Defining Relationships Between Urban Form and Travel Energy

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ABSTRACT

The objective of this study was to define some of the relationships between urban form and transportation energy consumption. Such knowledge should be useful in generating and evaluating alternative plans for guiding the future development of metropolitan areas. A three-part approach was designed to attain this objective. First, a land use/transportation simulation model and a spatial statistics software package were obtained in order to make quantitative measures of urban form and associated travel requirements. Second, a number of experimental cities were designed with simulated travel requirements. Various urban form measures and associated travel measures (including transportation energy consumption) of these cities were computed by the statistics package and the simulation model. Third, these measures were interpreted and analyzed to test the main hypothesis of this study: the less centralized the urban form, the greater the travel distances between home and various destinations and thus the greater the city's transportation energy consumption.

In this study two computer programs were used to investigate the relationships between urban form and energy consumption in passenger transportation: the MOD3 simulation model and the Urban Form Statistics (UFSTAT) program. The MOD3 model, developed by Peskin and Schofer (1), is a large-scale computer program used to simulate the effects of alternative transportation and land use policies, such as those aimed at reducing transportation energy consumption. By simulating the travel requirements of a particular urban form, the MOD3 model can calculate a variety of transportation performance measures such as total vehicle miles traveled, level of congestion, transit ridership, and average trip length, and determine the total energy requirements resulting from work and nonwork passenger travel.

The conceptual structure of the MOD3 model is shown in Figure 1. It consists of four major submodels: a Lowry-type land use model, a binary logit modal choice model, a capacity-restrained equilibrium assignment model, and a transportation energy consumption model. The Lowry-type model locates residence and service employment given the structure of the transportation network, descriptors of urban travel behavior such as travel time and cost, and the location of basic employment. Using a gravity model concept, the model locates population on the basis of accessibility to basic employment. The gravity concept causes locations close to employment to be more desirable than those more distant, resulting in higher densities near employment locations. Service employment locations are based on accessibility to population, so the model has to be iterated through several cycles before it arrives at a spatial distribution of activities that is in equilibrium. The Lowry-type model predicts work trips by distributing workers to home sites and service employees to work sites using travel impedance factors. The work trip estimate is split between automobile and transit based on free-flow travel times and the dollar costs of travel. Automobile trips are assigned to the highway network using a capacity-restrained equilibrium assignment algorithm

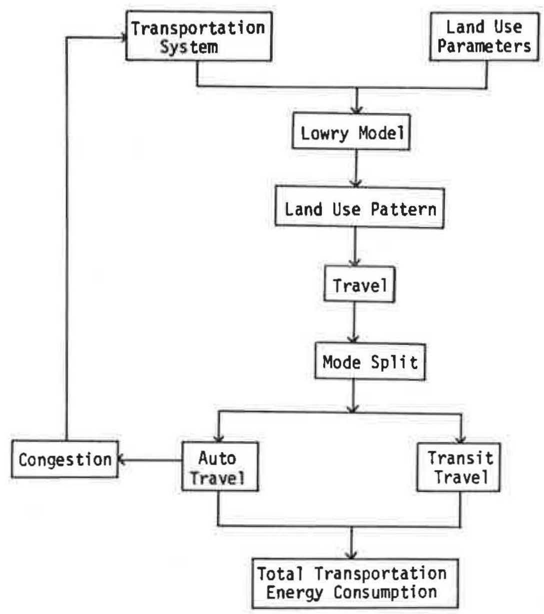

FIGURE 1 Conceptual structure of MOD3 model.

that explicitly considers congestion. The energy consumption of each vehicle on each link of the network is then summed to compute the total energy required for transportation. This process is repeated until an equilibrium between transportation and land use is reached, or, in other words, until differences between iterations become suitably small.

The UFSTAT program, initially developed by Schneider et al. (2), was designed to calculate various urban form measures. UFSTAT computes 57 urban form measures grouped into six categories: the Lorenz curve and derived measures; Bachi measures; centrographic and related measures; and potential, aggregate travel, and density gradient measures.

