Relationships Between Transportation Energy Consumption and Urban Structure: Results of Simulation Studies

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If the urban transportation planning process is to deal with the problem of providing transportation in a future characterized by fuel shortages, a long-term perspective is needed. The study described documents the relationships between energy consumption in urban passenger travel and the spatial structure of cities, which is an important determinant of travel demand. Experiments were conducted with 37 hypothetical cities in which combinations of urban form, transport network, and resulting travel patterns were varied in order to identify structural characteristics contributing to increased energy consumption. Preliminary findings suggest that structural changes in transportation and land use patterns can produce significant reductions in energy consumption for urban passenger travel.

The 1974 petroleum crisis illustrated the possible future of energy in the United States: reduced fuel availability and increased fuel price. Among responses considered by urban travelers, the private sector, and government were reductions in trip making, increased use of public transport, car pooling, increased preferences for smaller, more economical automobiles, fuel price increases, and gasoline rationing. Some of these were implemented at the peak of the gasoline shortage. Yet, such responses represent only marginal improvements in the energy efficiency of urban transportation (1).

High prices and restrictions in fuel supplies may be common in the future. Thus, it is appropriate to explore alternative strategies for increasing energy efficiency of travel in urban areas.

Fuel shortages strongly impacted urban passenger transportation because, in many cities and for many types of trips, there is no alternative to the automobile. The spatial structure of cities and their transportation networks has shifted from a strong transit orientation to a strong automobile orientation and is characterized by extensive land use patterns and freeway networks. Transit has declined, as much as for any other reason, because it is not economically feasible to serve such patterns with public modes.

To respond to a long-run problem with a long-run solution depends on an understanding of the fundamental relationships among urban structure, transportation networks, and energy consumption in passenger travel. The policy options considered during the recent fuel shortage were short term. At present, with gasoline readily available, little public concern is expressed about options considered in 1974. Research and development have, to a large extent, focused on technology rather than on changes in policies and the spatial structure of activities.

Solutions entailing intervention in the land market received little interest because of the implications of such options for a free-enterprise land economy. Yet, part of the disinterest in the relationships between land use and energy consumption in transportation stems from the fact that little is known about these phenomena; and without such knowledge, it is unlikely that such policy options will receive appropriate consideration.

The structure of urban land use and transportation networks may have a significant effect on energy consumption in urban passenger travel. Understanding the magnitude and direction of these effects may provide guidance for future long-term policy development. The availability of such information may also provide a basis for adopting policies that now run counter to public preferences but that may provide future benefits.

APPROACH

Several investigations (2, 3, 4) have significantly increased our understanding of the connections between urban travel and spatial structure; however, little guidance for formulating planning policies oriented toward energy-related issues has emerged. Two strategies for conducting a policy-oriented investigation are considered here. One is to gather data on land use patterns and travel behavior from current metropolitan transportation planning studies; however, this demands great expenditures of time and effort to collect and manipulate such data sets.

Another possibility is to approach the problem abstractly by using normative models to allocate persons to homesites and worksites to optimize a travel-related objective. Such approaches characterize the works of

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Dantzig and Saaty (5) and Hemmens (6), which are based on the assumption of aggregate optimizing behavior. Yet, it is unlikely that persons behave in such a manner as to achieve a social optimum.

Difficulties inherent in the empirical approach and uncertainties of the normative approach suggest a compromise: Data from an existing city are used along with mathematical models to simulate travel behavior in a series of hypothetical cities. Such an approach may be more robust than the others in that many elements in the urban spatial structure can be varied to determine the effects on energy consumption.

Several previous efforts (7, 8, 9) used similar approaches to the problem of relating spatial patterns to travel patterns; each centered on the exogenous specification of residential and employment sites and then applied a gravity trip distribution model to distribute work trips over the network.

Although those studies were useful in investigating the travel requirements of various urban structures, each contains one troubling aspect: Preselecting activity sites (residential, retail, and employment centers) before the travel modeling process is initiated can create biased results. Exogenous allocation of activities to sites can portray an unrealistic location behavior of residents and workers of each city. It would be desirable to lessen the possibility of introducing bias by reducing the number of exogenous attributes.

Can the interaction between land use and transportation in a hypothetical city be adequately described without prejudicing the study results by overspecifying the behavior of its residents? It is this question that this study addresses.

