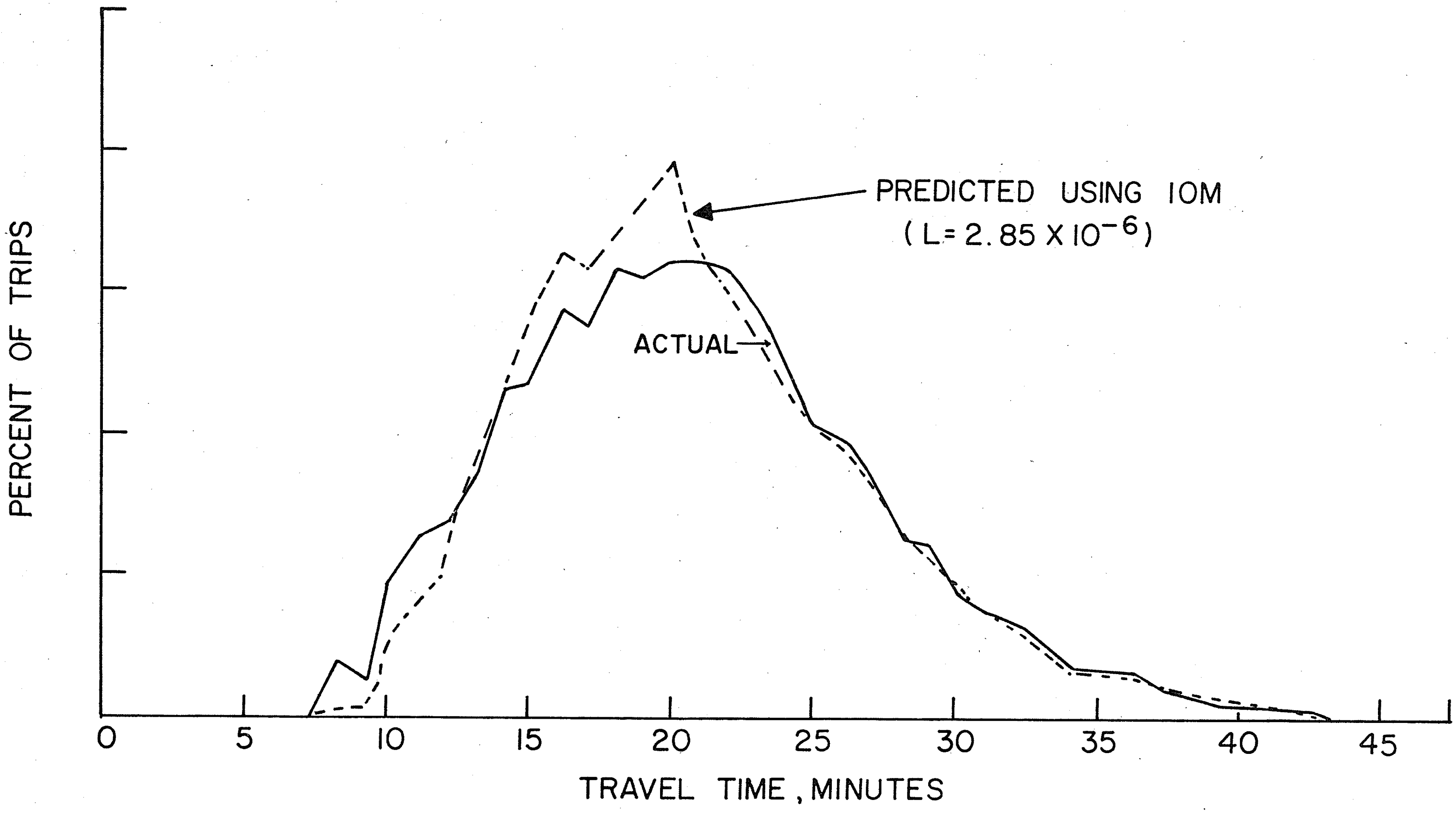

Fig. 5.15 Actual and Predicted Trip Distribution Using the IOM With Constant L Parameter, Work Trips, Washington, D.C. (Pyers, 1965)

between the distributions. The nature of such an error is clarified in Fig. 5.16, in which error factor (actual percentage/predicted percentage) is plotted as a function of travel time. The shape of this plot is generally similar to the error plots in Fig. 5.2 for the sample of the present study and suggests that the IOM with a variable probability parameter, as introduced in this study, would provide better agreement in Pyers's case, as well.

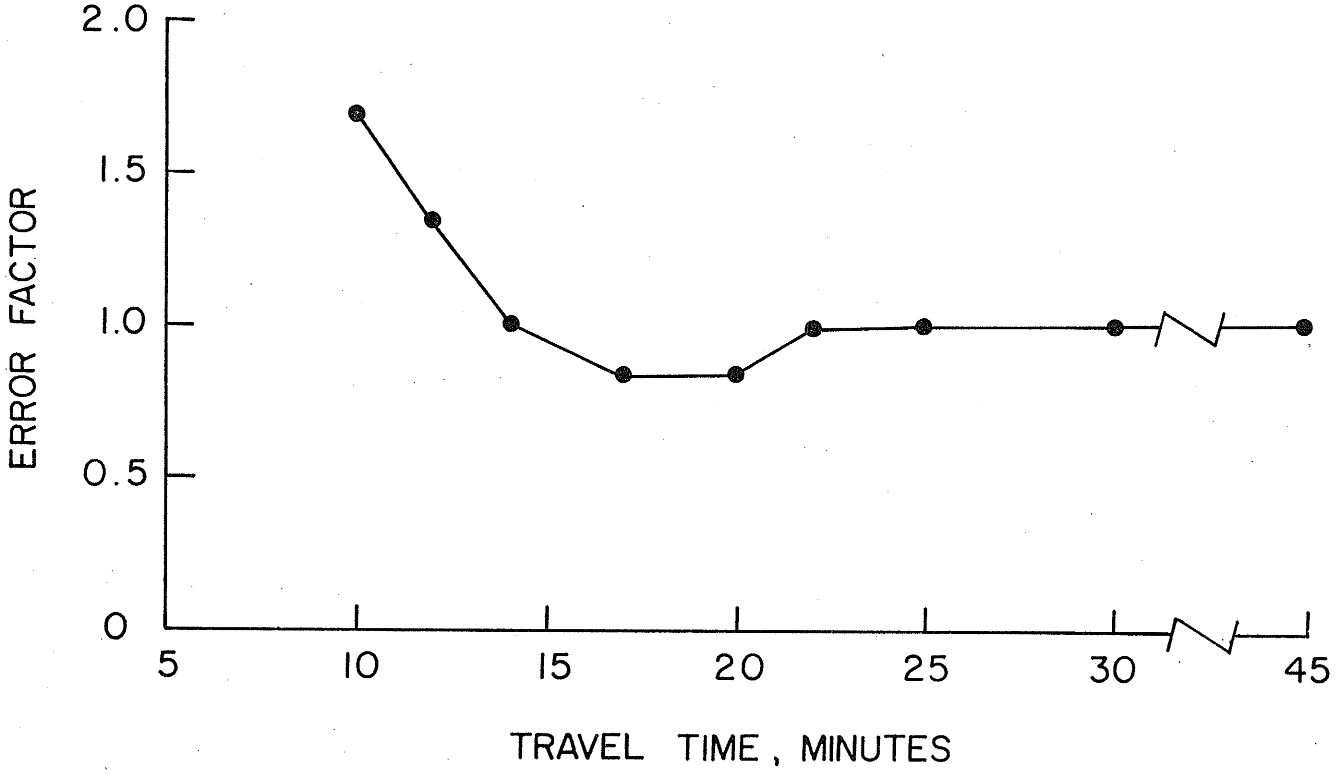

Fig. 5.16 Analysis of Error in Prediction Using the IOM with Constant L Parameter, Work Trips, Washington, D.C. (Pyers, 1965)

CHAPTER VI

GRAVITY MODEL OF RESIDENTIAL LOCATION DISTRIBUTION

6.1 Introduction

The earliest use of the theory of gravity in the field of transportation planning was an application to studies of intercity travel (Astrom, 1953). Martin, Memmott, and Bone (1961), Olsson (1965), and Smith (1971) reviewed the uses of the gravity model in urban transportation studies, migration research, and commodity flow studies respectively. Further work on the model by many researchers has appeared in the literature frequently in recent years. Considering the variety of viewpoints and the numerous studies undertaken, any attempt at reviewing the literature covering the transportation-related use of the gravity model would constitute a major study in itself. The present author will include, therefore, only those findings on the gravity model which are pertinent to the analysis and development of the gravity model of residential location distribution.

6.2 Analytical Derivation with Adaptation to the Problem

In the initial portion of this section the general form of the gravity model is derived from the theory of probability. The derivation is a combination of the methods introduced to the transportation field by Cohen (1959), Wilson (1967) and Zaryouni (1974). Here, other than conceptual clarification of the model in the context of the present problem, no claim of originality is made for this derivation. Next, using some hypotheses on the concept of marginal perceived travel cost, different forms of the distribution function of the gravity model are derived.

Let us consider an employment centre A which provides jobs to individuals who seek suitable housing opportunities in the entire urban area comprised of numerous residential districts. Neither the workers nor the opportunities in the residential districts are homogeneous; therefore, a given individual prefers a given opportunity over the other opportunities available to him. While searching for a suitable housing location in a residential district, the individual is concerned about such considerations as the quality of housing, transportation cost between the location of housing and the employment centre, and availability of other neighbourhood services, such as shops, churches, schools, parks, and similar local foci of activity in the district. Let p_i be a preference function which is proportional to the probability that a worker (employed at A) of a particular socioeconomic group would choose a suitable housing opportunity in residential district i if the cost of reaching all opportunities were the same and there were no limitation on the number of available opportunities for all the districts in the urban system. In other words, p_i is a certain intrinsic preference that a worker gives to locate his household in a given residential district. Of course, this preference will be a function of other neighbourhood services as mentioned earlier.

The probability that an individual worker seeks a residence in district i is by definition proportional to p_i, if transportation were not costly and there were no restrictions on the number of available housing opportunities for each district. In the real world, however, the resources used in transportation and the number of available opportunities are limited. Therefore, the probability of choosing a residence in district i (while employed at a particular job place) is not simply p_i. The problem then is to find the best estimator for T_i, the residential locations sought in district i, given the probability p_i, the transportation cost and the available opportunity constraints. The following notations are used in the analysis:

T_i = number of workers of a socioeconomic group who reside in district i when employed at A,

O = total number of workers seeking residences in the urban area,

d_i = number of suitable housing opportunities for the group available in district i,

C_i = perceived cost of travelling between district i and the employment centre A,

C = total resources (cost) spent in transportation within the system.

