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Volume Title: Empirical Models of Urban Land Use: Suggestions on Research Objectives and Organization

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Volume Publisher:

Volume URL: http://www.nber.org/books/brow72-1

Publication Date: 1972

Chapter Title: Land-Use-Transportation Planning Studies

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Chapter URL: http://www.nber.org/chapters/c3975

Chapter pages in book: (p. 6 - 16)

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Land-Use–Transportation Planning Studies

INTRODUCTION

"COMPREHENSIVE" METROPOLITAN land-use–transportation studies have been conducted in virtually every U.S. metropolitan area since World War II. The earliest studies were unashamedly and unabashedly highway planning studies. More recently a variety of local pressures, as well as the increasing participation of the Department of Housing and Urban Development (HUD) in the planning process, have caused these studies to give greater emphasis to transit planning, although highway planning remains their predominant concern. In the twenty years following World War II, analytical methods used in the studies have grown in both complexity and sophistication. The six studies evaluated in Chapters 2 through 8 reflect this growth.

To forecast future traffic volumes, the earliest urban transportation studies simply multiplied existing traffic volumes by a constant growth rate. The inadequacy of this technique soon became clear, and transportation planners began to search for improved methods. One early elaboration permitted recognition of the wide variations in growth rates within the metropolitan areas and allowed some adjustment for the rapid growth in traffic caused by new development in suburban areas.

Soon thereafter a number of planners began to think 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. If these relationships were fairly regular and stable, the quantity of various kinds of land use could be a measure of both current and future urban travel. This concept became the basis of the land-use–transportation method that has been employed in all recent studies. The Detroit Area Transportation Study (1953) is widely regarded as a landmark in the development of this method. The Detroit study's principal contribution was the development of systematic quantitative relationships between travel and land use which, in combination with land-use forecasts, were utilized to predict future travel. The land-use–transportation model developed in that study has been used with minor conceptual modification and great elaboration by nearly every urban transportation study since that time. Mitchell and Rapkin's study[1] provided additional theoretical justification for the procedure, and was highly instrumental in insuring that the techniques received widespread adoption by other transportation studies.

THE "STANDARD" METHOD

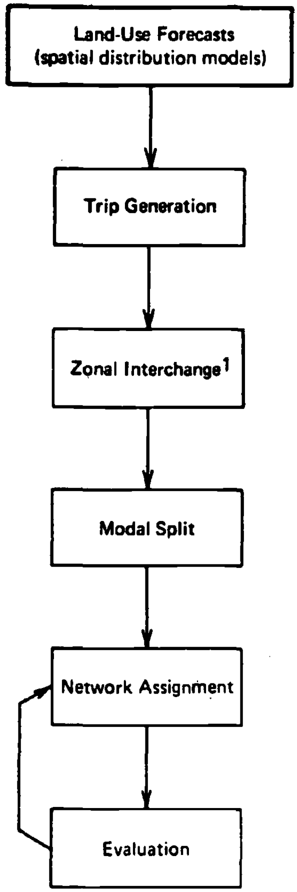
The general conceptual framework developed for use in the 1953 Detroit study is illustrated in Figure 1. The survey of land-use modeling and forecasting, which is the primary subject of this report, relates to only the first of the six boxes portrayed in the figure. The discussion that follows illustrates the manner in which the land-use forecasting models to be discussed later relate to the overall method employed in the land-use–transportation planning studies.[2]

One of the most important characteristics of this methodology is the unidirectional relationship between land use and transportation assumed in the model. The location and intensity of land use affect transportation demand and determine the amount and location of transportation facilities. However, the model incorporates no feedbacks between transportation and land use. Transportation investments are assumed, implicitly, to have no effect on the location or intensity of land use. This aspect of the standard model has been widely criticized. Critics

[1] Robert B. Mitchell and Chester Rapkin, *Urban Traffic: A Function of Land Use*, New York, 1954.

[2] For a more extensive and complete discussion of the material in this chapter, the reader is directed to John R. Meyer and Mahlon R. Straszheim, *Techniques of Transport Planning, Vol. I: Pricing and Project Evaluation*, Washington, D.C., 1970, Chapters 7 and 8. See also Richard M. Zettle and Richard R. Carll, "Summary Review of Major Metropolitan Area Transportation Studies in the United States," Berkeley, November 1962; and John F. Kain, "Urban Travel Behavior," in Leo F. Schnore and Henry Fagin, eds., *Urban Research and Policy Planning*, Beverly Hills, 1967, pp. 161–92.