This study (a) chooses a representative city in which aggregate travel behavior has been observed and documented; (b) resettles the residents of that city into different patterns and analyzes the travel and accessibility characteristics and the transportation energy requirements arising from changing the spatial variables (shape, form, density patterns); and (c) identifies those factors that most strongly affect transport energy requirements and activity accessibility.

In the experimental design, values of the activity variables (population, employment, and so on) must be consistent across all designs so that the travel required to connect activities within each design can be compared and the effects of changing the media (such as the highway network) through which these activities interact can be assessed. Activity variables, therefore, are fixed in quantity but not by location for all designs; interaction variables can differ across the designs.

Fixed city attributes were taken from an existing city to ensure that the results would be well grounded. These attributes include population, employment by category, labor force participation rate, interzonal impedance (friction) factors by trip type, and trip rates per capita by trip type. Impedance factors represent the propensity to make trips of various lengths and vary between cities. Therefore, these factors belong to the set of spatial variables and should not be fixed across different spatial patterns. The same is true of trip rates per capita by trip type, which also depend on the spatial arrangement of activities and the transport system (10). However, there is no theory that can be used to account for the variation; thus, a single set of factors was applied for each trip purpose across all urban designs. Similarly, trip generation was assumed to depend solely on distance from the city center, a surrogate reflecting the effects of automobile ownership, income, and family size.

Construction of land use designs for alternative cities was accomplished with a Lowry type of land use model (11), which applies the attributes to interaction variables specified in the context of a given hypothetical city. The model was used to ensure that the design of the hypothetical cities was realistic. The interaction variables included urban form (density patterns and shape), network characteristics (highway speeds, transit routes), transport technologies (automobile, automobile-transit, transit), and modal split by trip type. A modal-choice model was not used; transit share was prespecified for each design because including a modal-choice model in the simulation package would have greatly increased computational requirements.

Given the location of basic (usually manufacturing) employment and the nature of the transportation network, the Lowry type of model allocates residential and retail activities to specific locations subject to constraints on available land, residential densities, and the minimum feasible size of retail employment centers (11). in the process, 24-h home-based trip types are generated and distributed (change-mode, serve-passenger, and social trips do not involve employment at the attraction end). The simulation of social and non-home-based trip making is accomplished by simple trip generation and gravity models (12). Change-mode trips are not considered; nor are through trips, external trips, or truck trips. Trips are allocated a priori to modes and assigned via a free-assignment method.

The Lowry model simultaneously estimates service trips and the allocation of workers serving such trips to the service sites. Service trips were separated into long and short trips by observing that, in the data set used (13), personal business, recreational, school, and durable-goods shopping trips on the average exceeded 6 min in length, whereas convenience shopping trips averaged about 5 min. This is because location behavior of service establishments to which the former trip types are made is less dependent on nearness to the clientele than that of establishments to which convenience shopping trips are made. Therefore, home-based service trips were categorized either as type S (shop location behavior sensitive to location of clientele) or type N (shop location behavior not sensitive to location of clientele). There are then five trip purposes: home-based work, service (type N or S), social, and non-home-based.

Trip tables for each purpose are computed either internal to the model (for the first three types) or through postprocessing by using gravity models (for social and non-home-based). Model calibration is obviated by using a given set of friction factors for each trip purpose. Successive iteration of the Lowry model gives rise to the allocation of the activities of interest (residential population and service employment for each service category). Products include total population and employment (by category) per zone, work and nonwork trip tables, and vehicle flows on the network.

Modal energy requirements are assessed by using data on automobile and bus fuel consumption as a function of traffic conditions (14) and Davis' formulas for frictional resistances of electric transit vehicles as a function of vehicle type and speed (15).

EXPERIMENTAL DESIGN

Three basic urban shapes were adopted as paradigms out of which emerged the hypothetical cities studied; comparisons were made between the cities to discover factors determining the relative amounts of transportation energy consumed and accessibility to activities. Experiments were conducted sequentially so that information from preceding experiments could influence the selection of subsequent experiments.

The three basic shapes selected for study are shown in Figure 1. The concentric-ring shape (7) has a total land area (381.4 km^2 or 147.25 $mile^2$) approximately equal to that of the study area from which much of the data for this research were collected (13). The linear shape (8) represents city forms having low transportation capital costs, good proximity to activities, and a compact land use pattern (25.2 km^2 or 9.75 $mile^2$). The polynucleated shape is attractive from the point of view of accessible open space but incorporates nuclei of fairly high density (a total developed area of only 15.8 km^2 or 6.1 $mile^2$) and neighborhood and community facilities within walking distance. Thirty-five experiments were conducted by using these three shapes. Two additional experiments were conducted by using a pure cruciform design that combines the best features of the linear and polynucleated shapes: physical separation of neighborhoods from commercial and industrial areas yet compact land use (26.5 km^2 or 10.25 $mile^2$ of developed land) spread out to provide good accessibility to open space.