The limitation of resources means:

$$C = \sum_i C_i T_i \tag{6.1a}$$

and the restriction on available opportunities means:

$$O = \sum_i T_i \tag{6.1b}$$

The development of the residential distribution model requires the best estimator for T_i, given the probability p_i, the availability of the housing opportunities d_i, and the constraints of Eq. 6.1a and Eq. 6.1b.

Other distribution problems of this type have been handled in different ways but conceptually with the same objective, i.e., to minimize bias when some prior information about the behaviour of the system exists. One of the ways is the maximization of the likelihood function of the system (Sasaki, 1967) as in the general probability theory.

According to the likelihood theorem, the best estimator is the one which maximizes the likelihood of T_i where the likelihood function of T_i is a joint distribution of all observed T_i's (Kendall, 1946). To determine this joint probability distribution, let us first consider a specific arrangement of workers on household sites. The probability that a given worker lives in the ith district is proportional to the number of suitable sites in that district times the preference factor p_i. In that case, the probability of the specific arrangement of all the workers over their household sites is simply the product of the probability of finding each worker in the district in which he lives

$$\prod_i (d_i \; p_i)^{T_i} \tag{6.2}$$

However, we are not interested in the probability that a specific group of T_i workers is in the ith district but only in the probability that any T_i workers are in the ith district. Hence, to get the required joint probability distribution, say Z, we must multiply Eq. 6.2 by the number of ways in which one can partition O objects into groups containing T_i objects each, which is

$$\frac{O!}{\prod_i T_i!} \tag{6.3}$$

Multiplication of Eq. 6.2 and Eq. 6.3 gives the desired result for Z,

$$Z = \frac{O!}{\prod_i T_i!} \prod_i (d_i\ p_i)^{T_i} \tag{6.4}$$

The method of Lagrangian multipliers can now be used to obtain the set of T_i's for which Z, or equivalently Ln Z, is a maximum. The problem is to maximize the Lagrangian ϕ (here ϕ = Ln Z) subject to the constraints of Eq. 6.1a and Eq. 6.1b:

$$\begin{aligned}\phi &= \text{Ln } O! - \sum_i \text{Ln } T_i! + \sum_i T_i \text{ Ln}(d_i\ p_i)\\ &+ \beta_1 (C - \sum_i T_i\ C_i) + \mu(O - \sum_i T_i)\end{aligned} \tag{6.5}$$

where β_1 and μ are Lagrangian multipliers.

By taking the first derivatives with respect to T_i and equating then to zero, we obtain

$$\frac{\partial\phi}{\partial T_i} = -\text{ Ln } T_i + \text{Ln}(d_i\ p_i) - \beta_1\ C_i - \mu = 0 \tag{6.6}$$

The derivative of Ln T_i! is obtained by using Stirling's approximation (Wilson, 1967) to estimate the factorial terms:

$$\begin{aligned}\text{Ln } T_i! &= T_i \text{ Ln } T_i - T_i\\ \frac{\partial \text{ Ln } T_i!}{\partial\ T_i} &= \text{Ln } T_i + \frac{T_i}{T_i} - 1 = \text{Ln } T_i\end{aligned} \tag{6.7}$$

Solving Eq. 6.6 gives

$$T_i = d_i\ p_i\ \exp(-\mu)\ \exp(-\beta_1\ C_i) \tag{6.8}$$

The optimum value of T_i obtained by Eq. 6.8 maximizes ϕ, and therefore, Z, because the second derivative of ϕ with respect to T_i is always negative:

$$\frac{\partial^2\phi}{\partial T_i^{\ 2}} = \frac{\partial}{\partial T_i} (-\mathrm{Ln}\ T_i) = -\frac{1}{T_i}$$

It can be shown now that the residential location distribution model given by Eq. 6.8 is the conventional form of the gravity model. Let us first consider the value of p_i equal to unity for all i's as in the conventional gravity model (and also in the derivation of Wilson, 1967), and therefore omit it from Eq. 6.8. This omission of p_i from the model assumes that the neighbourhood services other than housing are uniformly distributed throughout the region. Moreover, it can also be assumed that, although the workers have particular preferences for some districts, these differences are averaged out.

The model (Eq. 6.8) without using p_i can be written as:

$$T_i = d_i \exp(-\mu) \exp(-\beta_1 C_i) \tag{6.9}$$

or

$$\sum_i T_i = O = \exp(-\mu) \sum_i d_i \exp(-\beta_1 C_i)$$

or

$$\exp(-\mu) = \frac{O}{\sum_i d_i \exp(-\beta_1 C_i)}$$

putting the above value of exp(-μ) in Eq. 6.9:

$$T_i = A\ d_i O \exp(-\beta_1 C_i) \tag{6.10}$$

where

$$A = [\sum_i d_i \exp(-\beta_1 C_i)]^{-1} \tag{6.11}$$

A may be called a normalization factor because its value is such that the total number of housing locations sought by the workers is equal to the total number of workers at the employment centre.

The above analysis shows that the use of the gravity model for distributing residential locations of workers of a large employment centre has a sound base in statistical theory. This theory is effectively stating that, given the total number of housing locations being sought and the number of available housing opportunities for each district for a homogeneous group of workers, and given the cost of transportation between employment centre and each zone, there is a most probable distribution of residential locations between the employment centre and the residential districts, and this distribution is the same as the one normally described as the gravity model distribution.

Mathematical Forms of Distribution Function

The expression $\exp(-\beta_1 C_i)$ in Eq. 6.10 is known as the distribution function. As mentioned earlier in this chapter, C_i in this expression is the cost of transportation as perceived by the seeker of the residential location and not the cost as decided by the planning authorities. It is difficult to know how a worker perceives the cost of travel between home and job because the matter is subjective and complex. It is therefore more appropriate to formulate the distribution function in terms of the actual travel cost t_i (usually expressed in terms of travel time or travel distance), by hypothesizing about the perceived cost, C_i. Let the distribution function in terms of actual travel cost be called $F(t_i)$. Some of the distribution functions which are utilized in this study can be derived as follows (Zaryouni, 1974):

i) Negative Exponential Function

To derive distribution functions in terms of actual travel cost, let us assume that there exists a predominant form of perceived cost for a given urban system and this predominant perceived cost can be stated as a function of the actual cost. To state this mathematically:

$$C_i = g(t_i)$$

where

C_i is perceived cost of travel between home and work place,

g is the predominant functional form for a given urban system,

t_i is actual travel cost between home and work.

The form of function $g(t_i)$ decides the form of distribution function. For example, if it is assumed that the perceived cost is proportional to the actual travel cost t_i, the exponential form of distribution function is obtained. Mathematically:

$$C_i \propto t_i$$

or

$$C_i = a\, t_i \tag{6.12}$$

which gives the distribution function:

$$F(t_i) = \exp(-\beta_1 C_i) = \exp(-a\beta_1 t_i)$$

$$= \exp(-\beta t_i)$$

It must be noted that this negative exponential form of distribution function will hold good only when the marginal perceived cost, MC_i, is constant, i.e.,

$$MC_i = \frac{dC_i}{dt_i} = a \text{ (from Eq. 6.12)}$$

The situation of constant marginal perceived cost may or may not be true for individual cases.

ii) Inverse Power Function

Intuitively, it appears that a unit of cost should be perceived as higher when the cost of transportation is small and as lower when the cost of transportation is great. In other words, the marginal perceived cost is a decreasing function of actual travel cost. This hypothesis can be stated mathematically in the following form:

$$MC_i = \frac{dC_i}{dt_i} = \frac{b}{t_i}$$

where b is a positive constant.

Integration of the above gives

$$C_i = b \text{ Ln } t_i$$

Then the distribution function becomes:

$$F(t_i) = \exp(-\beta_1 C_i) = \exp(-\beta_1 b \text{Ln } t_i)$$

$$= t_i^{-\alpha} \quad \text{where } \alpha = \beta_1 b$$

This is the well-known inverse power function of the gravity model.

Many other mathematical forms of distribution function have been suggested and used by researchers in the past. Morrall (1971) presents a brief description of such forms of functions, including their advantages and disadvantages. None of these forms can be considered as a universally acceptable form. This deficiency has often been regarded as a shortcoming in the forecast of the future travel in urban areas.

A more detailed discussion of the different forms of distribution functions is omitted from this thesis not only for the sake of brevity, but also because it has little direct bearing on the present work. However, it is important to note the work of Ashford and Covault (1969), Morrall (1971), and Zaryouni (1974) in this field.

6.3 Model Development and Analysis of Results

Selection of Distribution Function

The residential distribution function, $F(t_i)$, expresses the effect that spatial separation exerts on the worker in the search of a suitable housing site. The main problem in developing a distribution model is the selection of the form of this function. Researchers in the past have suggested both simple and complicated functions. As mentioned earlier, no universally accepted function is available at present to distribute the trips or residential locations successfully. Examination of small and medium-sized cities has revealed that there is no need to use a complicated distribution function for such areas. Zaryouni (1974) has demonstrated that the inverse power and negative exponential functions provide practically the same goodness of fit for the gravity model as any more complicated function does.

The inverse power and the negative exponential forms of distribution functions which were investigated for various socioeconomic groups of workers may be written as:

i) Inverse power function,

$$F(t_i) = t_i^{-\alpha} \qquad (6.13a)$$

ii) Negative exponential function,

$$F(t_i) = \exp(-\beta t_i) \tag{6.13b}$$

where

t_i = travel time between the employment centre and residential district i,

α and β are model parameters for a particular group of workers.

Using distribution function $F(t_i)$ in Eq. 6.10, the gravity model of residential location distribution for a particular group can be written as:

$$T_i = \frac{O\ d_i\ F(t_i)}{\sum_{i=1}^{n} d_i\ F(t_i)} \tag{6.14}$$

where all the variables are the same as defined previously in this chapter.

Calibration Procedure

The determination of the parameters α or β provides the calibration of the distribution model. The essence of calibration technique is to find α or β such that T_i (the number of residential locations sought by a group of workers in district i) as computed by using Eq. 6.14 agrees with the observed number of residential locations. The calibration methods are generally iterative processes.

