Experiments in Urban Form and Structure

GEORGE C. HEMMENS, Associate Professor of Planning,
University of North Carolina at Chapel Hill

•EVALUATION of alternate land development patterns is an important, unsolved task in urban planning. There are many reasons for the rather slow progress in developing methods for evaluating alternate development plans. Perhaps chief among them is disagreement on what are the proper criteria for evaluation. However, part of the difficulty lies in the limited understanding of the relationships among the components of urban form. For example, what difference does it make in the operation of an urban area if workplaces are concentrated downtown, or concentrated in a few suburban locations, or scattered throughout the urban area? What difference would it make if residential density were highest in the suburbs and lowest near the downtown area instead of the reverse pattern which exists today?

We have difficulty in answering these questions because we are not able to examine the various alternatives in nature, nor do we have the freedom to reconstitute cities according to our designs in order to observe the effects of variations in urban form. The solution to a part of this problem will be found, I think, in the development of fairly simple experimental models of an urban community which are designed specifically for the exploration of the relationships among elements of urban form, and which can be easily manipulated and readily understood by urban planners.

This paper is a report on a simple model for examining the impact of changes in components of urban form on urban spatial structure. The distinction made here between urban form and urban structure is quite simple. Urban form is the physical arrangement of residences, work places, etc. Urban structure is the pattern formed by the connection of these elements in the daily activities of the area's residents. Urban structure implies an allocation rule. Given a physical pattern of places, the connections between them—from home to work, from home to shopping center—must be established. Another way of making the distinction is to say that urban form describes the static, physical setting itself and that urban structure describes the dynamics of a particular physical setting. The nomenclature is arbitrary, but the distinction is necessary.

The approach developed and examined here is only one of many possible approaches to the problem. The purpose of this effort has been to test the utility of using a simple linear programming formulation as an allocation rule for evaluating urban form alternatives by two criteria: the efficiency of the alternatives in terms of minimal travel requirements, and the equity of the alternatives in terms of locational advantage of residence locations. These criteria are evaluated by the primal and the dual problem of a "transportation problem" in linear programming.

The problem with which we deal is this. Given alternate distributions among subareas of an urban area of each of the urban form elements of workplaces, shopping places, and residences; alternate systems of transportation service; and an allocation rule which specifies the way residences will be linked with workplaces and shopping places—what is the impact of changes in the components of urban form on urban spatial structure? The basic question might better be put as a series of questions. What effect do changes in the components of urban form have on travel requirements, given a particular allocation rule? What is the relative impact of individual elements of urban form on urban spatial structure? Do changes in the residential pattern have more or less

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impact than changes in transportation service? Is there a best combination of elements of urban form in the sense that this particular combination requires less travel than any other combination of elements? The list of questions could be continued almost indefinately. They all add up to the same concern: Can we demonstrate the effect of changes in urban form on urban spatial structure?

THE ALLOCATION RULE

The allocation rule is a linear programming allocation to minimize total travel required for establishing a linkage between each residence and a workplace and a shopping place. The LP allocation is used as a diagnostic of urban form in this application and is not intended to simulate in realistic detail the behavior of persons in urban areas. As a diagnostic, the LP allocation provides an evaluation of the potential efficiency of alternate urban forms under conditions of aggregate optimizing behavior. It is true that a person does not always go to the nearest shopping center on each shopping trip, nor does every family choose to live in the house meeting its requirements which is closest to the head of the household's place of work. Furthermore, the LP allocation produces a community or system minimization of travel requirements rather than an individual minimization. However, it has been shown that the majority of daily work and shopping trips in a large urban area conform closely to the time requirements of an LP minimizing allocation (1). The output of the allocation model provides three kinds of information about the activity structure for a particular urban form—the travel required by the minimum solution; the linkage pattern selected; and from the dual of the minimizing problem, the comparative locational advantage of residential zones.

