Transportation Energy Effects on Urban Growth: Results of Simulations

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This paper evaluates the impact on urban growth and spatial structure of policies aimed at conserving energy in the transportation sector through a series of simulations that employ an optimization urban development model. In the model, transportation energy becomes an integral part of the land use component and thus trip making and land use allocation are determined simultaneously. After a brief presentation of the model, which is characterized by a highly nonlinear objective function, the solution method used is discussed at length. A major feature of the solution is the use of the out-of-kilter algorithm, which is accomplished by representing zonal activities by nodes and the number of acres of each activity by the flows in the arc. The paper reports extensively on the results of simulations performed under various assumptions. These tests reveal that, under transportation energy minimization objectives, central zones are considerably more attractive than outlying zones to both households and business. They also show the availability of transit service as a major determinant of the direction of urban growth. In addition, they reveal that, although energy minimization would produce considerable fuel savings, it would also cause an increase in mean trip lengths and mean trip cost over those generated by a cost-minimization model.

The recent shortage of fuel in California and the nationwide spiraling price of gasoline indicate the beginning of a new era for urban transportation, an era in which energy is one of the most critical and limited resources. Different ways to cope with the limited supply of energy include the use of higher-efficiency automobiles, the shift from the automobile to public transportation, and a restructuring of our cities to encourage the development of new urban centers in a more energy-conserving manner. Because the first two measures can result only in marginal reductions of total energy consumption and changes in the existing urban structure are difficult to implement in the short run, the need for policies to govern the future allocation of land uses (with the objective of increased transport energy efficiency) becomes pressing.

The impact of these policies could be evaluated by using existing models of urban development, properly modified to include energy consumption among their variables. In their current form, these models do not consider energy efficiency when allocating activities to zones. In the Lowry model, for example (the best-known model of this kind), population and service employment are forecast and, together with exogenously supplied basic employment, are allocated to zones through the use of a gravity model and based on zonal accessibility. After the allocation is completed, the trips generated are estimated and distributed among the possible destinations and modes. Total energy consumption could then be computed, given the average energy consumption per rider of each mode (1).

Models of this type, when used to evaluate the impact of alternative energy policies, are characterized by the insensitivity of the allocation process to the energy consumption of the transportation component. This insensitivity arises from the recursive structure of the models, which does not allow consideration of energy efficiency when activities are allocated to zones. Both trip matrix and energy consumption are estimated after the allocation is completed, and no iterative procedure is included that would permit the modification of the results obtained in the allocation process on the basis of transport energy concerns.

MODEL OF ENERGY-EFFICIENT LAND ALLOCATION

In an earlier paper we developed a land use model that attempted to overcome the above shortcomings (2). In that paper, transportation energy becomes an integral part of the land use component, and thus trip making and land use allocation are determined simultaneously. The model is concerned with the minimization of total transportation energy consumption and specifically with the interaction among land uses, the existing transportation network, and the trip distribution and modal choice components of trip making.

To minimize transportation energy, the model does not dispense with realistic urban location and travel behavior. The current urban structure as well as the existing zoning restrictions are taken into account, individual travel behavior is simulated by introducing an entropy-maximizing model, and travelers are assumed to select their trip ends and their mode on the basis of the travel costs involved and some realistic parameters that explain their behavioral characteristics. In this paper we report on the solution procedures and the results of extensive testing.

THE DEVELOPED MODEL

In mathematical terms, the full model is

$$\text{Min } Z = \sum_i \sum_j \sum_k e_{ij}^k T_{ij}^k \quad (1)$$

$$\text{subject to } \sum_i X_i^r = X^r \quad \text{for all } r \quad (2)$$

$$\sum_r X_i^r \leq L_i \quad \text{for all } i \quad (3)$$

$$X_i^r \leq C_i^r \quad \text{for all } i \text{ and } r \quad (4)$$

$$X_i^r \geq 0 \quad \text{for all } i \text{ and } r \quad (5)$$

where

- Z = total operational energy consumed by the transportation system,
- e_{ij}^k = energy consumption per person trip from zone i to zone j by mode k,
- T_{ij}^k = volume of person trips by mode k from zone i to zone j,
- X_i^r = number of acres of activity r to be allocated in zone i,
- L_i = number of acres of vacant land in zone i, and
- C_i^r = exogenously specified upper limit on the number of acres of activity r to be allocated in zone i.

The objective function (Equation 1) requires minimization of the total energy consumed by the trip makers, subject to constraints that assume that (a) all the new land must be allocated (constraint

2), (b) the land allocated in each zone should not be greater than the land available for development in that zone (constraint 3), and (c) the land to be allocated in each zone should not exceed a certain amount for some activities. The solution variables are the X_i^r's.

In order to relate the number of trips to the land use configuration, a trip-distribution and modal-shift model derived through entropy maximization is introduced. The volume of trips between any two zonal pairs is written as

$$T_{ij}^k = A_i B_j O_i D_j \exp(-\beta \tilde{c}_{ij}) \exp(-\lambda c_{ij}^k) / \sum_k \exp(-\lambda c_{ij}^k) \quad (6)$$

where A_i and B_j are the Lagrangian multipliers that ensure that the trip conservation constraints for both origins and destinations are met and are equal to

$$A_i = [\sum_j B_j D_j \exp(-\beta c_{ij})]^{-1} \quad (7)$$

$$B_j = [\sum_i A_i O_i \exp(-\beta c_{ij})]^{-1} \quad (8)$$

where

- O_i = number of trips with origin in zone i,
- D_j = number of trips with destination in zone j,
- β = behavioral constant of trip distribution that determines the willingness of trip makers to select other than the nearest destination,
- $\tilde{c}_{ij}$ = composite cost between i and j that indicates the relative costs of traveling (4),
- λ = behavioral constant of modal choice that determines the willingness of trip makers to use other than the least-cost mode, and
- c_{ij}^k = generalized travel cost between zones i and j by mode k.

The total number of trips generated in a zone is obtained by multiplying the rate of trip generation per acre of each activity by the number of zones of the activity to be allocated. In order to account for the existing land uses, the number of trips generated by the existing activities is added on. That is

$$O_i = \sum_r OR^r (X_i^r + E_i^r) \quad \text{for all i} \quad (9)$$

$$D_j = \sum_r DN^r (X_j^r + E_j^r) \quad \text{for all j} \quad (10)$$

where

- E_i^r = existing amount of land (in acres) in zone i currently developed in land use activity r,
- OR^r = trip production rate per acre of type r land use, and
- DN^r = trip attraction rate per acre of type r land use.