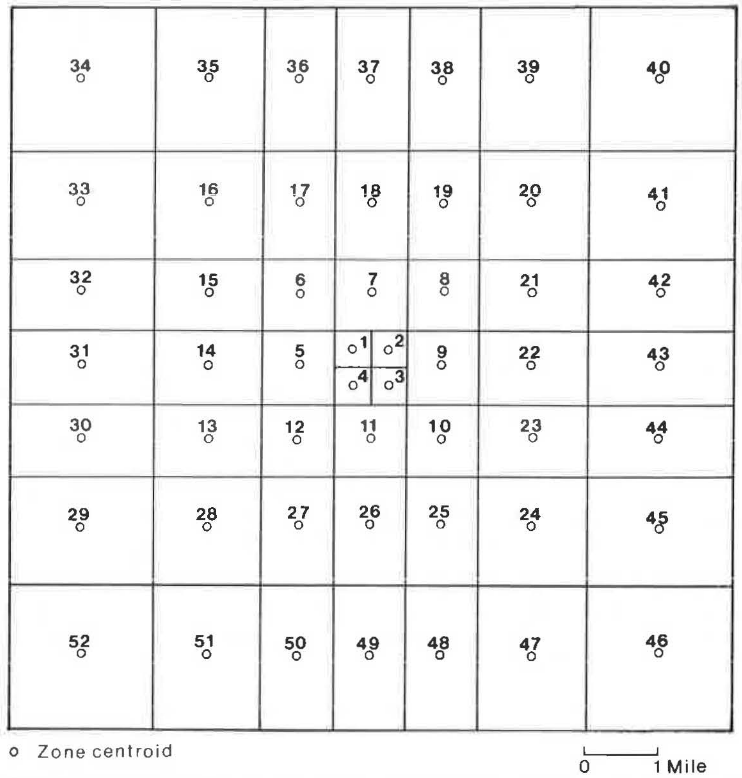

FIGURE 2 Geographic structure of the hypothetical city.

Some of these measures describe the degree of concentration of population, employment, or other attributes in an urban area. Others measure the degree of dispersion, the mean and standard distance from a central point, the directional tendency of the distribution, the shape of the distribution, and the slope of the density gradient. The mathematical definitions of the urban form measures are discussed elsewhere (3).

EXPERIMENTAL DESIGN

A hypothetical test city was used as a base for various experiments. The basic attributes of this test city were constructed from the urban transportation studies and land use plans of several American cities. The selection of a small hypothetical city for the experiments was based on several factors. First, by avoiding the complexities of a large metropolitan area, data requirements and computational difficulties are reduced considerably. Second, a smaller city model allows all the policies to be simulated in a realistic environment and also allows for a thorough analysis of the results. Finally, it is possible to isolate the effects of one or more independent variables on a dependent variable, thus allowing direct inferences to be made about relationships between the two.

The test city is composed of 52 zones arranged in a square 10 mi on each side (see Figure 2). It consists of a central business district (CBD) with an area of 1 mi^2 divided into four zones. Three additional rings of zones surround the CBD, resulting in a grid pattern. Zone sizes increase progressively toward the periphery in a symmetrical manner. The population is 100,000 and includes 15,000 employees in basic industries (out of a total employment of 40,000) for the base run of the MOD3 model. Given the location of basic employment, the model allocates population and service employment among the zones. Figures 3, 4, and 5 show the locations of basic and total employment and population, respectively, for the base case. It should be noted that, by virtue of the city structure and the assumptions in the model, the base-case city is quite centralized; that is, over 50 percent of the population

0	0	0	0	0	0	0
0	460	305	305	305	460	0
0	305	1000	1000	1000	305	0
0	305	1000	375 375 / 375 375	1000	305	0
0	305	1000	1000	1000	305	0
0	460	305	305	305	460	0
0	0	0	0	0	0	0

FIGURE 3 Basic employment distribution pattern for the base case.

105	162	231	242	229	166	110
174	751	773	766	760	778	175
260	746	2032	2012	2053	799	247
283	794	2017	1591 1589 / 1589 1590	2024	778	258
281	828	2051	2019	2046	762	241
203	808	775	779	789	777	172
134	196	265	265	242	172	111

FIGURE 4 Total employment distribution pattern for the base case.

281	458	776	784	675	457	357
448	897	1472	1634	1632	1134	517
955	1368	5417	5260	5551	1690	810
957	1864	5245	4281 4283 / 4274 4277	5334	1772	892
994	2010	5320	5256	5465	1623	704
694	1265	1727	1663	1539	1130	535
426	715	891	871	693	520	317

FIGURE 5 Population distribution pattern for the base case.