The formal statement of the problem is:

find the X_{ij} such that

$$\sum \sum C_{ij} X_{ij} \text{ is a minimum} \qquad (1)$$

subject to

$$\sum_{j=1}^{n} X_{ij} = O_i \qquad i = 1 \ldots m \qquad (2)$$

$$\sum_{i=1}^{m} X_{ij} = D_j \qquad j = 1 \ldots n \qquad (3)$$

$$X_{ij} \geq O, \; C_{ij} \geq O \qquad (4)$$

and

$$\sum_{i=1}^{m} O_i = \sum_{j=1}^{n} D_j$$

where

C_{ij} = travel time from zone i to zone j,
X_{ij} = trips from zone i to zone j,
O_i = trip origins in zone i, and
D_j = trip destinations in zone j.

The dual problem is

$$\sum_{j=1}^{n} r_j v_j - \sum_{i=1}^{m} s_i u_i = \text{maximum} \tag{5}$$

where the constraints are

$$v_j - u_i \leq C_{ij}$$

and

$$u_i, v_j \geq O$$

and where

s_i = trips sent from zone i, and
r_j = trips received at zone j.

The value of u_i is the rental value of location in zone i as an origin point for trips to a particular activity. We interpret v_j as the value of the trip maker of the activity in zone j (2). The values are measured in travel-time units, since these are the cost data of the original problem. The rental value of a site is a measure of its attractiveness as a location point. A high rental value means that the zone has a relatively advantageous location. Since the values assigned to the dual variables are based on minimization of total travel time in the system, the values assigned to residential origins measure the comparative locational advantage of residential locations under conditions of efficient travel.

EXPERIMENTAL DESIGN

The components of the urban area model are a set of zones comprising the urban area, a set of alternate residential patterns, a set of patterns of work places, a set of patterns of shopping places, and alternate systems of transportation service. The number of residences equals the capacity of the work places and the capacity of the shopping places. In other words, one trip is to be made from each residence to a work place and to a shopping place.

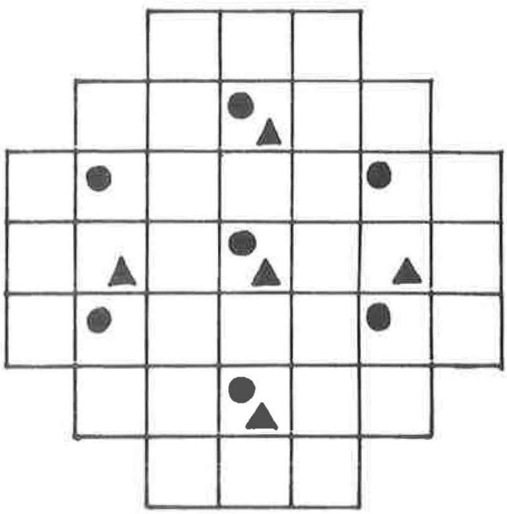

Figure 1. Experimental urban form: ● = commercial centers; ▲= work centers.

The hypothetical urban area is shown in Figure 1. There are 37 zones of equal size. Thirty-two of these zones may contain residences. No residences are permitted in zones containing work centers. There are seven commercial centers. One is in the center of the urban area and the other six are distributed regularly around the center. There are five work centers. Again, one is in the center of the urban area and the others are regularly spaced around the center. Three zones contain both work centers and commercial centers.

This is obviously a highly simplified representation of an urban area. However, it does resemble the general pattern of many large urban areas. The central zone can be interpreted as the central business district. The outlying commercial centers

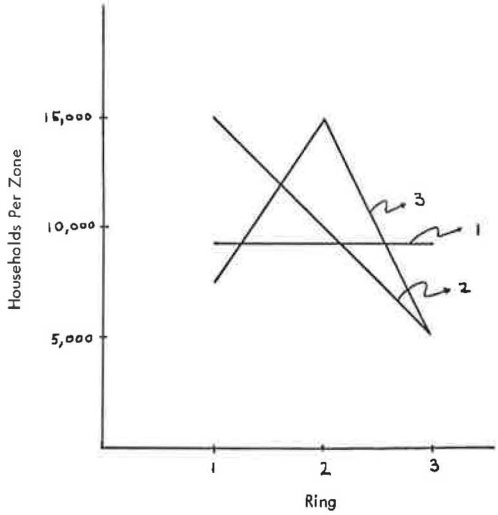

Figure 2. Alternate residential density patterns.