In this research, an iterative procedure was utilized to determine the values of the travel time (cost) parameter α of the inverse power function using the sample for FGIP. The algorithm on this procedure began with a random distribution model with $\alpha = 0$ in the power function and $\beta = 0$ in the exponential function. This random model provided the initial estimates of residential locations, which were then compared with the actual values from the survey. The principal measure used as the criterion for the predictive ability of the model was the relative deviation S, defined as:

$$S = \sum_{i=1}^{n} (T_i - \hat{T}_i)^2 \qquad (6.15)$$

where

T_i = predicted number of residential locations in district i, and

$\hat{T}_i$ = actual number of residential locations in district i.

The second step of the algorithm was to increase the value of α by adding a constant of 0.10, re-estimate the dependent variable, and calculate a new value of S. This latter step was repeated until S failed to decrease. The value of α corresponding to the lowest S value was chosen as the model parameter for the power function. Similar steps were followed to determine the model parameter for the exponential function by adding 0.01 to the value of β.

The above procedure was used to determine the values of α and β for various socioeconomic groups of workers at FGIP. Fig. 6.1 demonstrates the relationship of model parameter α and the deviation S for the low income group of workers at FGIP. The figure shows that the best fitting value of α equals 1.2.

Table 6.1 compares the magnitudes of minimum deviations achieved for different groups at FGIP with the inverse power and the negative exponential function. It may be noted from the magnitudes of the deviations that the power function yields better results as compared to the

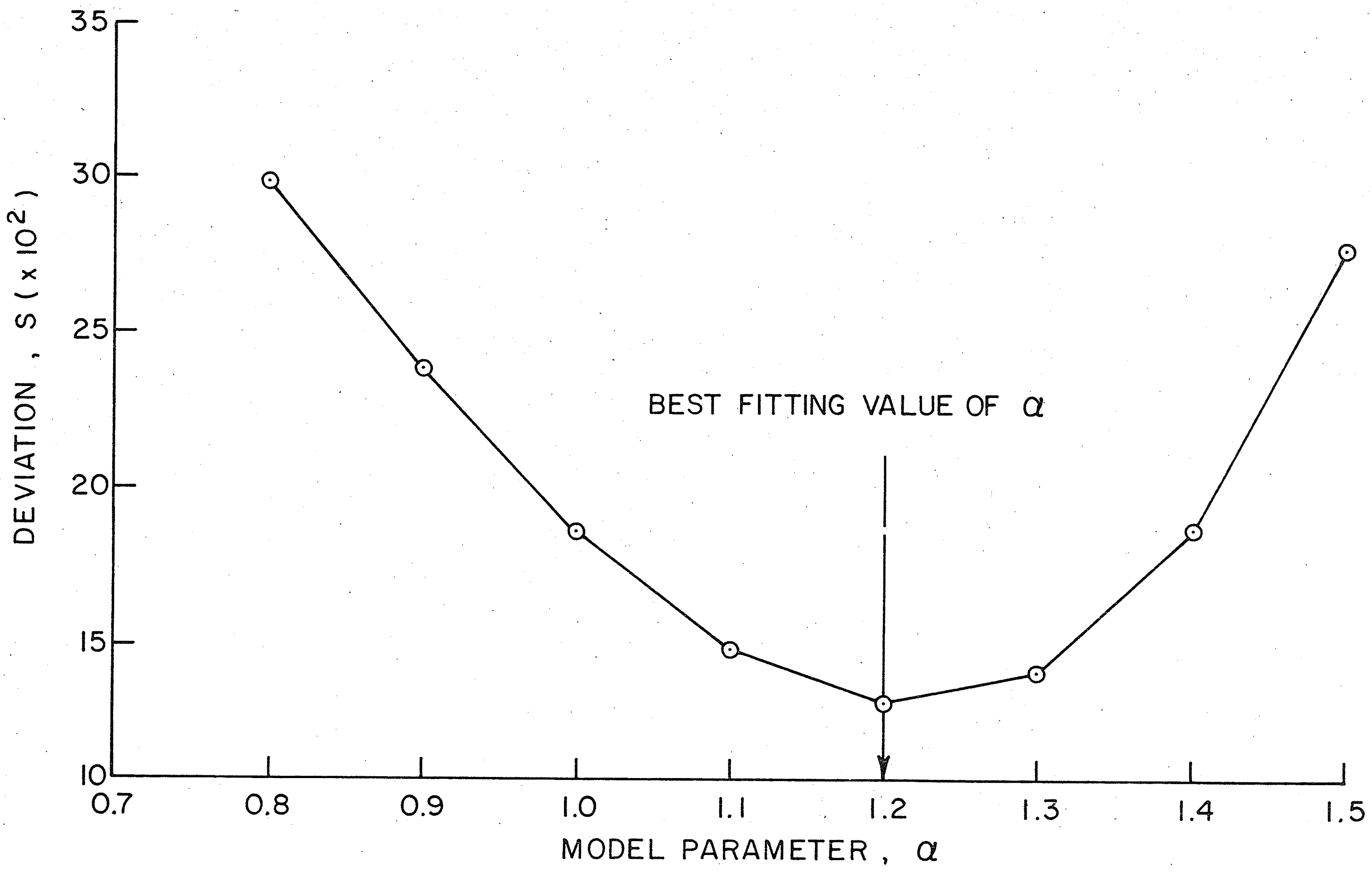

Fig. 6.1 Model Development Relationship for Low Income Group of FGIP

exponential function for all socioeconomic groups of workers of the community under investigation. The better performance of the power function in this investigation is quite consistent with the findings of other studies. Tomlin (1968) compared the conventional inverse power function for Adelaide, Australia. The power function produced better prediction when he considered the whole Adelaide area including the suburban communities (similar to the present study in which the whole of the Greater Winnipeg area is considered). But when he considered only central Adelaide, the negative exponential form did better than the inverse power form.

Figure 6.2 demonstrates the closeness of the agreement between the actual and the predicted residential frequency distribution using the inverse power function for various groups of workers at FGIP.

Table 6.1 Comparison of Deviation S with Different Distribution Functions for the case of FGIP

Income Group of Workers	Inverse Power Function, $F(t_i)=t_i^{-\alpha}$		Exponential Power Function $F(t_i)=\exp(-\beta t_i)$	
	α	S	β	S
Low	1.2	1,315	.13	2,301
Medium	0.9	829	.08	947
High	0.5	424	.04	473

Discussion of Model Parameters of Various Income Groups

Fig. 6.3 shows the distribution functions which use the values of α for different income groups. The concept of function $F(t_i)$ as used in the gravity model for spatial distribution is considered as a basic will-

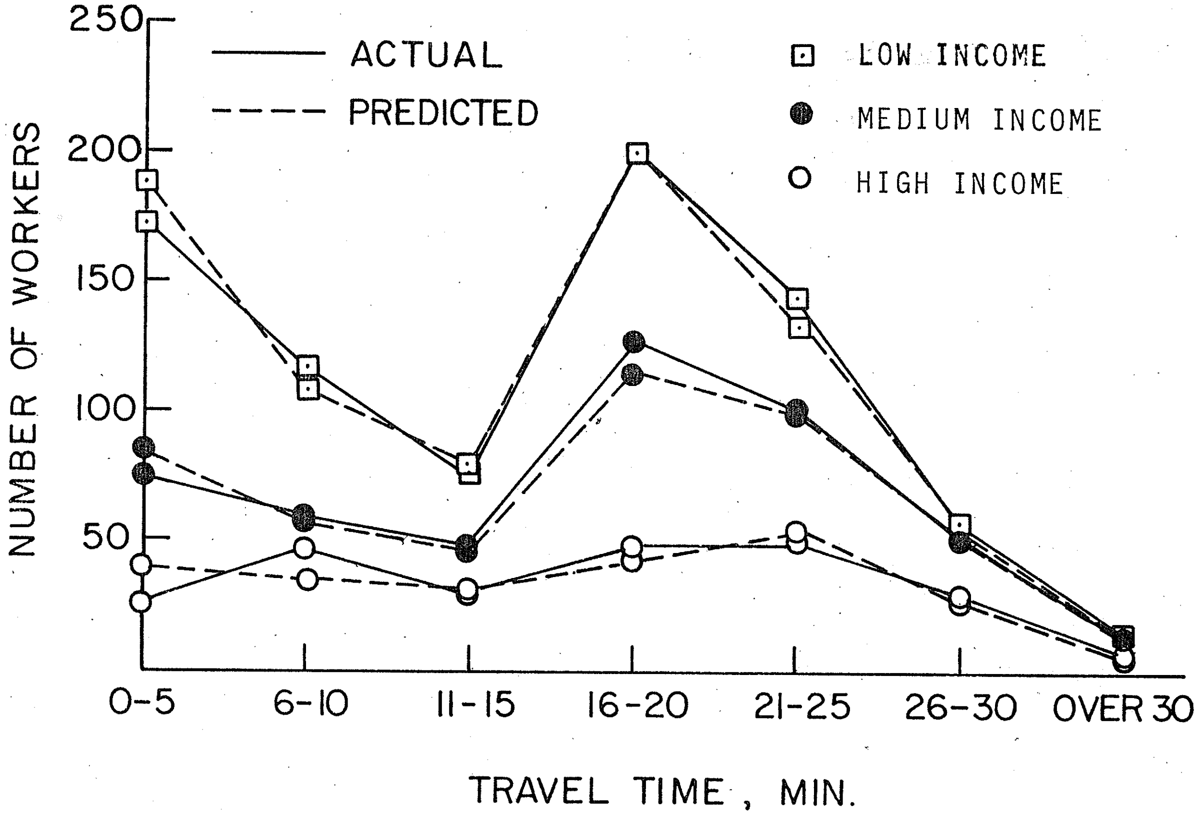

Fig. 6.2 Actual and Predicted Residential Location Distribution of FGIP workers by Income.