By using Equations 6, 9, and 10, the objective function of the optimization model is then written as follows:

$$\text{Min } Z = \sum_i \sum_j \sum_k e_{ij}^k \left\{ A_i B_j \left[\sum_r OR^r (X_i^r + E_i^r)\right] \left[\sum_r DN^r (X_j^r + E_j^r)\right] \exp(-\beta \tilde{c}_{ij}) \left[\exp(-\lambda c_{ij}^k) / \sum_k \exp(-\lambda c_{ij}^k)\right] \right\} \quad (11)$$

In its final form, therefore, the model is composed of the objective function (Equation 11) subject to constraints 2-5. The nonlinearity of the objective function and the similarity of the model to the network flow problems necessitate the use of special solution techniques.

Solution Method

The developed model is composed of a highly nonlinear objective function and a set of linear constraints. Since algorithms of nonlinear problems require excessive computer time and often do not converge, it was decided to use a heuristic technique for the solution of the land use-energy model. The procedure employed is based on the TOPAZ model solution technique [Brotchie and others (5)], which consists of solving successive transportation problems until convergence is reached. The objective of these problems is the original objective function reduced to a linear form by substituting for enough variables subject to constraints 2 and 3. In our model, the addition of the zoning constraint (Equation 4) does not permit the use of the transportation algorithm for solving the reduced linear model. For this reason, the out-of-kilter algorithm is used instead by properly converting the problem to resemble that of the flow of capacitated networks, as explained below.

The solution algorithm shown in Figure 1 includes the following steps:

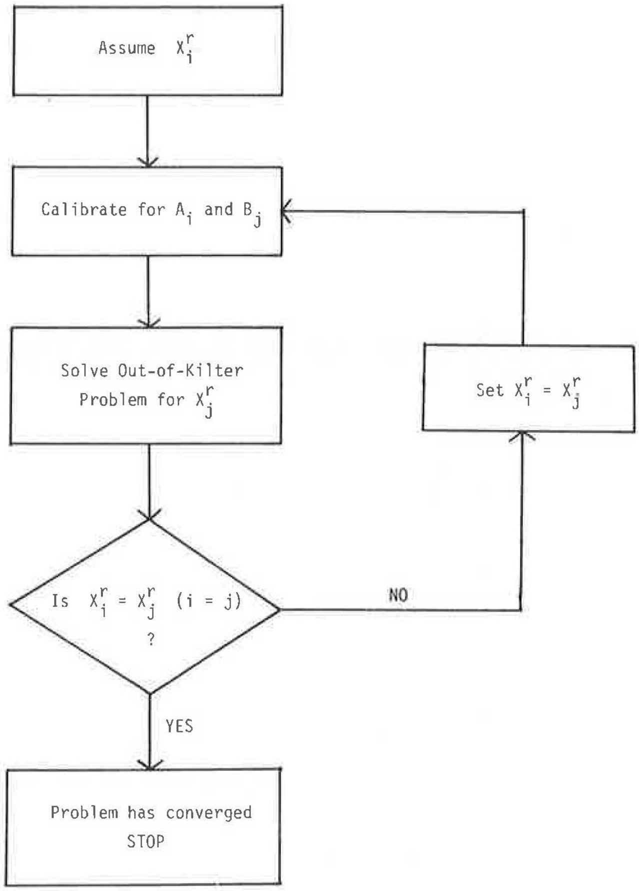
1. Assume values of X_i^r's; the assumed values must satisfy constraints 2-5;
2. Substitute for the values of X_i^r in A_i and B_j and calibrate the model given by Equations 6-8 through iteration; in calibrating for A_i and B_j, the variables X_j^r take the values of the assumed x_i^r's for i equal to j;
3. Substitute for the values of X_i^r, A_i, and B_j in the objective function; the result is a linear function in which the X_j^r's are the set of unknown variables; the out-of-kilter algorithm is used to solve the model given by Equations 11 and 2-5; and
4. Compare the assumed values of X_i^r with the values of X_j^r obtained in step 3 for i = j; if all of them are equal or almost equal, then the problem has converged and the iteration terminates. If not, go back to step 2 and substitute for X_i^r the values of X_j^r obtained in step 3 (i-j).

The iterative procedure described above continues until convergence is reached or until the maximum permitted number of iterations is exhausted. Although no formal proof exists on the convergence of this algorithm, we were able to reach convergence within six iterations in all the tests we performed. In most of these tests, convergence was accomplished within three iterations only.

Although the reduced linear model could be solved by the regular simplex method, special network algorithms were selected because of their efficiency in solving problems of network structure. Network problems are concerned with determining the flows between any two points in a network in such a way that the total cost is minimized. The collections of points are called nodes and they are connected through arcs that have cost and often capacity characteristics; the former represent the cost incurred by moving a unit of flow through the arc. If there are no capacity constraints, then the resultant problem is called the transportation problem and special algorithms exist that can solve problems that involve even hundreds of thousands of arcs (6).

The land use-energy model presented above resembles the network problem. Each activity and each zone can be represented as nodes connected by arcs, where the number of acres of a type of activity located in a zone is the flow on the arc.

Figure 1. Solution by using out-of-kilter algorithm.



If there are no constraints on the amount of any activity to be allocated in any zone, the problem can be solved readily by applying the transportation algorithm.

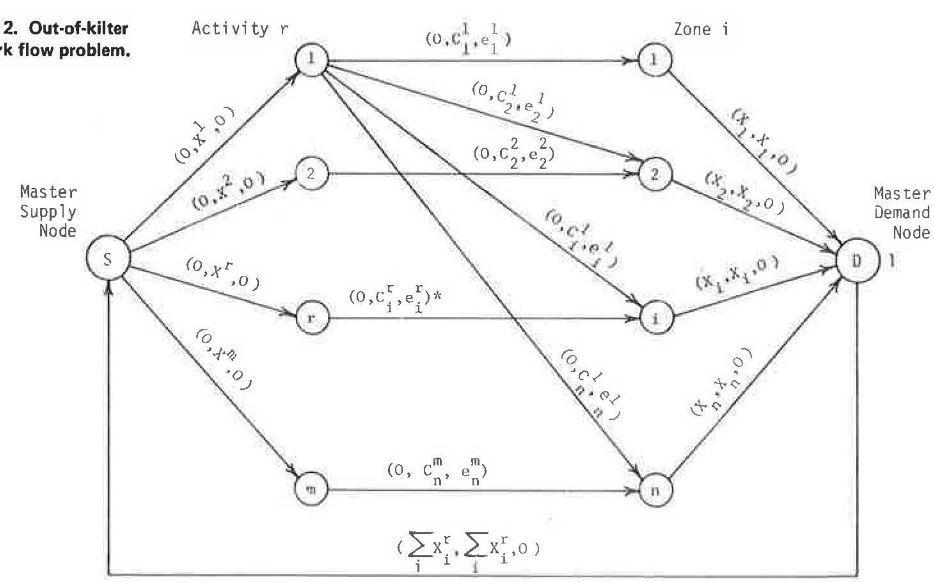
The use of a transportation problem algorithm, however, strains the realism of the resulting land use allocation. With this algorithm, the only constraints are the row (or supply constraints) and the column (or demand constraints). The supply constraints require that all of the acres of the different types of activity be allocated across the zones. The demand constraints require that all available land in each zone is filled, either by allocation of some of the land use activities or by allocation of vacant land. A realistic solution requires that an upper limit be placed on the amount of certain activities that is allowed in a particular zone. For example, zoning ordinances will limit some land uses in different zones--a constraint that may be violated by a simple transportation algorithm allocation.

