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The Impacts of Urban Transportation and Land Use Policies on Transportation Energy Consumption

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FINAL REPORT

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16. Abstract

This report explores relationships between energy consumption in urban passenger travel, land use, transportation system characteristics, and travel behavior. Findings are based on 112 experiments conducted with an integrated, equilibrium transportation-land use simulation model. This model simulates urban growth, is sensitive to a broad range of transportation and land use actions, accounts for congestion, accomodates auto and transit modes, and responds to the generalized costs of travel. Three city shapes, concentric ring, one-sided, and polynucleated, were tested. It was found that significant improvements in energy efficiency resulted from coordination of urban growth with transportation network capacity to limit congestion. Where the network permitted, centralized, corridor, and nodal growth were found more efficient than dispersed growth. The structure of the transportation network was an important factor in determining energy efficiency: critical improvements in connectivity reduced consumption more effectively than simple capacity increases. The role of peak hour transit service was found vital to limiting total energy consumption. Further transit improvements failed to improve energy costs. Certain low capital cost options produced important energy benefits. These included car pooling and increased commuter parking costs. Finally, results indicate that vehicle-miles of travel is a poor indicator of energy consumption because it fails to account for congestion.

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Energy, Transportation planning, Land use, Simulation, Transit, Travel behavior, Energy conservation, Transportation, Policy evaluation

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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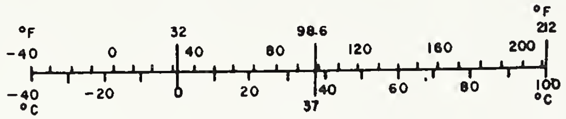
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

This report describes a systematic exploration of relationships between energy consumption and urban passenger travel and land use, transportation characteristics, and travel behavior. The purpose of the study was to develop and apply an analytic technique for the prediction of consequences of some of the more promising options for energy conservation in urban transportation. In particular, this study attempted to capture the effect of the interrelationships between transportation and land use, as influenced by energy-conservation policies. A number of policies were identified which could lead to significant reductions in energy consumption for urban passenger travel. These were used as the basis for constructing a set of guidelines for achieving more energy-efficient urban transportation through improved transportation and land-use planning.

The results of this research are based on the application of a large-scale, integrated transportation and land-use computer simulation system developed for this effort. This system simulates the spatial development of a city, the passenger travel which takes place in that city during a single day, and the energy consumption resulting from that travel. The core of the system is a Lowry-type land-use model incorporated within an algorithm which explicitly considers the relationships between transportation and land use as they are influenced by congestion on the highway network, patterns of modal choice, and the generalized costs of travel, including the cost of energy. Inputs for the operation of this model include the location of basic (exporting) employment, the structure of the highway and transit networks, land-use development policies, operating policies for the transportation system, and general parameters of travel behavior as typically devel-

oped in a contemporary urban transportation study. As its products, the model produces a detailed description of land use in the city; descriptions of travel on the highway and transit networks; and a variety of aggregate measures of performance, including indicators of congestion, trip length and, finally, several measures of energy consumption, for several categories of work and non-work trips, and for automobile and transit. Results of the model may thus be analyzed on a disaggregate basis, in terms of the number of residents and jobs allocated to each analysis zone, and the number of travelers using each link in the transportation systems; or, they may be viewed from a more aggregate perspective, using indicators of performance applicable to the entire city.

The experimental program itself consisted of 112 runs of the simulation system, applied to three different hypothetical test cities. These cities included a concentric-ring city, a one-sided or shoreline city, and a more radical, polynucleated city. Each of these cities was simulated at a population level of approximately 100,000 persons. Policy inputs were defined to reflect the typical, pre-energy crisis transportation and land-use policies. Subsequently, specific experiments were conducted by allowing these cities of 100,000 to grow to a population of 125,000 under the application of the particular transportation and land-use policies to be tested. Thus, the results of these experiments give an indication of the way an existing city would respond to the implementation of new energy-conserving policies.

Figure 1 provides a simple illustration of selected results of these experiments. In it, the effectiveness of various policies in terms of their abilities to reduce energy consumption is displayed by ranking them on a scale of total energy consumption. The figure compares results of similar experiments in each of the three prototypical city forms. The standard incremental run, noted on the figure, is the principal basis for comparison. This is the experiment which permitted growth from 100,000 to 125,000 population with no change in the transportation or land-use policies. The policy changes tested in other experiments are indicated briefly in the figure.

The most obvious finding is the similarity in the ordering of effectiveness of the alternative policy changes across the test cities. This is an indication that the results are indeed generalizable to real-world situations. The lower sensitivity of the polynucleated city to policy changes is due to its clustered distribution of land use, which results in shorter trips and lower total energy consumption. Encouraging increased average work-trip auto occupancy (simulating commuter carpooling) is the most effective policy change in reducing energy consumption. The mechanism for this is that by reducing the number of vehicles travelling, average congestion on the highway network is reduced. Other policy changes, including many different pricing, urban growth, and transportation system changes, are far less effective.

Policy guidelines extracted from these and other experiments center on four major areas of interest. First, it is apparent that directed urban growth, particularly when coordinated with the existing transportation network or improvements to that network, was shown to result in more energy-efficient urban forms than uncontrolled, sprawled growth. This was particularly noticeable for radial corridor developments supported by radial arterials or freeways, a combination which proved to be particularly energy-efficient in the context of the concentric-ring city. Coordinated, nodal growth was found to be energy-efficient in the concentric-ring city only where it is supported so effectively by its transportation system as to preclude the development of significant localized congestion. This suggests

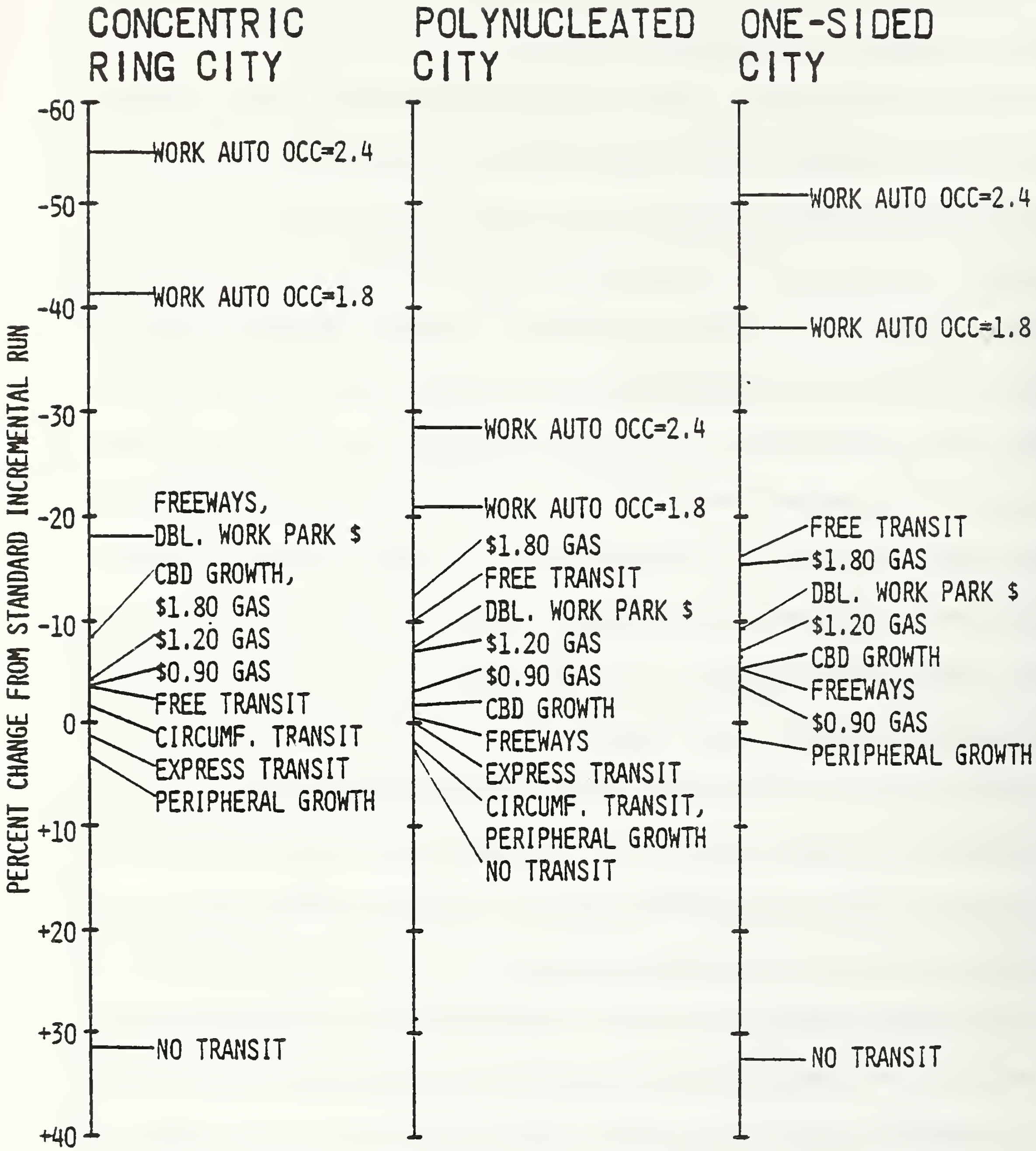


Figure 1: Effectiveness Ranking in terms of Total Energy Consumption

that efforts to imitate the polynucleated form within a basically concentric-ring structure are not likely to be promising unless major changes in the transportation network are introduced.

Generally, the value of integrated transportation and land-use planning to promote energy conservation was clearly shown. The effect of this strong relationship between patterns of land development and the transportation network on energy consumption appears to be salient at the microscopic level as well as at the larger, regional scale. This is because the major impact on energy consumption is due to changes in localized street congestion. Thus, it appears to be desirable, based on the results of this research, to evaluate individual development proposals not only in terms of their effect on highway safety and street system capacity, but also in terms of their likely impacts on overall patterns of energy consumption.

A second major finding of this study is that the general structure of the transportation network appears to be an important determinant of the energy-efficiency of a particular city. For example, the structural orientation of additional links inserted in a highway network (i.e., the changes in connectivity) was found to be more important in determining overall energy consumption of the city form than simply the addition of capacity to the network, even where that capacity was added at places of high congestion. For example, diagonal freeways added to a concentric-ring city having a rectangular-grid highway network reduced gasoline consumption significantly; much of this reduction was due to a lowering of average highway-network congestion. The structural change in the network provided new paths between origins and destinations and relieved some of the dense traffic on the old paths. Further analysis of the results of simulation runs indicated that the benefits derived from the diagonal facilities were due to their structural orientation, and not simply their large capacity increase over the original network. Tests with diagonal arterials rather than diagonal freeways provided energy savings which were almost as large as those observed using the higher-type facilities. It should be noted that there was a fairly clear indication that the introduction of diagonal freeways would encourage a spreading-out of activities in the city, which in the long run might result in an increase in energy consumption. Thus, long-term implications of network structure changes on urban development patterns need to be pursued, and actions need to be taken to avoid adverse effects where they are likely.

Experiments showed that maintaining the existing level of service on typical CBD-oriented transit networks was essential to the conservation of transportation energy. Such networks appear to skim a small but significant proportion of trips off the network during periods of peak congestion. If transit is not available to play this role, congestion appears to increase very significantly and thus energy consumption goes up accordingly.

A third general finding was that several less capital-intensive, short-term transportation system management actions seem to have significant potential for reducing energy consumption in urban transportation. Successful carpooling programs and increases in commuter parking costs were found to contribute significantly to energy conservation. Raising gasoline prices produced a much less apparent effect. While protecting an existing peak-period transit service to high-density areas was found to be essential for an energy-conservation program, a variety of other transit improvements and innovations were found to be ineffective in terms of energy savings.

A combination of transit incentives (e.g., free transit) and automobile dis-incentives (e.g., increased gasoline prices or commuter parking charges) resulted in greater reductions in energy consumption than any of those individual policies implemented separately. This suggests that significant benefits can be achieved through the selection of a well-integrated package of transportation energy actions.

A fourth result of this research which should be of significant interest to transportation planners is that total vehicle miles travelled (VMT) was shown to be a poor measure of energy consumption associated with alternative transportation and land-use development policies. The principal reason for this is that, while VMT is an important factor in determining energy consumption, congestion is also of considerable importance, and using VMT alone ignores the influence of congestion. Thus, some policies were tested which produced increases in VMT but major reductions in congestion; the net effect was a reduction in energy consumption, which would not have been indicated by the VMT measure. Changes in vehicle-miles of travel as an indicator of energy consumption may exaggerate the impact of increased gasoline prices, underestimate the impact of carpooling and increased commuter parking charges, and fail to show that certain additions to network structure can lead to more efficient travel even though trip length may increase.

A fifth, and more general, finding of this research is that large-scale and systematic testing of transportation and land-use policies, using state-of-the-art techniques, indicates a significant range of variation in energy consumption among those policies. The results of simulation studies such as these can provide useful evaluative information to guide transportation and land-use planning in the face of increasing resource constraints.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

CHAPTER ONE

INTRODUCTION

A. Goal and Objectives of the Research

The goal of this research is to answer some key policy questions regarding the relationships between land use, transportation system characteristics, travel behavior, and transportation energy consumption. Three objectives, which constitute the major contributions of this research, have been identified to attain this goal. First, a mathematical model was developed to provide the framework in which to simulate alternative proposed transportation energy conservation policies. The point of departure for this was previous work at Northwestern University by Edwards (1,2) and Bowman, et al. (3). Significant improvements were made to the models developed in these two studies in terms of realism, efficiency, and responsiveness to policy options. Second, an extensive experimental program was undertaken to explore a broad range of policy changes concerning urban growth, transportation networks, and transportation pricing. Third, the results of this experimentation were analyzed to formulate practical guidelines for the development of both national and local policies regarding transportation and land use planning. The model is a complete, self-contained package requiring a minimum of data preparation and computational time. As such, it should be a useful educational and research tool for transportation and land use planners.

B. Problem Definition

The transportation sector of the U.S. economy consumes directly 25 percent of the national energy budget, amounting to 18.3 quadrillion (10^{15}) British thermal units (Btus) in 1974 (4). The urban automobile accounts for 42 percent of this figure and this helps to explain why over one-half of domestic petroleum consumption is used for the movement of people and goods (5). This dependence has been growing during the past two decades and is due, in part, to the growing influence of the automobile on the shape of the city and on urban travel behavior. The problems caused by increased automobile ownership and automobile trips per capita have been compounded by user demands for increased levels of service, in terms of speed, comfort, convenience, and reliability. These considerations plus the urban sprawl common in most U.S. cities have resulted in a shift away from energy-efficient public transportation. In addition, the energy efficiency of the automobile itself had been decreasing until the past few years.

Short-term supply fluctuations serve to show the dependence of urban travellers on the petroleum fueled automobile. The impact of the gasoline shortages of the winter of 1973-1974 was relatively minor, however, among those households with a higher level of automobile ownership (6). The journey to work was the most resistant to change while the greatest energy savings appeared to come in linking many non-work trips together (particularly shopping trips). Increases in public transportation ridership were reserved, for the most part, to denser urban areas and to lower income groups, i.e., where transit service was already good (7). It is most disconcerting to note that public transportation ridership increases were short-lived and that gasoline consumption has surpassed 1972 levels, now that supplies are readily available again. The American public has become much less conservation conscious during the past few years, and it seems this trend will continue so long as gasoline supplies and prices remain relatively stable.

Until the development of the current federal administration's proposed energy conservation program (1977), national goals useful for guiding energy conservation decisions were not well specified. The federal approach was far from comprehensive and focused on the long term. Relying on technology to provide a solution (8), regulations concerning automobile fuel consumption, for example, have conflicted with environmental restrictions concerning engine emissions.