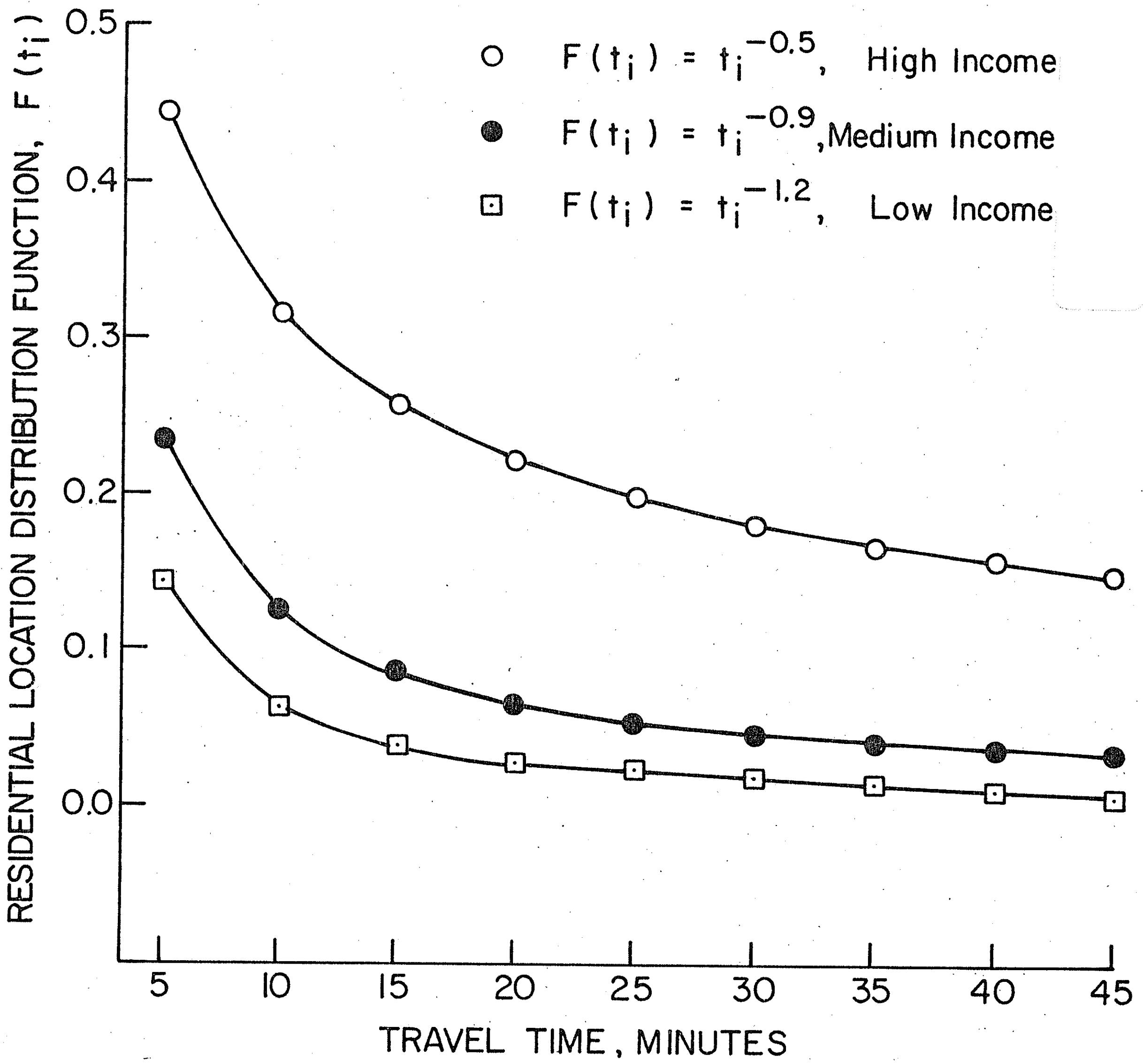

Fig. 6.3 Residential Location Distribution Function of Various Income Groups

ingness to travel for various groups of workers. The distribution function $F(t_i)$ decreases as the travel time between the residential location and the employment centre increases. In other words, $F(t_i)$ may be interpreted as a measure of the decrease in attractiveness of a particular location of residence as the travel time to that location increases.

Fig. 6.4 demonstrates the effect of travel time parameters of various groups on the distribution of residential location. This figure uses the total number of workers in a residential district as an attraction variable d_i for all the values of α. The plots of trip length distribution in the figure clearly indicate (for the community under investigation) that the workers of the low income group live closer to their places of employment ($\alpha = 1.2$) as compared to the workers of the high income group ($\alpha = 0.5$) in the figure. This fact is also corroborated in the application of the model for other employment centres to be discussed in the following section of this chapter. For example, 51% of the low income group live within 15 minutes from their work place as compared to only 33% of the high income group. As mentioned in the previous chapter, the low income group may choose to live close to the employment centre depending on neighbourhood affiliation, land use infrastructure, type of housing, or merely because the part of the income spent on commuting seems disproportionately large.

6.4 Testing of the Model

Similarly to the competing and the intervening opportunities models, the gravity type of residential location distribution model was also tested for CNRY and IIP.

The actual and predicted residential location distribution of CNRY

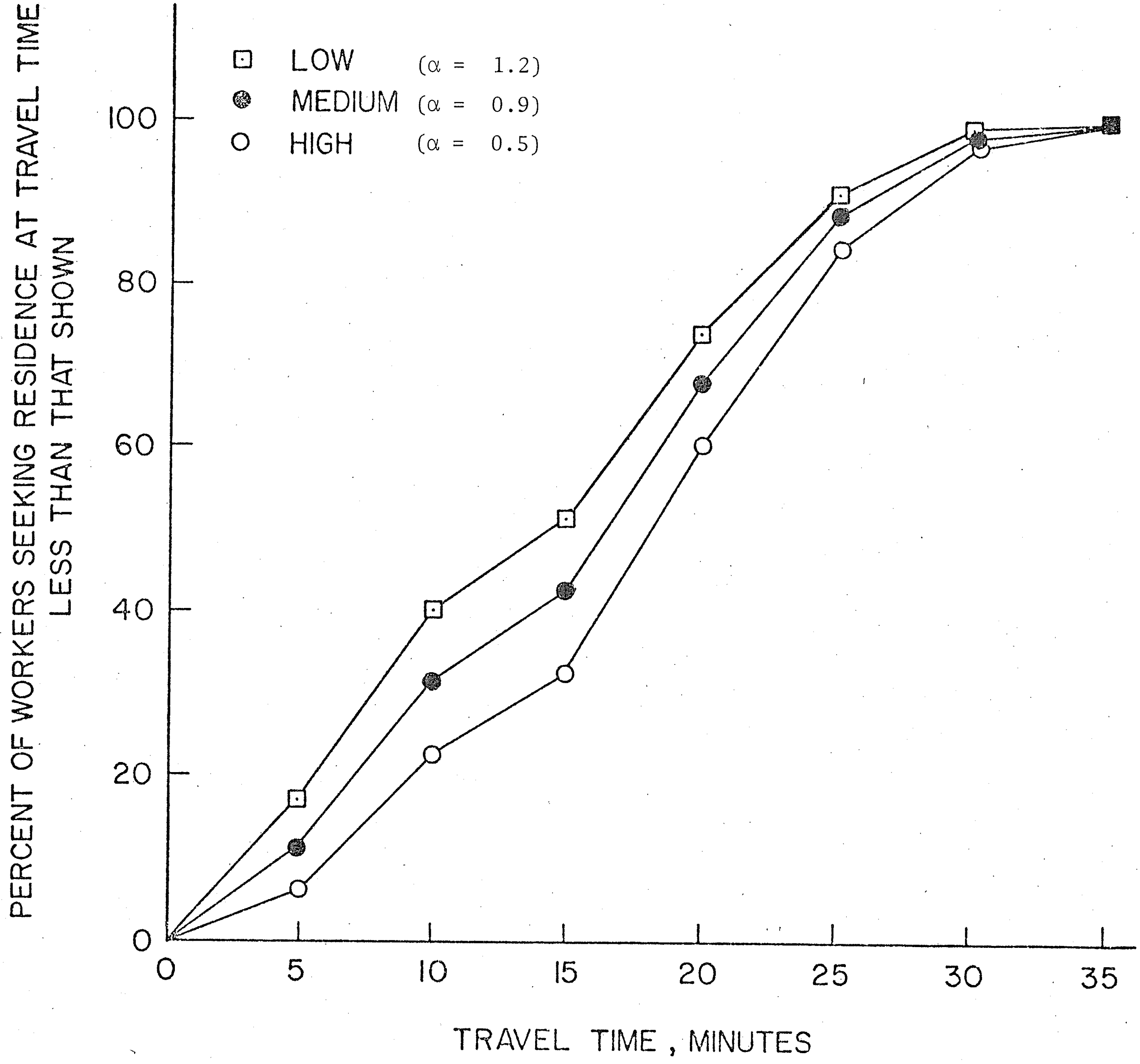

Fig. 6.4 Effect of Travel Time Parameter of Various Income Groups on the Distribution of Residential Location

workers is shown in Fig. 6.5. The prediction utilizes $\alpha = 1.2$ for the low, $\alpha = 0.9$ for the medium, and $\alpha = 0.5$ for the high income group of workers. The closeness of observed residential location distribution of CNRY workers to the predicted results using the model (that was developed by using data from FGIP) suggests that this model can successfully simulate the behaviour of the workers of different socioeconomic groups in choosing residential location in the City of Winnipeg.

The developed model was also tested using the data of Saccomanno (1972) for IIP. It was noticed in the testing of the COM and IOM type of models that the model parameters of the low and the medium groups of this study were found appropriate for the labour and clerical groups, respectively, of Saccomanno's classification. Expecting the same behaviour for the gravity model parameters, $\alpha = 1.2$ for the labour group, and $\alpha = 0.9$ for the clerical group were used to predict the residential location distribution for IIP. The closeness of the actual and the predicted results in Fig. 6.6 demonstrates the adequacy of the model for predicting the residential location of the workers of various socioeconomic categories in the City of Winnipeg.