In order to prevent such unrealistic solutions, a zoning constraint (constraint 4) has been added in the model and an alternative network algorithm has been adopted. The out-of-kilter algorithm (7,8) allows a solution of network flow problems that have upper and lower bounds on the flows through the arcs. Reformulation of the transportation algorithm requires creating an artificial master supply node (with arcs to each of the supply activities), an artificial master demand node (with arcs that come from each demand node), and an arc that connects the master supply and demand nodes. Figure 2 shows the graphical representation of the land use-energy model in its network form. The complexity of the problem is increased slightly, but very large problems may still be solved rapidly and efficiently.

Testing of the Model

Sioux Falls, South Dakota, was selected as the test site because of the availability of data and because of its manageable size. The area of consideration, which has a population of approximately 100 000 over 24 zones, offers enough complexity to be realistic

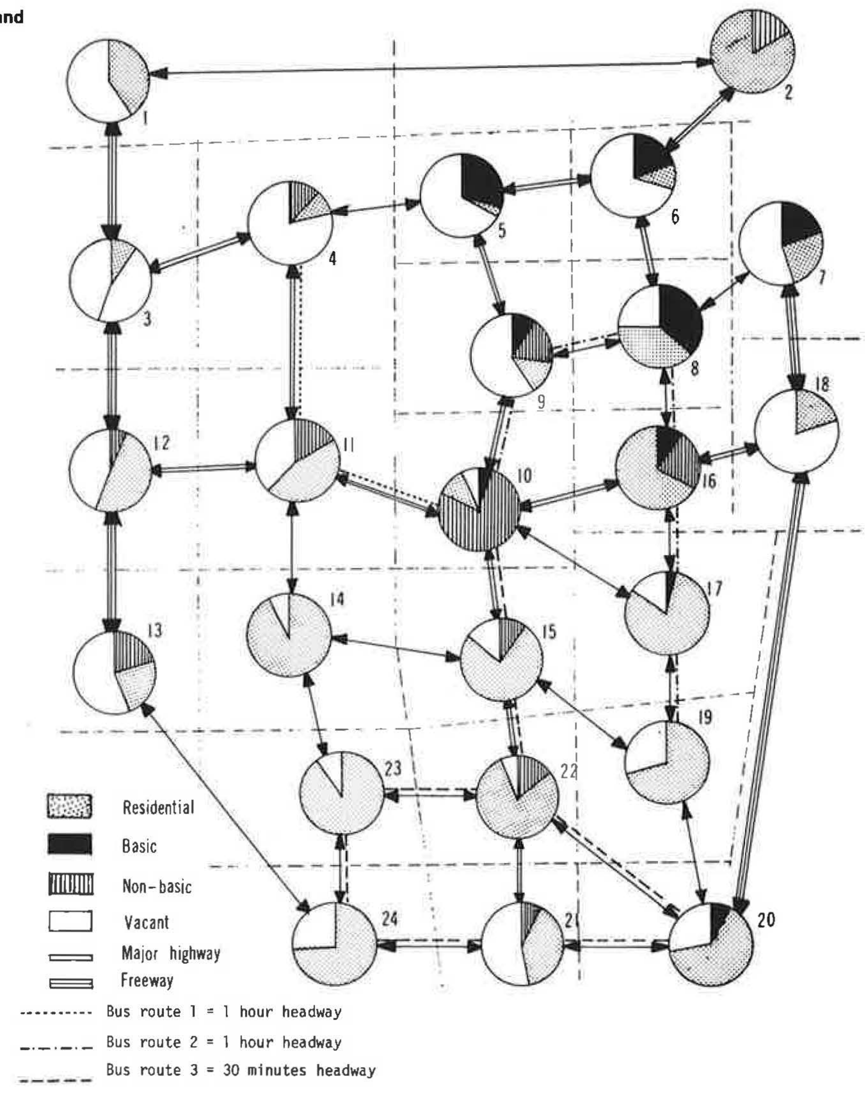
Figure 2. Out-of-kilter network flow problem.



Quantities within the parenthesis represent:
(Minimum Allowable Flow, Maximum Allowable Flow, Cost Per Unit Flow).

Absence of a subscript or superscript indicates summation over that dimension.

Figure 3. Existing land uses.



without being too unwieldy for convenient experimentation.

Although the Sioux Falls case was adopted for this experiment, it was determined that the analysis would be simplified if elements of a "toy city" were developed from the base of the actual city. For example, if the locations of existing land uses can be made more concentrated than the actual land use pattern indicates, the results of the model will be more exaggerated and interpretable. A sensitivity analysis will thus produce more distinguishable results than if a less organized, dispersed land use pattern is used for the base.