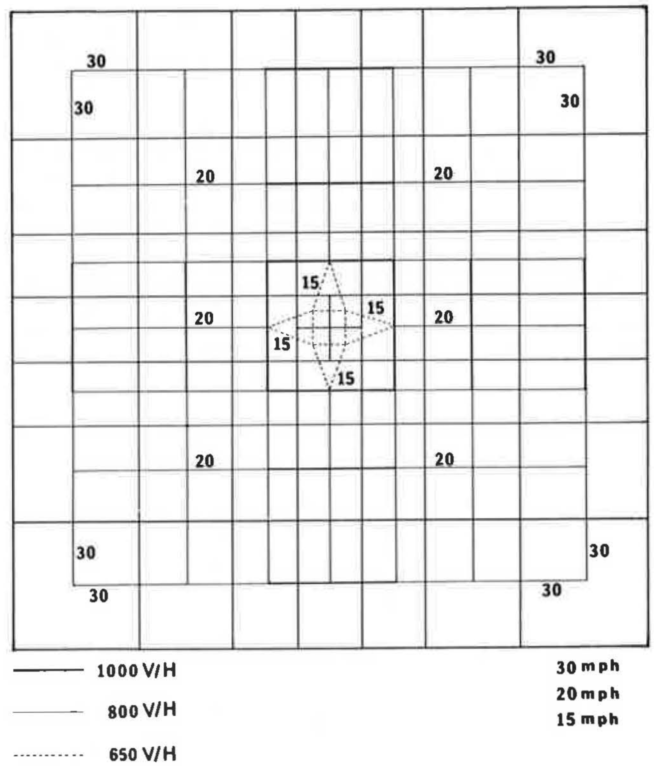

FIGURE 6 Link capacity and speed.

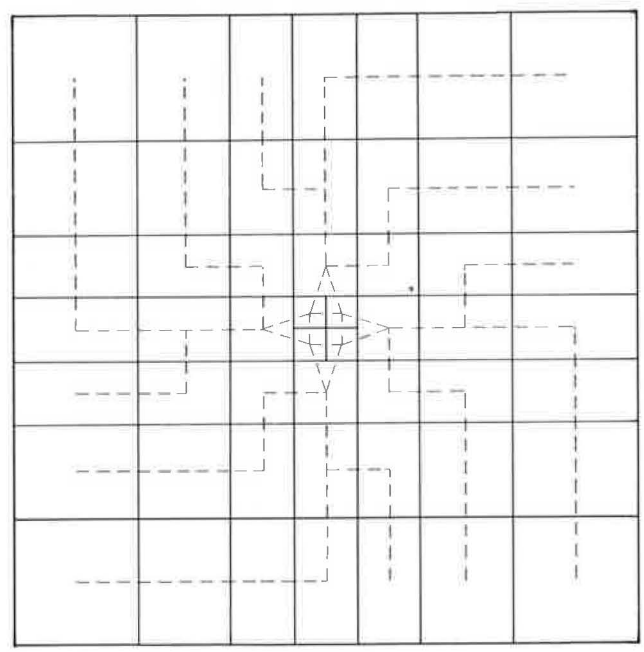

FIGURE 7 Transit network.

and total employment are located in the CBD and its fringe. This is because 63 percent of the basic employment is also located in this area.

The street network was initially defined as arterial streets that form a grid network. Local access and collector-distributor streets are not modeled. Highway link intersections meet at zone centroids. With 184 one-way interzonal links, the link-to-node ratio is 3.538 and the total one-way roadway length is approximately 233 mi. Free-flow capacities, free-flow speed, and the overall highway link structure are depicted in Figure 6. The transit network is a set of radial bus routes focused on the CBD. As shown in Figure 7, all zones, including the CBD, are served by at least one of the six bus routes, and each route begins and ends in an outlying residential area of the city. One would expect that the modal share of transit in the downtown area would be much higher than that of the outlying areas because the CBD has better service in terms of walking time to, and wait time at, a transit stop.

In order to simulate the experimental cities and obtain useful results with limited resources, three design principles were established in this study: (a) all urban forms were to have a 20 percent increment of basic employment growth, (b) three types of urban growth patterns (concentration, dispersion, and polynucleation) were to be examined, and (c) no other changes in input variables other than the location of basic employment were to be made. With these design principles, 18 experiments were formulated and simulated to obtain the data needed to examine the relationships between the urban form and transportation requirement measures. These experiments were classified according to three urban form groups, each containing six different forms. All 18 experiments were compared with the spatial attributes of the base case to derive measures of spatial change in the population distributions.

The first set of experiments was in the concentrated urban form category. As shown in Figure 8, it included six urban forms, numbered 201 to 206. In general, all additional basic employment, a total of 3,000 new jobs, was assigned to the CBD and CBD-fringe zones to create a strongly centralized city. The primary difference between the experiments in this group was the quantity of new jobs assigned to each "growth" zone. The second set of experiments, numbered 301 to 306, was designed to define several dispersed urban forms. The distinguishing characteristic of these experiments was that the additional basic jobs were allocated to zones beyond the CBD and the first ring of zones. Figure 9 shows the location and number of new jobs assigned to each zone. The last set of experiments was conducted to