Figure 1
The Land-Use – Transportation Forecasting Model



[1] In some studies zonal interchange and modal split are performed in the opposite order.

argue that land-use–transportation models may prove "correct" simply because they are self-fulfilling prophecies. Future urban travel may result from the transportation investments of the plan rather than from the future urban development as postulated by the model. Despite widespread dissatisfaction with this aspect of the model, no existing land-use model contains anything but the most trivial feedbacks of transportation investments on patterns of urban development. A fuller discussion of this question, particularly as it relates to the six land-use modeling efforts surveyed, is presented in later chapters.

Trip Generation

Transportation studies have probably devoted more time and more resources to the analysis of trip generation than to any other aspect of urban travel behavior. Trip generation refers to the number of trips produced per capita, per household, per acre, per worker, per dollar of retail sales, per square foot of floor space, or per other unit of land use.

The standard approach to estimating the number of trips originating in, or destined for, each area or zone is to assume that trip generation rates depend on the type and intensity of land use. Residential, commercial, and industrial land of various kinds usually generate a different number of trips per unit. The basic assumption of trip generation models is that the level of generation in each zone can be estimated by applying appropriate parameters for each specific class of land use. If these rates remain constant over time, and if land uses can be accurately forecast, the number of origins and destinations by zone can also be forecast accurately.

In particular applications, land area, employment, population density, and number of dwelling units have been used to estimate trip generation. The earliest land-use–transportation studies applied physical measures of land use, such as acres of land or square feet of floor space. Recent studies have stressed economic activity measures, such as employment, retail sales, and school enrollment.[3] A great deal of interest has focused on the development of behavioral trip-generation models for "home-based" trips (trips originating at or destined for

[3] For a brief survey of practices to date, see Paul W. Schuldiner, "Land Use, Activity, and Non-Residential Trip Generation," *Highway Research Record,* 141, Washington, D.C., 1966, pp. 73–88; B. C. S. Harper and H. M. Edwards, "Generation of Person Trips by Areas Within the Central Business District," *Highway Research Board Bulletin,* 253, Washington, D.C., 1960, pp. 44–61; Alan Black, "Comparison of Three Parameters of Nonresidential Trip Generation," *Highway Research Record,* 114, Washington, D.C., 1966, pp. 1–7; Paul H. Wright, "Relationships of Traffic and Floor Space Use in Central Business District," *Highway Research Record,* 114, Washington, D.C., 1966, pp. 152–68; and Donald E. Cleveland and Edward A. Mueller, *Traffic Characteristics at Regional Shopping Centers,* New Haven, 1961.

home). These models relate person or vehicle trips per household, per capita, or per dwelling unit to variables such as car ownership, net residential density, distance of the residence from the central business district, family income, and family size. Virtually every study has estimated a number of simple and multiple regression models that relate trips to one or more of these explanatory variables. While much has been learned from these analyses, a number of statistical and conceptual problems have been treated in a rather cavalier fashion and the nature of the underlying structure of these behavioral relationships remains unclear.

Zonal Interchange

Given an accurate forecast of the number of trips originating in, or destined for, each zone, the next step in the land-use–transportation procedure is to convert these origins and destinations into interzonal trips. Attempts to model zonal interchanges for urban areas almost always start by mapping the present interzonal flows. This requires an origin and destination survey. The earliest studies projected future interzonal travel by applying a constant growth rate to observed interzonal travel volumes. When the results of this crude procedure proved unsatisfactory, more sophisticated procedures were developed. The most widely used of the improved methods fall into three categories: the Fratar expansion method, the gravity model, and the intervening opportunities model.

The Fratar expansion method is a logical extension of the simple growth factor method.[4] It corrects the most obvious inadequacies of the growth factor model by allowing the rate of growth of interzonal travel to vary within the metropolitan area. In essence, the Fratar expansion method is an iterative technique that makes use of a different growth factor in each zone. Forecasts of interzonal travel are derived from the present level of interzonal trips and the different zonal growth factors. In an effort to incorporate more behavior into interzonal trip forecasts, transportation planners have moved from the Fratar method to other formulations.