Zone size in each urban shape was determined by (a) the need to capture as much interzonal vehicle traffic as possible and (b) the need to minimize the total number of zones, inasmuch as computation time increases geometrically with the number of zones. Except in the concentric ring shape, where intrazonal traffic in zones 26 to 100 traveled by automobile, all intrazonal transactions are assumed to be on foot.

Automobile, conventional bus, and rail rapid transit were selected for study, and specific combinations of the modes used in each experiment are given in Table 1.

Except in the polynucleated shape, automobiles and buses traveled on a grid network of links connecting zone centroids. In experiments using the polynucleated shape, the streets were coincident with the interzonal radial routes shown in Figure 1. In those experiments using the ring shape, a freeway network was provided. Rapid transit routes are shown for each of the remaining city types in Figure 1 and, with the exception of six experiments (28, 32, 33, 34, 35, 37), they were assumed to be fixed-rail systems (12). In the remaining experiments, a bus rapid system was assumed to operate on separate guideways.

RESULTS

Transportation energy and regional accessibility to population for each experiment are shown in Figure 2. Total energy refers to that energy required for daily person travel from home to work, to service type N, to service type S, for social purposes, and one-half of the total daily non-home-based travel. The total energy required for all person travel (except serve-passenger and change-mode trips) can be estimated by doubling the amounts shown in Figure 2. Zonal accessibility is measured by using the denominator of the gravity trip distribution equation. Because the original study (12) showed that accessibility measures based on different activities were highly correlated, accessibility to population was selected as the representative measure.

Figure 2 shows wide variation in energy requirements for differing urban structures. Structures with sprawling land use patterns have larger energy requirements than relatively compact structures. For example, the first five experiments have energy requirements 9 to 10 times that of the least energy-intensive structure (experiment 20). Those five structures have the greatest dispersion of population and employment—measured by the second moments of population and employment—of all cities examined; experiment 20 is a more compact pattern.

Cities with compact land use patterns occupy energy-efficient locations in the space of feasible structures. For example, the linear forms (experiments 24 to 29), the cruciforms (experiments 30 and 31), and the polynucleated forms (experiments 32 to 37) occupy the lower left portion of the trade-off space and represent cities with low energy costs but concomitant low levels of regional accessibility to population.

Cities using only the automobile have much larger energy requirements than cities using transit. For example, experiments 1 to 13, 22 to 25, and 36 have only the automobile. Only one city (experiment 14) having an automobile-transit network exceeds the energy value of 2110 GJ (2 000 000 000 Btu), and only one city (experiment 25) having the automobile as its sole means of transport has a lower energy requirement. Hence, 2110 GJ is, in these experiments, the threshold above which nearly all of the automobile-oriented energy costs lie and below which almost all of the energy requirements of automobile-transit cities are found.

Structures with the same shape have varying energy requirements and accessibility based on their density patterns and the relative importance of the automobile. For example, experiments 1 to 5 and 9 to 13 represent cities with large land requirements (381.4 km^2 or 147.25 $mile^2$), but the first five are sprawled patterns, and experiments 1 to 5 and 9 to 13 represent cities having more concentrated activities. Experiments 1 to 5 and 9 to 13 might be visualized as lying on a line from upper left to lower right in which movement downward and to the right is accompanied by increasing concentrations of activities. When transit is introduced, the energy requirements fall, but accessibility is decreased as well. For example, experiments 14 to 21 represent the same city as experiment 13 but with differing levels of transit service and modal splits. For the same relative transit service (ubiquitous service and a frequency of 10 buses per hour), an increase in transit share brings about a drop in both energy required for accomplishing that travel and accessibility. The latter is the result of longer travel time by transit than by automobile.

Several structural components affect energy requirements and accessibility patterns, explaining most of the variation in Figure 2. These are urban form, transportation level of service, and role of transit in the transportation system. Four distinct dimensions of urban form are apparent contributing factors: shape, geographic extent, population concentration about the centroid, and employment concentration about the centroid.