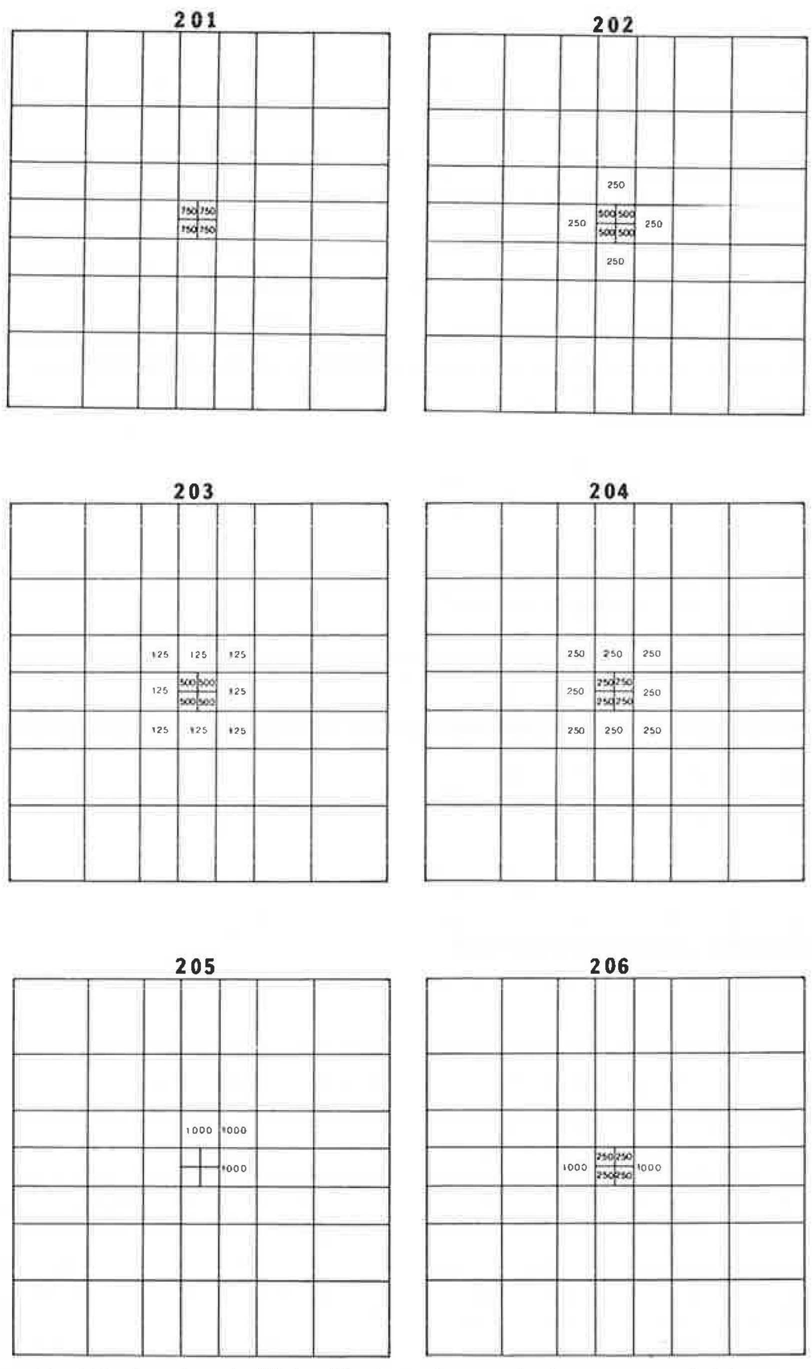

FIGURE 8 Location of additional basic employment in six concentrated cities.