become major shopping centers, and the outlying work centers may be interpreted as large industrial parks or historic employment concentrations. What is missing is the widespread distribution of smaller commercial opportunities, the neighborhood shopping centers and the strip commercial development, and the almost equally widespread distribution of small capacity work places which are typical of a metropolitan area. Also missing is the widespread distribution of jobs. For example, we are not including work trips to shopping centers in order to keep the model simple.

There are three alternate residential density patterns, two alternate patterns of commercial center and work center capacity, and three alternate systems of transportation service. The alternate residential density patterns are: R1, uniform density throughout the urban area; R2, high central density declining regularly with distance from the center; and R3, crested density rising from a low value in the center to a high point and then decling (Fig. 2). There are 300, 000 residences. This places the population of the urban area at about one million persons. There are two alternative patterns of work center and commercial center capacity, and they are similar. In the first (W1 and C1), 70 percent of the jobs and 70 percent of the shopping opportunities are in the (geographic) center zone. The remaining 30 percent of the jobs are equally divided among the four outlying work centers, and the remaining 30 percent of the shopping opportunities are equally divided among the six outlying commercial centers. The second alternative (W2 and C2) is the reverse of the first. Thirty percent of the work and shopping opportunities are in the central zone and the remaining 70 percent are divided among the outlying centers. These alternatives have obvious interpretations. In the first case, there is a traditional strong metropolitan core complemented by relatively weak suburban centers. The second case depicts a sharp decline in the relative importance of the core and a corresponding increase in the importance of suburban centers. However, even in the latter case the core capacity is greater than the capacity of an individual suburban center.

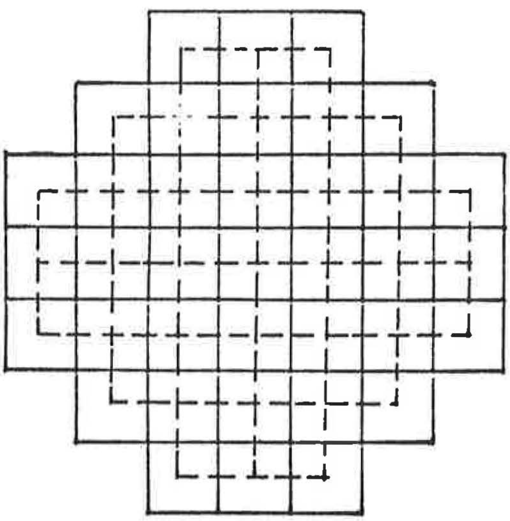

Figure 3. Transportation alternative 1: travel time on each link = 2.

There are three alternate systems of transportation service. The only routes permitted are in north-south and east-west directions from the center of a zone to an adjacent zone. So a diagonal path through the area is composed of zigzag right-angle links. The travel time or cost of travel from one zone to another is defined in terms of level of service provided rather than in terms of the design capacity and speed of physical facilities. Since the allocation model will impose different loads on different links, the network of physical transportation facilities must be differentiated. For convenience, assume

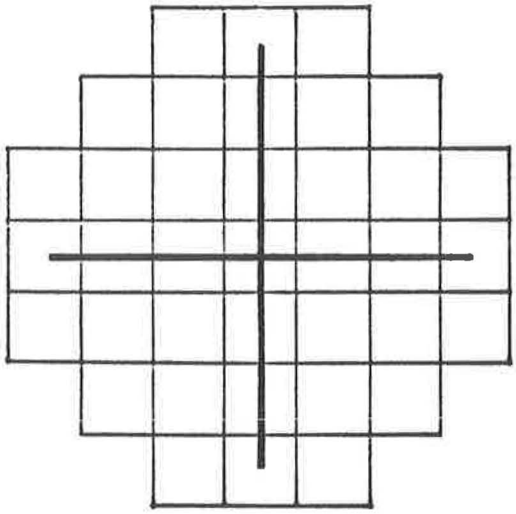

Figure 4. Transportation alternative 2: travel time on major links = 1; all others = 2.

that the roads are the only elements of the system and all travel is by individuals in private vehicles.