The concentric ring is the most energy-intensive city type; it also provides the highest levels of accessibility to population and employment. Of 18 automobile-only experiments (Figure 2), 13 are associated with the group to the upper right (numbers 1 to 13) and have the basic concentric ring shape. Experiments 24 and 25, linear forms, appear more nearly central in the space. Experiment 36 is highly energy-intensive in spite of its low level of accessibility. Thus, it appears that, where automobiles are used exclusively, the concentric-ring city provides best accessibility, followed by the linear structures; the cruciform and polynucleated shapes offer low accessibility to population, though within-nuclei accessibility may be good.

Expansiveness of land use was measured by developed land area in square kilometers. This variable seems to have a clear, though imprecise, effect on energy consumption. When total energy is related to developed land area (Figure 3), a clear upward trend in energy is detected as the amount of land area in the city increases. This suggests that expansive land use patterns characterized by low density consume larger amounts of transportation energy than do compact urban structures. However, developed area does not by itself determine the absolute level of energy consumption. Indeed, among the most land-intensive cities, experiment 22 exhibits a level of energy consumption not greatly different from that of experiment 14, which is far less land intensive.

Table 1. Specification of experiments.

Experiment	Urban Form		Location of Basic Employment	Population Distribution	Service Employment Distribution	Mode	Transit (%)	Network Level of Service (km/h)
	Shape	Area (km^2)						
1	Sprawled concentric ring	381.4	Central 25 zones of ring	Sprawled, peaks around freeway, not in zones of basic employment	Sprawled, peaks around freeway	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
2	Sprawled concentric ring	381.4	Central 25 zones of ring	Sprawled, peaks around freeway, not in zones of basic employment	Sprawled, peaks around freeway	Automobile only	0	38.6 on arterials, 72.4 on freeway
3	Sprawled concentric ring	381.4	Central 25 zones of ring	Sprawled, peaks around freeway, includes zones of basic employment	Sprawled, peaks around freeway	Automobile only	0	38.6 on arterials, 72.4 on freeway
4	Sprawled concentric ring	381.4	Two antipodal zones adjacent to central 25 zones	Sprawled, peaks around freeway, not in zones of basic employment	Sprawled, peaks around freeway	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
5	Sprawled concentric ring	381.4	Uniform through first and second suburban rings	Sprawled, peaks around freeway, includes zones of basic employment	Sprawled, peaks around freeway	Automobile only	0	38.6 on arterials, 72.4 on freeway
6	Compact spread concentric ring	52.4	Uniform through all zones	Uniform through all zones	Uniform through all zones	Automobile only	0	38.6 on arterials, no freeway
7	Extensive spread concentric ring	233.7	Uniform through all zones	Uniform through all zones	Uniform through all zones	Automobile only	0	38.6 on arterials, no freeway
8	Extensive spread concentric ring	233.7	Uniform through all zones	Uniform through all zones	Uniform through all zones	Automobile only	0	38.6 on arterials, 72.4 on freeway
9	Extensive concentrated concentric ring	381.4	Uniform through first and second suburban rings	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
10	Extensive concentrated concentric ring	381.4	Uniform through first suburban ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
11	Extensive concentrated concentric ring	381.4	Central 25 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile only	0	38.6 on arterials, 72.4 on freeway
12	Extensive concentrated concentric ring	381.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
13	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile only	0	19.6 in central area, 38.6 on other arterials, 72.4 on freeway
14	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	10	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
15	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	10[a]	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
16	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peak in central zones	Automobile, conventional bus	36	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
17	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	33	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
18	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	43	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
19	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	38	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
20	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	66	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in central area, 24 elsewhere
21	Compact concentrated concentric ring	109.4	Central 9 zones of ring	Concentrated with peak in central zones	Concentrated with sharp peaks in central zones	Automobile, conventional bus	62	Automobile: 19.6 in central area, 38.6 on other arterials, 72.4 on freeway; Bus: 19.6 in contral area, 24 elsewhere
22	Quasi-cruciform	381.4	Cruciform in central zones	Concentrated with peaks adjacent to basic employment zones	Concentrated with peaks adjacent to basic employment zones	Automobile only	0	38.6 on arterials, 72.4 on freeway
23	Quasi-linear	233.7	Four corner zones of circumferential freeway	Uniform through two rings adjacent to circumferential freeway	Within and adjacent to freeway corridor, not in basic employment zones	Automobile only	0	38.6 on arterials, 72.4 on freeway
24	Pure linear	25.3	Two zones, each end of spine	Uniform through zones parallel and adjacent to spine	All zones, peaks in spinal zones	Automobile only	0	38.6 at the spine, 19.6 elsewhere
25	Pure linear	25.3	Two zones, each end of spine	Uniform through zones parallel and adjacent to spine	All zones, peaks in spinal zones	Automobile only	0	38.6 at the spine, 28.5 elsewhere

Table 1. (continued).