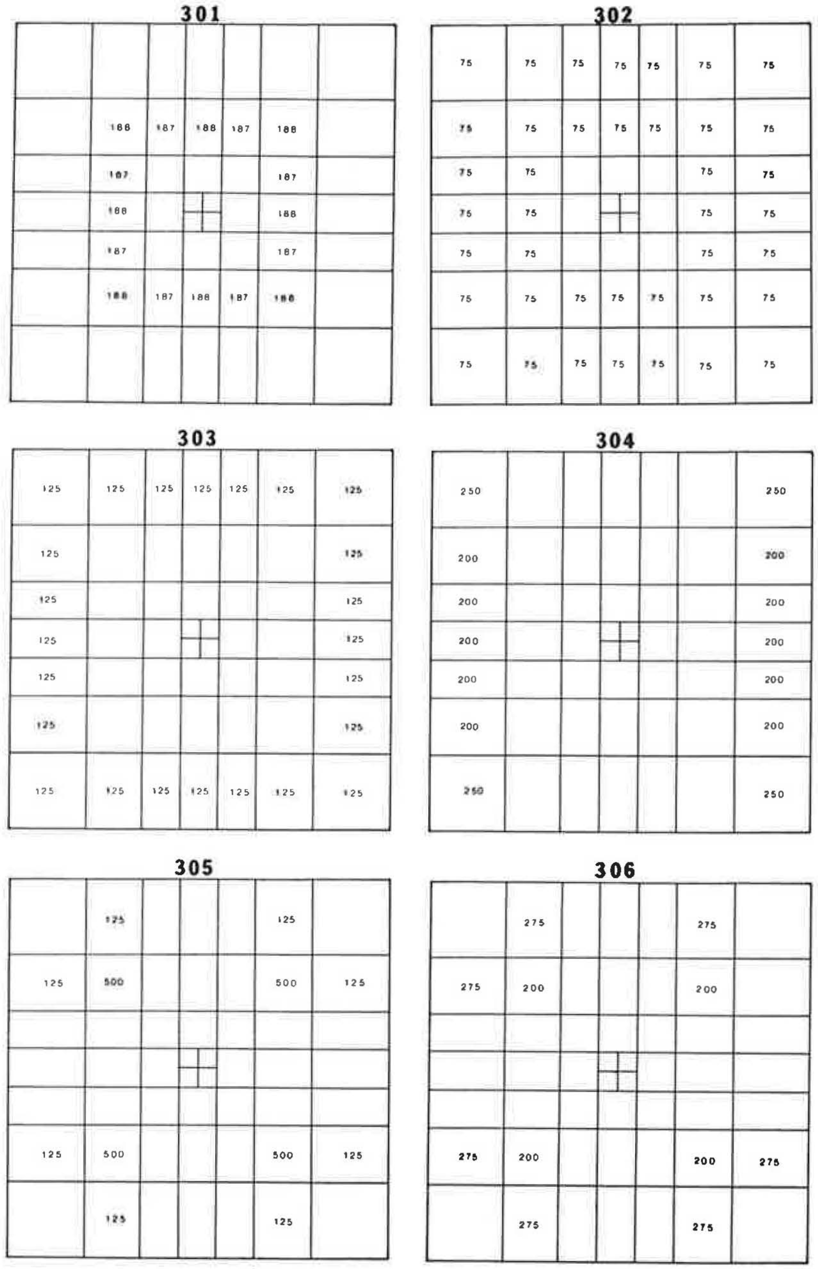

FIGURE 9 Location of additional basic employment in six dispersed cities.

define several polynucleated urban forms, each of which had several relatively high-density clusters of activity. As can be seen in Figure 10, four growth centers were selected for experiments 401, 402, 405, and 406; two centers for experiment 403; and eight centers for experiment 404. These growth centers included a high concentration of retail and service activities located within a relatively compact land area, blended with high-density residential development and certain kinds of basic industries.

ANALYSIS OF THE RELATIONSHIPS BETWEEN URBAN FORM AND TRANSPORTATION ENERGY CONSUMPTION

This section describes some functional relationships between urban form and transportation energy consumption that are based on the measures derived from the experimental cities. Hypothetically, the more compact an urban form is in terms of population distribution, the less travel energy requirements it will have. This hypothesis is based on the assumption that as the degree of urban spatial concentration increases, various urban activities locate closer together, resulting in a decrease of automobile vehicle miles of travel and average trip length. This in turn results in a decrease of transportation energy consumption.

A simple linear regression model was used to test this hypothesis. Total energy consumption is the dependent variable and each urban form measure is an independent variable. The urban form measures used in the regression analysis are the Gini coefficient, standard distance, potential measure, aggregate travel measure, and population density in CBD.

There are two reasons why simple regression rather than multiple regression was used in this analysis. First, the small sample size would have resulted in a marked decrease in statistical power