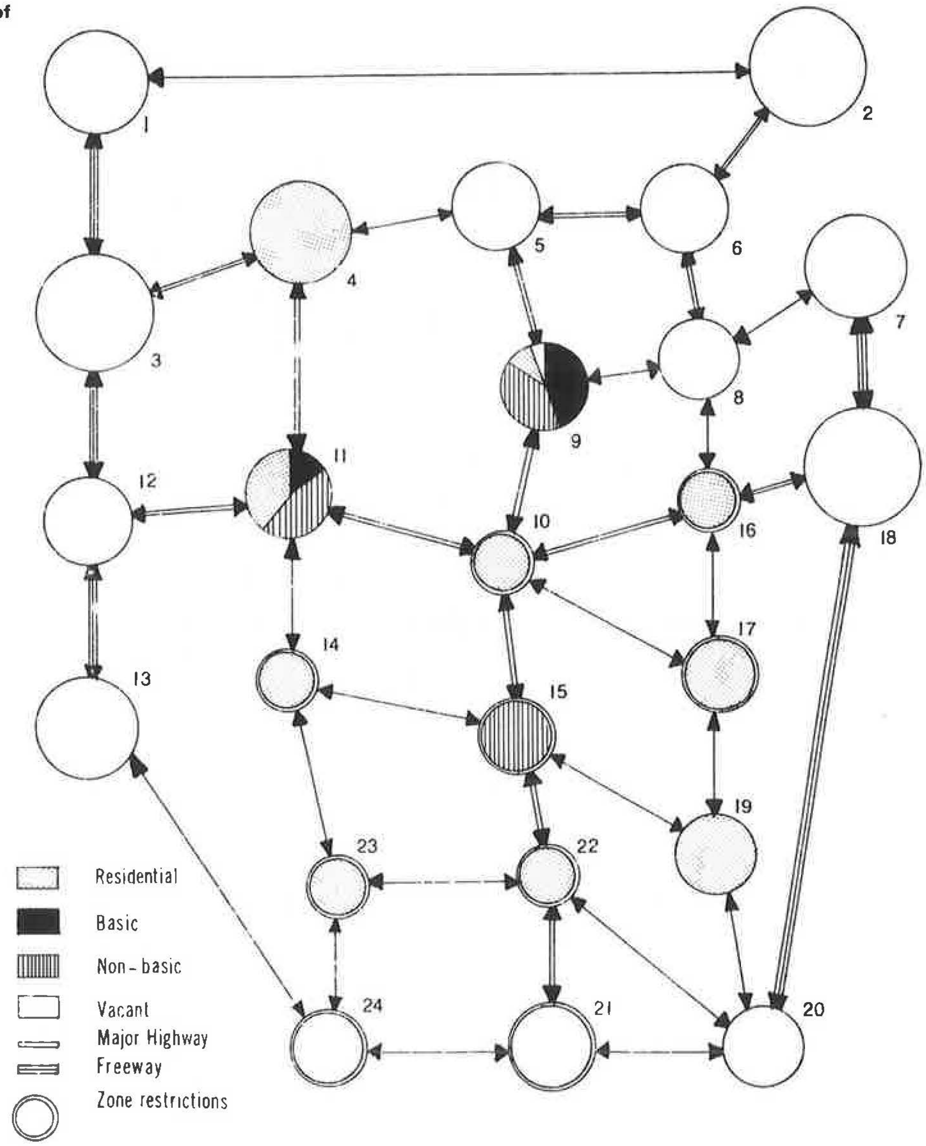
Existing Land Use and Transportation System

A simplified network used by LeBlanc (9) was adopted. It connects the 24 centroids with 37 two-way links. The population and economic activity in the city were taken from census and county business patterns sources. Maps and census tract data were used to allocate the existing activity among the 24 zones. The observed origins and destinations of trips for the zones were maintained. However, after this somewhat aggregate information was used for a framework, the treatment of the data at a more disaggregated level departed from the actual situation. The acres of land use activity of each type were placed in zones so that the basic characteristics of the land use pattern were maintained. But the pattern that was created was intended to be more concentrated and exaggerated than what may be observed in reality. The initial design was intended to produce an obvious central business district (CBD), industrial area, commercial areas, residential areas, and undeveloped open space. The design was adjusted so that the acreage of various types of land use in a zone would produce the observed number of trip ends when the trip generation rates were applied.

The configuration of the city is illustrated in Figure 3, which also displays the allocation of land use activities. The CBD centers around zone 10. Commercial uses are distributed along the highway routes. The industrial area is concentrated in the northeast in zones 5-9. A college and related high-density housing are developed in zones 14, 15, and 21-24. Other high-density housing is located near the central part of the urban area. The major park is in zone 13, and most of the vacant land is in the outlying zones.

A very simple transit system was added to the transportation network. Three routes were coded, as shown in Figure 3. Two of the routes are operated in the base year with a one-hour frequency. The third route, which extends through the higher-density college district, runs with a half-hour frequency of service.

Figure 4. Minimization of energy consumption, $\beta = 0.2, \lambda = 0.2$.



*Circle size indicates area of vacant land in each zone.

Zoning Limitations

In addition to specification of the existing situation, the development that may reasonably take place in the future must be considered. For the experiments described, a very limited amount of intervention in the form of zoning was included in the model constraints. The primary zoning limitations invoked were a limit to the amount of residential development that could occur in the industrial areas and limitations on industrial activities in some residential zones.

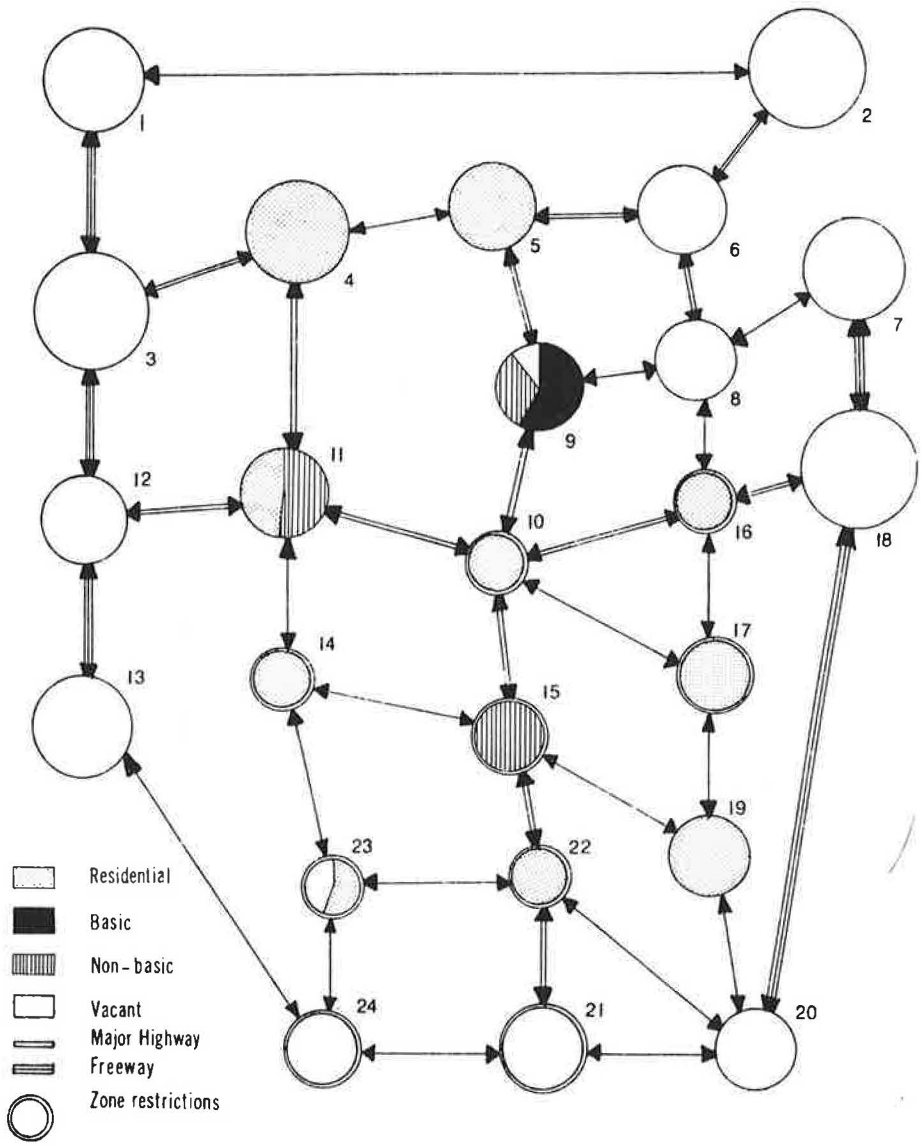
Travel Demand Parameters

The experimental problem involves minimization of transportation energy consumption where the available modes are private automobile and bus mass transit. Data are not available for Sioux Falls on which destination or modal choice models may be calibrated for this choice set. In the absence of calibrated models, a series of experimental optimizations was run in which the parameters and modal cost variables were systematically varied as a sensitivity analysis. The experiments and sensitivity analyses conducted produced a series of results, only a sample of which is reported here. The tests performed were of two types:

1. Division of the optimization time frame into subintervals with increments of growth optimized over the shorter time periods and
2. Change in the objective function to require minimization of travel costs rather than transportation energy.

In the first set of tests, the analysis consisted of varying the parameters and variables in three nested loops. For given values of the destination choice parameter (β) and the modal choice parameter (λ), the value of time for users of the three modes was increased in steps. Then λ was increased successively. Finally β was increased in steps. This analysis was intended to trace the effect on energy-efficient land use allocation of trip makers' sensitivity to modal and interzonal

Figure 5. Minimization of energy consumption, $\beta = 0.2$, $\lambda = 0.8$.



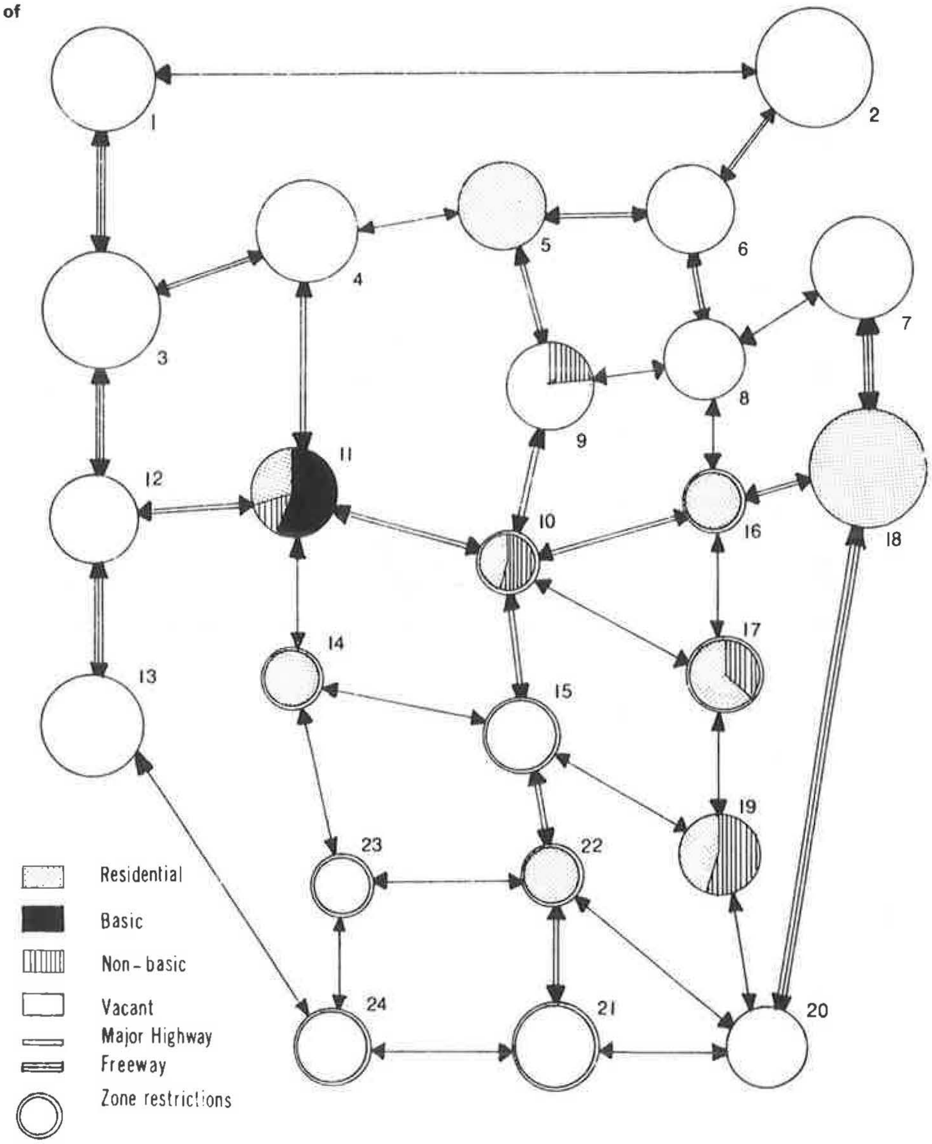
travel costs. Therefore, the influences of interest with regard to the optimal location of new land use activities are (a) the existing land use pattern, (b) the willingness to travel to other than the minimum-cost destination, and (c) the willingness to travel by other than the minimum-cost mode.

The values of the parameters were not found to have a great effect on the locations of manufacturing, construction, and public utilities. Almost all of the tests allocated these activities to zones 11 and 9; however, at higher values of β (where transportation costs become more important), some of the activity was allocated to zone 8. Service and office activity was generally allocated to zones 9 and 11, although at higher levels of λ zone 17 replaced zone 11. With few exceptions, regional shopping center land use was placed in zone 15, and local shopping was located in zone 11 (Figures 4-6 show three land use types).

The variation in parameter value also had little effect on higher-density housing location. High-density housing was generally located in zone 17. Medium-density housing was generally divided between zones 10 and 17. However, at high values of λ, zone 16 replaced zone 10. The location of low-density housing was affected more by the willingness to use other than least-cost choices. In all the tests, zones 11, 14, 17, and 19 were filled to capacity with allocations of low-density residential land use. This, however, did not happen with the rest of the zones. For example, at low values of λ, which indicate that transit is an acceptable choice, zone 4 usually received an allocation and zone 5, which has no transit, was usually developed less intensely for small values of λ. However, as λ increased, the low-density residential land use was shifted to zones such as 18 (Figures 4-6).