Experiment	Urban Form: Shape	Urban Form: Area (km^2)	Location of Basic Employment	Population Distribution	Service Employment Distribution	Mode	Transit (%)	Network Level of Service (km/h)
26	Pure linear	25.3	Two zones, each end of spine	Uniform through zones parallel and adjacent to spine	All zones, peaks in spinal zones	Automobile, conventional bus, rail rapid transit	50	Automobile: 38.6 at the spine, 19.6 elsewhere Bus: 19.6 Rail: 36.2
27	Pure linear	25.3	Two zones, each end of spine	Uniform through zones parallel and adjacent to spine	All zones, peaks in spinal zones	Automobile, conventional bus, rail rapid transit	50	Automobile: 38.6 at the spine, 19.6 elsewhere Bus: 19.6 Rail: 36.2
28	Pure linear	25.3	Two zones, each end of spine	Uniform through zones parallel and adjacent to spine	All zones, peaks in spinal zones	Automobile, conventional bus, rail rapid transit	50	Automobile: 38.6 at the spine, 19.6 elsewhere Bus: 19.6 Rail: 36.2
29	Pure linear	25.3	4 nonadjacent zones along spine	Uniform in parallel zones, plus high-density zones on spine	All zones, peaks in spinal zones	Automobile, conventional bus, rail rapid transit	50	Automobile: 38.6 at the spine, 19.6 elsewhere Bus: 19.6 Rail: 36.2
30	Pure cruciform	26.5	Central 5 zones	Outlying zones	All zones except central 5 zones	Automobile, conventional bus, rail rapid transit	90	Automobile: 19.6 at the spine, 38.6 elsewhere Bus: 19.6 Rail: 80.5 top speed
31	Pure cruciform	26.5	Central 5 zones	Outlying zones	All zones except central 5 zones	Automobile, conventional bus, rail rapid transit	50	Automobile: 19.6 at the spine, 38.6 elsewhere Bus: 19.6 Rail: 80.5 top speed
32	Polynucleated	11.7	Central and 4 outlying zones	Uniform in all except central and 4 outlying zones	All zones except 4 outlying basic employment zones	Automobile, conventional bus	50	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed
33	Polynucleated	11.7	Central and 4 adjacent zones	Uniform in all except central and 4 adjacent zones	All zones except 4 outlying basic employment zones	Automobile, conventional bus	50	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed
34	Polynucleated	11.7	Central zone	Uniform in all except central and 4 adjacent zones	All zones except central zone	Automobile, conventional bus	50	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed
35	Polynucleated	11.7	Central zone	Uniform in all except central and 4 adjacent zones	All zones except central zone	Automobile, conventional bus	50	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed
36	Polynucleated	11.7	Central zone	Uniform in all except central and 4 adjacent zones	All zones except central zone	Automobile only	0	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed
37	Polynucleated	11.7	Central zone	Uniform in all except central zone	All zones	Automobile, conventional bus	50	Automobile: 19.6 in central area, 38.6 elsewhere except 56.3 at circumferential beltway Bus: 72.4 top speed

Note: 1 km^2 = 0.38 $mile^2$; 1 km/h = 0.62 mph.

[a]Automobile occupancy increased by 50 percent for each trip purpose.

This is because population and service employment are concentrated around the cruciform distribution of basic employment in experiment 22, and trip lengths to work and to shop are relatively short.

The automobile-only experiments in Figure 2 (numbers 1 to 5, 8 to 13, 22) that have common urban form exhibit a strong negative correlation between regional accessibility to population and total energy consumption. This correlation (-0.918), the strong positive correlation (0.985) between the second moment of population and total energy, and the strong negative correlation (-0.905) between the second moment of population and accessibility suggest that trade-offs between the 12 points can be accounted for by the extent to which population is concentrated about the city centroid.