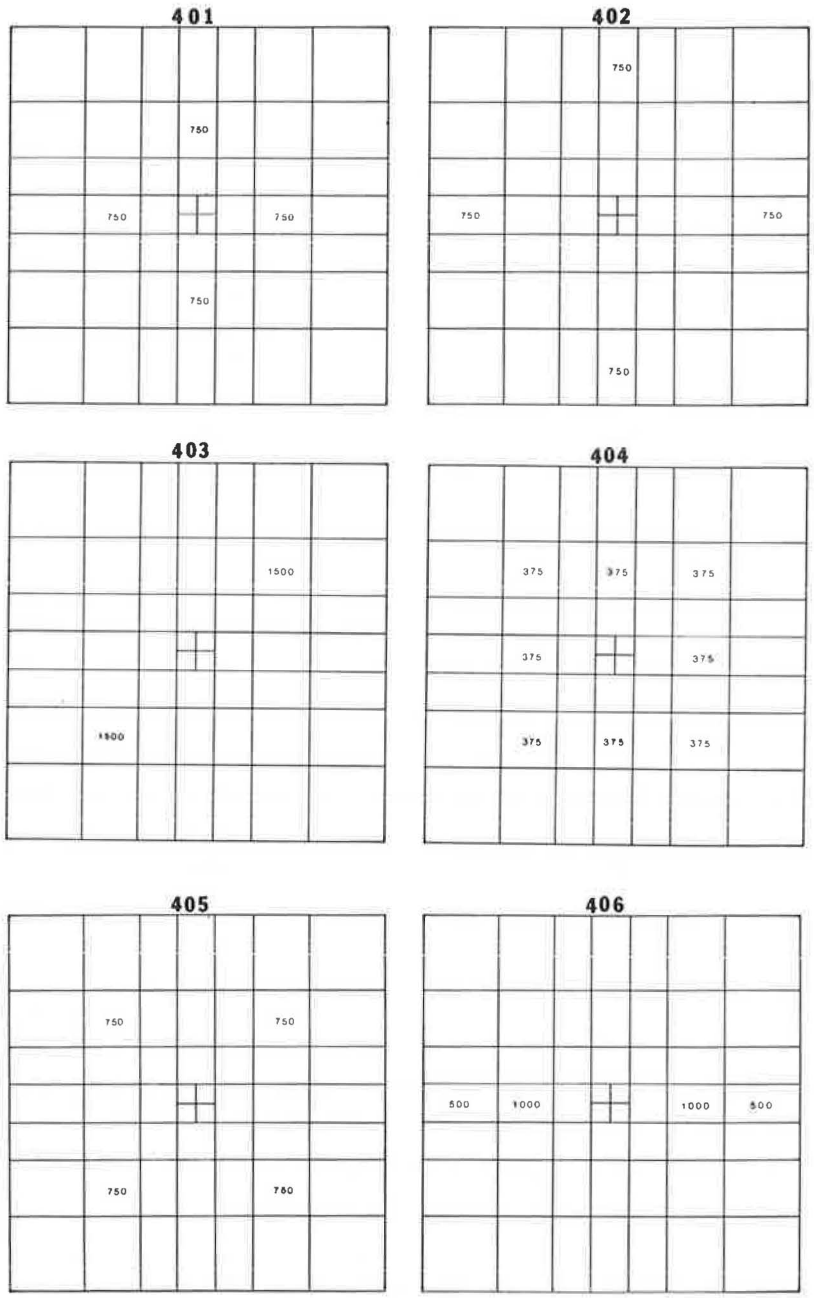

FIGURE 10 Location of additional basic employment in six polynucleated cities.

if several independent variables had been used. In this research, only 18 cases were designed to simulate different types of urban form. Second, the high level of intercorrelation among the urban form measures would prevent multiple linear regression from discovering the relative importance of each measure. It was important to avoid this multicollinearity problem.

The results of the regression analyses relating total energy consumption to each of the five urban form measures are shown in Table 1. Looking at the correlation coefficients (r), it can be seen that total energy consumption is highly and inversely related to the measures of spatial concentration such as the Gini coefficient, potential measure, and population density in CBD. Energy consumption is also highly and positively related to spatial dis-

TABLE 1 Regression Results of Transportation Energy Consumption Versus Urban Form Measures

Regression Equation	r	r^2
ENERGY = 21,602 - 15,158 GINI	-0.87	0.76
ENERGY = 19,695 - 158 RELOC	-0.85	0.73
ENERGY = 2,896 + 2,798 MEANDIST	0.88	0.78
ENERGY = 6,482 + 357 DISTVAR	0.89	0.79
ENERGY = 1,349 + 2,711 STANDIST	0.89	0.79
ENERGY = 19,392 - 0.108 POTENT	-0.85	0.73
ENERGY = 2,868 + 0.23 AGGREG	0.89	0.79
ENERGY = 16,180 - 0.693 DENSITY	-0.86	0.75
ENERGY = 19,641 + 14,230 GRADIENT	0.88	0.78

Note: Variables are defined as follows: ENERGY = total energy consumption by automobile for all trip purposes in 10^6 Btu, GINI = Gini coefficient, RELOC = reallocation index, MEANDIST = mean distance, DISTVAR = distance variance, STANDIST = standard distance, POTENT = potential measure, AGGREG = aggregate travel measure, DENSITY = population density in CBD, and GRADIENT = density gradient.

persion measures such as the standard distance and aggregate travel measure. The coefficients of determination (r^2) range from 0.73 to 0.79, indicating that 73 to 79 percent of the variance in total energy consumption among the 18 cases can be explained by any one of the urban form measures.