Many studies of the energy crisis have been generated both inside and outside government (9,10,11). The issues are so huge, however, that only a limited exploration is possible and often many of these analyses can be faulted by the simplest of economic arguments (12). To further cloud the issue is the growing federal bureaucracy in both the executive and legislative branches. For example, no fewer than 33 congressional committees (and 65 subcommittees) had some jurisdictional claim over the Energy Research and Development Administration in 1976 (13).

The absence of a comprehensive, coordinated, consistent, long-term policy on transportation energy has resulted in the lack of an overall framework for planning and analysis of transportation-oriented solutions to the energy crisis. This could make the short-term policies developed so far ineffective at best and potentially harmful, should they be leading in the wrong direction. It is quite possible, as Lindblom has suggested, that only an incremental approach can handle such a massive policy question (14). In any event, it seems necessary to develop analytical techniques to project more of the consequences of some of the policy actions currently contemplated.

Two critical determinants of transportation energy consumption, the number of trips taken and the length of those trips, are closely associated with the spatial structure of cities, including the shape, density patterns, and the arrangement of land uses. Several studies in the past decade have shown that some urban forms require less transportation, and hence consume less energy, than others (15,16). This research will continue where these studies have left off by developing a simulation model that is broadly sensitive to many energy policy variables. It will be possible to perform many experiments to determine how transportation energy changes as policy parameters are altered.

If policies can be identified that will result in urban growth and transportation systems usage patterns which consume less energy, they might serve as the basis for establishing more responsive guidelines for future urban development. This might be accomplished at the macroscopic level through the proper allocation of federal resources for urban development and redevelopment and the establishment of new towns. At the regional level, such guidelines might be introduced in land use planning and the implementation of new regional transportation services. Finally, at the microscopic level, an appropriate understanding of land use/transportation energy relationships might support the design of more efficient urban and suburban communities, providing guidelines to short-term zoning decisions as well as longer-term land use planning.

C. Approach of this Research

A broadly sensitive transportation energy simulation model was developed in order to test a wide range of alternative transportation network and pricing and urban growth policies. In order to insure a realistic simulation which is sensitive to transportation energy consumption, a causal structure is incorporated in the model which captures a strong relationship between transportation and land use through an equilibration process. A conceptual model of the simulation approach used is shown in Figure 1-1. The solid flow lines represent the computations performed in Edwards' model. Here the demographic characteristics of the population, zoning ordinances, and descriptors of urban travel behavior interact with the transportation network to create a land use pattern as defined by the distribution of population and employment. Gravity models are used to distribute trips which are assigned to the transportation network. The energy consumption of each vehicle on each link of the network is then summed to compute the total energy required for transportation. The broken flow lines depict a feedback which occurs as the costs of travel, partially determined by fuel consumption, modify the land use pattern by influencing travel behavior, particularly mode choice (which was exogenously specified in Edwards' model) and route selection. This feedback process was defined by Bowman, et al., in terms of a static equilibrium. This research operationalized this process in terms of future policies being implemented in an environment of urban growth.

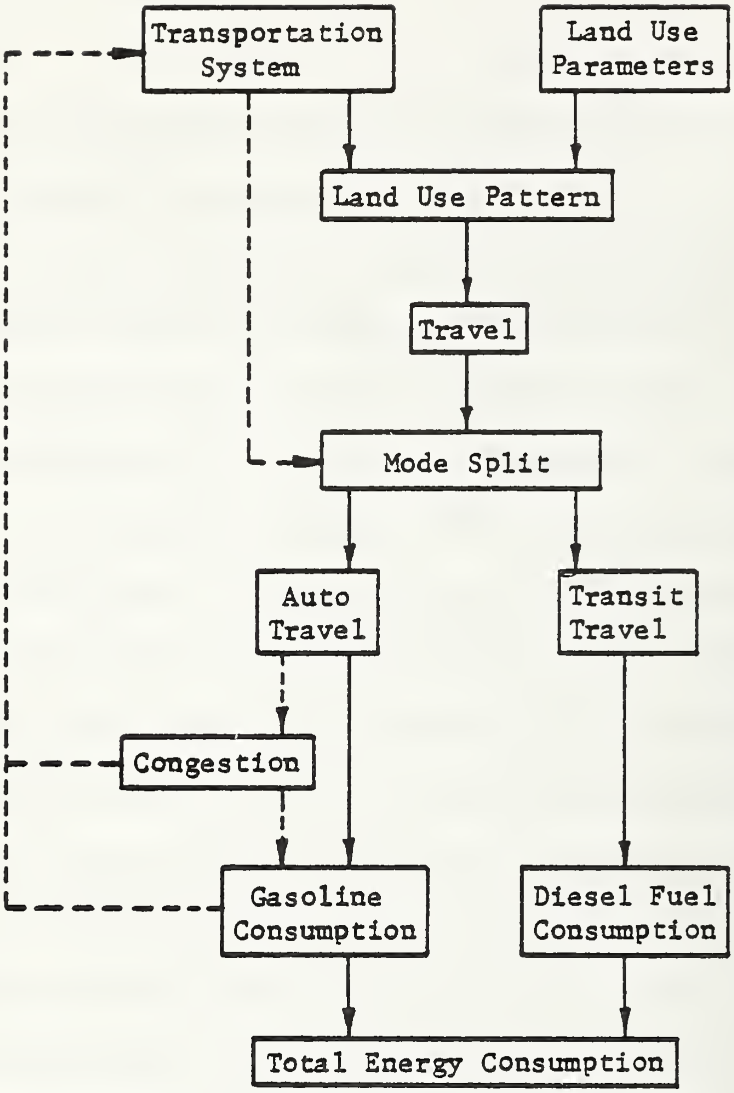


Figure 1-1. Conceptual Model of Transportation Energy Consumption

An experimental program was undertaken which first identified most promising policies from the large number currently being contemplated. These policies were then explored further to determine how and why they are so effective in reducing transportation energy consumption.

D. Remainder of this Report

A brief discussion of the early development of this line of research, particularly the work by Edwards and Bowman, et al., follows in Chapter Two. Included here is some of the motivation for improving the theory, structure, operation, and application of the simulation model. Chapter Three is a description of the simulation model developed for this research. Particular attention is paid to features of the model which affect the experimentation and the analysis of the results. Some important considerations regarding the interpretation of the model results are presented in Chapter Four. Due to some limitations in the model design, it is shown that an intuitive assessment of the experimental results becomes a crucial part of the analysis. Chapter Five discusses the experimental program and the results. Chapter Six concludes with an interpretation of the experimental results and the development of guidelines for transportation and land use energy policy.

The appendices of this report include a user's manual of the simulation model (including complete documentation), a listing of the FORTRAN program, a description of the experiments conducted, and a summary of the results of each of the experiments.

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CHAPTER TWO

DEVELOPMENT OF AN ENERGY POLICY EVALUATION MODEL

A. Objective and Overview

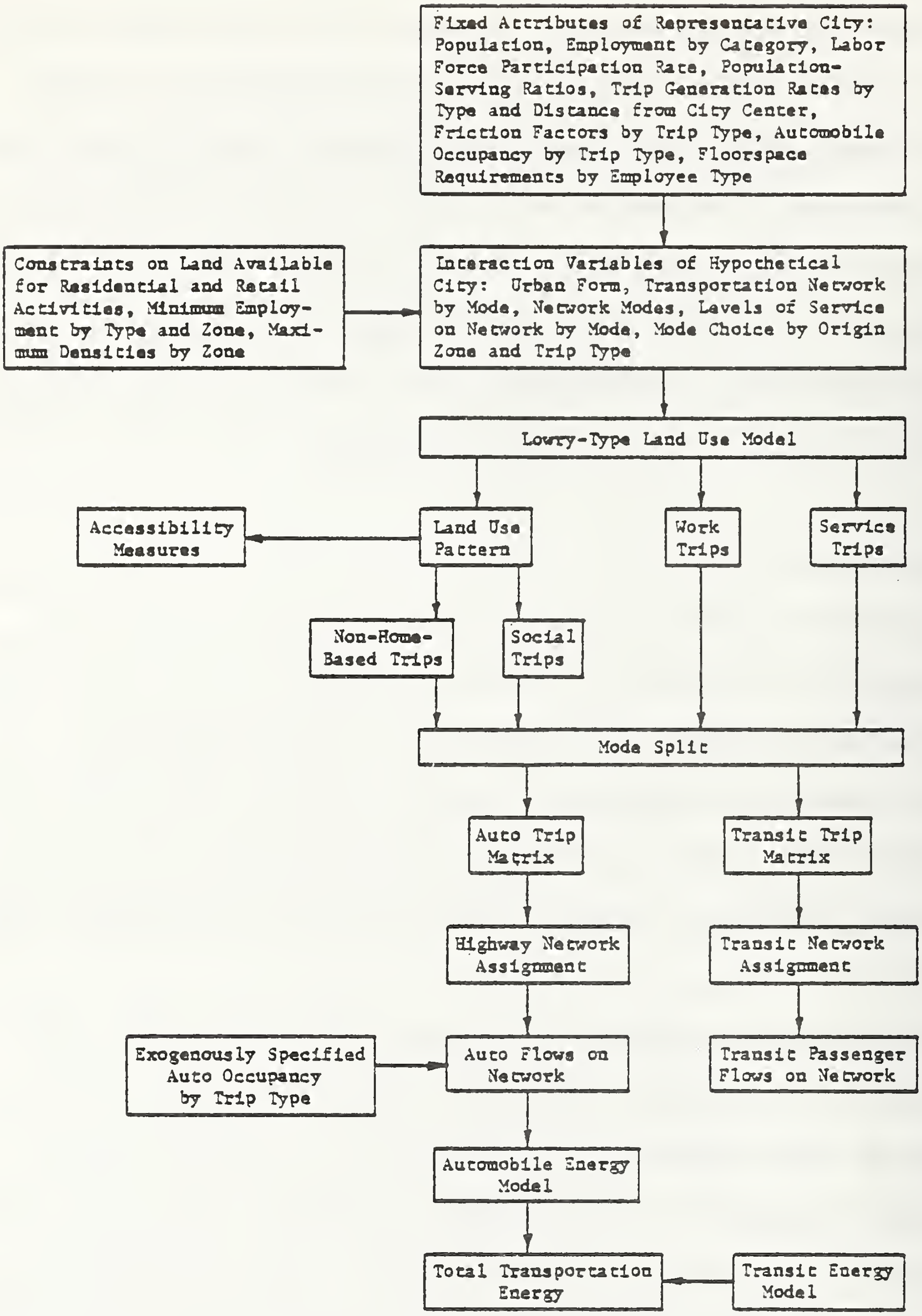
The objective of this chapter is to present a summary of relevant contemporary research sufficient to provide the motivation for the improvements to be made to the simulation model developed by Bowman, et al. (1). Since it is policy evaluation and not the development of new models that is most important in this research, it will be shown that the research objectives can be attained by extending the earlier simulation approach. Rather than a complete search of the literature of urban development, travel demand, and transportation system models, this discussion will summarize the immediate predecessors of this research, identifying those deficiencies which require modification. This is followed by a description of other related models which can provide additional direction for the development of the model to be used in this research.

It must be noted that while this study builds on the earlier work of Edwards (2) and Bowman, et al., the research objectives are different. Edwards constructed what amounts to the core of the simulation approach for the purpose of investigating the relationships between transportation energy use and urban form. Bowman, et al., extended this to include a more well-developed linkage between transportation and land use. While their intent was to apply the model for policy analysis, their principal contribution was providing major advancement in the theory and, to a lesser extent, validating the model structure. The next sections explore these two studies in terms of their objectives, methodology, findings, and limitations, pointing out those assumptions and simplifications which must be eliminated. The discussion of other contemporary research is oriented toward justifying some of the characteristics in the model developed by Bowman, et al., and some of the modifications to be made to it. The chapter concludes with a specification of new capabilities and characteristics that should be built into the revised model.

B. Edwards' Model

The objective of Edwards' research was to define the relationship between urban form (as defined by shape, distribution of land uses, and the transportation network) and transportation energy consumption. By simulating different arrangements of typical concentric ring cities and more radical polynucleated and linear urban forms, Edwards was able to isolate those forms which were most energy-efficient yet maintained high accessibility.

Figure 2-1 presents the overall structure of Edwards' model. The initial step is the specification of the fundamental attributes of the test city and their conversion to a land use plan. These attributes include total population, total employment by category, the labor force participation rate, and a description of travel behavior including an exogenous specification of modal shares, trip length distributions (a reflection of the preference for shorter trips), and automobile occupancy by trip type. Detailed land use patterns are then constructed, using a Lowry-type land use model (3) which applies the given attributes to a set



Source: Jerry L. Edwards, Relationships Between Transportation Energy Consumption and Urban Spatial Structure, unpublished Ph.D. dissertation, Department of Civil Engineering, Northwestern University, June 1975.

Figure 2-1. Operation of Edwards' Model

of interaction variables specified in each experiment. These variables include the urban form as defined by the arrangement of zones and the transportation network connecting these zones, including the specification of levels of service on the network (as defined by the average operating speed per link for automobiles and headways and travel times for transit service).

The Lowry-type model allocates commercial and residential land uses based on the exogenously specified distribution of basic employment and the free-flow travel times between all zone pairs subject to a set of constraints regarding the land available for development, minimum commercial development allowed per zone, and maximum residential densities. Trips from work-to-home and from home-to-service site are generated simultaneously with the Lowry-type land use allocation process. Non-home-based and social trips are distributed subsequently outside of the Lowry-type model, based on the land use pattern.

Edwards' simulation study showed that the energy intensities associated with a particular urban form increased with:

- the expansiveness. or land area covered;
- the spread of population and employment, as measured by the second moments of their spatial distributions;
- the level of congestion on the transportation network; and
- the predominance of the automobile as the mode of travel.

In addition, Edwards showed that energy intensity increased with increased accessibility, a reflection of the fact that accessibility improves as the dependence on the automobile and level of service on the highway network increases. This represents an important conflict since it is apparent that high levels of accessibility are preferred by urban dwellers. For example, it was found that the polynucleated urban forms tested were somewhat more energy-efficient than spread cities, but their regional accessibility characteristics were not as attractive.

Edwards' work was an excellent first step toward developing an integrated energy policy simulation package. The selection of the Lowry-type land use model as the heart of the simulation system resulted in minimal data requirements and a strong, intuitive causal structure permitting the inclusion of many modifications. There were many assumptions and simplifications in the model which reduced its policy sensitivity and realism, however. The exogenously specified modal shares, for example, limited the influence of the contrast between the levels of service on the highway and transit networks, particularly as they are affected by energy policies. More significant than this was the need to consider explicitly the effect of congestion on the highway network. Since vehicle speed is an important determinant of fuel consumption, it would seem that traffic congestion and estimated highway levels of service would be important factors in further study of the relationship between urban form and energy consumption.

C. Improvements by Bowman, et al.

In an attempt to apply Edwards' modelling framework for policy evaluation, Bowman, et al., made many improvements regarding the relationship between transportation and land use. The revised model was named MOD2. The most important improvement was that of defining a relationship between interzonal transportation and the land use allocation process which explicitly considers the effect of energy costs of travel. This is illustrated conceptually in Figure 2-2. Briefly, the feedback from transportation to land use (shown by the broken flow lines) is achieved by iterating through the land use allocation many times, guiding each successive iteration by the relative interzonal accessibilities for work trips, based on travel time, in the previous iteration. Congestion effects are considered by assigning the distribution of automobile trips between employment sites and places of residence using a capacity-restrained equilibrium assignment algorithm. Within each iteration the split between automobile and transit is recomputed, based on the most recently computed highway travel times and the transit free-flow times. The transit minimum time path algorithm is modified from Edwards' original version. A more realistic treatment of transit, it allows for an unlimited number of routes to pass through each zone, overlapping of routes, and walking to zones with transit service from zones not so served.