The effects of increasing population concentration is shown in Figure 4, where vectors represent direction and magnitude of change. Experiments 2 and 3 represent the same city, except that residences are absent from the central 25 zones of experiment 2, whereas in experiment 3 residences are in all zones except number 1. Experiment 11 assumed the same city as in number 3, except for a more intense concentration of residences about the central 25 zones. Experiments 5 and 9 differ in that 5 is a sprawled configuration, and activities in 9 are confined to the central 41 zones. Experiment 13 differs from 12 solely in that the developed area is smaller (109.4 km^2 or 42.25 $mile^2$ versus 381.4 km^2 or 147.25 $mile^2$).

The elasticities of energy and accessibility with respect to population concentration (measured by the second moment) are less than one, suggesting that a large change in the concentration of residential activities is required to bring about a change in either dimension.

Figure 5 shows that concentration of employment (measured by the second moment of employment) has an important effect on energy consumed in travel. In experiment 5, basic employment is located in two suburban

Figure 1. Urban shapes: (a) concentric, (b) pure linear, (c) polynucleated, and (d) pure cruciform.

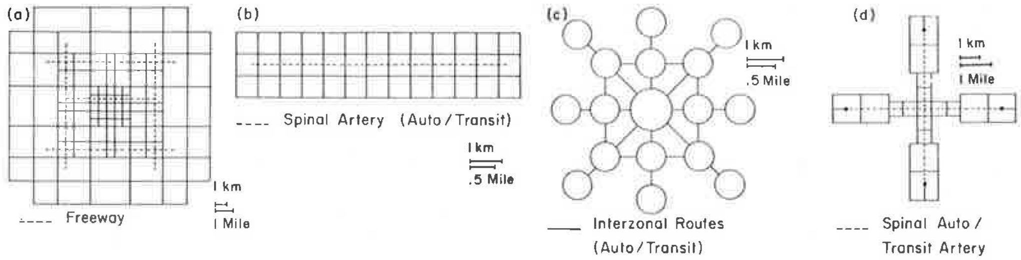


Figure 2. Total energy and regional accessibility to population for each experiment.

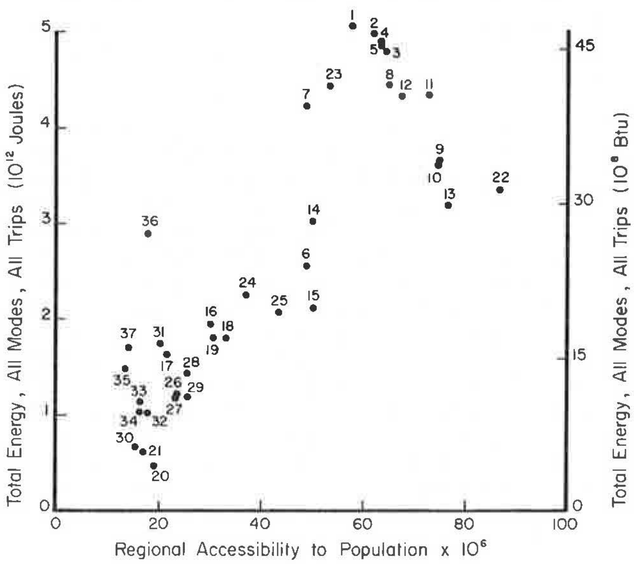


Figure 3. Total energy for all modes and all trips as a function of geographic extent.

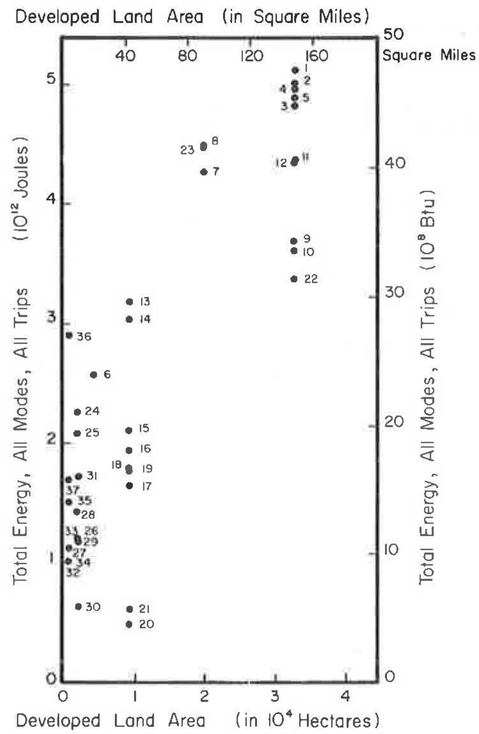


Figure 4. Effect of increasing population concentration on energy and accessibility in seven automobile-only experiments.