The first transportation system consists of uniform transportation service (Fig. 3). The travel cost of all zone-to-zone links is given the same arbitrary value of 2 time units. It is assumed that sufficient capacity to maintain this level of service will be provided. The second and third transportation systems superimpose higher service level facilities over this basic transportation surface. In the second system, north-south and east-west links through the central zone from the periphery are established at a travel cost of 1. This creates four high service level radial routes (Fig. 4). The third transportation system adds to the first and second a ring of high service level links (Fig. 5). Taken as a sequence over time these transportation service systems resemble the radial-circumferential networks of transportation facilities which have been developed in many metropolitan areas.

The three transportation alternatives, three residential alternatives, two commercial center alternatives, and two work center alternatives can be combined into 36 different urban forms. To clarify the alternative urban forms possible, each is given a description. Basically, all combinations with the first residential alternative are variants of a spread city. With the second residential alternative, all combinations are variants on a cone-shaped form which is called a centric city. Combinations with the third residential alternative are called variations of a ring city. The alternative forms are

R1, C1, W1: Spread city with strong core,
R1, C1, W2: Spread city with spread employment, but strong commercial core,
R1, C2, W1: Spread city with spread commercial, but strong employment core,
R1, C2, W2: Spread city,
R2, C1, W1: Centric city,
R2, C1, W2: Centric city with dispersed employment,
R2, C2, W1: Centric city with dispersed commercial,
R2, C2, W2: Centric city with dispersed commercial and employment,
R3, C1, W1: Ring city with strong commercial and employment core,
R3, C1, W2: Ring city with commercial core,
R3, C2, W1: Ring city with employment core, and
R3, C2, W2: Ring city with weak core.

The alternative transportation systems can be intuitively related to the alternate development patterns. The first system, providing uniform transportation service is essentially neutral. It is indifferent to urban form. We would expect the second system, featuring high-level radial access to the center of the urban area, to be well matched with the centric city. The third system provides a high level of service through the outer ring and might be expected to best match the dispersed forms of both the spread and ring city.

IMPACT OF ALTERNATE URBAN FORMS ON MINIMUM TRAVEL REQUIREMENTS

First we will look at the minimum travel requirements of alternate urban forms when the transportation system is constant. Figure 6 shows the travel requirements

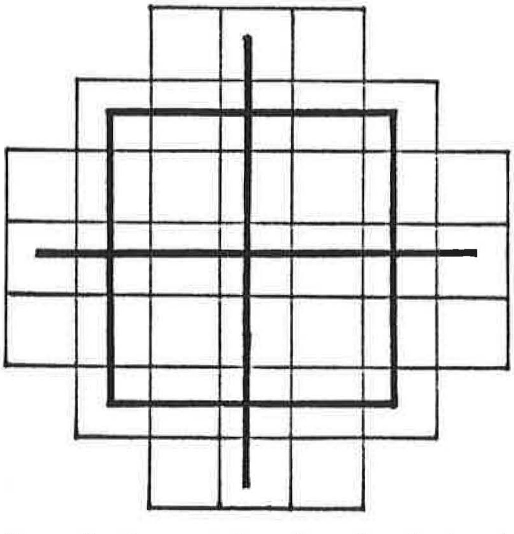

Figure 5. Transportation alternative 3: travel time on major links = 1; all others = 2.