A limited experimental program with MOD2 provided some interesting results for guiding further research. Travel behavior variables were found to be more influential in determining transportation energy consumption than many land use variations. It was noted that unless urban growth policies can be identified that result in large enough reductions in transportation energy to be socially and politically attractive, the trend may be for travellers to respond to higher energy costs by altering their behavior (in terms of trip frequency, trip length, and energy-efficiency of the vehicle driven) rather than submitting to new growth policies. Since alternative urban growth policies may achieve shorter trips by forcing households to locate closer to employment and services,

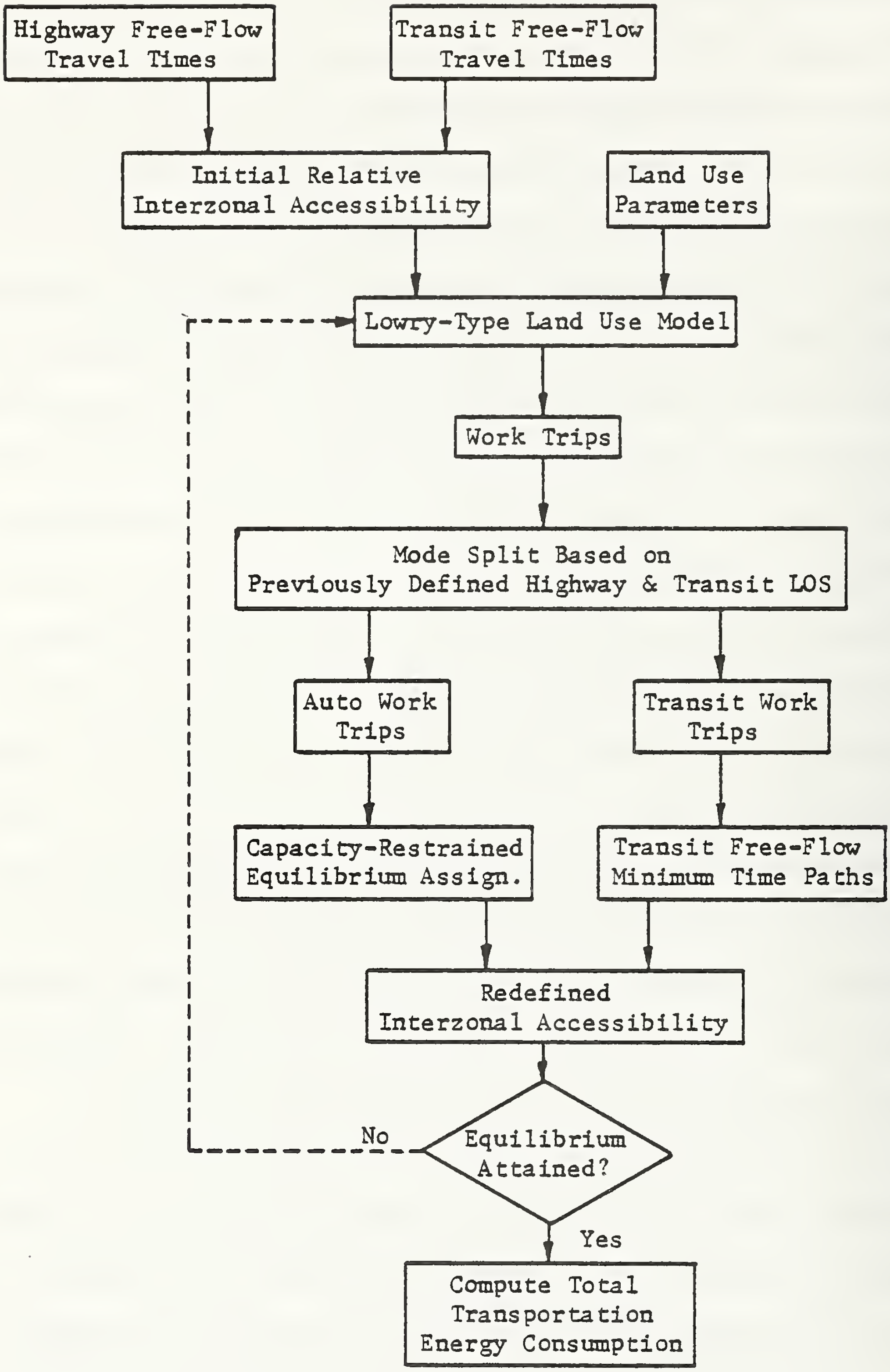


Figure 2-2. Operation of Energy Simulation Model Revised by Bowman et al.

further investigation of such policy actions is indicated.

Bowman, et al., noted that the impedance to travel function should be redefined to include not only travel time but also out-of-pocket travel costs, particularly gasoline costs. The use of such a generalized cost approach should make the model more broadly sensitive to policy changes. They also noted that while fringe growth or low density development alone did not necessarily result in increased energy-intensiveness, a failure to shape growth could result in higher energy consumption and reduced accessibility, due primarily to longer trip length if the urban form is heavily reliant on the central business district.

The development of a generalized cost approach would be in itself a major contribution toward a more realistic policy evaluation model. More important than this, however, is the need for a more realistic methodology toward simulating urban growth. The allocation of population and service employment in the Lowry-type model is intended to be a long-term equilibrium, based on the assumption that the urban area has developed exclusively under the conditions initially specified, using the initial distribution of basic employment as the "seed" for growth. The transportation/land use feedback described above assumes a static equilibrium condition. Such a process is not entirely realistic, however, since the current state of the city is the result of the continuous location of new basic employment, new services, and new residences; changing land use patterns and densities; an expanding transportation network; and changing travel behavior. This is not so much a problem in attempting to replicate the current state of a city since the model inputs could be altered to "force" the city into a desired form. However, in the context of this research, in which the impacts of various future policy actions are to be ascertained, it is imperative that the model be structure recognizing that the current state of the city is the point of departure and that it is the growth from that time forward which will be influenced by policy change.

Bowman, et al., handled urban growth in what can be termed a naive approach. Recalling that the Lowry-type model effectively "grows" a city upon the transportation network using unaltered initial conditions to guide the development, the naive approach simulates growth by simply starting out with a larger set of basic employment (resulting in a larger population) and altering initial data parameters to simulate the new policy change(s). While the intent of such an approach is to simulate the future change in the state of the city caused by the altered policies, the model would actually simulate a city assuming the growth had always been guided by the new conditions. It would not allow the allocation of the current population and employment to remain fixed, but would force an equilibrium based solely on the new conditions. The fundamental problem with this approach is that it is unrealistic to assume that every time there is a change in the size and location of basic employment, the entire set of population and services would readjust to create a new equilibrium. Indeed, the city is never really in a state of fixed equilibrium, but is in a constantly changing, dynamic condition.

The question now becomes one of deciding whether the approach to be used to simulate urban growth should be an outgrowth of the framework developed by Edwards and Bowman, et al., or be based on some alternative approach, perhaps used in related research by others.

D. Other Contemporary Research

The use of MOD2 as a starting point in the development of the simulation model would allow for a more efficient attainment of the research objectives if its use can be justified. In this discussion, several relevant contemporary research efforts are examined in order to justify the continued use of some MOD2 components and to identify other desirable characteristics for the simulation model for this research not previously considered.

Since the land use model is the heart of MOD2, the discussion of contemporary models concentrate on this point. The Lowry-type land use model was used by Edwards and Bowman, et al., primarily because of its transparent causal structure, which allows for simple modification and construction of important linkages between submodels, and because of its success in real world applications. Goldner (4) reports on the use of the Lowry model and its derivatives for both urban and regional development planning and for impact studies of major facilities (airports) in urban areas. With regard to integrated urban development/transportation system modelling efforts, there are three relevant studies that use the Lowry-type model.

One application of the Lowry-type model is by the North Central Texas Council of Governments (5,6) to evaluate alternative transportation plans ranging from investment in an all-transit system to investment in highway improvements only. Currently under study is the use of the Lowry-based Urban Growth Simulation Model (USGM) (7) to determine transportation impacts on public service utilities, social equity, environmental considerations, and energy. USGM allocates population in a manner similar to

MOD2 except it uses two entropy maximizing models rather than gravity models. There are three important similarities with MOD2. The computation of modal shares is internalized, a function of the relative levels of service on the highway and transit networks. The assignment of automobile trips explicitly considers the differences between peak and off-peak highway level of service. Finally, USGM explicitly considers energy costs in travel decisions.

There are other important features in USGM not found in MOD2 that could be included in the modified version. The first is the consideration of generalized costs of travel by automobile and transit for trip distribution. In MOD2 trip distribution and traffic assignment are based solely on travel time. Out-of-pocket costs only come into play in the computation of mode split. The model to be used in this research could be much more correctly policy sensitive if out-of-pocket costs were considered in the land use allocation process. A second important feature of USGM is the explicit consideration of the differences between peak and off-peak transit level of service. While this would certainly allow for a more realistic simulation, it is likely that the additional model development required would not be worthwhile, especially in light of the limitations in the current transit minimum time path algorithm. Without the specific computation of the effect of transit vehicles on highway flow or congestion on transit level of service, it would not be wise to develop the transit supply-side of the model much further. The third feature of USGM is that it estimates truck and taxi vehicle-miles travelled based on the land use allocation. These trips will not be built into the simulation mode used in this research primarily because they are outside the MOD2 framework.

A study by Brookhaven National Laboratory and the State University of New York at Stonybrook used a Lowry-based model to examine the impacts on energy consumption of decentralized industrial employment given a dispersed pattern of regional development (8,9). In addition to transportation, their model also considers the commercial, industrial, and residential consumers of energy. While such a broad analysis would certainly be desirable in this research, it would require extensive revision of the model and thus be beyond the scope of this research. Further, the disaggregate computations used in the Brookhaven/Stonybrook model, needed to accurately model the housing market, would greatly increase the data requirements and computational time. Although the Brookhaven/Stonybrook model does consider a more comprehensive view of energy consumption, it does not handle the transportation sector in as sophisticated a manner as MOD2. The feedback between transportation and land use to be used in this research is not defined. Automobile trips are assigned to the highway network solely on the basis of minimum time paths, ignoring the energy costs of travel.

A third relevant application of the Lowry-type urban development model was by Echenique (10) for use in regional planning in Santiago, Chile, and Caracas, Venezuela. The most important aspect of this modelling effect was that it applied a static equilibrium activity allocation model in a dynamic regional forecasting context. The modelling process involved two stages. First, a dynamic regional model forecasts the location of additional basic employment for a future time interval, based on regional economic parameters. A Lowry-type model then generates the land use pattern that results. While it would be beyond the scope of this research to develop a basic employment forecasting model, the Echenique model does provide some important directions toward simulating the implementation of future policy changes in a more realistic framework than that used by Bowman, et al. This is particularly true since Echenique explicitly considers the feedback from transportation to land use in a manner very similar to that used by Bowman, et al. He also considers the generalized costs of travel in the land use allocation process.

Putman (11) developed another simulation framework to investigate the evolution of a transportation network in an urban setting, particularly the congestion that follows the construction of new transportation facilities. The Projective Land Use Model (PLUM) (12), a Lowry derivative, is used as the heart of the simulation process. In a manner similar to Echenique, basic employment forecasts are provided by a regional economic model (13). The most important feature of this approach is that the feedback from transportation to land use is accomplished in an incremental manner in the context of urban growth, resulting in the continuous alteration of the land use pattern caused by exogenously specified changes in the transportation network. This is a major step toward developing a realistic policy simulation framework for the revised version of MOD2.

These three studies provide most of the guidance for refining the simulation models developed by Bowman, et al. There are many other urban development models discussed in the literature, but few simulate the city at the same scale or degree of detail as the ones discussed above. Some of these other models greatly simplify the urban activity allocation process, achieving reductions in the size of the data set and computational time. The model developed by Dajani and Reinhardt (14) is an example of this. Interzonal accessibility is computed by an algorithm which requires the land use pattern to be a square matrix of zones. This model is in an early stage of development and contains many simplifications which would restrict the types of policy actions that could be simulated if applied to this research.

At the other extreme is the dynamic urban activity model developed by Crecine (15). His Time Oriented Metropolitan Model (TOMM) is Lowry-based but requires a disaggregate consideration of housing types in order to model the housing market accurately. This includes allowing land uses to relocate over time. Although this would be a desirable characteristic for the revised model to be used in this research since it would greatly increase the realism of the simulation, it requires a large amount of data and exceedingly long computational time. Such an approach is therefore not well-suited for this research.

E. Summary of Additional Capabilities of the Revised Simulation Model

The previous discussion shows that the continued use of the key elements of MOD2, i.e., the Lowry-type model base and the feedback between transportation and land use, is justified since they have been used successfully by other researchers. Some additional desirable features were shown to require excessive model development and data preparation. These included internalizing the location of future basic employment and the dynamic simulation of urban activity allocation. Other desirable features were shown to be more easily attainable and, therefore, fall within the realm of this research. This includes the incorporation of the generalized costs of travel and modelling urban growth through an incremental process using static equilibrium techniques. These two features form the heart of the theory, structure, and application of the revised simulation model described in the next chapter.

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CHAPTER THREE

THE MODEL

A. Introduction and Overview

The objective of this chapter is to present the theory and operation of the analytical tool developed for this research in sufficient detail to facilitate the interpretation of the experimental results in Chapter Five. Rather than discuss all of the basic theory in each of the algorithms used in the model, the intent is to highlight only the more important features of the simulation framework. The discussion is oriented more toward explaining why various computations are made, leaving the interested reader the option of further exploring the theoretical development of these procedures by referring to the original research papers. A detailed documentation of the model structure, theory, data requirements, output reports, and operational characteristics is found in Appendix A.

The analytical tool, which is hereafter referred to as MOD3, is a large-scale computer model which simulates the spatial development of a city, the passenger travel that takes place in that city during a single day, and the energy consumption resulting from that travel. It is based upon the modelling structure and algorithms first developed by Edwards (1) and later extended by Bowman, et al. (2). Since the most important interest in this research is policy analysis, primary model development has been kept to a minimum. It was felt that the most efficient manner in which to attain the research goals, as outlined in Chapter One, was to build around a proven analytical tool, adding those modifications necessary to achieve the following three objectives:

- estimate intraurban passenger travel as realistically as possible;
- explore a broad range of alternative policy actions;
- accomplish the above objectives efficiently.

The next section is a discussion of the important conceptual issues in the operation of MOD3. This is followed by a more detailed description of the more important algorithms and the overall operation of the model. The many output reports are then briefly summarized. The final section is a short discussion of the application of MOD3 in this study.

B. Important Conceptual Issues

There are three major factors influencing the amount of automobile gasoline consumption for travel on the highway network from any zone i to zone j:

- the length of the trip
- the energy efficiency of the trip, largely a function of speed, given a technology
- the number of trips

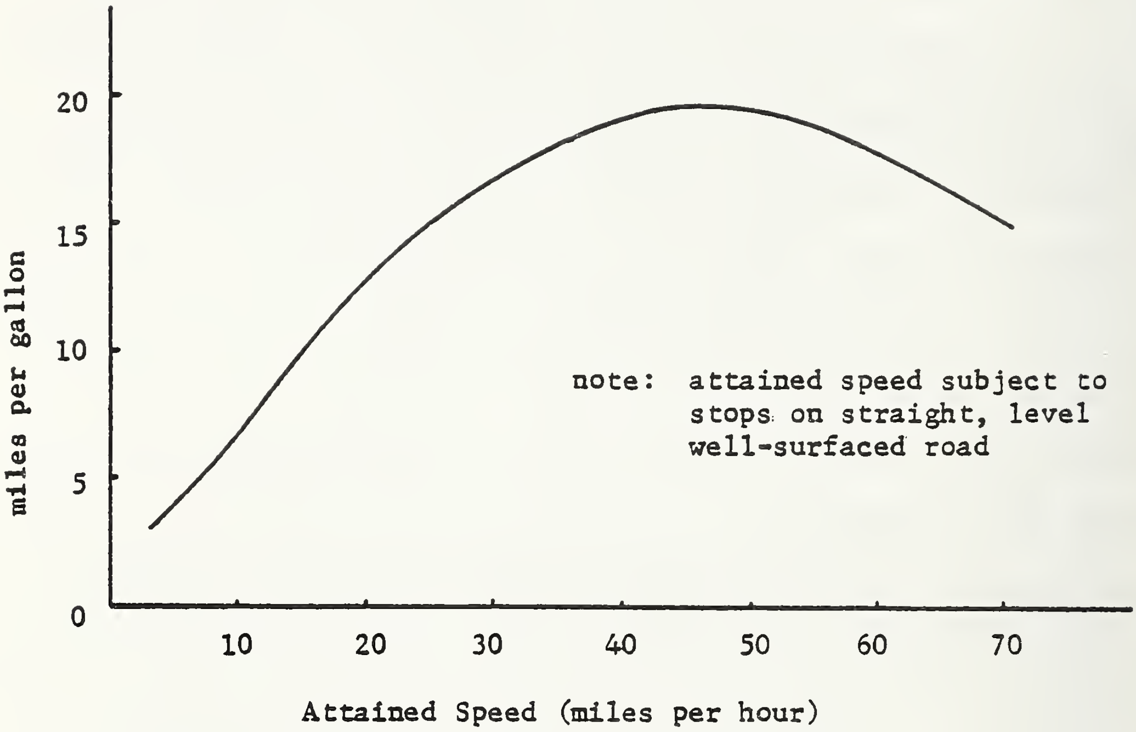
Each of these factors is important in structuring the feedback between transportation and land use that is hypothesized in this research.