To gain a broader view of the results of the sensitivity analysis, it is necessary to look at these changes from a more aggregate level. Although distance and modal cost differentials remained unimportant in the choice functions, the major impact of development was west and northwest of the CBD. However, as modal cost differentials made transit less attractive, the northwest direction disappeared in favor of the eastern area, especially around the interchange of the freeway and the east-west highway in zone 18. A higher sensitivity to distance also pushed development to the northeast, around the industrial corridor of zones 7-9. Interestingly, at very high values of β and

Figure 6. Minimization of energy consumption, $\beta = 0.2$, $\lambda = 2.0$.



low values of λ, almost all new land use was forced into the northeast. All land use except low-density residential was placed in zone 6 in one run. Low-density residential was placed in zones 5, 7, and 15-17.

In this set of analyses, several points become evident. As would be expected, the close-to-center zones are filled to capacity before outlying zones become attractive. The most distant zones are completely neglected. The direction of growth depends on trip makers' willingness to travel farther than the nearest satisfactory destination, their acceptance of mass transit as a feasible modal alternative, and the availability of transit service. In these tests, however, the level of service for transit was held constant, even after growth allocations were made. These allocations, on the other hand, should have an effect on the demand for transit services and should ultimately result in better service to satisfy that demand, thus altering mass transit costs. An even more obvious effect of the allocations is the congestion that might result on some of the links. Some of the zones and corridors received massive new growth, which should cause link travel costs to increase. These and other observations will be considered in greater detail later in this paper.

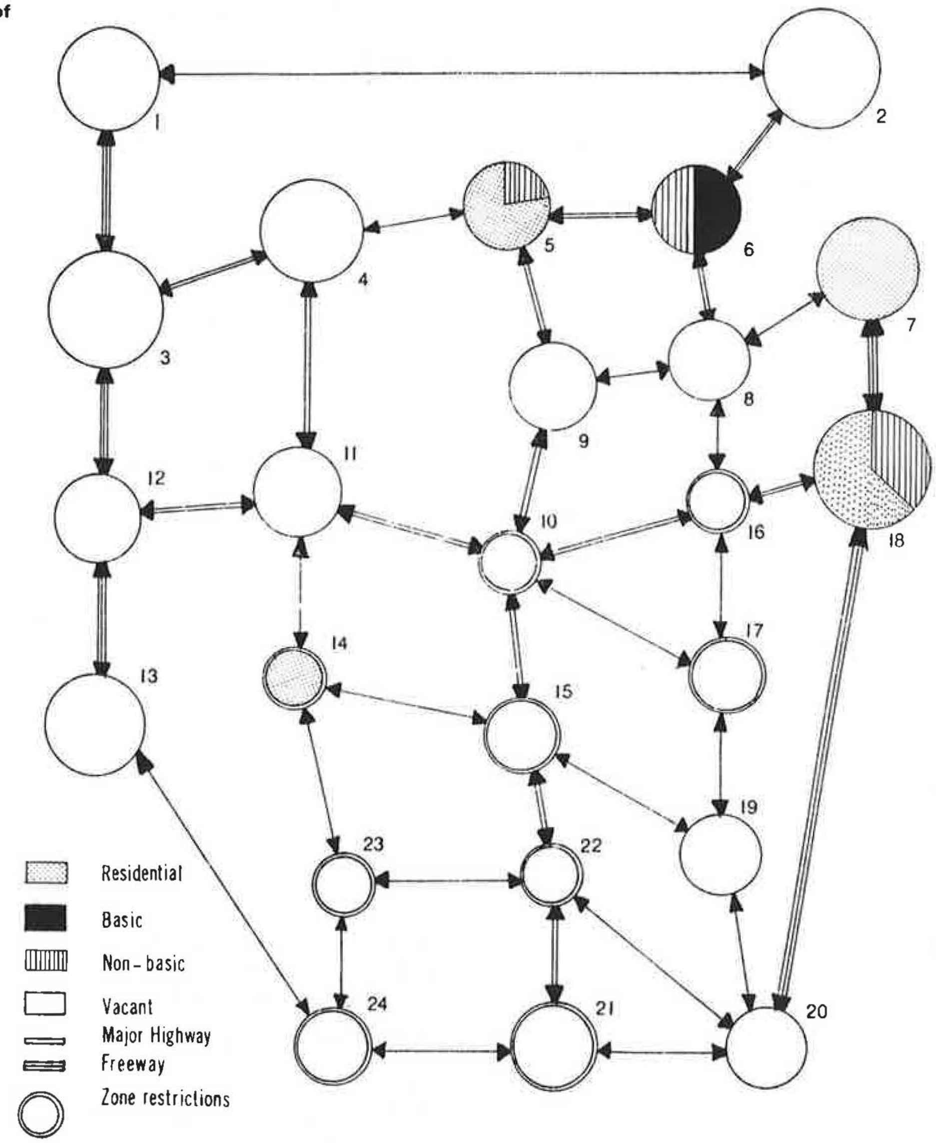
The runs summarized above held the values of time for users of each mode constant. Some tests were also made in which the relative values of time were allowed to vary. To simplify the analysis, the value of β was held constant at a value of 0.2 so that the trip-interchange matrix could have a substantial degree of diffusion.

Two land use types--regional shopping center and high-density housing--were allocated to zone 15 by every run. This zone is served by the mass transit route that has twice-hourly frequency.

Mass transit was found to be an important element in the land use patterns that developed in this series of runs. At low values of λ or low values of time, the only zones that received allocations were those served by transit. The only exception was zone 9, which received varying amounts of industrial land use and park land.

In all runs, zone 11 is quite important as the location of many of the nonindustrial land uses, including housing. The sensitivity to the cost of travel and value of time is most easily seen in zones 4, 5, and 18. As trip makers become less willing to use transit or place more value on time, zone 4 loses new development. Zone 5 is the first

Figure 7. Minimization of transportation cost, $\beta = 0.2, \lambda = 0.2$.



nontransit zone to receive an allocation of low-density residential land use. Finally, as transit becomes unacceptable, zone 18 is developed.

The Cost-Minimization Solution

The preceding optimizations were based on a minimization of transportation energy consumption. The results were compact patterns for the new development. As may be seen in Figure 3, the test city has not historically developed in an energy-efficient manner, since the outlying zones that have existing development received little or no development in the allocations. Since the results have shown that the development of transportation energy efficiency would be a deviation from past trends, it was decided to produce the transportation cost-efficient allocation discussed above, for comparison. The resulting allocations were significantly different from those previously observed (Figure 7). Most importantly, the zones that had transit service were left out of every optimal land use pattern.

The allocations based on transportation costs can be divided into two groups based on the values of λ. One grouping of results occurred for low values of λ where the land uses, except some low-density housing, were allocated to zone 7. Larger values of λ, on the other hand, shifted all the land uses except low-density housing from zone 7 to zone 18 (Figures 4-6).

The cost-minimization solutions are quite different from the transportation energy minimization solutions. There are at least two possible interpretations for this distinction. On the one hand, it could be interpreted that the differences in transportation system characteristics are such that the energy-efficient links are not correspondingly cost efficient. On the other hand, the difference could be the result of energy consumption and transportation cost data that are inconsistent with each other.