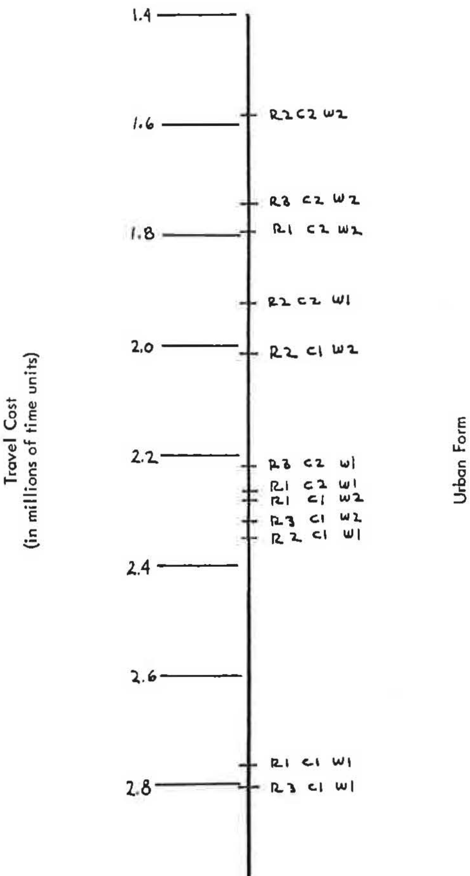

Figure 6. Minimum travel requirements of alternate urban forms.

of all 12 possible urban forms with the system of uniform transportation service.[1] The least cost solution is the centric city with dispersed commercial and employment opportunities. The most costly form is the ring city with a strong core, and it is closely followed by the spread city with a strong core. In general, the urban forms with a weak commercial and employment core have the lowest travel requirements, and those with a strong core have the greatest travel requirements.

In the individual elements, a change in the commercial pattern when the residence and workplace pattern are the same has the greatest impact on travel requirements. Next in significance is a change in workplaces. Changes in the residential pattern have the least effect on travel requirements. In the travel requirements of alternatives of each element, a weak commercial and employment core always requires less travel than a strong core under the travel minimizing allocation. Any combination of the commercial and employment opportunities requires less travel with the centric residential pattern than does the same employment and commercial pattern with either the ring or spread residential pattern.

These results suggest that, given uniform transportation service, the most efficient urban form couples dispersed employment and commercial opportunities with residential density that is high in the center and declines with distance from the center. The results also suggest that major variations in the residential pattern do not have a very significant influence on travel requirements.

It is difficult to evaluate these results because the differences in the alternatives of the several elements are not necessarily of the same magnitude. For example, the difference between uniform residential density and a regular density gradient does not necessarily involve the same proportional change as the difference between a spread

[1]Each experiment contains two allocations—trips to a given distribution of work places and trips to a given distribution of commercial centers—from a common residential distribution. The travel times for work and shopping trips are summed to give the total travel time for the specified urban form.