Trip lengths are affected by the network structure and level of service, through the determination of minimum cost paths. These paths, in turn, are influenced by the land use pattern since higher densities of development result in higher link volumes causing slower travel speeds and higher energy costs.

The fuel consumption for travel between two zones is determined by summing, for each link on the minimum cost path, the aggregate fuel consumption for all vehicles, a function of the speed on that link. Gasoline consumption for automobiles is a function of speed for the average vehicle in the automobile fleet. This relationship, based on the research by Claffey (3), represents gasoline consumption corrected to account for the effect of congestion (especially the number of stops per mile) for the typical automobile distribution in 1969: 20 percent large luxury, 65 percent standard, 10 percent compact, and 5 percent subcompact. As shown in Figure 3-1, the most efficient speed range is between 40 and 45 miles per hour. Thus free-flow arterial streets experience the least fuel consumption per mile while congested (slower) arterials and high speed freeways have higher fuel consumption.

Transit fuel consumption is based on data collected by the Chicago Transit Authority (4,5) for diesel-fueled buses. This relationship is shown in Figure 3-2. Three data points represent average consumption at average running speeds for downtown, suburban, and express freeway service. The influence of bus age, number of stops per mile, time of year, and number of passengers is ignored due to a lack of data. A data point at 1 mile per hour comes from Claffey's research on diesel-powered vehicle idling and acceleration.

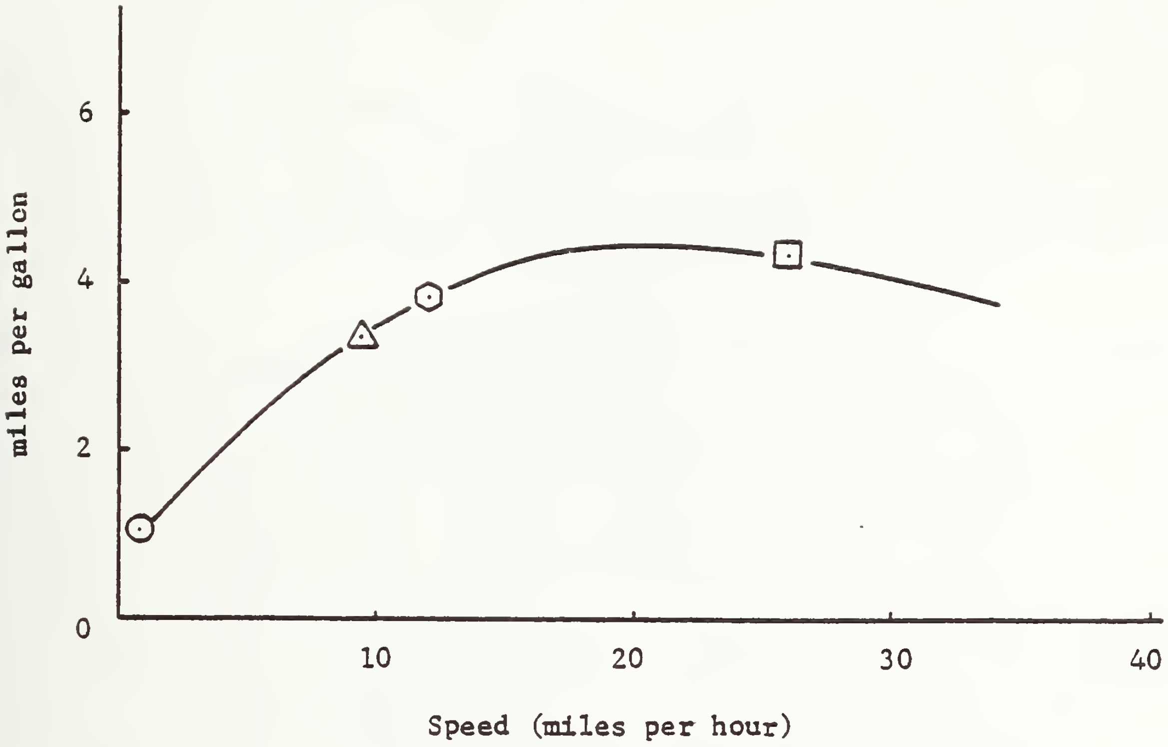
The number of trips between any zone pair is governed by two principal factors. First, the allocation of land uses determines the total number of interactions between the zones. Most trips occur where the land development is most intense. Once the total number of interchanges between a zone pair is determined, the only other factor that can affect



note: attained speed subject to stops on straight, level well-surfaced road

Source: Paul J. Claffey, Running Costs of Motor Vehicles as Affected by Road Design and Traffic, National Cooperative Highway Research Program Report No. 111, Highway Research Board, Washington, D.C., 1971.

Figure 3-1. Automobile Gasoline Consumption



⊙ Data point based on consumption for a diesel semi-tractor trailer idling for 50 minutes and accelerating 20 times for 10 minutes

△ Data point based on consumption of 289 diesel-powered buses of various makes and ages operating on downtown routes

⬡ Data point based on consumption of 29 diesel-powered buses, mostly air conditioned, of various makes and ages operating on semi-suburban routes

⊡ Data point based on consumption of 5 six-year old air conditioned buses operating primarily on express freeway routes

Source: Martin J. Bernard III, Environmental Aspects of a Large Transit Operation, Regional Transportation Authority (of northeastern Illinois) Technical Report No. TR-75-01, November 1975.

Figure 3-2. Transit Diesel Fuel Consumption the number of automobile trips is the split between automobile and transit. A submodel which compares the level of service between the two modes computes this. It should be noted that the land use submodel assumes one worker per household and that the trip generation rates for non-work trips and average automobile occupancy for each trip type are exogenously specified.

With the three important factors affecting energy consumption thus defined, it is possible to structure an algorithm which incorporates the feedback from transportation to land use while explicitly considering energy costs. Such an algorithm is shown in Figure 3-3. This algorithm, originally applied by Bowman, et al., begins with an initial estimate of the interzonal accessibilities, based on free-flow travel costs, and generates the land use pattern and the associated work trip origin-destination matrix. Modal shares are computed based on free-flow travel times and dollar costs of travel and the automobile trips are assigned to the highway network using a capacity-restrained equilibrium assignment algorithm which explicitly considers congestion. Based on the new automobile travel times and energy costs, and the free-flow transit costs, a revised computation of the interzonal accessibilities is made. This is then applied to the land use model which recomputes the allocation of population and employment and the work trips. Modal shares are computed based on the congested highway travel costs and transit travel costs (which are assumed to be unaffected by congestion). The cycle continues until the differences between the interzonal accessibility for each zone pair between iterations become small (i.e., converge). It is at this point that an equilibrium between transportation and land use is achieved.

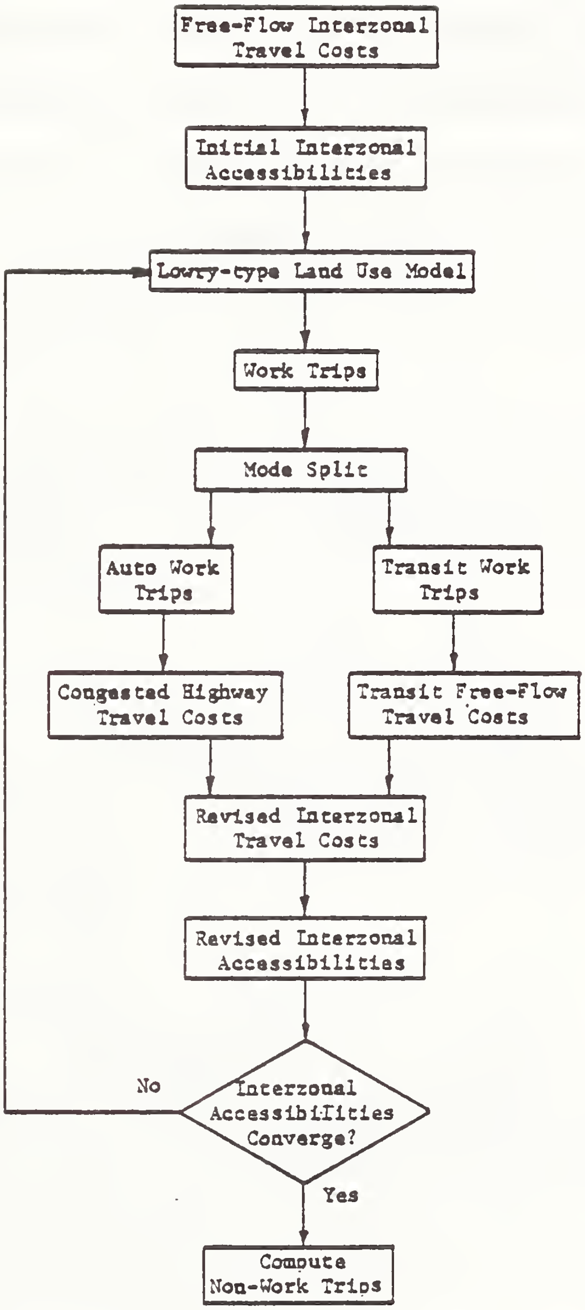


Figure 3-3. Transportation/Land Use Feedback

In the simulation it is necessary to accommodate the notion that energy policies would be implemented in existing cities and that their effects would largely influence future growth. The urban development simulation process developed for this research reflects this consideration. In it sequential, incremental, static "layers" of land use are generated and combined to model the continuous dynamic process of urban growth. This procedure is shown diagrammatically in Figure 3-4. While the number

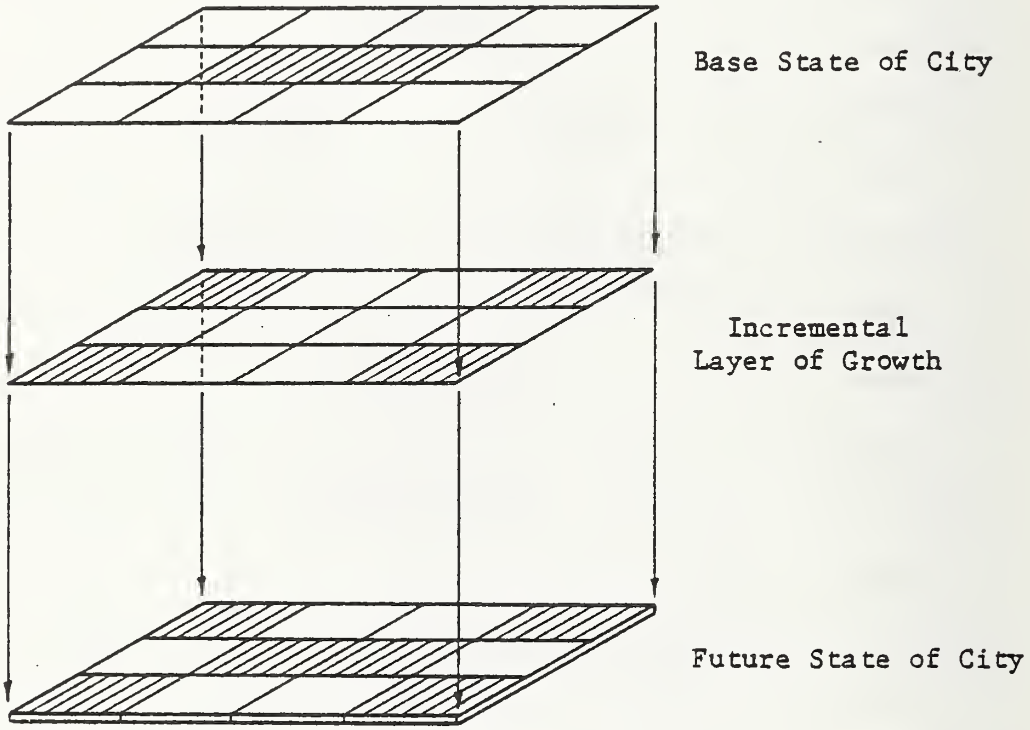


Figure 3-4. The "Layering" Approach to Urban Growth

of "layers" of growth could be quite large, in this research only two are simulated: a present or base layer representing the city as it currently exists and an incremental growth layer representing the distribution of additional population and employment and the resulting travel during the period when new policies are in effect. This process is used to structure the experimental program for policy testing. As shown in Figure 3-5, the experimental process begins with a base run or layer of the city simulated. It is possible to force the model to replicate some real city in this run or, as is done in this research, model parameters could be chosen so that representative hypothetical cities are simulated. With this as a base to work from, future urban growth is instituted by running the model with an additional set of basic employment, thus simulating a new layer of population and employment.

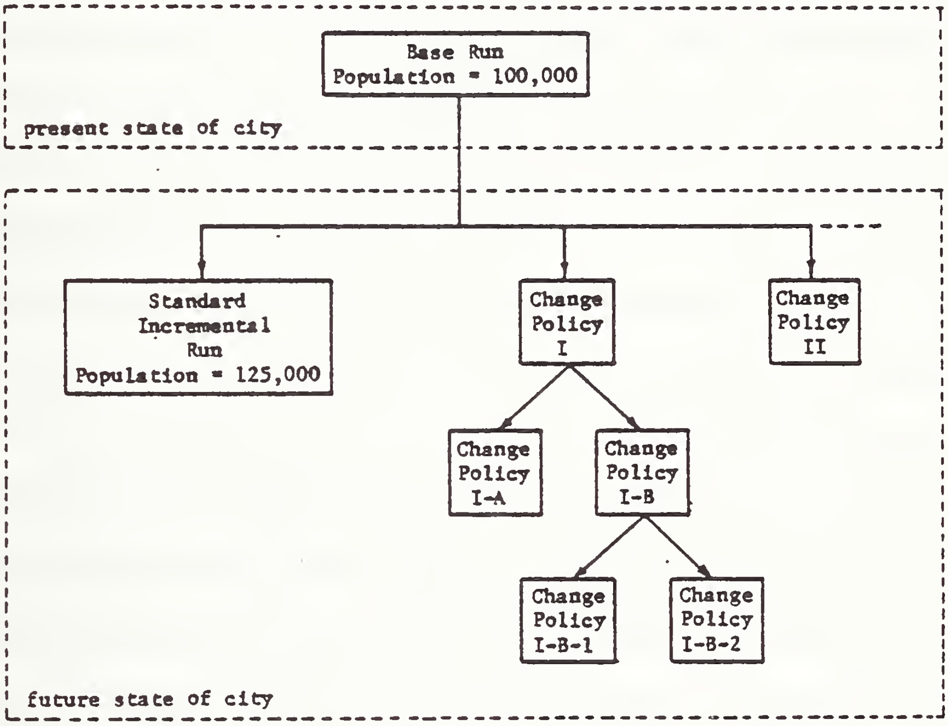


Figure 3-5. Experimental Process

The experimental program is primarily concerned with this second, or incremental, mode of MOD3 operation. First, an incremental run is made to represent some future state of the city in which all policy parameters remain unchanged from the base run, i.e., the do-nothing condition. This is termed the standard incremental run. Next, a series of experiments is undertaken in which individual parameters are altered to simulate policy changes. In those cases where a particular change seems promising, additional experiments are conducted to further explore this type of change. Such a "policy excursion" is shown extending from the initial experiment on Policy I in Figure 3-5. Much of the analysis consists of comparisons between the standard incremental run and individual policy runs or between pairs of policy runs.