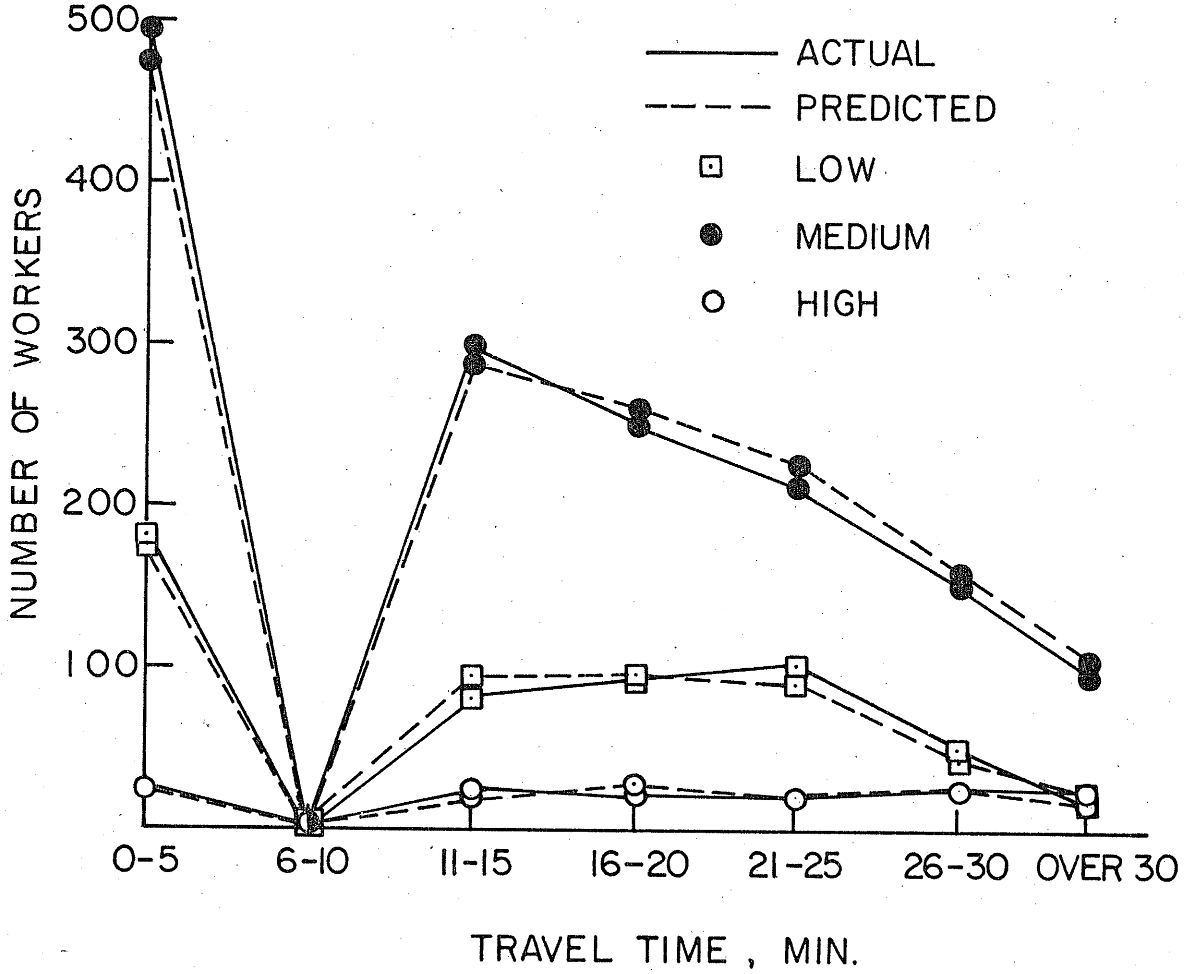

Fig. 6.5 Actual and Predicted Residential Location Distribution of CNRY Workers of Various Income Groups.

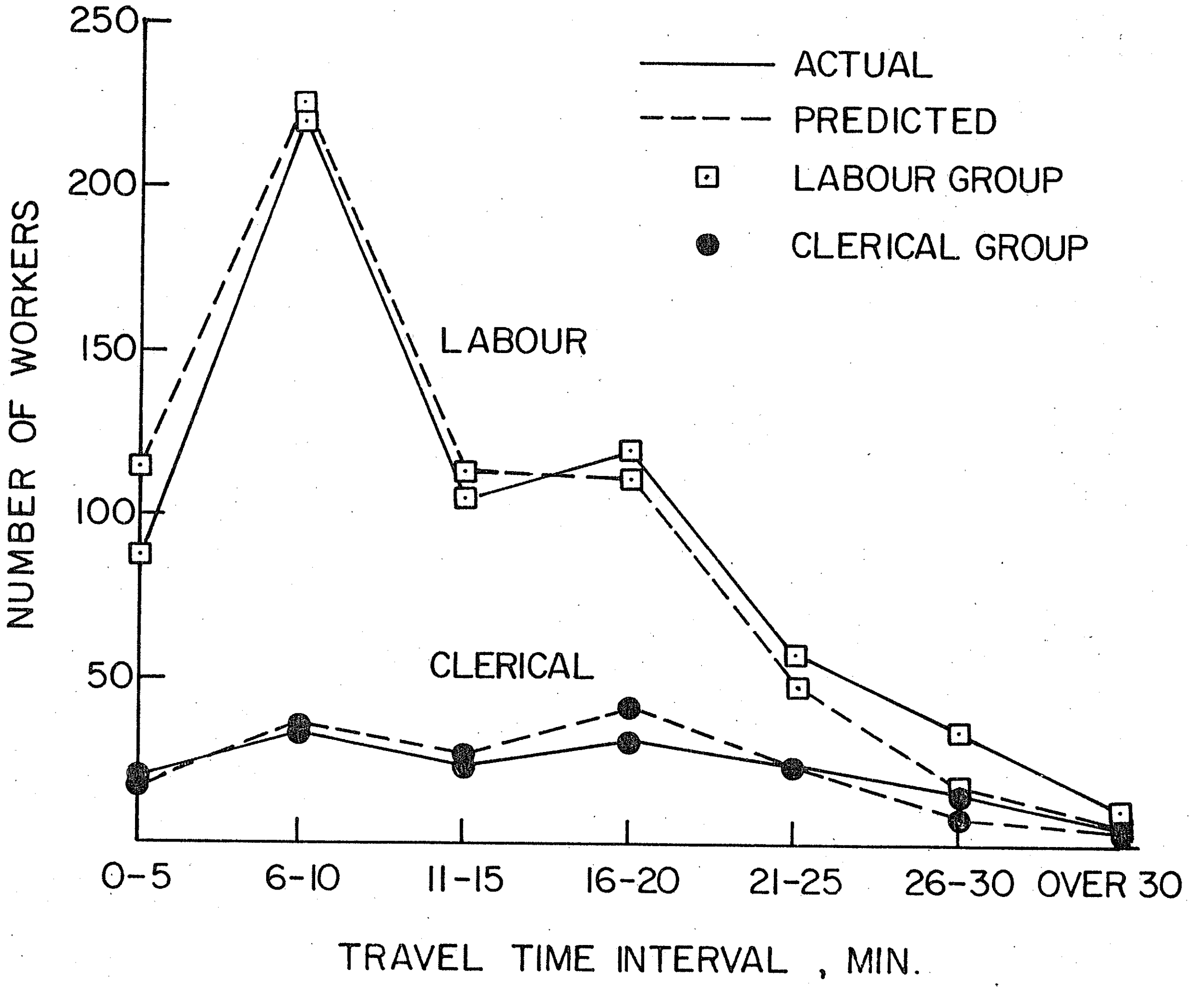

Fig. 6.6 Actual and Predicted Residential Location Distribution of IIP Workers

CHAPTER VII

A FURTHER INTERPRETATION OF THE MODELS

7.1 Introduction

Chapters 4, 5, and 6 described the development and testing of the competing opportunities model, the intervening opportunities model, and the gravity model, respectively, for the purpose of distributing residential locations of employees working in large employment centres in Winnipeg. This chapter expands further on the interpretation of these models in terms of (i) a comparative evaluation of the three models, and (ii) their use for planning purposes. Before embarking on the description of these items, a discussion of the effect of location of the employment centre in the study region on the residential distribution is included. Such a discussion will be useful to the subsequent interpretation of the models.

7.2 The Effect of the Location of the Employment Centre on the Residential Distribution

The development of different types of residential models in previous chapters used the data from FGIP. The testing of models was carried out for the sample of CNRY and IIP. Figs. 4.12, 5.10, and 6.5 were drawn to compare the actual and predicted residential distribution using the COM, the IOM, and the GM, respectively, for workers at CNRY employment centre. The effect of the location of the employment centre can be conveniently discussed by taking the example of CNRY's location in Winnipeg and examining the actual and predicted patterns of residential distribution for this employment centre in the above-mentioned figures.

It is obvious from Fig. 4.12, 5.10, and 6.5 that, for all the models, underprediction results to a varying degree for the residential districts nearer to the employment centre. For most other bands, therefore, an overprediction is caused in the distribution. As was also mentioned in chapter 5, such a discrepancy between the actual and the model distribution can perhaps be attributed to the location of CNRY employment centre in Winnipeg. There is an apparent discontinuity in residential development between Transcona community (where the CNRY is located) and its nearest neighbouring communities such as East Kildonan and St. Boniface. This discontinuity of residential development probably forces some additional workers to choose their residences in Transcona because otherwise they would have to choose from other communities which might be located too far for their consideration.

This type of discrepancy in results may also be attributed to the presence of another major employment centre in the vicinity of the employment centre under consideration. The CNRY does not have any major employment centre in its surrounding districts, unlike the FGIP, which is near the University of Manitoba. It is perhaps this absence of a major employment centre near CNRY which makes Transcona less sought after by the workers from any other employment centre, thus making it less competitive for seeking residential location. Such an explanation of the discrepancy implies that the ratio of the number of households and the number of jobs available in a locality should affect the residential location pattern of the workers in that locality. While a low value of this ratio may drive the employees to seek household location away from this high competition area, a high ratio may encourage workers to seek residences in the vicinity of the employment centre.

The preceding explanation may be supported by including the example of IIP. An examination of Fig. 5.11 (and, also of Fig. 6.6) reveals that, in contrast to the CNRY sample, an overprediction is observed for residential districts nearer to the IIP. The St. James Industrial Park and several other small and medium-sized employment centres are located close to the IIP. Due to the competition from workers of these nearby employment centres, it becomes harder for IIP workers to find a suitable household as near their workplace as they would wish.

The location of the employment centre with respect to the CBD is another aspect which may be included at this point. Several studies in the past have indicated that residential patterns of persons employed in suburban workplaces are different from those employed in the CBD. For example, Carroll (1952), and Bell (1970) found that residences of workers employed in non-CBD workplaces are concentrated most heavily in the immediate vicinity of the place of work. Since all the employment centres of the present study, namely, FGIP, CNRY, and IIP are located in the suburbs of Winnipeg and all have approximately the same travel time (or distance) from the CBD, the effect of employment centres location with respect to the CBD could not be recognized for the community under investigation.

7.3 A Comparative Evaluation of the Models

A great deal has been written about the comparison of trip distribution models in the past. The advantages and problems associated with the use of the gravity model, the competing opportunities model, and the intervening opportunities model for the purpose of distributing aggregated trips in urban areas are well known (Hutchinson, 1974; Finney, 1974; Bruton, 1971; Heanue and Pyers, 1966). The general conclusion of most studies on comparative evaluation has been that the gravity model possesses the most desirable properties of the three trip distribution models. In the present study these models have been used for residential locations. In this context models are used at a finer aggregation level than in the past studies for trip distribution. It is intended therefore to include a few comments about their predictive ability within the framework of the community under investigation.