TABLE 1

TIME UNITS REQUIRED FOR MINIMAL LINKAGES IN URBAN FORM EXPERIMENTS

Experiment	Commercial	Work	Total	Rank
T1 R1 C2 W2	827, 500	960, 000	1, 787, 500	3
T1 R1 C2 W1	827, 500	1, 440, 000	2, 267, 500	7
T1 R1 C1 W2	1, 320, 000	960, 000	2, 280, 000	8
T1 R1 C1 W1	1, 320, 000	1, 440, 000	2, 760, 000	11
T1 R2 C2 W2	680, 000	900, 000	1, 580, 000	1
T1 R2 C2 W1	680, 000	1, 240, 000	1, 920, 000	4
T1 R2 C1 W2	1, 112, 000	900, 000	2, 012, 000	5
T1 R2 C1 W1	1, 112, 000	1, 240, 000	2, 352, 000	10
T1 R3 C2 W2	760, 000	980, 000	1, 740, 000	2
T1 R3 C2 W1	760, 000	1, 460, 000	2, 220, 000	6
T1 R3 C1 W2	1, 340, 000	980, 000	2, 320, 000	9
T1 R3 C1 W1	1, 340, 000	1, 460, 000	2, 800, 000	12
T2 R1 C2 W2	629, 375	742, 500	1, 371, 875	2
T2 R1 C2 W1	629, 375	982, 500	1, 611, 875	5
T2 R1 C1 W2	894, 375	742, 500	1, 636, 875	6
T2 R1 C1 W1	894, 375	982, 500	1, 876, 875	9
T2 R2 C2 W2	580, 000	700, 000	1, 280, 000	1
T2 R2 C2 W1	580, 000	880, 000	1, 460, 000	3
T2 R2 C1 W2	815, 000	700, 000	1, 515, 000	4
T2 R2 C1 W1	815, 000	880, 000	1, 695, 000	8
T2 R3 C2 W1	612, 000	1, 040, 000	1, 652, 000	7
T3 R1 C2 W2	545, 000	592, 500	1, 137, 500	2
T3 R1 C2 W1	545, 000	832, 500	1, 377, 500	7
T3 R1 C1 W2	772, 500	592, 500	1, 365, 000	6
T3 R1 C1 W1	772, 500	832, 500	1, 605, 000	9
T3 R2 C2 W2	460, 000	540, 000	1, 000, 000	1
T3 R2 C2 W1	460, 000	720, 000	1, 180, 000	3
T3 R2 C1 W2	690, 000	540, 000	1, 230, 000	4
T3 R2 C1 W1	690, 000	720, 000	1, 410, 000	8
T3 R3 C2 W1	495, 000	800, 000	1, 295, 000	5

commercial pattern and a concentrated pattern of shopping opportunities. So we must qualify the statement that changes in the commercial pattern have a greater influence on minimum travel time than changes in the residential pattern by saying that this has been shown to be so if the changes are comparable.

Table 1 gives the minimal travel requirements for all the experiments conducted. In addition to the full 12 form combinations with the uniform transportation service, experiments have been conducted with 9 form combinations with each of the other transportation alternatives. The most important finding is that the general ranking of urban forms by travel requirements found with uniform transportation service holds for all transportation alternatives. This means that at least for the particular alternatives we have examined, the system of transportation service has little influence on the relative efficiency of alternate urban forms. If this is generally true, i. e., if it holds for other transportation systems and other residential, commercial, and employment patterns that we have examined, it is a significant finding.

The obvious implication for urban planning is that the spatial pattern of land use and the pattern of transportation service can be planned somewhat more independently than is commonly thought. Independence is implied in a peculiar sense. The results do not imply that the land-use pattern and the transportation system are not interrelated. They imply that evaluation of alternative land-use patterns may be considered without reference to particular transportation systems. The reverse situation is clearly not implied. If this implication is correct, then the proper order of attack on the problem of selecting an efficient urban form is to examine alternative land-use patterns and then to examine alternate transportation systems to serve the selected land-use pattern.

While alternate transportation systems do not significantly affect the relative efficiency of alternate land-use patterns, they do affect the absolute efficiency of these patterns. Figure 7 shows the range of minimum travel requirements for all the experiments with the three transportation systems. For any urban form the minimum travel requirements are reduced as the quality of transportation service is improved. This is not surprising. Any other result would make us suspect that the model was totally irrelevant to the conditions it is being used to examine. Two results are worthy of note however. First, improvement of the quality of transportation service results in a reduction of the absolute difference in travel requirements between alternate land-use forms. The total range of travel requirements is reduced. This also is to be expected. But it is interesting to note that after the first improvement, the addition of higher level radial service, the range of travel time required is not further reduced by the addition of more high-level service in the third alternative.

Second, the results of the experiments begin to suggest ways in which changes in the land-use pattern can be traded off against changes in the transportation system to achieve the same level of improvement in minimum travel requirements. For example, if we start with the centric city with a strong core, approximately the same improvement in minimum travel requirements can be achieved by improving the quality of radial transportation service to the core as by dispersing commercial and employment opportunities to the outer zones. The potential for this type of trade-off is shown by the areas of overlap in Figure 7.