A comparison of the results of the most characteristic test cases discussed so far was attempted in the graphs of Figures 8-10. The three curves of the graphs represent base-year conditions and conditions under energy cost minimization and transportation cost minimization. Although variations in these graphs are associated with trip cost changes and the values of λ, it is obvious that energy minimization as a transportation policy objective would produce considerable fiscal savings

Figure 8. Average energy consumption, $\beta = 0.2$.

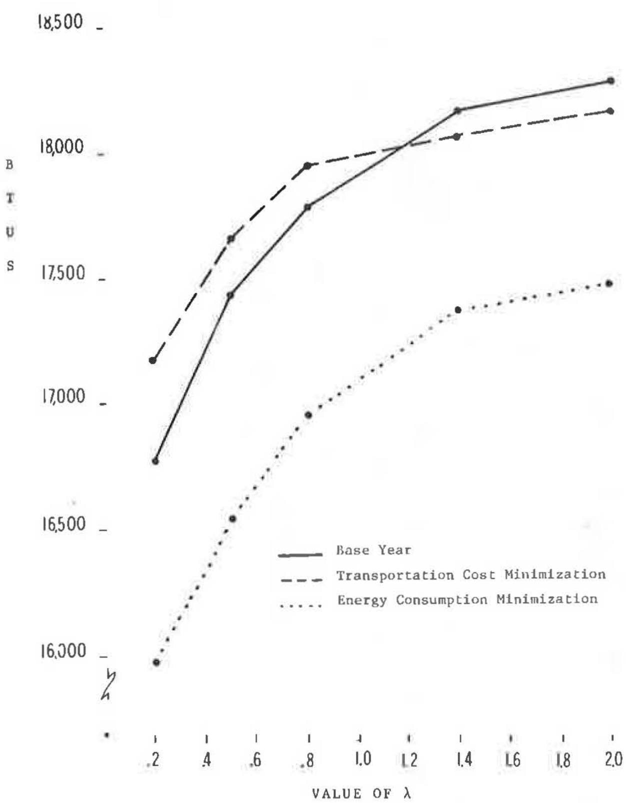


Figure 10. Mean trip cost, $\beta = 0.2$.

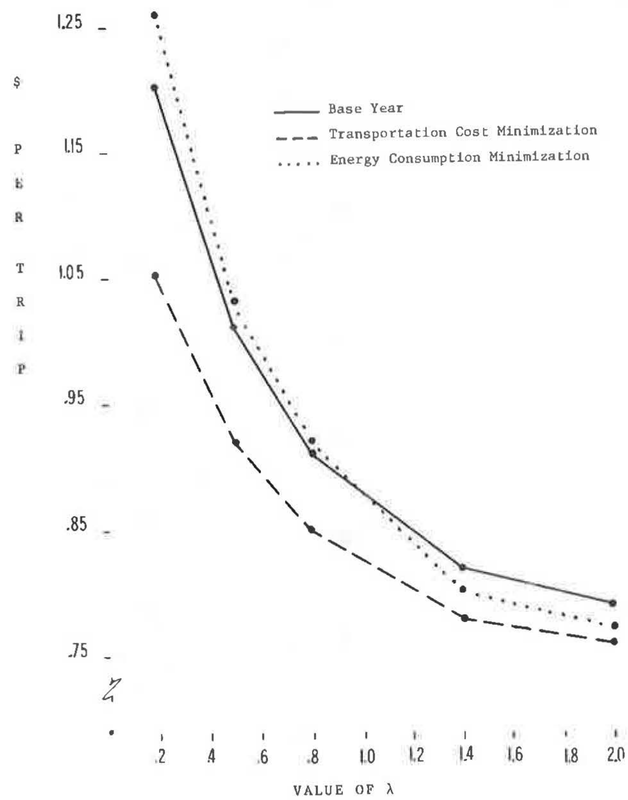
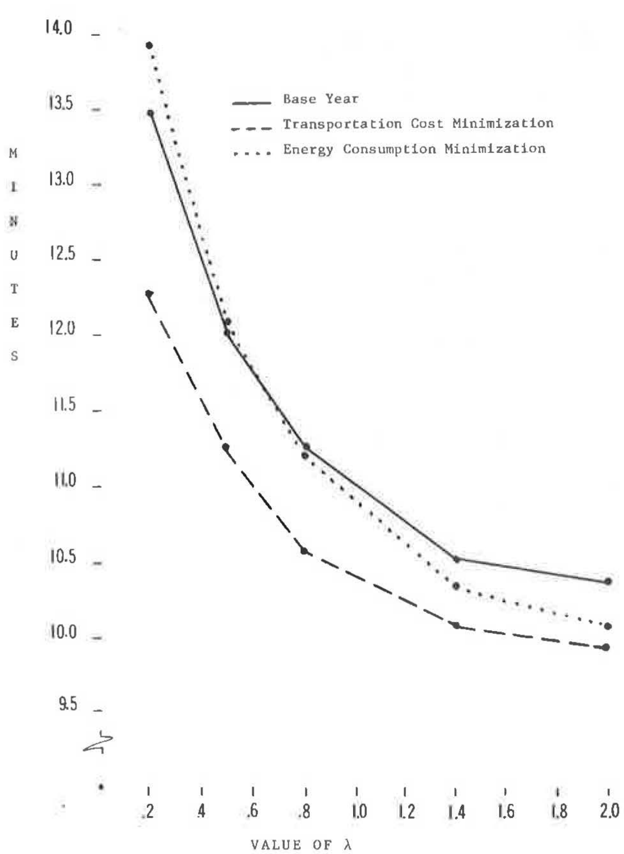


Figure 9. Mean trip length, $\beta = 0.2$.



(Figure 8) but would also ensure an increase in mean trip lengths and mean trip cost over those generated by a cost-minimization model.

DISCUSSION AND EXTENSIONS

The land use allocations summarized in the previous section were obviously a diversion from the development patterns that had previously occurred in the city. The model incorporated elements to simulate observed travel behavior in the choice of destinations and modes but was biased in the direction of generating a transportation energy-efficient city while still allowing suboptimal travel choices. Its biased output, therefore, could reveal points that should be considered in the policy implications of the allocations and in the incorporation of further refinements in the model. This is especially true with respect to the availability of mass transit and the determination of the model's planning horizon.