A final important feature of MOD3 is the explicit consideration of the generalized costs of travel. While out-of-pocket costs are considered, in addition to travel time, in the computation of interzonal modal shares in the work by Bowman, et al., it is important that trip distribution, land use allocation, and traffic assignment take into consideration all of the costs of travel in order to model transportation energy consumption more correctly. Generalized costs of travel are considered in MOD3 for these reasons and to make the simulation generally more realistically responsive to policy changes.

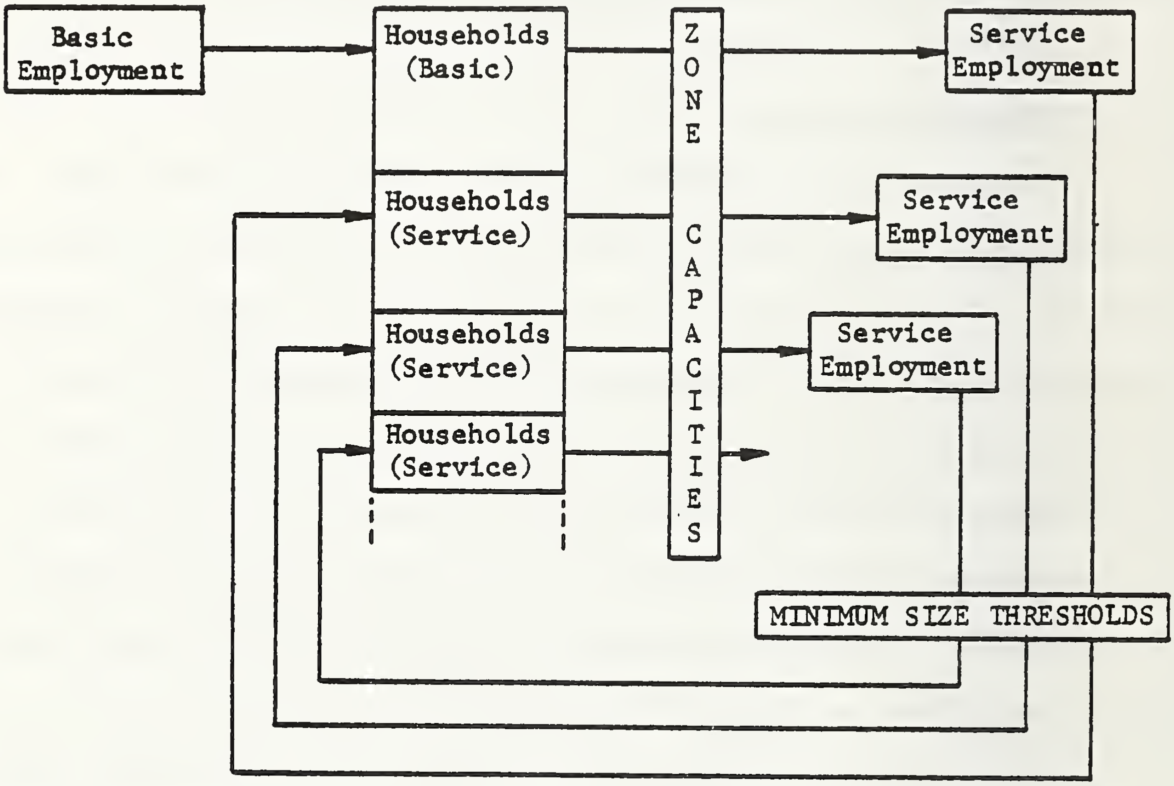
C. Details of MOD3 Structure and Operation

The most relevant conceptual details in the structure and operation of MOD3 are presented in this section. No attempt is made to explain all of the theoretical development of the algorithms used, however. The reader is referred to the earlier works by Edwards and Bowman, et al., as well as the original research papers cited below for this information. The purpose of this section is simply to provide enough background to allow for an intelligent analysis and interpretation of the experimental results in Chapter Five. A discussion of the limitations in the model structure and application is found in Chapter Four. Most of the model details appear in the program documentation in Appendix A.

1. The Land Use Model

The allocation of land uses and the distribution of work and service trips (in the base run) are achieved using a Lowry-type land use model (6). This is a static equilibrium model with relatively small data requirements and a simple causal structure. Beginning with an exogenously defined distribution of basic (usually manufacturing and other land-intensive) employment located on the transportation network, the Lowry-type model allocates urban activities (service employment and population), subject to a pre-specified set of constraints on available land, acceptable residential densities, and minimum sizes of employment centers.

Figure 3-6 illustrates the causal structure of the Lowry-type model and demonstrates the cyclical nature of the activity allocation process. It begins by allocating the basic employees in each zone to residences based on the relative accessibilicy (to be defined below) to all other zones. The population associated with these residences is found by applying the inverse of the labor force participation rate. This population demands services and the Lowry-type model allocates service workers to the surrounding zones, again based on the relative accessibility to all zones, and the size of the client population and the population-serving ratio for services. Employees at these service sites are then allocated to residences and the associated population, in turn, demands more service workers who are then allocated. This cycle continues, with smaller additional amounts of population and service employment being allocated to each iteration until they approach zero.



Source: William Goldner, "The Lowry Model Heritage," Journal of the American Institute of Planners, Vol. 37, No. 2, March 1971.

Figure 3-6. Causal Structure of Lowry-Type Land Use Model

Originally solved as a series of simultaneous equations in an iterative manner, Garin (7) has modified the Lowry model computation to allow the cyclic allocation process to be solved in a single matrix manipulation. Batty (8) devised an algorithm to incorporate this more efficient computation with the constraint set. A thorough discussion of this modelling framework is found in Edwards (9).

The process which allocates population and service employment (and in so doing distributes work to home and home to service trips) is based on the determination of the relative accessibility from each zone to all other zones in the city. The accessibility from zone i to zone j for trip k is defined by a gravity model of the form:

$$a_{ij}^{k} = \frac{U_j \, G_j^k \, f_{ij}^k}{\sum\limits_{j} U_j \, G_j^k \, f_{ij}^k} \; r^k \qquad (3\text{-}1)$$

where

U_j = a balance factor in the iterative structure of the Batty version of the Lowry model, used to prevent over-allocation of workers to residences in zone j.

G_j^k = the exogenously specified utility or locational attraction of zone j for receiving population (for work trips) or service workers (for service trips).

f_{ij}^k = the interzonal friction factor, a relative measure of the impedance to travel from zone i to zone j for trip type k, a function of the travel time and the dollar cost of travel (including gasoline costs for automobile trips).

r^k = the trip generation rate per household for trip type k, assumed equal to 1.0 for work trips and exogenously specified for service trips.

The denominator in equation 3-1 is the interzonal accessibility from zone i to all zones j. Thus, a_{ij} can be interpreted as the probability of interaction between zone i and zone j for the purpose of travel between work and home or between home and service site. It must be noted that this computation actually defines only half of the travel for a single day. It is necessary to multiply the number of trips for each zone interchange by 2 in order to simulate both trips from work to home and home to work and trips from home to service site and service site to home.

2. Transportation/Land Use Feedback

The value of the interzonal friction factor, f_{ij}, in equation 3-1 is the heart of the feedback between transportation and land use. An equilibrium can be achieved if the friction factor value reflects the impact of congestion on the highway network. Since this depends on the arrangement of land uses, which are allocated based on relative accessibility, the iterative computation of land use in Figure 3-7 is used. A further description of the components of this process is presented in this subsection.

a. Generalized Costs of Travel

It is hypothesized that the cost of gasoline for automobile travel, as well as other out-of-pocket costs, has a role in determining the perceived impedance to travel. The dollar cost of travel is combined with travel time in the following linear function to compute the generalized cost of travel:

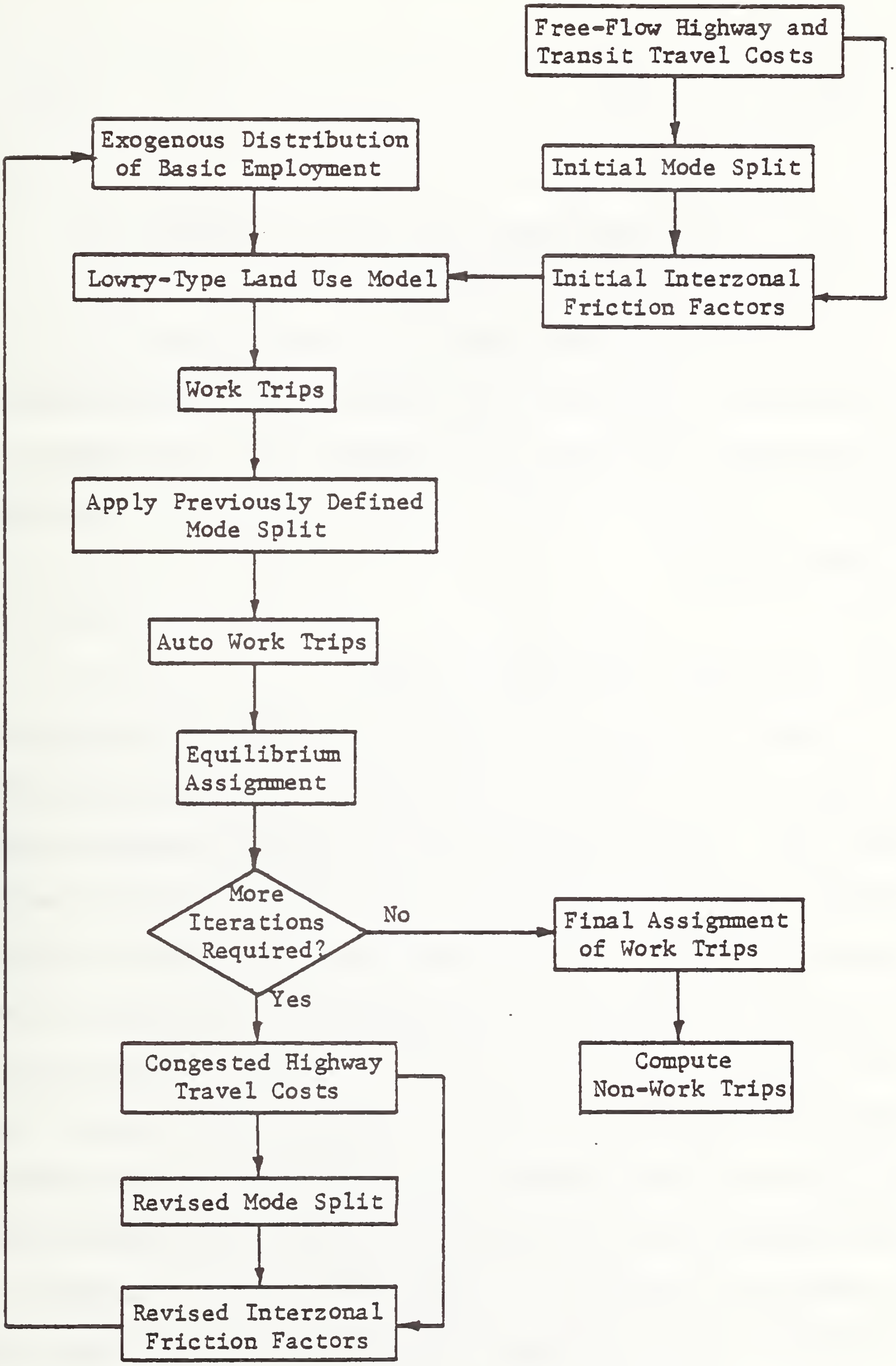


Figure 3-7. Details of Transportation/Land Use Feedback

$$gc_{ij} = t_{ij} + \frac{c_{ij}}{v} \qquad (3\text{-}2)$$

where

t_{ij} = travel time between zone i and j in minutes

c_{ij} = dollar cost of travel between zones i and j

v = value of travel time in dollars per minute.

The generalized cost of travel is used to define friction factor values and to select minimum cost paths on the highway network. The value of travel time is exogenously specified, based on representative values from the literature (10,11).

b. Congestion on the Highway Network

The initial values of interzonal accessibility are based on a linear combination of the free-flow automobile and transit travel times and dollar costs. Congestion is ignored for the first iteration because it is unknown exactly where congestion would occur since the land use pattern is as yet undefined. After the first iteration, however, it is possible to consider congestion. This is accomplished by assigning automobile trips generated by the land use model to the highway network using a capacity-restrained equilibrium assignment algorithm first developed by LeBlanc (12) and applied by Bowman, et al. (13). This algorithm assumes that link travel time is solely a function of the free-flow speed and the volume of vehicles on the link. It ignores the influence of intersections and transit vehicles entering and leaving the traffic stream. Congestion is considered only for work trips for two reasons. First, only work trips have a well-defined peak period in most U.S. cities. Non-work trips tend to be spread more evenly throughout the day. The length of the work trip peak period must be exogenously specified in terms of the free-flow volume per unit of time for each link of the highway network. The longer the specification of the peak period, the higher the free-flow volume. It is assumed in this research that the peak period lasts one hour. The second reason for only considering congestion for work trips is that the algorithm is slow to converge and thus expensive to use. It is more cost-effective to use a simple free-flow assignment (14) for non-work trips.

Transit trips are not specifically assigned to the transit routes. There are several reasons for this. First, the minimum time path algorithm, first developed by le Clerq (15) and refined by Bowman, et al. (16), is very complex, considering the possibilities of walking between zones to gain access to transit service and transfers between routes, including those with pulse-scheduled service. Minimum interzonal travel times can be found without assigning trips to the routes. Second, the assignment of transit trips would only be useful if it is likely that transit usage would be high enough to result in some overloading of passengers. Earlier experience by Bowman, et al., showed that this would not be the case with the small test cities simulated in this research. Third, even with its explicit consideration of walking and transfers between routes, the transit minimum time path algorithm is rather unsophisticated. It does not consider the impacts of automobile congestion (notably the time required to enter and leave the traffic stream to pick up and discharge passengers) nor that of time required for passengers to board and alight. Considering that the primary purpose of this research is policy analysis and not model development, it seems unreasonable to further expand the transit minimum time path algorithm to include passenger assignment when it already includes so many simplifying assumptions.

c. Mode Split

The computation of modal shares between automobile and transit is required to compute interzonal accessibilities (as shown in the next subsection) and to identify the portion of trips between each zone pair to be assigned to the highway network. A binary logit mode split model is used for this:

$$P_{ij} = \frac{e^G}{1 + e^G} = \text{probability of trip from zone i to zone j by automobile} \qquad (3\text{-}3)$$

where

$$G = q + r(W_A - W_T) + s(T_A - T_T) + t(C_A - C_T) + u(Own) \qquad (3\text{-}4)$$

and

q,r,s,t,u = constant and coefficients from model calibration for each trip type

W_A, W_T = automobile and transit walk times

T_A = automobile in-vehicle travel time, including parking

T_T = transit in-vehicle travel time

C_A = automobile out-of-pocket costs (gasoline and parking)

C_T = transit out-of-pocket costs (fare and transfer fees, if any)

Own = average automobile ownership per household.