It appears from Fig. 4.10, 5.8 and 5.9, and 6.2 corresponding to the COM, the IOM, and the GM, respectively, that all the three models produce approximately similar prediction results when the models are developed for the FGIP. However, when the developed models are tested for CNRY employment centre, Fig. 4.12, 5.10 and 6.5 suggest that the GM produced the best results, and the COM produces better results than the IOM. Before making any firm conclusion about the superiority of one model over the other it is useful to consider the sensitivity of these models to travel time.

At the time of developing the different types of residential models in this study it became apparent that the performance of these models when used as such would be more sensitive to travel time (the measure of spatial separation between the employment centre and residence) than in their conventional use as trip distribution models. When the area-wide trips are aggregated by travel time for all the origin zones any inaccuracies in travel time that may exist are averaged out. However, when the residential-distribution pattern of a large employment centre (single origin zone) is analyzed, a small variation in travel time value, especially between the employment centre and the nearest residential district, may significantly affect the simulation or prediction results. Since the gravity model makes the most explicit use of travel time, it should be more sensitive to travel time than the other models.

An example of CT 122, a residential district in the Transcona community may be quoted in support of the gravity model's sensitivity to the travel time. This residential district is located very close to the CNRY employment centre. While making travel time measurements for this project, CT 122 appeared to be located 2 to 4 minutes away from the CNRY. Such deviation in the travel time value, which was (or may be) caused due to variation in traffic conditions, can now be used to show its effect on the model prediction results. Using $\alpha = 1.2$, in Eq. 6.13a and Eq. 6.14, for distributing residential locations of the 520 CNRY-workers of low income group the following results are obtained, corresponding to the two values of travel time:

$$T_{122} = 54 \quad , \quad \text{when } t_{122} = 2 \text{ minutes;}$$

$$T_{122} = 25 \quad , \quad \text{when } t_{122} = 4 \text{ minutes;}$$

where T_{122} is the predicted number of low-income workers seeking residences in CT 122, and t_{122} is the travel time between CNRY and CT 122. These predicted numbers compare to the observed number of 60 workers.

The above example clarifies that the prediction of residential location for districts nearest to the workplace may be affected considerably due to slight variation (in the absolute sense) in the travel time measurement. Indeed, this example points out the limitation of using travel time as a measure of spatial separation for the analysis of residential locations using the gravity model employing a simple inverse power function. This limitation can be rectified by using an objective measure of separation, perhaps travel distance or some generalized travel cost function which may require a more complex distribution function in the model. It is obvious that the competing opportunities model and the intervening opportunities model will be much less sensitive to travel time. As a matter of fact, a change of travel time from 2 to 4 minutes will not at all change the predictive results of this study.

As mentioned earlier, the gravity model of trip distribution has provided, in general, better simulation and prediction results than other models in the past. This success of the gravity model has been attributed to "the refined degree of adjustment made during the calibration phase" of the model (Heanue and Pyers, 1966). In other words, it is the degree of sophistication, such as including socioeconomic adjustment factors in the parent model, which is responsible for better performance of the model. On the other hand, the competing opportunities model and the intervening opportunities model still remain unexploited, even though they are based on sound theoretical background. The attempt made in this thesis towards their refinement points out that the opportunity models may provide as good spatial distribution results as does the more accepted gravity model. A particular reference may be made to Fig. 5.14 which shows that, when applied to Ipswich City, the new form of the IOM (as developed in this study) provides superior results than the previous models of Schneider (1960) and Golding and Davidson (1970). As a matter of fact, the closeness of actual and predicted distribution using the new model makes it certain that any other model, even the gravity model, is unlikely to provide any better agreement for the Golding-Davidson sample of Ipswich City.

7.4 Use of Models for Planning Purposes

The previous exposition makes it clear that the models of this study are developed with a view to assessing traffic generated from new land developments, such as industrial parks, hospitals, shopping centres or high-rise office buildings. The main purpose of this section is to indicate more specifically the manner in which residential location models may be used to predict the traffic implications of new development proposals.

A procedure for analyzing the traffic impacts of a new development is proposed in Fig. 7.1. The simplified flow diagram of the traffic assessment model in the figure is divided into two stages; first, model development and simulation, and second, model application and prediction. The first phase uses the existing land use and transportation characteristics of an urban region for the development of the required model and the second phase then uses the developed model for future prediction. The following comments would further serve to clarify the flow diagram which considers the example of assessing traffic generated from a newly proposed industrial park.

The location of an employment centre has appeared as an important factor in the analysis of choice of residential location of its employ-

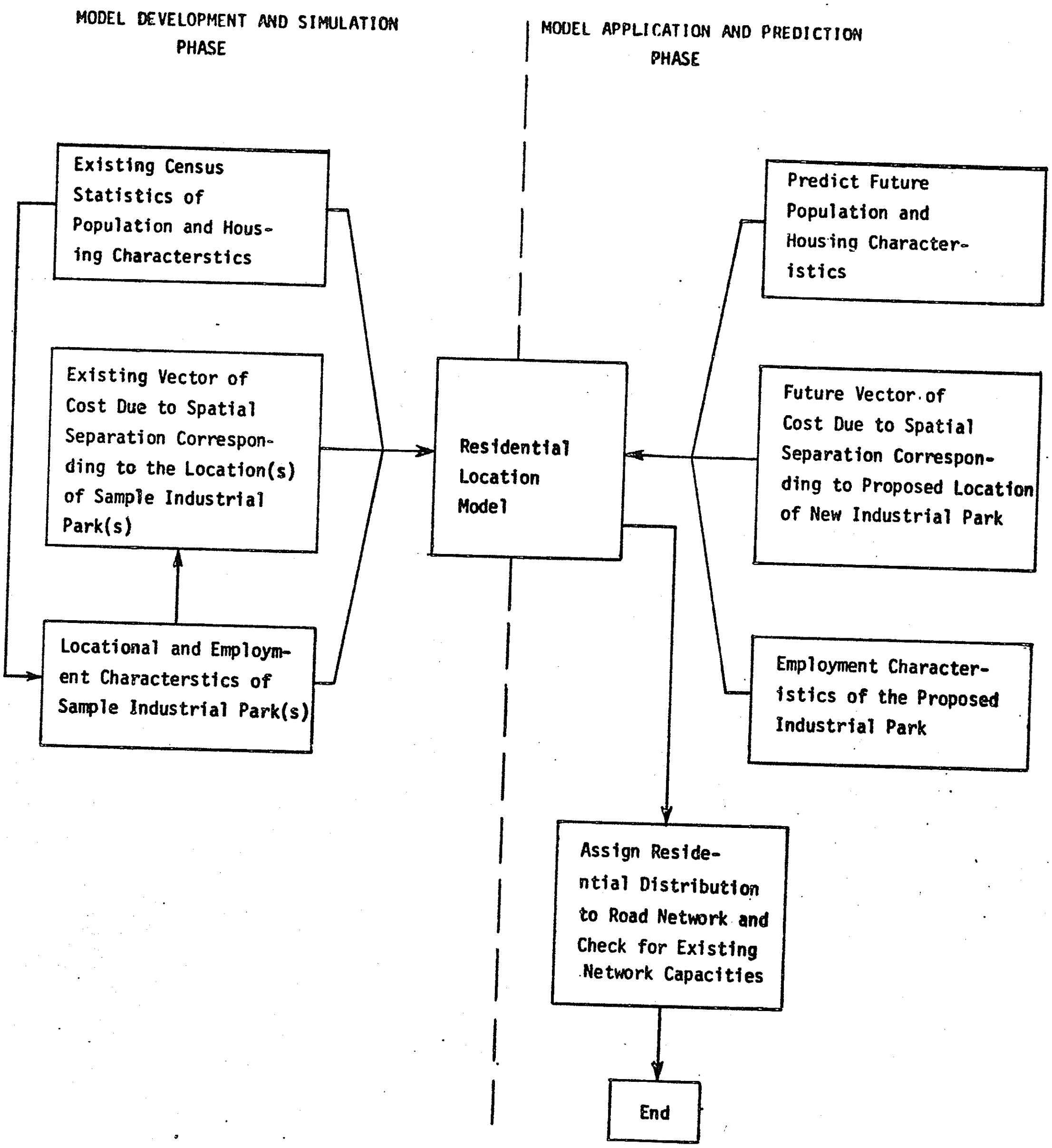

Fig. 7.1 Simplified Flow Diagram of Traffic Assessment Model.

ees. It is therefore essential to consider the factor of location while selecting a sample, which may contain one or preferably more employment centres, for the development of the residential distribution model. If, for example, a traffic engineer is interested in knowing what effect a new suburban-based industrial park would have on the existing transportation network he should preferably,include those existing industrial parks or employment centres in his study sample which are situated in suburban areas of the city.

A question which emerges at the prediction stage of the application of the model is concerned with the future date at which the traffic implications should be assessed. Of course there is no single answer to such a question. A significant period of time can be envisaged to elapse before the establishment or re-establishment of all the firms in the newly proposed site of industrial park is completed. A shorter period of time may be expected to elapse before the construction of a single high-rise office building is completed. Once the traffic assessment date is decided as a matter of policy, the future predictions for the independent variables can be made by the traffic engineer.

The adoption of a traffic assessment date will naturally have impact on other factors. For example, other land use and network changes, as well as changes in the trip-making or residential-choice behaviour of the population may occur by then. It is therefore essential that these additional factors should be accounted for at the prediction stage by the planner.

The final step shown in the analysis procedure of Fig. 7.1 is an assignment of the predicted distribution of residential locations (or in other words, the work trip distribution predicted for employees of the proposed industrial park) to the existing road network between the development zone and residential zones of the urban centre. This task may perhaps be carried out by a multipath assignment technique based on the least cost principles in order to reveal the extent to which the roads in the city will be affected by the development.

The preceding description briefly indicates a way in which the models of this study may be used in land use planning with particular reference to the site of a new industrial park in an urban area. As indicated earlier, the residential models of this study are basically trip distribution models, differing mainly at the level of disaggregation. These residential models essentially simulate a work trip distribution phenomenon associated with a single employment zone. Other types of trips, such as shopping or recreational trips, may also be simulated at a disaggregated level. It is also indicated earlier that the approaches advanced for the models, particularly the competing opportunities model and the intervening opportunities model, may be used to predict trip distribution more accurately.