Figure 11 is a scatterplot of the total transportation energy required in each experimental city in relation to the Gini coefficient. As would be expected, there is a wide variation in transportation energy consumption for different urban forms. The 300-level cities, which are characterized by decentralized urban spatial patterns, have energy consumption levels much larger than the compact 200-level cities, with the polynucleated urban patterns of the 400-level cities falling in between. For example, experiments 201 through 204, which have higher Gini coefficients, occupy the more energy-efficient locations in the trade-off space. By contrast, experiments 302 through 306, which have lower coefficients, occupy the upper left-hand portion of the space, representing high energy consumption.

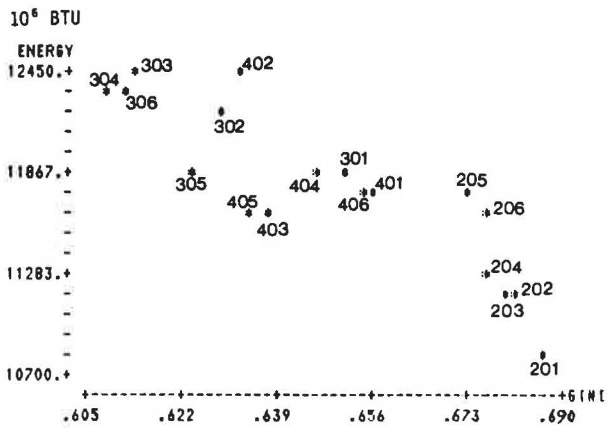

FIGURE 11 Transportation energy consumption versus Gini coefficient.

It is interesting to observe that, with the exception of the 402 city, the polynucleated cities do not vary much in terms of energy consumption, although their spatial concentration measures show a wide range of variation. Another interesting observation is that experiments 403 and 405, which are not very concentrated, are more energy-efficient than experiments 205 and 206, which are highly concentrated. This suggests that polynucleated urban patterns are comparable with some concentrated urban forms in terms of energy consumption. This result was expected because higher concentrations of activity in the city center create traffic congestion, which increases the gasoline consumed per mile.

Figure 12 is a plot of total energy consumption as a function of the standard distance. The plot clearly shows that there is a positive relationship between energy consumption and this spatial dispersion measure. A longer standard distance produces a greater level of transportation energy consumption. Although the dispersion measure does not take urban travel behavior into account, it suggests that a spatial dispersion measure can be used as a macroscale indicator of the level of transportation energy consumption in an urban area. The rationale for this argument is that if the population distribution pattern is dispersed around the CBD, longer trips are made and more transportation energy is consumed.

Figure 13 is a plot of energy consumption and the

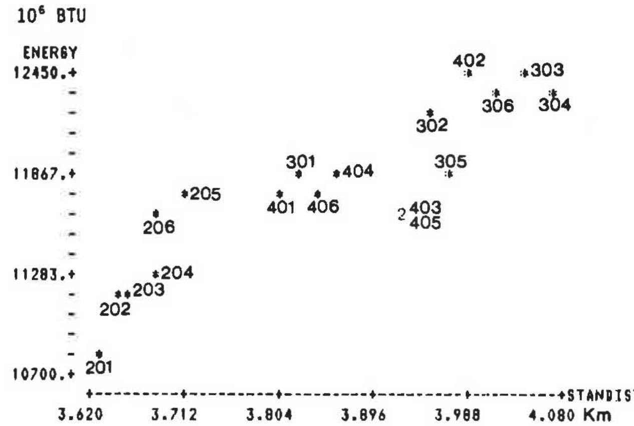

FIGURE 12 Transportation energy consumption versus standard distance.

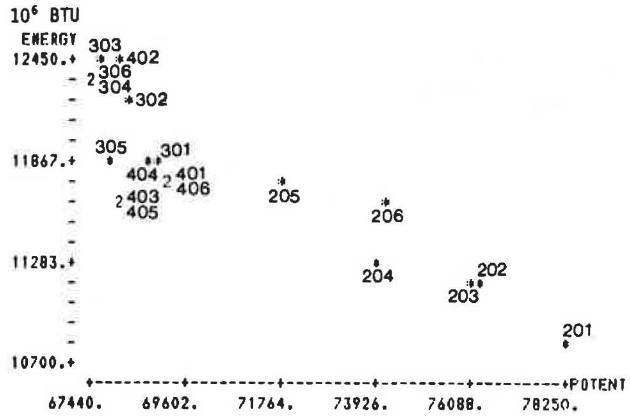

FIGURE 13 Transportation energy consumption versus potential.

potential measure of the CBD, a measure of aggregate accessibility. The general trend shows the two variables to be inversely correlated, indicating that higher accessibility levels in the inner city reduce energy requirements. As expected, the dispersed 300-level cities require more energy, whereas the concentrated 200-level cities are more energy-efficient. The polycentric (400-level) cities fall in between. An exception is the 402 case, which is probably due to an edge effect caused by the boundaries of the city.