The gravity model, in its simplest form, determines a set of flows from each point of origin to all other points (destinations). These flows

[4] T. J. Fratar, "Forecasting Distribution of Integral Vehicular Trips by Successive Approximations," *Highway Research Board Proceedings*, 33, 1954, pp. 276–384; and Walter Oi and Paul W. Schuldiner, *An Analysis of Urban Travel Demands*, Evanston, 1962, Appendix D.

are assumed to be directly proportional to the "attraction" at each destination and inversely proportional to the travel impedance (transportation cost or time) between the origin and the destination. Usually the travel impedance is some nonlinear function of the more direct measures of transportation cost. A typical formulation is

$$T_{ij} = P_i \frac{S_j A_j / D_{ij}^b}{\sum_k S_k A_k / D_{ik}^b} \tag{1}$$

where

T_{ij} = the number of trips from origin zone i to destination zone j;

P_i = some parameter of the origin zone, such as the population;

A_j = some parameter of the destination zone, usually called the "attraction," and frequently reflecting floor area or acres of land;

D_{ij} = the direct measure of "distance" or transportation cost between the origin and the destination;

b = parameter, usually depending on trip purpose;

S_i = scalar determined from an iterative calibration procedure which requires $\sum_j T_{ij} = P_i$ and $\sum_i T_{ij} = A_j$, for those formulations where P_i is the number of trips "produced" and A_j is the number of trips "attracted."

The calibration of the gravity model is interpreted to be the determination of the parameter b, which is assumed to be invariant over time and therefore is a determinant useful in future trip distributions. The exponent b was consequently considered to be the only parameter to affect the distribution.[5] All other variables were either

[5] In situations where there is only one demand point or one supply point, the exponent can assume any positive value less than infinity with no effect at all on the resultant distribution. This is due to the requirement that $\sum_j T_{ij} = P_i$ and $\sum_i T_{ij} = A_j$. As the number of supply or demand points increase, the exponent begins to have an effect on the distribution. Since the attraction $(S_j A_j / D_{ij}^b)$ is standardized by the sum of the attractions as a denominator, the constant S_j will be unity when b is zero. When b assumes a nonzero value, this equation does not generate flows in such a way that the sum of terminating flows at every point is equal to the demand at that point. Hence, to maintain the equality of the sum of inflows to the demand at every demand point, S_j must assume a value different from unity.

measured directly or were forecast using standard trip generation techniques. When the value of the exponent is large (values of 2.5 typically have been associated with shopping trips), flows tend to be satisfied as close to the demand point (origin zone) as possible. A small value (the value of 1.0 is often associated with work trips) results in a more dispersed pattern. In the extreme, a zero exponent would allow demands (trip origins) to be satisfied at each destination in direct proportion to the per cent of the total supply (trip ends) available at the destination zone. The parameter b has been observed to vary between urban areas as well as between trip purposes.[6] More complicated formulations have been developed to account for some observed biases.[7]

Intervening opportunities, the third zonal interchange model in wide use, employs a stated probability of every destination being accepted. Total travel time is minimized for every origin, subject to the constraint that every potential destination is considered. Equations 2 and 3 summarize the intervening opportunities model. The expected interchange from zone i to zone j (T_{ij}) is the number of trip origins at zone i (O_i) multiplied by the probability of a trip terminating in j.[8]

$$T_{ij} = O_i[P(v_j) - P(v_{j+1})] \tag{2}$$

or

$$T_{ij} = O_i\,(e^{-lv_j} - e^{-lv_{j+1}}) \tag{3}$$

where

$P(v)$ = total probability that a trip will terminate by the time v possible destinations are considered;

v_j = "subtended volume," or the possible destinations already considered; that is, the trip destinations which could be reached before traveling far enough to reach zone j;

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

[6] For a discussion of these differences, see J. Douglas Carroll and Howard W. Bevis, "Predicting Local Travel in Urban Regions," *Papers and Proceedings for the Regional Science Association,* 3, 1957, pp. 183–97.

[7] W. G. Hansen, "Evaluation of Gravity Model Trip Distribution Procedures," *Highway Research Board Bulletin,* 347, Washington, D.C., 1962, pp. 67–76; R. J. Bouchard and C. E. Pyers, "Use of Gravity Model for Describing Urban Travel: An Analysis and Critique," *Highway Research Record,* 88, 1965, pp. 1–43; U.S. Bureau of Public Roads, "Calibrating and Testing a Gravity Model in Any Size Urban Area," Washington, D.C., 1963, and "Calibrating and Testing a Gravity Model with a Small Computer," Washington, D.C., 1963.