CHAPTER VIII

CONCLUSIONS AND DIRECTION FOR FURTHER RESEARCH

8.1 Conclusions

The following conclusions can be made from this investigation:

(1) Residential location of employees in relation to their workplaces can be simulated and predicted by using any of the approaches advanced for the competing opportunities model, the intervening opportunities model, and the gravity model. Other than for the purpose of the present investigation of large industrial parks, the models may be used to predict the residential location distribution, leading to an assessment of the traffic patterns generated by other types of land development, such as schools, hospitals or shopping centres. One notable feature of the study is that the models make use of standard census data to predict the behavioural choice of residential location as opposed to models which call for expensive and time-consuming data collection procedures, such as origin-destination surveys.

(2) Socioeconomic factors, such as income and occupational status appear to affect significantly the pattern of residential distribution of workers in relation to their workplaces. The parameters of the models developed for this study indicate for the community under investigation that, on the average, workers of the low income group live close to their places of employment as compared to the workers of the high income group. The low income group may choose to live closer to the place of employment depending upon neighbourhood affiliation, land use infrastructure, type of housing, or merely because the part of their income spent on commuting

seems disproportionately large. The medium income group would appear comparatively less susceptible to the influence of the cost of transportation in choosing a residential location; the high income group perhaps may be considered completely unaffected in this respect.

(3) The competing opportunities model calibration procedure (as developed in previous studies), which consists of (a) selection of a suitable uniform width of time bands for the study area and (b) determination of the width of first time band to achieve the best possible results, may not adequately simulate trip making or the behavioural choice of residential location in urban areas. A new calibration procedure, as introduced in this study, can considerably enhance the predictive ability of the competing opportunities model. The new procedure includes an additional step for improving the accuracy of prediction of the dependent variable for the study zones within the first time band. In this step, the total number of residential locations (or trips) predicted for the first time band are redistributed among the residential districts (or destination zones) within the first time band by applying the competing opportunities model. Such repeated application of the concept of competing opportunities confined only to the residential districts within the first time band of the previous stage of application of the model is termed a 'nested model' for redistribution of residential locations.

(4) The width of first time band, W_1, wider than the remaining uniform bands in the competing opportunities model, may suggest an existence of two areas of competition for residential opportunities in the entire study region: first, the area within W_1 minutes of travel time from the Employment centre (or origin zone) as the low competition area,

and second, the area beyond W_1 minutes time as the high competition area. It is evident from the values of W_1 for different groups of workers at the employment centres of this study that, as the socioeconomic status of the workers increases, the line of demarcation of low and high competition areas (i.e. W_1) moves outward from the employment centre. For example, it is obvious from the values of W_1 that the high income group workers compete for housing location more discerningly beyond 20 to 25 minutes of travel time from their job place as compared to 10 to 15 minutes for the low income group. Also, the analysis of the choice of the residential location of workers within the first time band of the competing opportunities model, which is carried out by using the 'nested model', further suggests a hypothesis of a very low competition area for each income group. These very low competition areas for housing opportunities around the sampled employment centres of this study are 0 to 5 minutes for the low income group, 0 to 15 minutes for the medium, and 0 to 20 minutes for the high income group of workers.

(5) Schneider's intervening opportunities model with a constant (or single) probability parameter, usually known as L-value, or Golding and Davidson's extension of the intervening opportunities model with a probability function may not accurately reproduce the actual spatial distribution in urban areas. The predictive ability of the model can be improved by using a variable L-value instead of a constant one. The variation of L appears to depend on the hypothesis that the probability of a destination being accepted, if it is considered, is a function of the number of destinations which have already been considered. This probability in Schneider's original model hypothesis is assumed constant,

independent of the order in which destinations are considered.

(6) The variable nature of the probability parameter can be formulated mathematically by using Hoerl's special function, $y = ax^b e^{cx}$, where y and x are dependent and independent variables, respectively, and a, b and c are constants. This relationship explains the variation in L-value rationally in terms of the attractiveness and repulsion to an individual of the proximity of a destination. Hoerl's function can easily take into account the variation of probability parameter due to socioeconomic status of trip makers, the purpose of the trip, and even the effect of location of the trip origin.

(7) The gravity model using an inverse power distribution function appears to produce better results than the two opportunities models when applied to the industrial parks in Winnipeg. However, the use of gravity model with such a simple distribution function requires more accurate travel-time measurements compared to opportunities model, because of its sensitivity to travel time, particularly for residential districts which are very close to the employment centre.

(8) Any discontinuity in the residential development in an urban area appears to cause a tendency for employees to choose residential location nearer to their employment centre. Such a tendency is apparent from the application of the developed models to the CNRY employment centre. Generally for all the models, and particularly for the application of the intervening opportunities model, an underprediction results for residential districts nearer to the employment centre. A discontinuity of residential development exists between Transcona community (where CNRY is located) and other communities, such as East Kildonan, and St. Boniface.

Such a discontinuity may force a few additional workers to choose their residences in Transcona as otherwise they would have to choose from other communities which might be located too far for their convenience.

(9) A presence of other major employment centres in the vicinity of the employment centre under consideration can also complicate the choice of residential location. For example, the absence of any major employment centre near CNRY makes it possible for the workers of this centre to find suitable housing as near their place of work as they desire without much outside competition from the employees of other workplaces. In contrast, FGIP and IIP have other major employment centres, the University of Manitoba and the St. James Industrial Park, respectively, in their localities. Due to competition from workers of these nearby employment centres, it becomes harder for the FGIP and IIP workers to find a suitable household as near their place of work as they would like to have. It is perhaps this presence of other major employment centres which causes a more dispersed residential distribution for FGIP and IIP as compared to CNRY in Winnipeg.

In summary, all the three models included in this study may be used in locating the residences of workers while partly incorporating the use of census data. In general, the gravity model provided better modelling results than the opportunities models for the purpose of this study. However, the attempts made in this thesis towards their refinements point out that the competing opportunities model and the intervening opportunities model have the potential to provide equally useful results.

This thesis embodies a number of significant contributions to a better understanding of the three trip distribution models. Firstly, different distribution parameters for the gravity model have been developed separately for different socioeconomic groups of workers for the community under investigation. These different parameters serve to indicate clearly the effect that spatial separation may exert upon the residential location choice of various socioeconomic groups of workers. Secondly, an extension has been provided to the calibration approach for the competing opportunities model which appears to improve considerably the predictive ability of this model. Finally, a new form of the intervening opportunities model has been introduced. The superiority of the new intervening opportunities model over its existing forms has been demonstrated clearly by applying the model for the data of this study as well as the data of several other studies in the past.

8.2 Direction for Further Research

Future work in the area of the present research may take several directions. One would be to undertake similar studies in other urban areas to generalize the findings of this research. These studies may also be undertaken in the subject applied to the same metropolitan area for different periods of time. In undertaking such an investigation, however, the researcher should be careful in choosing a proper measure of cost associated with a particular housing location. If housing prices in the urban area vary significantly from one location to the other, the concept of "gross price" (the sum of housing price and household transport costs) should be used in the analysis.

Another suggestion for further research is to investigate the effect of the presence of other major employment centres on the residential distribution of employees of the centre under consideration. Such a presence appeared to affect the residential choice in this study. Perhaps, one way of taking the presence of other employment centres into account would be to incorporate in the study a ratio of the number of households and the number of jobs available in a residential district.

Yet another suggestion for further research is to investigate the effect of the mode of travel on residential location decisions. The present study did not include the mode of travel in the analysis because only a very small proportion of sampled workers used public transport as compared to the private automobile. An inclusion of CBD (Winnipeg) employees and university (of Manitoba) employees in the analysis might have provided some conclusions to this effect. The CBD and the University were not included for the purpose of limiting the data requirements in the study.

A possibility for further research in this direction would be a further testing of the calibration procedures as developed in this study for the intervening opportunities model and the competing opportunities model. The testing of calibration procedures for trip distribution purposes may be carried out by utilizing the existing data collected for the urban transportation study of any urban region.

Additional research may be required towards the assignment of predicted distribution of residential locations to the road network between the development zone and residential zones. It is merely indicated in this study that this task may perhaps be carried out by a multipath assignment technique based on least cost principles.

All of the preceding research directions will contribute to the understanding of the spatial distribution of different activities in the urban areas. Such an understanding will not only help in siting of new land development proposals in the existing infrastructures of an urban area, but also in the context of the problem of regional planning beyond urban areas.

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APPENDIX

TABLES OF (1) CENSUS TRACT POPULATION DISTRIBUTION

(2) OBSERVED RESIDENTIAL LOCATION DISTRIBUTION

TABLE A1

CENSUS TRACT POPULATION DISTRIBUTION BY INCOME FOR
METROPOLITAN AREA OF WINNIPEG
(SOURCE: STATISTICS CANADA, 1971)

TRACT NO.	POPULATION DISTRIBUTION BY INCOME		
	LOW GROUP	MEDIUM GROUP	HIGH GROUP
1	1065	495	395
2	1580	690	265
3	1915	620	180
4	2450	1110	750
5	720	425	1250
6	685	505	420
7	840	425	415
8	525	270	650
9	520	345	635
10	1525	505	925
11	2210	715	870
12	1805	440	220
13	470	80	30
14	1675	485	245
15	2610	400	270
16	1210	250	70
17	1585	430	130
18	940	335	160
19	915	410	165
20	840	305	110
21	2255	565	150
22	1890	295	85
23	1215	290	120
24	200	20	10
25	880	110	30
26	835	130	35
27	850	230	80
28	1770	375	90
29	1380	440	125
30	995	440	110
31	580	315	170
32	1815	645	145
33	420	100	15
34	785	140	40
35	635	150	35
36	220	70	5
37	935	470	175
38	1435	545	170
39	1405	395	105
40	710	290	85

TRACT NO.	POPULATION DISTRIBUTION BY INCOME		
	LOW GROUP	MEDIUM GROUP	HIGH GROUP
41	1000	410	215
42	900	230	75
43	1505	320	100
44	790	190	50
45	1855	610	130
46	800	195	70
47	1275	495	245
48	1365	600	125
49	715	475	170
50	1715	760	245
51	100	30	30
52	5	0	0
53	230	110	40
54	1135	810	705
55	3015	1285	485
56	630	365	415
57	845	425	155
58	925	365	150
59	930	580	505
60	770	665	595
61	1450	950	645
62	925	395	100
63	1200	380	185
64	905	350	345
65	1980	680	235
66	815	270	105
67	795	575	225
68	535	395	230
69	1040	780	265
70	1025	755	290
71	1610	1060	470
72	1080	395	120
73	675	370	405
74	1145	645	240
75	1420	680	540
76	170	105	60
77	2155	1110	610
78	1145	700	415
79	1620	726	1278
80	1475	635	735
81	530	285	240
82	680	370	660
83	270	65	790
84	420	310	330
85	520	410	410
86	635	430	315
87	520	265	310