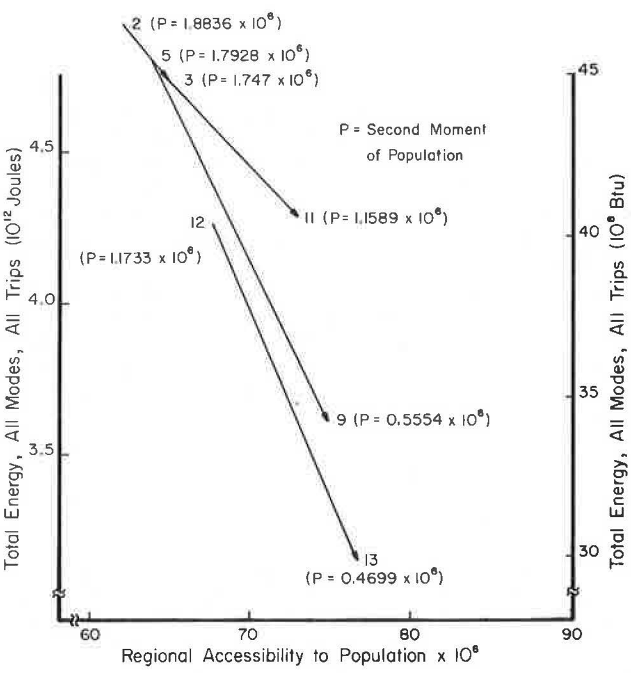
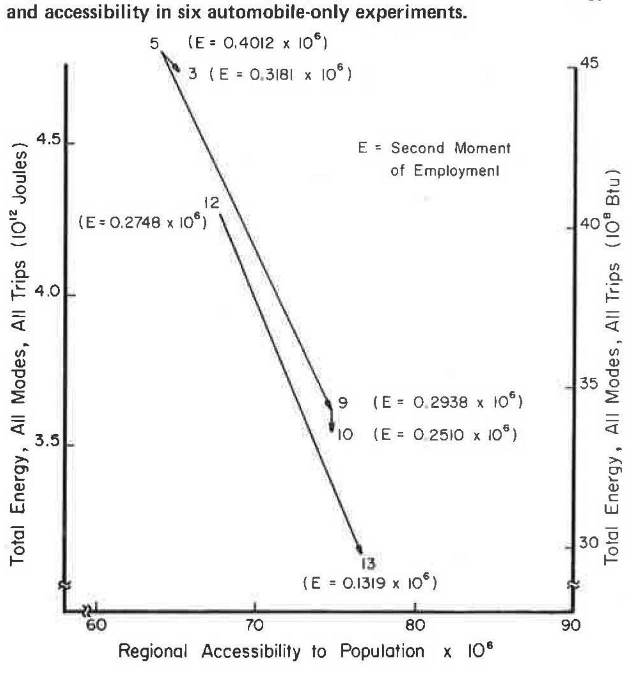


Figure 5. Effects of increasing employment concentration on energy and accessibility in six automobile-only experiments.



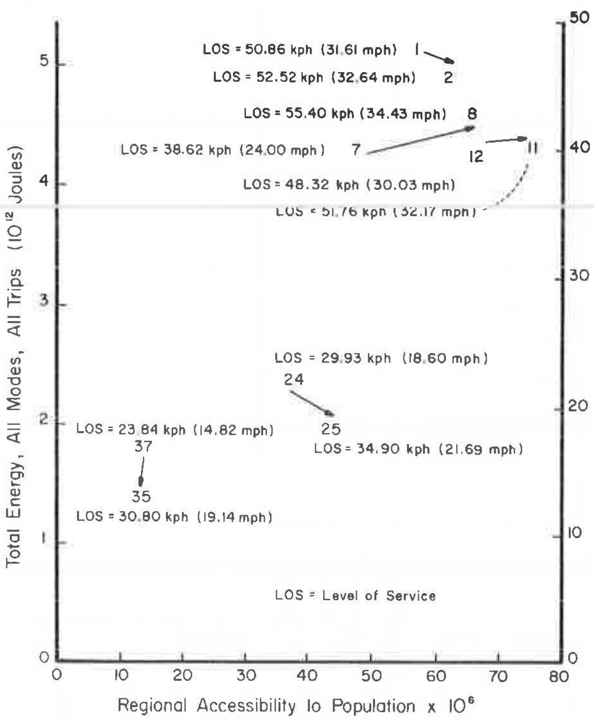
rings whereas in experiment 3 employment is in the central 25 zones. Basic employment distribution in experiment 9 is the same as that in number 5, but service employment is concentrated about the most central zone. Basic employment is tightened about the central zones in experiment 10 (located in one ring instead of two), but location of service employment remains largely unchanged. Because experiment 13 is a compact version of experiment 12, employment distribution is more compact as well.