These conclusions may seem somewhat at odds with the earlier observation of independence of the transportation system and the land-use pattern, but there is no conflict. Our earlier observation was that changes in the transportation system do not appear to affect the relative efficiency of alternate land-use patterns. These second observations simply show that a superior transportation system can make an inferior land-use pattern as efficient as a superior land-use pattern. The implication for planning is equally clear. If, for example, a level of minimum travel requirements is specified as an objective, alternate means of achieving it can be demonstrated, and a clear policy choice between investment in transportation service and control and direction of land development can be formulated.

Locational Advantage as a Measure of Urban Form

Thus far our experiments have shown that alternate residential patterns have relatively little effect on minimum travel requirements of the experimental urban forms. However, alternate residential patterns may nevertheless represent significantly different locational qualities for residents of individual zones. To examine this question, we turn to an aggregate statistic—the range of locational advantage.

The range of values of locational advantage is simply the difference between the highest zonal value and the lowest zonal value defined in a particular experiment. The significance of the choice of a residential zone increases with increases in the range of values of locational advantage. If the range were zero, i. e., if all zones had an equal value of locational advantage, there would be no reason to select one zone over another as a residential location. If the range of values were very large, the choice of a residential zone would be more significant, since it would involve the potential for travel savings.

The range of values of comparative locational advantage defined by all 30 experiments conducted is given in Table 2. As expected, the range of locational advantage decreases with improvements in the quality of transportation service. This is simply a result of decreases in the average travel expenditure. Alternate urban forms with any one transportation system show considerable stability in range of locational advantage. This stability is due in part to the grossness of the experiments. The small number of zones and the small range of possible travel requirements limit the variations in locational advantage. The centric city with dispersed work and commercial opportunities has the smallest range of values.

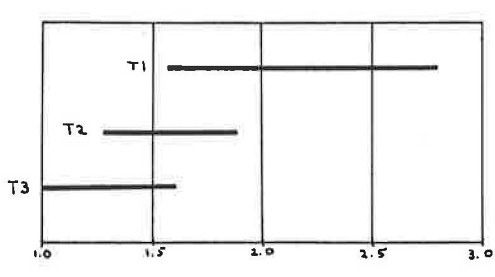

Figure 7. Range of travel requirements with alternate transportation systems.

One further outcome should be noted. The dual problem, as we have said,

TABLE 2

RANGE OF VALUES OF COMPARATIVE LOCATIONAL ADVANTAGE OF ALTERNATE URBAN FORMS

Experiment	Commercial	Employment	C + W/2
T1 R1 C2 W2	6	6	6
T1 R1 C2 W1	6	6	6
T1 R1 C1 W2	6	6	6
T1 R1 C1 W1	6	6	6
T1 R2 C2 W2	6	6	6
T1 R2 C2 W1	6	6	6
T1 R2 C1 W2	6	6	6
T1 R2 C2 W2	6	6	6
T1 R3 C2 W2	6	6	6
T1 R3 C2 W1	6	6	6
T1 R3 C1 W2	6	6	6
T1 R3 C1 W1	6	6	6
T2 R1 C2 W2	4	5	4.5
T2 R1 C2 W1	4	5	4.5
T2 R1 C1 W2	4	5	4.5
T2 R1 C1 W1	4	5	4.5
T2 R2 C2 W2	4	3	3.5
T2 R2 C2 W1	4	5	4.5
T2 R2 C1 W2	4	3	3.5
T2 R2 C1 W1	4	5	4.5
T2 R3 C2 W1	4	5	4.5
T3 R1 C2 W2	4	4	4
T3 R1 C2 W1	4	4	4
T3 R1 C1 W2	4	4	4
T3 R1 C1 W1	4	4	4
T3 R2 C2 W2	2	2	2
T3 R2 C2 W1	2	4	3
T3 R2 C1 W2	4	2	3
T3 R2 C1 W1	4	4	4
T3 R3 C2 W1	4	4	4