The constant and coefficient values used in this research come from a study by Charles River Associates for Pittsburgh (18).

d. Selection of Interzonal Friction Factors

Once the interzonal travel times, dollar costs, and modal shares are determined, a weighted average travel cost is computed for each zone pair. This is of the form:

$$t_{ij} = t^{a}_{ij} (p_{ij}) + t^{t}_{ij} (1 - p_{ij}) \tag{3-5}$$

where

t^{a}_{ij} = interzonal automobile travel cost

t^{t}_{ij} = interzonal transit travel cost

p_{ij} = probability of trip from zone i to zone j by automobile.

Based on the weighted average travel cost, t_{ij}, for each zone, the appropriate values from the friction factor curve are selected. In the work by Edwards, friction factor curves from a representative city were used (19). Bowman, et al., devised an algorithm that converts a travel time distribution to an approximation of a calibrated friction factor curve. It assumes that the friction factor for each time interval t is estimated to be equal to the ratio of the observed percent of all trips within that interval to the numerical value (the time in minutes) of the interval. Measures of interzonal impedance to travel are selected from this synthetic friction factor curve.

Since generalized cost distributions are not found in the literature for U.S. cities, it is not possible to base friction factors on generalized costs in the base run. In the incremental run, however, the friction factor curves are based on the generalized cost distributions for each trip type simulated in the base run. Synthetic generalized cost-based friction factor curves are developed using the same algorithm developed by Bowman, et al., to convert travel time distributions. From these, the appropriate interzonal friction factors are selected based on the generalized cost between zone pairs in the incremental run.

e. Procedure to Expedite Convergence of Interzonal Accessibility Values between Iterations

It is intended that the iterative process shown in Figure 3-7 continues until values of interzonal accessibility converge, i.e., until differences between iterations become small. Since it is desirable to keep the number of iterations as low as possible, due to the complex computations required to perform the matrix manipulations in the Lowry-type model and to assign work trips to the highway network, a procedure has been developed to insure that the interzonal accessibility values rapidly approach the equilibrium values. This process, shown in Figure 3-8, involves repeating the allocation of land uses and assignment of work trips based on subsets (pre-specified percentages in each zone) of basic employment of ever-increasing size. In earlier iterations the population of the city is small and congestion is rather low. With each succeeding iteration, the population grows larger and congestion increases. It is intended that the shifts in land use between iterations will be more gradual and more directed toward the equilibrium land use pattern using

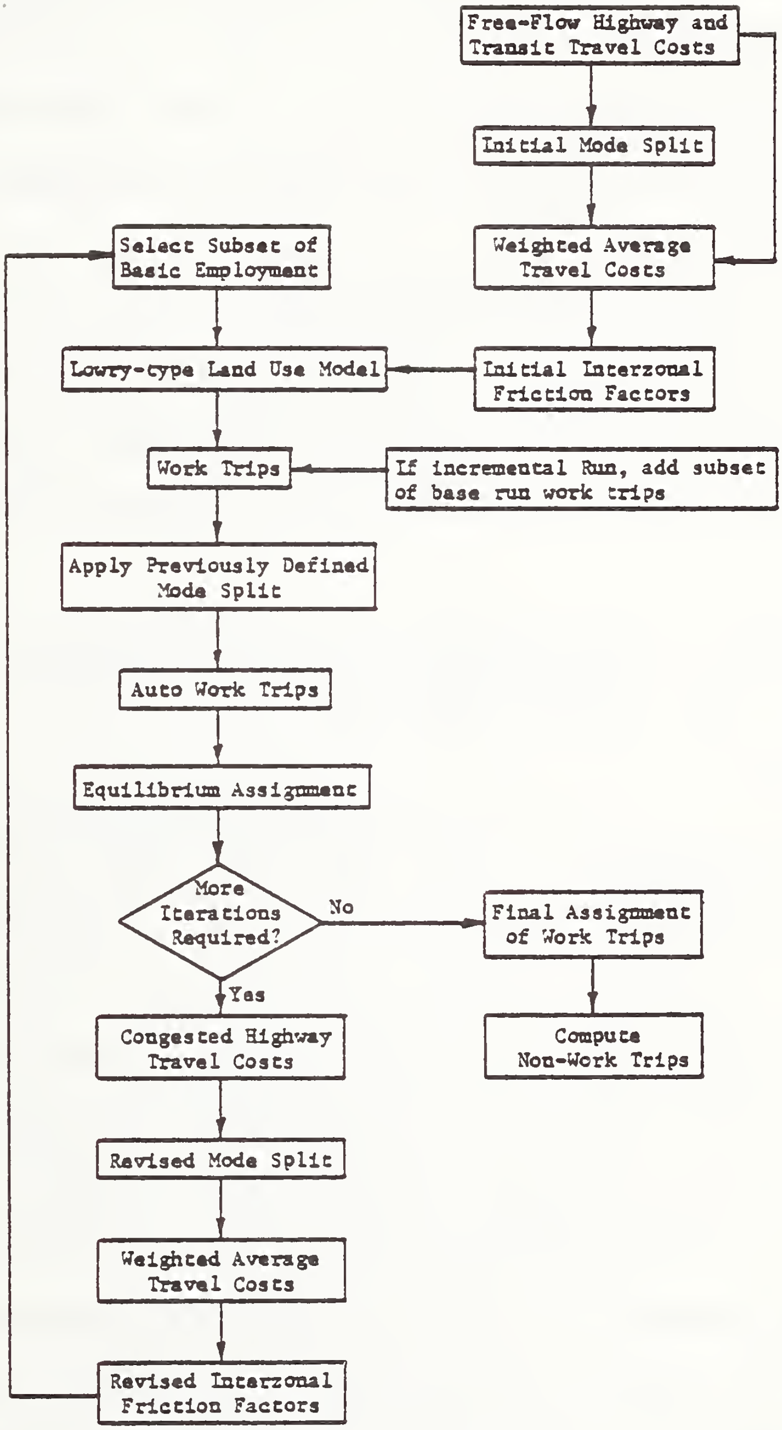


Figure 3-8. Revised Transportation/Land Use Feedback to Expedite Convergence of Interzonal Accessibility

this procedure than if the iterations were based on the complete population and employment distribution each time through. In the incremental run, a subset of the base run work trip set is added to the subset of the incremental work trip set prior to the assignment of automobile trips to the highway network.

Preliminary experience with MOD3 showed that a fairly small initial subset size and additional subset increments of progressively smaller magnitudes gave results that rapidly approached convergence. The series of subset sizes shown in Table 3-1 are used in the experimental program.

Table 3-1. Basic Employment Subset Sizes Used in Land Use Allocation and Work Trip Traffic Assignment

	Percent of Total					
Subset increment	30	25	20	15	10	0
Total subset size	30	55	75	90	100	100

The reason for repeating the land use allocation with the full set of basic employment is to insure that the final allocation is based on the most accurate values of interzonal accessibility. The next to last iteration is based on the accessibility values computed in the previous iteration, based on 90 percent of the basic employment, and thus does not consider all of the congestion effects that might occur. The final iteration uses accessibility values based on the allocation of the entire population, reflecting the complete impact of congestion.

3. Incremental "Layers" of Urban Growth

As noted above, there are two distinct applications of MOD3 required to simulate the implementation of a policy change. The first is the base run, in which the current state of the city is simulated. A city size of 100,000 was selected for this study. The second is the incremental run, in which the city grows in the context of a policy change. A twenty year planning horizon was envisioned for this study and 25 percent growth, or 25,000 persons, was assumed for the incremental runs. Figure 3-9 shows the relationship between the base and incremental runs in greater detail.

The heart of this relationship is the data that are transferred to the incremental run from the base run. These data fall under four categories. The first is the work trip matrix. Prior to the assignment of automobile trips to the highway network, a subset of base run work trips is added to the subset of incremental run work trips. It is assumed that none of the base work trips change their origin or destination zones. Modal shares may change in the incremental run, however. The second category of data is the distributions of population and employment. These are used in the computation of non-work trips. It is assumed that population and employment remain fixed from the base run. The third type of data is the land available for residential and retail development. This is the land previously unused in the base run. Fourth are the generalized cost distributions for each trip type. These are used to generate synthetic generalized cost-based friction factor curves for computing interzonal accessibility.

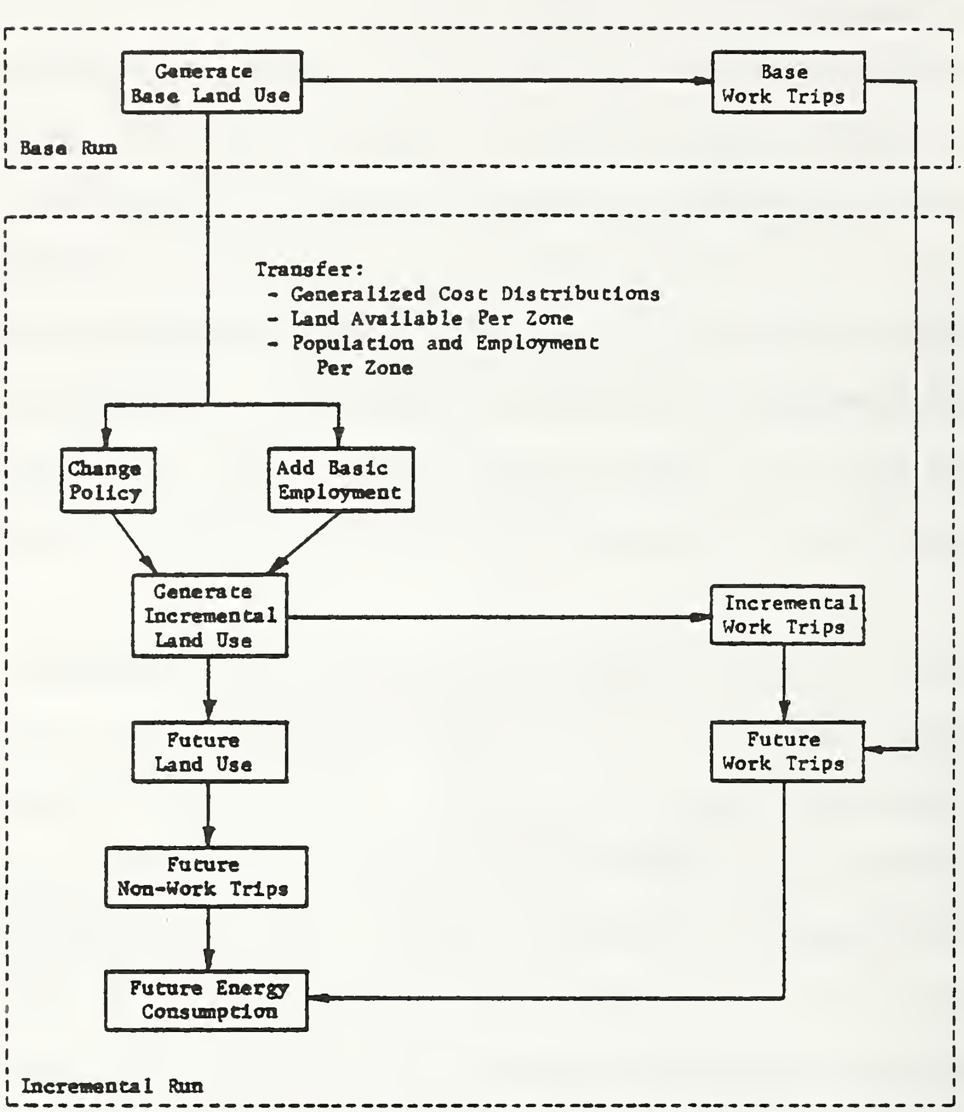


Figure 3-9. Relationship Between Base and Incremental Runs of MOD3

4. Non-Work Trips

The major difference between the treatment of work and non-work trips in MOD3 is that work trips are computed considering the effect of congestion on the highway network while non-work trips are not. Four categories of non-work trips are defined in the model. The trip generation and distribution submodels for each are described below.

a. Service Trips

The Lowry-type model simulates trips from home to two categories of service sites:

- service sites sensitive to the location of the client, including food stores, gasoline service stations, drug stores, liquor stores, laundries and dry cleaning shops, automobile repair shops, and other service sites commonly categorized as convenience shopping
- service sites not sensitive to the location of the client, including general merchandise stores, new and used car dealers, apparel and accessory shops, and furniture and home furnishings stores.

This dichotomy was defined by Edwards (20). Different friction factor curves, trip generation rates, and automobile occupancy rates are used for each.

In the base run, service trips are a direct output of the Lowry-type model. In the incremental run it is assumed these trips can change. This is based on recent experience that showed that destinations for service trips are much more sensitive to fluctuations in relative accessibility due to changes in gasoline availability than work trips (21). Rather than combining the base and incremental run service trip matrices, future service trips are computed using the following gravity models based on the combined land use patterns of both runs:

$$T_{ij}^{k} = \frac{2\, r^{k}\, P_{i}\, A_{j}^{k}\, f_{ij}^{k}}{\sum_{j} A_{j}^{k}\, f_{ij}^{k}} = \text{trips between home and service type } k \qquad (3\text{-}6)$$

where

r^k = trip generation rate per household for service type k

P_i = population in zone i (including base population in incremental run)

A_j^k = service employees of type k in zone j (including base service employees in incremental run)

f_{ij}^k = interzonal friction factor for service trip type k.

The constant value of 2 is included in order to account for trips both to and from home.

b. Non-Home-Based Trips

The procedure for computing non-home-based trips lies completely outside the framework of the Lowry-type model, relying solely on the land use pattern. Zonal attraction, A_j, is estimated by the formulation (22):

$$A_j = P_j + M_j + 7 R_j \qquad (3\text{-}7)$$

where

P_j = population in zone j (including base population in incremental run)

M_j = basic employment in zone j (includes base basic employment in incremental run)

R_j = service employment in zone j (includes base service employment in incremental run)

Non-home-based trips are then distributed using the following gravity model (23):

$$T_{ij} = \frac{r\, E_i\, A_j\, f_{ij}}{\sum\limits_j A_j\, f_{ij}} \qquad (3\text{-}8)$$

where

r = non-home-based trip generation rate (for one-way trip) per employee

E_i = total employment in zone i (including base employment in incremental run)

f_{ij} = interzonal friction factor for non-home-based trips.

c. Social Trips

A simple gravity model is used to distribute social trips in MOD3:

$$T_{ij} = \frac{r\, P_i\, P_j\, f_{ij}}{\sum\limits_j P_j\, f_{ij}} \qquad (3\text{-}9)$$

where

r = social trip generation rate per household

P_i = population in zone i (including base population in incremental run).

D. Model Outputs

MOD3 presents a fairly detailed description of the land use pattern, automobile travel, and transit travel similar to information found in most transportation studies. It also provides a summary of energy consumption for automobile and transit transit travel. The output is similar in format for both the base and incremental runs.

1. Description of Land Use

The population and service employment allocated per zone are listed to assure that the land use pattern is reasonable. Since the plotting of these values on a zone map is a tedious process, simple measures of spatial dispersion are also displayed. These are the second moments about the centroids of population and total employment.

2. Description of Travel

The assignment of automobile trips is described for work and non-work trips. For work trips, link flows for the journey from work to home are shown. This can be interpreted as the evening peak period. Also shown for each link is the congestion index, the ratio of the actual (congested) to free-flow travel time. A weighted average congestion index for the entire network is also computed. For non-work trips, the total travel volume for each link is displayed.

The following summary statistics are computed for automobile trips of each type:

- total person-trips
- total vehicle-trips
- total vehicle-miles
- total vehicle-minutes
- average trip length in miles
- average trip time in minutes
- average trip speed in miles per hour.

While transit trips are not specifically assigned to the transit routes, MOD3 does report the following summary statistics for transit travel for each trip type:

- percent of total trips by transit
- total person-trips
- total person-miles

- total person-minutes
- average trip length in miles
- average trip time in minutes
- average trip speed in miles per hour.