[8] Morton Schneider, "Gravity Models and Trip Distribution Theory," *Papers and Proceedings of the Regional Science Association,* 5, 1959, pp. 51–56.

A trip originating in zone *i* thus has less probability of ending up in zone *j* as the number of intervening opportunities increases.[9]

The two terms in the brackets are, respectively, the probability of a trip getting to zone *j*, and the probability that, having reached zone *j*, the trip will not continue farther.[10] The parameter *l* shapes the distribution of interchanges, with a larger value of *l* leading to a more concentrated set of trips, given any surface of opportunities. Basically, the model allocates trips on an incremental basis over an opportunity surface rank ordered in descending fashion by travel time to the zone of origin, *i*.[11] Theoretically, the value of *l* is the slope of a log-linear relationship between the accumulated number of opportunities and the probability of continuing a trip. In practice, the relationship has not been linear and more than one *l* has been used in an additive form of the model.

Modal Choice

There are two basic approaches to modeling the number of trips that use various modes of travel in an urban area. These methods are generally referred to as "trip-end modal split models" and "trip-interchange modal split models." The names are derived from the particular variable that is "split" between modes. Each approach has its faults since the problem of trip frequency, destination choice, and mode choice is a simultaneously determined outcome in the real world.

Trip-end models were originally developed in conjunction with highway-oriented origin and destination studies, where they still have

[9] The mathematical formulation as the basis of this derivation is as follows:

$$dP = l\,[1 - P(v)]\,dv$$

where dP = probability that a trip will terminate when considering dv possible destinations. Other notation is as above.

The solution of this differential equation,

$$P(v) = 1 - e^{lv},$$

implies the equation in the text. (See Earl R. Ruiter, "Improvements in Understanding, Calibrating, and Applying the Opportunity Model," *Highway Research Record,* 165, Publication 1443, Washington, D.C., 1967, pp. 1–21.)

[10] Basically, the model premises a linear equation between the logarithm of the probability that a trip from zone *i* has not yet been satisfied by the time it "reaches" zone $j\,[1 - P(v)]$, and the number of intervening destinations or "opportunities" already considered by the time zone *j* is reached (v). The parameter *l* is the slope.

[11] Ruiter (see footnote 9) has attempted to explain the parameter *l* in behavioral terms of trip making. As a first approximation, *l* is related inversely to trip-end density and to the square of average trip length.

their most widespread use. As noted earlier, these studies are concerned primarily with forecasting automobile travel. In the simplest trip-end modal split models, some proportion of trips originating in each zone are simply subtracted from total trip generation before the remaining trips are assigned to the highway network. This transit-use proportion is often specified as a function of car ownership, net residential density, income, or a combination of these variables. An example of a modal split model of this kind is illustrated by equations 4 and 5:

$$F_i{}^b = \alpha_0 + \alpha_1 A_i + \alpha_2 D_i \tag{4}$$

and

$$F_{ij}{}^b = F_i{}^b \cdot T_{ij}, \tag{5}$$

where F_{ib} is the fraction of trips originating in i by mode b, A is auto ownership, and D is net residential density.

The most common elaborations of trip-end models have been the development of separate relationships by trip purpose. The purposes most commonly used in stratifying modal split models are school trips and work trips, since transit is generally more competitive with other travel modes for these purposes. Occasionally, special relationships are estimated for transit travel to and from the central business district (CBD) as identified separately from the remaining parts of the region, in recognition of the large differences in the levels of transit service to the CBD and to the remainder of the region.

Trip-interchange models initially were developed for transit feasibility studies, where they are still most widely used. The important characteristic of these models is that they emphasize comparative travel time, costs, and service by competing modes. The emphasis is easily understandable. A major rationale for transit feasibility studies is the diversion of current and future automobile commuters to transit as a result of service improvements.[12]

One of the most elaborate trip-interchange modal split models was developed in a transit feasibility study for the National Capital Transportation Authority in Washington, D.C. In this study, zonal interchange data for 1955 were stratified by trip purpose (work and nonwork), the ratio of highway trip costs to transit trip costs, the ratio of transit "service" to auto "service," and the median income of residence zones. One hundred and sixty subclasses were defined in this way.

[12] For a survey of these studies, see U.S. Department of Commerce, Bureau of Public Roads, Office of Planning, *Modal Split: Documentation of Nine Methods for Estimating Transit Usage*, Washington, D.C., December 1966.