The elasticities of energy and accessibility with respect to concentration of employment are not great. For the experiments examined, energy efficiency might be better served by concentrating population, with less concern for centralization of employment.

Network level of service, measured by average trip speed, affects both energy consumption and accessibility to population. Figure 6 shows the results of 10 experiments wherein, in all but one case, an increase in level of service effects an increase in the level of regional accessibility. This is not the case in experiments 35 and 37, both polynucleated; employment is concentrated in the central zone in 37, and population is tightly concentrated about that zone. This means congestion on routes to the central zone; hence, level of service suffers, but accessibility is heightened by the concentration.

The effect of increasing level of service depends on degree of congestion in the central area; the service improvements that alleviate congestion decrease the energy consumed as in 24 and 25 or 1 and 2; an increase in level of service where there is little congestion can mean higher energy consumption. The U-shaped automobile-energy versus speed function (14) explains what is observed.

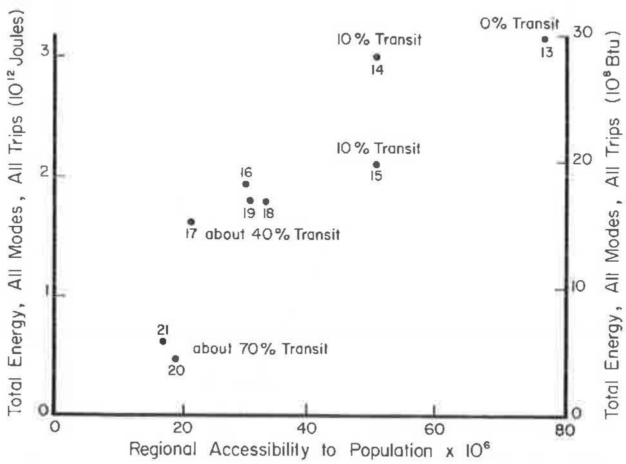
Figure 6. Effects on energy and accessibility of increasing levels of service in eight automobile-only and two automobile-transit experiments.



A shift in modal share to transit results in energy savings because of the lower joules per passenger-kilometer consumption of transit vehicles with high load factors, compared with that for automobiles. Figure 7 shows energy savings and accessibility values at differing levels of transit use. Each experiment represents a concentric-ring city with basic employment in the central nine zones and service employment concentrated about them. Experiment 13 is an automobile-only city, while, in experiment 14, 10 percent of all trips are by transit. Experiment 15 was identical to 14, except for increased levels of automobile occupancy. Modal split levels for experiments 16 to 19 are around 40 percent transit, and the differences between them arise from differences in bus routing schemes and operating frequencies. Experiments 20 and 21 use transit to a greater extent (70 percent of all interzonal trips), and the difference between them is due to frequency of service (10 buses/h in 21 versus 6 buses/h in 20).

Tremendous energy savings accrue from greater transit patronage. However, and perhaps equally important, accessibility decreases as well because of time penalties paid by transit travelers.

Figure 7. Energy and accessibility as functions of different levels of preference for transit modes in nine concentric-ring cities.



CONCLUSION

This research suggests the desirability of controlling the spread of cities and of channeling development into higher density, nucleated forms. Whereas this is an objective for existing cities and a design principle for new towns, it may also serve in the short term as a policy on rezoning requests and building permits and as a criterion for construction of increments to urban infrastructure.

There is a need to improve traffic operations to reduce the congestion, yet this should be done without building new high-speed facilities, which are likely to be self-defeating (because they encourage horizontal spread of cities) unless strict land use controls are applied.

Moving more people by transit is a promising energy-minimizing strategy; but, because transit solutions reduce accessibility, better ways of providing service must be found if people are to use transit by choice.

Finally, there is a need to explore the behavioral assumptions inherent in both the models used in this study and the urban forms that have been analyzed. If the assumptions are wrong, predicted futures may not be so desirable as expected. More likely, however, if the behavior required to bring about one of the desired urban forms is significantly different from that that would occur otherwise, society will not permit that policy option to be implemented.

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