TRACT NO.	POPULATION DISTRIBUTION BY INCOME		
	LOW GROUP	MEDIUM GROUP	HIGH GROUP
88	1710	795	195
89	265	125	55
90	1105	575	480
91	1190	510	500
92	745	625	530
93	1085	580	1005
94	1070	920	1410
95	185	140	320
96	705	470	255
97	1390	1115	1140
98	170	115	10
99	800	275	75
100	780	350	250
101	1790	790	380
102	1065	760	850
103	980	430	205
104	370	205	70

TABLE A2

OBSERVED RESIDENTIAL LOCATION DISTRIBUTION OF WORKERS BY INCOME, AND TRAVEL TIME DATA FOR FORT GARRY INDUSTRIAL PARK (FGIP)

TRACT NO.	TRAVEL TIME FROM FGIP, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
1	12	4	14	3
2	8	31	10	2
3	9	21	8	1
4	5	39	18	5
5	5	9	5	2
6	9	5	3	2
7	15	5	6	4
8	14	1	0	4
9	11	11	2	2
10	10	18	11	11
11	13	15	12	10
12	14	16	9	4
13	17	2	0	0
14	15	15	1	1
15	16	10	9	1
16	16	5	3	0
17	16	5	7	0
18	17	3	2	1
19	18	5	4	2
20	18	4	3	0
21	18	10	14	0
22	18	11	3	1
23	18	5	4	0
24	20	1	0	0
25	19	8	2	0
26	19	9	2	0
27	19	6	0	0
28	18	5	6	3
29	19	5	4	2
30	19	2	2	0
31	20	4	2	1
32	22	14	4	0
33	21	2	2	0
34	22	7	6	0
35	22	3	1	0
36	21	1	1	0
37	26	2	2	0
38	24	9	2	1
39	23	1	2	0
40	23	4	2	0

TRACT NO.	TRAVEL TIME FROM FGIP, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
41	24	3	2	0
42	23	3	2	1
43	23	7	3	0
44	23	0	2	1
45	24	9	4	0
46	24	4	4	0
47	26	4	5	0
48	24	8	3	0
49	26	4	1	1
50	24	5	4	1
51	26	1	2	0
52	30	0	0	0
53	17	3	0	1
54	18	15	8	6
55	19	22	15	7
56	13	5	2	5
57	15	3	3	0
58	16	3	6	0
59	16	12	2	4
60	21	3	7	4
61	21	10	9	9
62	21	2	2	1
63	19	1	4	0
64	20	1	2	3
65	21	4	6	1
66	21	2	7	0
67	32	3	2	1
68	30	0	3	1
69	31	6	4	2
70	32	2	2	2
71	27	8	5	1
72	24	5	4	2
73	26	2	1	3
74	27	4	2	1
75	27	6	2	2
76	30	0	2	4
77	29	5	7	6
78	33	4	5	2
79	7	40	24	24
80	3	73	29	4
81	4	31	10	6
82	5	16	11	5
83	8	2	1	9
84	20	12	10	3
85	20	7	6	4
86	18	4	3	4
87	16	0	0	0

TRACT NO.	TRAVEL TIME FROM FGIP, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
88	16	10	1	2
89	17	4	1	0
90	18	8	2	3
91	21	8	3	2
92	21	1	1	1
93	22	3	2	4
94	25	8	3	10
95	24	2	1	3
96	25	5	3	0
97	24	5	4	7
98	22	0	0	0
99	23	6	6	0
100	27	2	0	0
101	27	5	4	4
102	29	11	3	4
103	29	1	2	1
104	26	2	9	2

TABLE A3

OBSERVED RESIDENTIAL LOCATION DISTRIBUTION OF WORKERS BY INCOME, AND TRAVEL TIME DATA FOR CANADIAN NATIONAL RAILWAY YARD (CNRY)

TRACT NO.	TRAVEL TIME FROM CNRY, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
1	20	1	17	3
2	20	7	18	2
3	23	6	11	3
4	25	8	21	1
5	28	1	5	0
6	29	1	3	1
7	29	3	2	2
8	27	0	2	3
9	27	0	10	3
10	25	3	8	4
11	19	5	15	0
12	18	5	2	0
13	17	1	2	0
14	20	4	1	1
15	21	6	3	0
16	24	4	3	0
17	25	3	8	0
18	26	1	8	0
19	28	2	4	0
20	26	1	9	1
21	24	9	11	0
22	23	5	5	0
23	19	5	7	0
24	16	0	3	0
25	19	1	3	0
26	22	3	6	0
27	24	2	6	0
28	24	3	6	0
29	25	4	7	0
30	26	2	5	0
31	28	2	3	0
32	26	8	9	0
33	24	1	2	0
34	20	1	9	0
35	20	2	2	0
36	16	0	2	0
37	11	9	35	1
38	12	12	29	1
39	14	7	17	0
40	17	3	11	0

TRACT NO.	TRAVEL TIME FROM CNRY, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
41	20	7	13	0
42	20	2	7	0
43	22	7	8	0
44	24	1	10	0
45	23	5	17	0
46	22	3	5	0
47	23	1	11	0
48	25	4	11	1
49	25	3	7	3
50	26	4	21	1
51	31	2	0	0
52	24	0	0	0
53	21	2	3	0
54	21	2	13	3
55	19	15	43	2
56	17	3	8	3
57	16	4	12	1
58	15	3	10	1
59	14	9	25	2
60	12	5	17	7
61	12	6	27	2
62	12	7	12	0
63	14	4	11	0
64	16	1	11	1
65	14	8	11	0
66	15	1	9	0
67	2	43	111	3
68	2	22	82	6
69	2	60	154	9
70	2	57	147	8
71	11	8	44	6
72	15	4	18	1
73	18	2	9	5
74	15	5	22	2
75	16	5	18	3
76	12	1	14	1
77	17	7	23	0
78	19	9	17	2
79	26	6	11	5
80	28	4	13	3
81	27	3	7	2
82	26	2	8	2
83	33	0	1	2
84	41	0	5	0
85	39	1	12	0
86	35	0	1	2
87	31	0	3	1

TRACT NO.	TRAVEL TIME FROM CNRY, MINUTES	OBSERVED NO. OF RESIDENTIAL LOCATIONS		
		LOW INCOME	MEDIUM INCOME	HIGH INCOME
88	31	4	15	1
89	31	0	9	0
90	33	1	6	2
91	36	2	2	0
92	36	0	10	3
93	37	1	1	3
94	39	0	12	3
95	43	0	0	0
96	43	0	4	0
97	40	4	14	5
98	34	0	1	0
99	30	0	3	0
100	21	0	5	2
101	22	6	12	2
102	26	4	12	1
103	24	2	15	0
104	27	7	16	2

TABLE A4

POPULATION DISTRIBUTION BY OCCUPATION, OBSERVED RESIDENTIAL LOCATION DISTRIBUTION AND TRAVEL TIME DATA FOR INKSTER INDUSTRIAL PARK (IIP).
SOURCE: SACCOMANNO (1972).

TRACT NO.	POPULATION DISTRIBUTION BY OCCUPATION		TRAVEL TIME	OBSERVED RESIDENTIAL DISTRIBUTION	
	LABOUR	CLERICAL	FROM IIP	LABOUR	CLERICAL
1	966	500	5	44	9
2	615	379	5	14	4
3	1200	540	5	14	7
4	621	211	5	14	0
5	1510	350	10	21	1
6	1701	626	9	23	4
7	1011	513	9	22	0
8	437	300	10	14	4
9	769	338	10	19	1
10	1073	186	10	12	0
11	357	70	11	1	0
12	857	156	15	6	0
13	687	443	10	10	2
14	418	306	15	7	2
15	694	390	15	3	3
16	870	419	17	10	0
17	546	359	18	2	0
18	268	51	12	1	0
19	1044	194	15	9	0
20	627	442	15	1	3
21	1412	767	15	13	4
22	929	197	10	6	0
23	360	83	7	8	0
24	552	322	9	3	1
25	2114	1333	14	21	4
26	552	522	12	3	3
27	1203	751	7	5	0
28	348	317	11	7	1
29	471	458	13	3	0
30	533	446	16	7	0
31	369	455	14	8	1
32	1317	928	15	18	1
33	815	783	17	13	1
34	676	548	17	5	0
35	1003	1428	16	11	0
36	203	168	18	2	1
37	356	920	19	2	3

TRACT NO.	POPULATION DISTRIBUTION BY OCCUPATION		TRAVEL TIME	OBSERVED RESIDENTIAL DISTRIBUTION	
	LABOUR	CLERICAL	FROM IIP	LABOUR	CLERICAL
38	489	740	18	5	2
39	424	514	23	1	3
40	834	680	21	9	1
41	1048	761	22	3	2
42	425	572	17	0	2
43	380	656	17	5	3
44	607	375	24	4	1
45	88	251	21	0	0
46	110	231	18	2	1
47	194	368	21	1	0
48	220	546	23	0	1
49	563	339	18	5	1
50	861	578	17	6	1
51	329	496	22	6	0
52	584	547	17	6	1
53	652	371	18	4	0
54	1247	665	22	5	3
55	0	0	29	0	0
56	622	320	29	2	1
57	91	20	29	0	0
58	39	44	30	1	0
59	700	198	6	6	0
60	349	161	26	4	6
61	261	189	26	4	1
62	257	163	35	0	1
63	265	173	25	0	0
64	201	538	27	1	2
65	521	369	26	4	1
66	298	332	18	3	2
67	1330	1059	16	13	1
68	726	439	15	4	1
69	741	506	18	2	4
70	1199	476	16	13	6
71	92	16	21	1	1
72	367	270	9	15	7
73	1333	845	10	43	13
74	440	355	10	8	0
75	154	65	7	5	1
76	15	16	15	0	0
77	164	105	16	1	0
78	876	752	16	2	0
79	139	271	17	1	0
80	371	653	22	0	0
81	564	758	22	5	4
82	516	416	25	0	1

TRACT NO.	POPULATION DISTRIBUTION BY OCCUPATION		TRAVEL TIME	OBSERVED RESIDENTIAL DISTRIBUTION	
	LABOUR	CLERICAL	FROM IIP	LABOUR	CLERICAL
83	158	374	23	4	1
84	231	470	22	5	1
85	400	469	28	6	1
86	969	809	27	12	3
87	234	118	20	0	1
88	217	100	21	3	1
89	804	670	21	11	3
90	54	93	31	1	0
91	345	206	31	2	0
92	178	160	33	7	4