The distribution of generalized costs for the travel simulated in each trip category is presented as the percent of total trips to occur in each one minute interval from 1 to 199+ minutes. In the base run, this is copied to a punched output file for use in the incremental run to generate synthetic friction factor curves. The mean values are used in the analysis.

Measures of regional accessibility are computed for work and service trips. They are based on values of the interzonal friction factor and are used in the earlier work by Edwards as an indicator of the quality of life. The regional accessibility for trip category k is computed using the following formulation (24):

$$A = \sum_{i} \sum_{j} P_j f_{ij}^{k} \qquad (3\text{-}10)$$

where

P_j = population in zone j (including base population in incremental run)

f_{ij}^{k} = interzonal friction factor for trip category k.

MOD3 computes a second quality of life measure termed the opportunity cost distribution. This is the distribution of generalized costs for all trip opportunities ignoring the influence of the impedance to travel. Origin-destination trip matrices are based solely on the attractiveness of each zone relative to all other zones in terms of the activities allocated there. This is computed using a gravity model with all friction factors equal to 1.0 of the form (25):

$$T_{ij} = \frac{P_i \, A_i}{\sum_j A_j} \qquad (3\text{-}11)$$

where

P_i = population in zone i (including base population in incremental run)

A_j = for work trips: total employment in zone j (including base employment in incremental run)

for service trips: service employees in zone j (including base service employees in incremental run).

The mean values of the distributions are used in the analysis.

3. Summary of Energy Consumption

Automobile gasoline consumption is computed separately for work and non-work trips because of the separate assignment algorithms used. In both cases the total consumption is found by summing, for each link in the highway network, the number of vehicles travelling on the link during a single day times the average vehicle gasoline consumption for the average operating speed on that link. This is computed in terms of gallons of gasoline and in British thermal units (Btus).

Transit energy consumption is a direct result of the characteristics of the transit route input data. For each route, the fuel consumption is found by summing for each link the number of buses per day times the fuel consumption for the exogenously specified average speed at which the buses operate. This is computed in terms of gallons of diesel fuel and in Btus.

Total energy consumption for transportation is found by summing the total Btus consumed by automobile and transit travel. This is presented in terms of total Btus, total equivalent gallons of gasoline (found by dividing the energy in Btus by the number of Btus per gallon of gasoline), and the equivalent gallons of gasoline per capita.

E. Application of MOD3 for Policy Testing

The experimental program was conducted using an IBM 370/195 computer using the Time Sharing Option. Data manipulation and program execution were performed using a remote terminal with the printed output received via a high speed line printer due to its length (30 pages). Stored on magnetic disk were the following files:

- a compiled version of MOD3
- data decks for the base and standard incremental run for each test city
- job control language decks for the base and incremental run for each test city.

Typical MOD3 execution time for an incremental run was under 65 seconds. Central processor storage requirements were under 61,000 words, not including off-line scratch files. A complete discussion of the operation of MOD3 is found in the program documentation in Appendix A. A listing of the FORTRAN program is in Appendix B.

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CHAPTER FOUR

GUIDELINES FOR INTERPRETING EXPERIMENTAL RESULTS

A. Introduction

In order to make use of the results of this research, planners and decision makers must be made confident of the validity of these results and the process through which they are obtained. In regard to the model, validity refers to the degree to which it is a sufficiently accurate representation of the real world. This includes not only its ability to replicate a given state of an urban area, but, more importantly, that it is correctly sensitive to stimuli in the form of altered policy parameters. MOD3, as any model of reality, is imperfect in theory and structure due to a lack of knowledge and many simplifying assumptions. In this chapter some of the deficiencies in MOD3 and its applications in this research are identified and the degree to which they can affect the results is discussed. Recognizing these limitations, the qualitative, intuitive approach to be used in the analysis is presented.

B. Limitations in the Model and Its Application

Intuitively the structure of MOD3 is very strong, insuring some degree of validity in the results. The component submodels have been proven in earlier research and are currently in use in many real world applications. In order to reduce the complexity of the model, many simplifying assumptions were built into the theory and structure. Some of these limitations could have a profound adverse influence on the experimental results. Others, while resulting in a less-than-perfect representation of reality, probably do not affect the results to any noticeable degree.

1. Important MOD3 Limitations

a. Fundamental Assumptions in the Land Use Model

The aggregate nature of the Lowry-type model in MOD3 could be a severe limitation in the realism of the results. All of the households simulated are assumed to be identical in terms of travel behavior and locational preferences. Combined with the static equilibrium approach of the activity allocation process, these limitations prevent any realistic simulation of the housing market. This could be particularly important in terms of the model being correctly sensitive to the effects of the implementation of future policy changes. By requiring that base land uses remain fixed and zonal interchanges for work trips remain constant, it is possible that an unrealistic overdevelopment of the central business district could result since this is where development is concentrated in the base run. The result of this could be an overestimation of energy consumption due to the highway congestion that might occur. Ignoring the distribution of population income segments and housing stock quality precludes the possibility of simulating low-cost housing in suburban areas. If policy changes encouraging decentralized employment are simulated with no provision made for inner-city workers to move to the suburbs, transportation energy savings may be less than predicted due to the longer work trips that would result.

b. Use of Current Travel Behavior Characteristics

It is possible that the experimental results could simply be an extrapolation of current travel behavior which may change drastically in the future. The cause of such change could be due to a growing awareness by the public of the energy costs of travel, changes in life-styles, the imposition of many automobile disincentives and transit incentives, or decreased availability of gasoline. The input data this concerns affects every stage of the simulation including land use allocation, trip distribution, mode split, and traffic assignment.

The use of representative travel time distributions to generate synthetic friction factor curves presents no problems in the base run. In the incremental run, however, the possible future alteration in travel behavior and locational preference would not be reflected in the generalized cost distributions transferred from the base run. As gasoline prices rise, or as availability decreases, places of residence could be chosen much closer to employment sites than is currently observed. Recent research (1) has shown that the selection of service sites is definitely affected by these considerations.

The constant and coefficient values in the logit mode split model ideally should be representative of all individuals having similar transit alternatives available. The degree to which it would remain an accurate descriptor of transit usage in the future, particularly as gasoline availability changes (2), remains subject to question. Another behavioral input calibrated from disaggregate data is the value of travel time. If the perceived value could be altered as energy-related transportation costs change, the experimental results may not be valid.

As applied in this research, the non-work trip generation rates are fixed and assumed constant across the urban area. It has been noted in many urban transportation studies that daily per capita trips increase with household income. It was not possible to apply this, however, since it is assumed that all households simulated by MOD3 are identical. The probable effect is that there are too many trips near the CBD and too few trips near the periphery since an average representative value was used in all zones. Another exogenously specified constant is the average automobile occupancy for each trip type. Ideally this should be a function of the levels of service offered by automobile and transit. This consideration was not included in MOD3 because it would have made the computation much more complex. It is possible that a less-than-realistic description of travel could result by using fixed values since it assumes a level of service for automobiles that may not exist in the transportation/land use equilibrium.

The exogenous specification of automobile occupancy to simulate commuter carpooling does not account for many indirect effects (3). It is possible that trip circuity could greatly increase as carpools pick up and deliver riders. Further, non-work trip generation could increase due to increased automobile availability when automobiles are left at home for the journey to work. It may be that the automobile availability parameter in the logit mode split model used in MOD3 could be better specified as the number of vehicles typically available for the trip rather than the total number of vehicles per household. These considerations could increase total energy consumption, yet are not represented in MOD3.

c. Iterative Solution of MOD3

The feedback between the allocation of land uses and travel on the highway and transit networks is not a truly simultaneous solution in MOD3, but rather an iterative one in which total energy consumption approaches an equilibrium value. Two algorithms in MOD3 result in some oscillation about that equilibrium state. The capacity-restrained equilibrium assignment for automobile trips attempts to minimize total travel costs on the highway network. In so doing, it oscillates between values higher and lower than the optimum, although having a value closer to the optimum on each iteration. It is possible that the limited number of iterations performed (in order to reduce computational costs) may result in the values of total fuel consumption in some experiments being less than optimum while others being greater, thus affecting the accuracy of comparisons between experiments. While the earlier research by Bowman, et al., identified a cost-effective number of iterations to use, they did note some oscillation, amounting to less than five percent, in the final solution of energy consumption. It is possible in the experimental program that some counter-intuitive results may be caused by this.

The iterative solution of the transportation/land use feedback also results in some oscillation about the equilibrium state. The number and sizes of the subsets of basic employment could effect the final values of interzonal accessibility. Preliminary experimentation provided subset sizes that resulted in rapid convergence. This could change, however, when altered policy parameters result in different land use patterns.

d. Application of MOD3

In order to keep computational costs at a minimum, the number of zones to which land uses are allocated and the number of highway links is kept small. This has two impacts on the structure of the cities simulated. First, it requires that the CBD be composed of a very small number of zones (between four and six). This severely limits the number of highway links in what would, in the real world, be a very congested area. It is possible that the degree of congestion in the central business districts of the cities simulated may be unrealistically low. Second, the limited number of zones placed the "edge" of the city fairly close to the CBD. This could affect the shape of urban growth in the incremental run, forcing population and services to locate closer to the CBD than would be realistic, thus reducing urban sprawl artificially.

e. Summary of Impacts of Important MOD3 Limitations

The exact degree to which these limitations affect the experimental results is unknown since there is little real world data to compare against. At best this discussion has identified some potential problems in interpreting the results. Any conclusions developed must clearly be qualified by the recognition that the model could be yielding misleading conclusions. There appear to be some offsetting limitations in MOD3, such as the simplified CBD network ignoring some congestion, thus promoting growth further from the CBD than is realistic while the number of zones may force growth closer to the CBD. Whether these influences are equal as well as opposite is unknown, however. The lack of an "exact" numerical value for the total energy consumption due to some oscillation about the optimum may affect the interpretation of results that differ by less than five percent with each other.

2. Less Important MOD3 Limitations

There are many relatively minor limitations in the theory and structure of MOD3 that probably will not adversely affect the accuracy or realism of the experimental results to any large extent. The first concerns the use of a single static layer of land use to simulate the dynamic process of urban growth. This highly simplified procedure is used to keep the complexity of the model to a minimum and to reduce the data requirements. Several layers of urban growth clearly would have been more realistic since this would have more closely approximated a continuous process. This is not done due to the following three considerations. First is the question of the appropriate number of increments of growth to simulate. A small number of layers might have been just as unrealistic as the single layer. The simulation of a great many layers is prohibited by the excessive computational time required. Second is the question of the proper amount of growth in each layer. It is unknown whether uniform sizes of layers of incremental population and services or, perhaps, a series of progressively smaller layers would have been more reasonable. Third is the question of staging or scheduling of evolving policy changes. An increase in the price of gasoline probably would not be implemented all at once, but would be experienced as a general increase over time. The rate at which this would be simulated could affect the results, although probably not severely. The answers to all of these questions are unknown and it is clearly beyond the scope of this research to attempt to seek them out. This would entail an extensive validation effort requiring a vast amount of time series data. It should be noted that the use of a single layer of growth is a much more realistic method to simulate the implementation of policy changes than that used by Bowman, et al.

A second limitation is that trips from outside the urban area, as well as commercial, recreational, change-mode, serve-passenger, and taxi trips are ignored by MOD3. This causes the total transportation energy consumption to be underestimated. It was therefore anticipated in the research by Bowman, et al., that their model simulated less than the reported gasoline sales for the real city they attempted to replicate. The influence of the trips not simulated on the highway network can be accounted for by simply reducing the free-flow capacity on the highway links. Bowman, et al., did this when replicating a real city, but this is not done in this research since the experimentation dealt with hypothetical cities and a network whose link capacities are subjectively defined.

Two limitations concern the realism in assigning automobile trips to the highway network. The length of the peak period is exogenously specified through the definition of free-flow capacities, in terms of vehicles per unit of time. In this research it is assumed the peak period lasts one hour. Clearly, the structure of the highway network and spatial dispersion of land uses are important determinants of where and to what extent congestion will be a problem. No reliable procedure is available to internalize the length of the peak period in MOD3, however. The second limitation is that congestion is completely ignored when determining non-work automobile interzonal travel costs. The reason for this was to reduce computational costs. It was felt that most non-work trips occur during the off-peak period when congestion is not so much a problem. Further, it was hypothesized that the transportation/land use feedback would be adequately simulated by dealing only with work trips. It is obvious that some degree of congestion affects every automobile trip. It does not seem cost-effective, however, to develop the methodology further and incur the additional computational cost when the benefit would be so small.

Related to this is the lack of consideration of congestion for transit trips. Neither the influence of buses on automobile traffic or automobiles on transit level of service is considered in MOD3. To do so would require a much more iterative solution, involving an equilibrium between automobile and transit levels of service. This would be complicated by the consideration of passenger boarding and alighting times as well as the time required for buses to leave and enter the traffic to pick up or discharge passengers. Instead, link travel times are exogenously specified at representative values for urban bus operations. Considering the relatively low transit usage in cities of the size simulated, this is probably not very important.

C. The Need for a Qualitative Approach in the Analysis

Since MOD3 is not intended for use in forecasting for a specific real city, it is not important the precise numerical results are unobtainable. As long as the correct direction and relative magnitude of the impact of alternative energy policy changes can be simulated, a valid and useful analysis can be performed. In this section the reasons why a more qualitative approach is used in the analysis are explained.

Conclusions based on the analysis of results from an experimental program carried out on one urban form would be of limited value. Any specific city is certain to have characteristics which would uniquely define its response to alternative energy policy actions. While this is especially true when attempting to replicate a real city, this reasoning still holds when simulating a hypothetical city. To avoid this problem, the experimental program is carried out across several test cities. The structure of these cities is representative of many real cities of the size being simulated. The shape and orientation of the transportation networks in the hypothetical cities are different in order to generalize the results. It is not anticipated that the impact of any given policy change will be identical in all the test cities. The results should be comparable enough, however, to draw some general conclusions. To this extent, the experimental results should be considered representative although not precise.

Most of the analysis is based on comparisons between pairs of incremental runs. In some cases, policy changes result in very little change from the standard incremental run. In addition, two different policy actions sometimes result in very similar impacts. It is not possible to say whether the difference between a pair of results is "significant" in the statistical sense, however. There is no random element in the calculation of energy consumption in the model. MOD3 does not use a stochastic simulation, but is purely deterministic in its computation. To this extent, the results are "exact." There is the possibility, however, that the equilibrium solution, in terms of the feedback between transportation and land use, may not be attained. The iterative nature of the transportation/land feedback, and the capacity-restrained equilibrium assignment contained within it, cause some degree of oscillation about the optimum. Preliminary experimentation showed that truly meaningful differences between results must have a magnitude of greater than one to three percent. The precise nature of what is a meaningful difference in the analysis will depend on the degree to which measures other than energy consumption (such as trip length or spatial dispersion or population) are different. The term "significant" is not used in analyzing the results. Rather, all conclusions are based on differences between alternative policy actions which are meaningful.

At some points in the analysis it may be desirable to assess a trend across a series of related experiments. It is not possible, however, to generate regression equations to quantify such relationships. To do so would imply that the states of the test cities included in the analysis are selected randomly from the space of all possible states. This is not the case. The experimental program consists of carefully designed experimental excursions from the standard incremental run. Other future states of the test cities may be possible (although not necessarily probable). The use of regression analysis under such circumstances could be misleading. Indeed, even where strong general trends are observed across many experiments, they must be considered as being tentative, for additional experiments could reveal a different relationship. Figure 4-1 presents this concept.