The series of tests of the optimization model was performed with a very basic form of the model. Even though the complexity was increased significantly to overcome some of the shortcomings of simpler models such as TOPAZ, there are several elements that could be improved in future experimentation. A simplifying assumption used in the optimization model was that the network was capable of satisfying increased demand for travel with no decrease in travel times due to congestion. It should be possible to introduce network congestion into the optimization process and produce a land use allocation in which the resulting network assignment is in equilibrium. Variations of gradient-descent methods have been used in the creation of user equilibrium traffic assignments with fixed demands (10,11). Evans (12) summarizes the problem and different approaches to achieving equilibrium with elastic demands by combining trip distribution and assignment. The treatment of congestion has been carried a step further in allowing network characteristics to affect the development of zones in a Lowry model (13). Bowman and others (14) and Peskin and Schofer (15) have included network congestion in Lowry-type land use models.

Congestion would affect the optimal land use in two ways in this optimization model. Generally, in a land use model (including the Lowry-type energy and land use models) the destination choices are determined by travel costs on the network. Congestion reduces speeds, increases the travel times, and changes the relative attractiveness of alternative destination zones. In this transportation energy-optimizing model, the costs of transportation time determine destination choice, but energy efficiency determines optimal location of trip-generating land uses. Congestion decreases speeds, increases travel time, and may also affect fuel consumption by automobiles. In general, automobiles are more energy efficient at lower speeds, unless a significant amount of starts and stops are made. If reduced speeds due to congestion do reduce fuel efficiency, then an objective of energy minimization in an automobile-oriented city should be to produce results similar to those of a cost-minimization objective. However, in the event that the two objectives are not synonymous, an interesting problem is presented that deserves further study: The question is whether transportation energy or some other variable should be the variable to be considered in the objective function. How can transportation energy efficiency or some other objective of urban design be modeled and congestion incorporated when travel decisions are based on a different variable?

Problems of multiple objectives in another sense are dealt with by Bammi and Bammi (16), as was mentioned earlier. Their formulation deals explicitly with goals whose achievement cannot be compared without devising a common measurement system for evaluating trade-offs. Transportation energy-efficient design should also be evaluated in comparison with other urban design objectives. Unfortunately, the economies of scale or advantages of dispersion that might be beneficial for energy conservation might be detrimental to achievement of other design objectives. Goals such as preservation of open space or reduction of air pollution or other policy objectives might contrast with the needs of energy conservation.

Despite these shortcomings, the land use allocation model described in this paper accomplished several objectives. An optimizing procedure was offered as an alternative to the more common practice of using Lowry-type models in studying energy-efficient urban development. The unrealistic solutions given by early optimization models were overcome by adopting a model based on the TOPAZ concept. In addition, some of the limitations of this approach were also dealt with, primarily in the addition of development of upper- and lower-bound constraints. Furthermore, many of the problems that will confront future attempts to extend this model were discovered and examined. Some of them appear to be easily solvable; others may be impossible. However, the fact that not all of them can be readily overcome in an optimization approach should not undermine interest in the optimization solution. Note that practically all of these problems are also present in simulation models, and most of them have not been dealt with in applications of Lowry models. The most important point introduced in this paper is that energy optimization can be incorporated directly in the objective function of an urban design problem, and that its use is highly desirable if transportation energy minimization is a development objective.

ACKNOWLEDGMENT

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Effect of Urban Development Patterns on Transportation Energy Use

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Many who have observed the large fraction of energy used in urban passenger transportation have suggested that this consumption could be reduced by encouraging higher densities and more compact settlements in urban areas. A study was carried out to investigate travel patterns and energy use in urban areas as determined by various descriptors of urban form. A statistical analysis of travel data from eight metropolitan areas found that energy use by urban passenger transportation is lower with some development patterns than with others. Some new neighborhoods would therefore be more energy efficient in their travel impacts than others. However, the transportation energy impacts of an extensive redevelopment (or growth) of an entire urban area would depend on the residential relocations that might occur with such drastic changes in overall housing availability. These were not examined. To calculate the energy use of various travel patterns, a simple direct approach developed at the General Motors Research Laboratories was used. This approach found that fuel consumption could be expressed as a linear function of a trip's travel time and travel distance, independent of complexities such as acceleration and deceleration rates or idle times.

Concern is now growing about the potential limits to the availability of petroleum fuel and the potential risks of our great dependence on the automobile for transportation. Even though many researchers are investigating alternative automobile fuels and energy sources that are not based on petroleum, others are concerned with additional courses of action. Increasing the efficiency of petroleum-based engines and vehicles is a major area of research that has been stimulated partly by federal legislation. In this area, making vehicles smaller, switching to lighter materials, and changing engine design are all receiving great attention.

Another approach to dealing with the potential fuel problem is to reduce our use of automobiles. Public transit, carpooling, and paratransit services are being considered as means of attracting drivers from their cars. In all of these cases, however, there is controversy over the extent to which energy use can actually be reduced (1). Part of the controversy is over the success levels attainable simply by promotion of the alternative modes. Some argue that automobile-restraint measures are necessary to get drivers out of their cars and that parking restraints, gasoline taxes, or road pricing must be used to coerce drivers to change modes. There is the additional question of whether the public transportation modes would actually save more energy than will the legislatively required efficient automobiles of the 1980s.

Other observers have suggested that the interrelated historical development of automobiles and cities during the last 50 years has led to a natural dependence on automobiles in low-density areas (2). This development has made public transportation noncompetitive in most urban areas for the majority of travelers who can afford their own automobiles. To reduce energy use, these observers suggest that we must change the structure of the cities to higher densities so that the resultant congestion would deter automobile use, and the higher densities would promote transit use as well as allow more walking. The remainder of this paper discusses this proposal to change urban form; the effectiveness of the approach is analyzed and various means for bringing it about are assessed.

Several analytical and simulation studies have been made of the relationship between urban form, transportation, and energy use. To understand their results, we must be clear about the possible ways in which urban form affects energy use. The next two sections set this background. First, the influence of travel patterns on energy use is discussed. This is followed by an analysis of the relationships between these travel characteristics and measures of urban form. The integration of these two pieces then provides the structure for the subsequent discussion.

ENERGY AND URBAN TRAVEL

The energy consumed by a single automobile trip depends on both travel time and travel distance. Research by Evans and others at the General Motors Research Laboratories has shown a simple linear relationship for a given vehicle for trip speeds less than about 35 mph (3-6):

$$F = a D + b T + c \qquad (1)$$

where a, b, and c are measured constants and

F = gallons per trip,
D = trip distance (miles), and
T = trip time (min).

The constant c represents the fuel required during cold starts compared to the use of an already warm engine and varies somewhat with ambient temperature.

Evans and others found that this relationship was a remarkably accurate representation of fuel use and that detailed trip characteristics such as acceleration and deceleration and idle times were not needed for the fuel estimate (4).

Based on the General Motors group's examination of 1973-1975 model cars, estimates of a, b, and c can be made for the fleet average. Also, Equation 1 can be written in terms of the distance and speed. The average fuel use per automobile then becomes

$$F = (0.039 + 0.078/v) D + 0.115 \qquad (2)$$

where v = average speed (mph), or