Diversion curves, relating the per cent of transit usage to the ratio of highway travel time to transit travel time, were then obtained for each subclass.[13] Travel time ratios for work trips were based on peak hour conditions, while those for nonwork trips were taken from off-peak periods. The latter had to be applied to both peak and off-peak periods, which probably contributed to the poorer results in modeling nonwork trips.

The major result of this study is its suggestion of a much greater sensitivity of modal split to the performance of the highway system (parking delays and costs, and walking time) than to transit system performance. The model implies that a fifteen cent across-the-board fare increase (about a 50 per cent increase) would result in only a 5 per cent decline in total transit trips. This relatively low fare elasticity is consistent with other empirical studies. Changes in transit operating time were also judged to be of somewhat limited significance: for example, a 50 per cent rise in waiting and transfer time would reduce transit use by about 15 per cent.[14]

Network Assignment

The forecasts of interzonal travel by mode, obtained from the land-use, trip-generation, zonal interchange, and modal split models, are

[13] Thomas B. Deen, William L. Mertz, and Neal A. Irwin, "Application of a Modal Split Model to Travel Estimates for the Washington Area," *Highway Research Record*, 38, Washington, D.C., 1963, pp. 97–123; and Arthur B. Sosslau, Kevin Heanue, and Arthur J. Balek, "Evaluation of a New Modal Split Procedure," *Highway Research Record*, 88, Washington, D.C., 1965, pp. 44–63.

[14] Arthur Sosslau, Kevin Heanue, and Arthur Balek, "Evaluation of a New Modal Split Procedure," *Public Roads*, 33, April 1964, pp. 48–63.

Domencich and Kraft, in a substantial departure from this conventional planning format, suggested a model that treats trip generation, interchange, and modal choice simultaneously. Rather than let price or other service characteristics affect only the modal choice of a predetermined level of "directed" trips (i.e., origins and destinations are determined), they suggest including the influence of these characteristics on the level of trip making as well. After stratifying demand by trip purpose, their model fits an equation to zonal interchanges by each mode, and uses both transport system supply characteristics (such as travel cost or time) and basic economic variables (such as the type of land use, income levels, family size) as explanatory variables. See Thomas A. Domencich, Gerald Kraft, and Jean-Paul Valette, "Estimation of Urban Passenger Travel Behavior: An Economic Demand Model," prepared for presentation at the Annual Meeting of the Highway Research Board, January 1968.

finally "assigned" to proposed highway and transit networks as an initial stage in evaluating the adequacy of particular plans. Urban transportation studies have rapidly developed techniques for performing these assignments. The earliest assignments were restricted to limited freeway networks. They were made manually and were highly subjective. Typically, forecast interzonal traffic was divided between two alternatives (usually an existing arterial road and a proposed freeway), depending on relative travel time and distance. These assignments generally were based on "diversion curves," similar to those described previously for trip-interchange modal split models.

In 1957, a new era of network assignment modeling began as George B. Dantzig and Edward F. Moores independently developed a computer algorithm for finding the path through a network that would minimize travel time or cost.[15] The Chicago Area Transportation Study was the first to apply these techniques to urban transportation planning. Since 1957, development has been rapid and other studies have devised increasingly sophisticated assignment methods.[16]

The earliest "minimum path" assignment techniques assumed an infinite capacity for each network link. This, however, produced peculiar and unrealistic results: Because all traffic was assigned to "high performance" expressways, an "all-or-none" mapping was produced, either overloading links or assigning no traffic to them. The need for feedback between capacity utilization and link performance was quickly recognized.

In recent years, a number of techniques have been developed to incorporate capacity constraints. All use some form of iterative procedure in which continually updated travel times are used in the minimum path algorithms. For example, in the Chicago and Pittsburgh studies the network assignments were made one node at a time (a node is an entry or exit point on the network). Travel speeds on the network were adjusted each time to reflect the traffic previously assigned.

[15] George B. Dantzig, "The Shortest Route Problem," *Operations Research*, 5, 1957, pp. 270–73; and Edward F. Moores, "The Shortest Path Through a Maze," a paper presented at the International Symposium on the Theory of Switching, Harvard University, June 1957. Dantzig and Moores developed the solution independently of each other.

[16] Robert B. Dial, "A Probabilistic Multipath Traffic Assignment Model Which Obviates Path Enumeration," to be published in the 1971 *Highway Research Record* series.