calculates value or prices at both origin and destination. The price at the destination is traditionally interpreted as the delivered price of the item being shipped. In our experiments, the shipped item is persons transporting themselves to work. So the price at the destination may be interpreted as the input cost of labor to the several employment centers. It can be interpreted as the average price in travel time which must be "paid" by each employment center to attract its work force, given the distribution of employment opportunities, the residential pattern, and the transportation system. Examination of these prices for the dual problem of all experiments conducted shows that for the centric city with dispersed employment and only for that urban form the prices are equal. In other words each work place "pays" the same price for its labor input. We can interpret this to mean that the locations of the employment centers are equally efficient.

CONCLUSIONS

This report has discussed some beginning efforts at one approach to examining the relationships among elements of urban form as a first step toward developing more satisfactory analytic methods of evaluating alternatives of the form and performance of cities. The allocation used provides a means for examining the effects of changes in urban form under conditions of travel minimizing behavior. Two criteria were used in the analysis: the potential efficiency of alternate urban forms, measured by the total travel required in the system; and the equity with which this efficiency is distributed, measured by the comparative locational advantage of residential locations. The allocation rule is used as a diagnostic of urban form and not as a simulation of behavior.

The results of the experiments performed show that, under the conditions established, the system of transportation service and alternate residential patterns have little influence on the relative efficiency of alternate urban forms. In the very simple experiments performed, the same urban form was selected as most satisfactory by the two criteria used. The potential for trade-offs between changes in the system of transportation service and the arrangement of land-based activities to achieve a given level of efficiency was identified in the experiments.

The results of these experiments should not be taken as conclusive. They are only intended to be suggestive of the approach to urban analysis, which I believe is necessary for improving the quality of public investment decisions. We need to supplement our often hortatory urban development plans with measured alternatives which spell out the usually general objectives of such plans in programmatic terms, and assess the cost and effectiveness of public actions proposed to achieve the objectives. But before we can do this we need a much better understanding of how cities function and how people use the physical city in the conduct of their daily activities. Because we cannot reconstitute cities or change the behavior of city dwellers in order to evaluate unexplored alternatives, and because past behavior of city dwellers may not be a reliable guide to their behavior in quite different environments, we can more profitably approach this problem through a form of laboratory experiments rather than observation or trend estimates alone.

One of the first tasks in developing a more satisfactory experimental method is the investigation of a variety of allocation rules. The one used here is somewhat unrealistic. Its virtues are simplicity, ease of use, and fidelity to a straightforward behavioral hypothesis. In the "as if" world of this diagnostic, experiments are easily performed and results are easy to interpret. On the other hand, most of the experience with mathematical models in urban analysis has been with statistical models or gravity and opportunity models which are carefully fitted to observed behavior. Transfer of these "fitted" models to new urban alternatives is conceptually difficult. Experiments should be made with different allocation rules to determine their relative merits. There is reason to suspect that the kind of allocation rule most useful for simulating urban behavior in order, for example, to validate a transportation scheme may not be the most useful allocation rule for examining the more abstract problem of urban form alternatives.

The results of these experiments do suggest that it may be worthwhile to reexamine some current emphases in urban analysis. Most attempts at mathematical models of urban development have concentrated on simulation of the residential pattern. This is in part due to a traditional preoccupation with residential settlement, but it is perhaps also partly because residential patterns are more amenable to aggregate statistical analysis than industrial and commercial location decisions. If the results of these experiments are indicative of the relative importance of alternate residential patterns on the functional structure of urban communities then, perhaps, the emphasis is misplaced. Similarly, there has been a great deal of emphasis recently in transportation analysis on the potential influence of the system of transportation facilities on the spatial structure of urban communities. The experiments suggest that this influence may be smaller than is often argued, and perhaps some further analysis of this hypothesis is in order.

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