The relationships between total energy consumption and the aggregate travel measure are plotted in Figure 14. The positive relationship is quite similar to that of the standard distance. It is evident that increases in passenger travel from each zone to the CBD increase the transportation energy requirements. The clustering pattern of each city group is similar to those shown in the previous plots.

Figure 15 shows total energy consumption plotted in relation to the population density in the CBD. This plot clearly shows that urban forms with higher population densities in the city core require lower levels of transportation energy. This observation agrees with the results of some previous research that examined the impact of urban spatial structure on transportation energy consumption, using population density as an urban form measure (4,5).

In summary, the regression results indicate that the concentrated urban form is the most energy-efficient and the dispersed urban form is the least energy-efficient, with the polynucleated form fall-

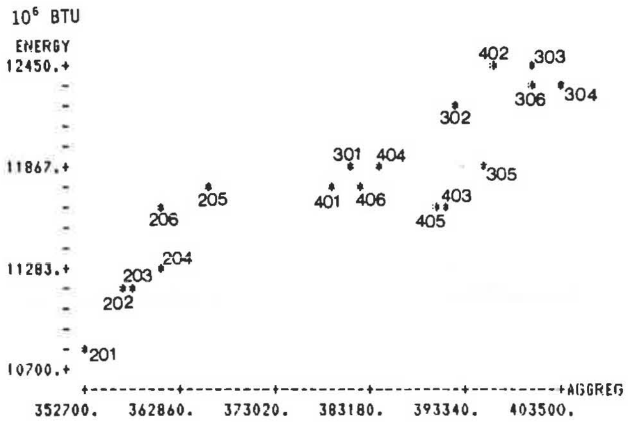

FIGURE 14 Transportation energy consumption versus aggregate travel.

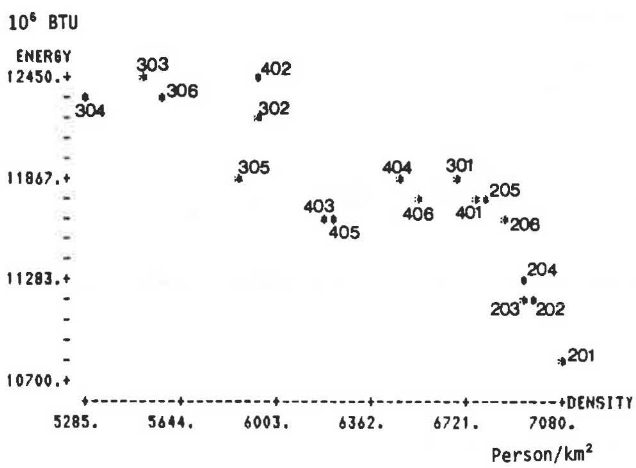

FIGURE 15 Transportation energy consumption versus population density.

ing in between. However, some polynucleated urban forms show lower transportation energy consumption measures than some concentrated urban forms, although the former is more spatially dispersed and less well served by transit in its outlying growth centers. A close examination reveals that the concentrated urban forms contain highly congested highway links in and around the CBD, resulting in high energy consumption.

CONCLUSIONS

The first conclusion is that the urban form measures used in this study are useful techniques for defining the major characteristics of an urban spatial structure. These measures clearly described the degree of concentration or dispersion and the shape of the urban form for all the experimental cities. None of these results was counterintuitive. This implies that planners and decision makers can use these measures as macroanalytical tools to obtain an overall sense of the spatial characteristics of various urban form concepts.

The second major conclusion of the study is that most of the urban form measures are highly correlated with transportation energy consumption. Overall, the regression results indicate that higher concentrations of population in the center of the city, better access to the center, and higher population densities can reduce transportation energy consumption. This suggests that marked reductions in transportation energy requirements can be made by altering urban spatial structure. However, congestion will increase substantially, necessitating large investments in expanded facilities and services.

The third conclusion of the study concerns the comparison of concentrated urban and polynucleated urban forms in terms of their transportation energy consumption requirements. The urban form measures indicated that the polynucleated urban form was more dispersed, less accessible, and less dense in the CBD than the concentrated urban form. Nevertheless, it was evident that transportation in some polynucleated cities was more energy efficient than in some concentrated cities due to the high congestion level of downtown access streets. The implication of this observation is that there is a great potential to reduce energy consumption by encouraging present polycentric urban form trends and policies. It is clear that the horizontal spread of cities must be controlled if energy consumption is to remain constant or be reduced. Compact urban forms consisting of major suburban employment centers with a relatively dense residential area surrounding them appear to be both feasible and desirable urban configurations for an energy-short future.

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