These considerations regarding trend analysis and significance of experimental results relate to the validation effort by Bowman, et al. (5). The first stage of their attempt to validate the experimental approach was to compare trends observed in the real world against those

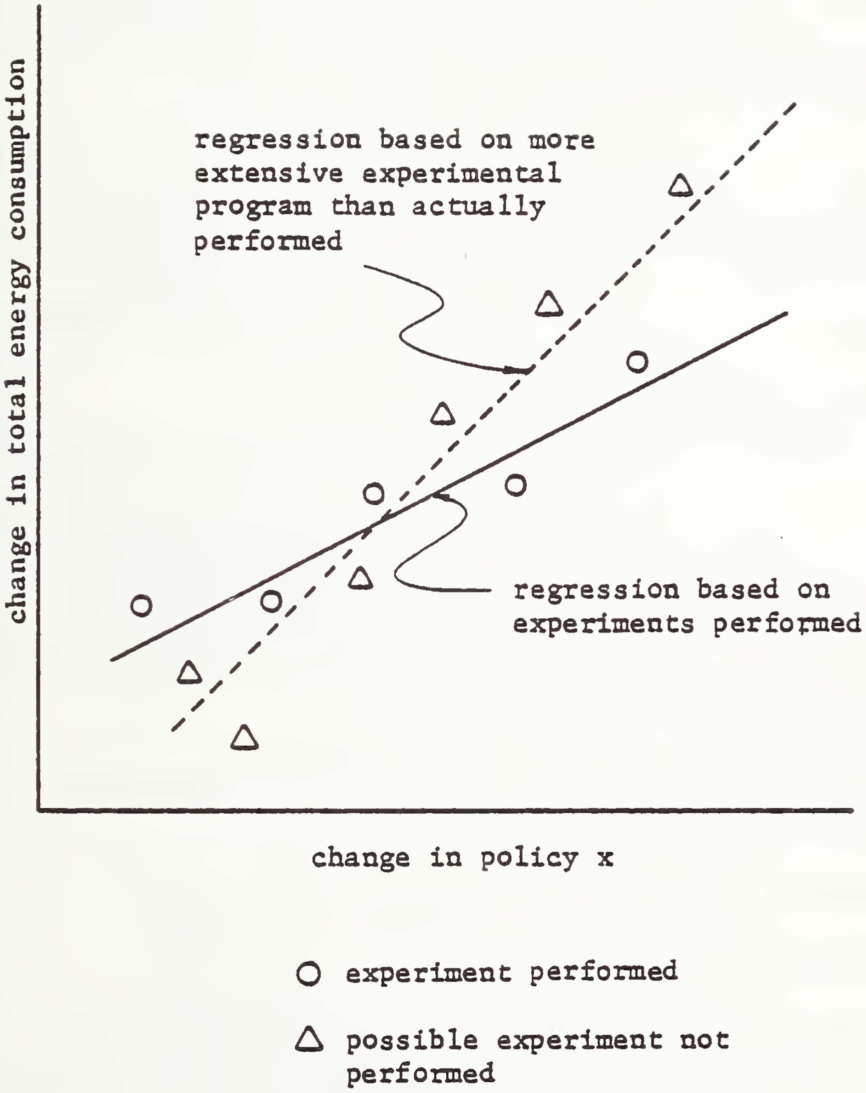

Figure 4-1. Misleading Regressions Resulting from Limited Experimental Program

observed by Edwards (6) in using his model, which forms the core of the model used by Bowman, et al. Ignoring the statistical considerations noted above, regression equations were computed for the 37 urban forms Edwards simulated and for 12 representative cities with a population around 100,000. The following relationships were examined:

- gasoline consumption as a function of percent of work trips by transit
- gasoline consumption as a function of the area of the city
- gasoline consumption as a function of the second moment of population.

While the trends were generally the same, the regression constants and coefficients were quite different.

The second stage of their validation attempt was to replicate a real city (Amarillo, Texas) using the model they developed. The following model outputs were compared against similar measures presented in the urban transportation study (7) and U.S. Census reports for that city:

- percent of work trips by transit
- travel time distributions for work, other home-based, and non-home-based trips
- highway network link flows
- gasoline consumption.

The model estimated only 30 percent of the total vehicle-miles travelled and only 37 percent of the gasoline consumption. Recognizing that some trips were ignored in the simulation and that gasoline sales data were far from precise, Bowman, et al., concluded that their model was doing a good job of simulating energy consumption since some of the aggregate measures of travel, such as link flows and travel time distributions, were close to those observed in the real city.

D. Intuitive Analysis

Since there are no exact quantitative results which can be validated by real world data, the analysis relies on a more subjective methodology to assure the development of useful conclusions based on realistic results.

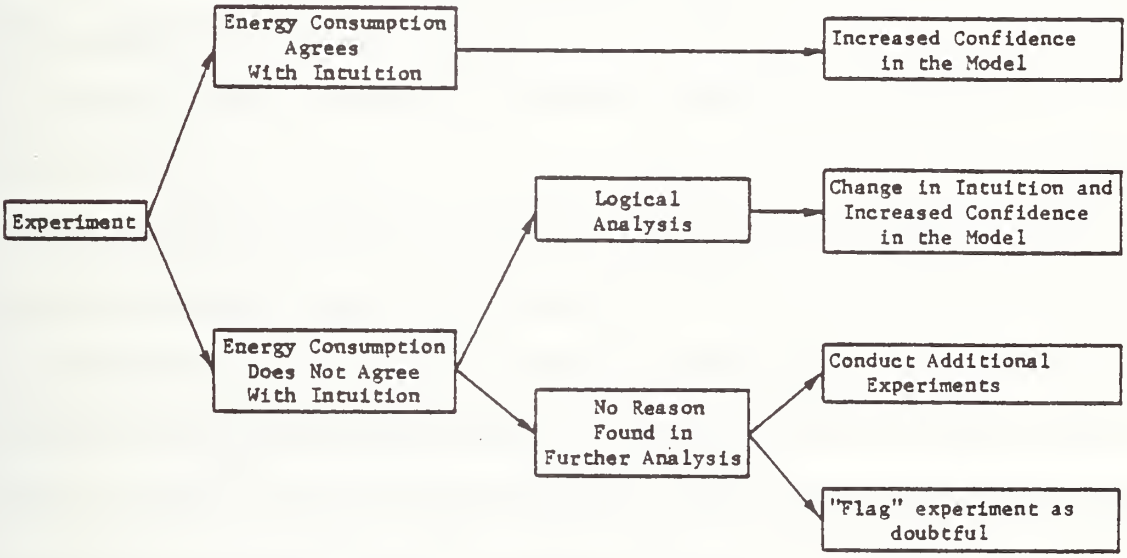

Figure 4-2. Intuitive Analysis

The heart of this procedure is the use of intuition to guide the interpretation of the results. A well-designed, structured intuitive assessment of the experimental results can be both efficient and relevant, considering that it will be the intuitive judgment on the part of planners and decision makers that will determine whether and how the results are used.

The analysis follows the framework shown in Figure 4-2. The initial determination made is whether the change in total fuel consumption due to a policy change agrees with intuition, both in direction and in magnitude. If it does agree, the experiment results in increased confidence in the model. If the change in energy consumption is unanticipated, however, and does not agree with intuition, further analysis of the land use pattern and travel in the city must be undertaken. This could include an examination of the allocation of population along major highway links, the average highway network congestion index, transit usage by trip type, or other factors which are directly or indirectly linked to total energy consumption.

In those situations where further analysis identifies why the change in energy consumption was not as anticipated, the model becomes a valuable educational tool, changing intuition. The intuition of planners and decision makers is far from perfect. The implementation of policy changes intended to reduce energy consumption can have many direct and indirect impacts that may result in changes in urban growth and travel very different than what is expected. Perhaps the most important contribution of this research may be the refinement of many intuitive perceptions of urban planners and decision makers regarding the impact of alternative proposed policy actions.

It is possible that additional analysis of the allocation of land uses and of travel will not explain why a particular policy change does not result in a change in energy consumption as anticipated. In such a case, both confidence in the model and in intuition are reduced. Two alternative courses of action are available in such a circumstance. The first is to conduct additional experiments in order to find out why the model behaves as it does. This could involve a sensitivity analysis on a single parameter or a series of experiments in which related policy changes are simulated which have similar results. The second course of action is to "flag" this experimental result as doubtful. It is recognized that MOD3 is not a perfect representation of the real world and it must be expected that in some ways it might give experimental results that are wrong. Such doubtful runs should be reviewed to seek out systematic errors in the model, if any.

Finally, throughout the remainder of this report, the reader should note that the outputs of the modeling system are determined by its general structure, the nature of the component models, the underlying assumptions, and the input data. In the absence of a comprehensive validation effort, these results must be viewed first as a description of the response surface of the modeling system itself. Only to the extent that this response surface is viewed as valid should the reader proceed to the use of these results as indicators of real world response to policy actions.

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CHAPTER FIVE

EXPERIMENTAL PROGRAM

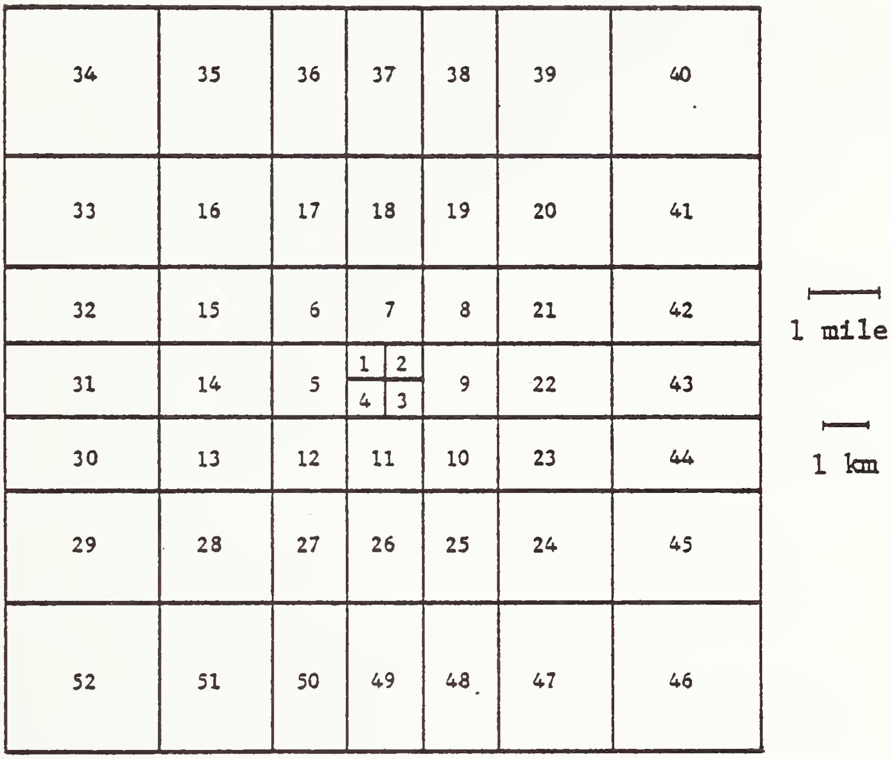
A. Introduction

The simulation model was applied in a total of 112 experiments across three hypothetical cities to examine and define the relationships between urban form and energy consumption and to identify some promising strategies for reducing transportation energy consumption. This chapter begins by describing the characteristics of the three test cities in terms of the input data. The analysis of experimental results which follows begins with a comparison of the standard incremental run for each of these cities. The intent here is to identify important differences between the urban forms in order to guide later experiments. Next, approximately 12 experiments, carried out across each of the test cities, are analyzed in order to rank the effectiveness of a set of representative policy actions. This analysis provides further input to the third and most important stage in the experimental program. This is the investigation of a broad range of policy excursions, pursuing only the more promising approaches to reducing transportation energy consumption. This largely heuristic process is concerned with alternative transportation network and pricing strategies and urban development policies. The analysis presented in this chapter concerns only the most salient findings and does not attempt to discuss all of the experimental results. A description of all experiments is found in Appendix C. A complete summary of the more important results for each experiment is in Appendix D.

B. Description of the Data Sets

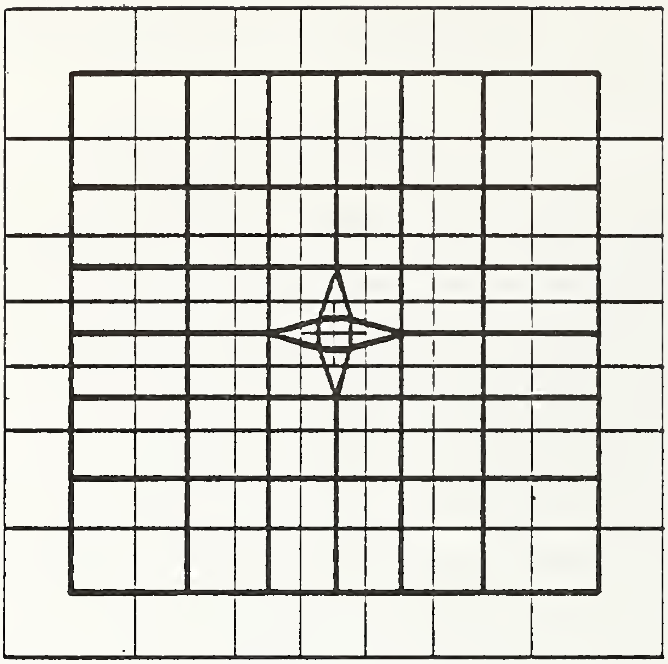
It was recognized that the results of this research might have been difficult to generalize had all the experimentation been performed in the context of a single city. The approach was rather to define a group of test cities, representative of typical urban forms in the U.S., as the test bed for the alternative transportation and land use policies simulated. City characteristics were extracted from the urban transportation studies and land use plans of several U.S. cities in order to be as realistic as possible (1,2,3,4). To avoid the complexities of large metropolitan areas and to reduce computer storage and computational requirements to a minimum, the hypothetical cities tested were limited to base population of 100,000, 52 zones or less, and less than 200 interzonal links on the highway network. It was felt that such a city size would allow all the policies to be simulated in a realistic environment and also allow for a thorough analysis by permitting a full range of experiments to be performed within a limited budget.

The first hypothetical city is similar to Edwards' (5) concentric ring city. The land use pattern, highway network, and transit network are shown in Figures 5-1 and 5-2. It is typical of post-industrial nineteenth-century cities and is very common in the U.S. It consists of a central business district (CBD), one mile square and divided into four zones, and three surrounding rings of zones, structured to result in a rectangular highway network. Zone sizes increase progressively toward the periphery in a manner common in the analysis performed by most urban

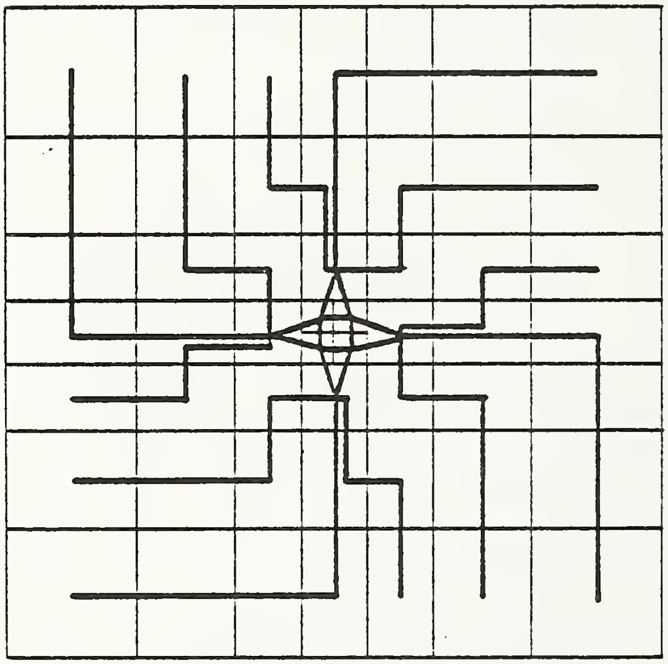


		Basic Employment Density (employees per sq. mile)	
	Zones	Base Run	Standard Incremental Run
CBD:	1 - 4	4000	1000
Ring 1:	5 - 12	1000	219
Ring 2:	13 - 28	203	0
Ring 3:	29 - 52	0	0

Figure 5-1. Concentric Ring City



Highway Network

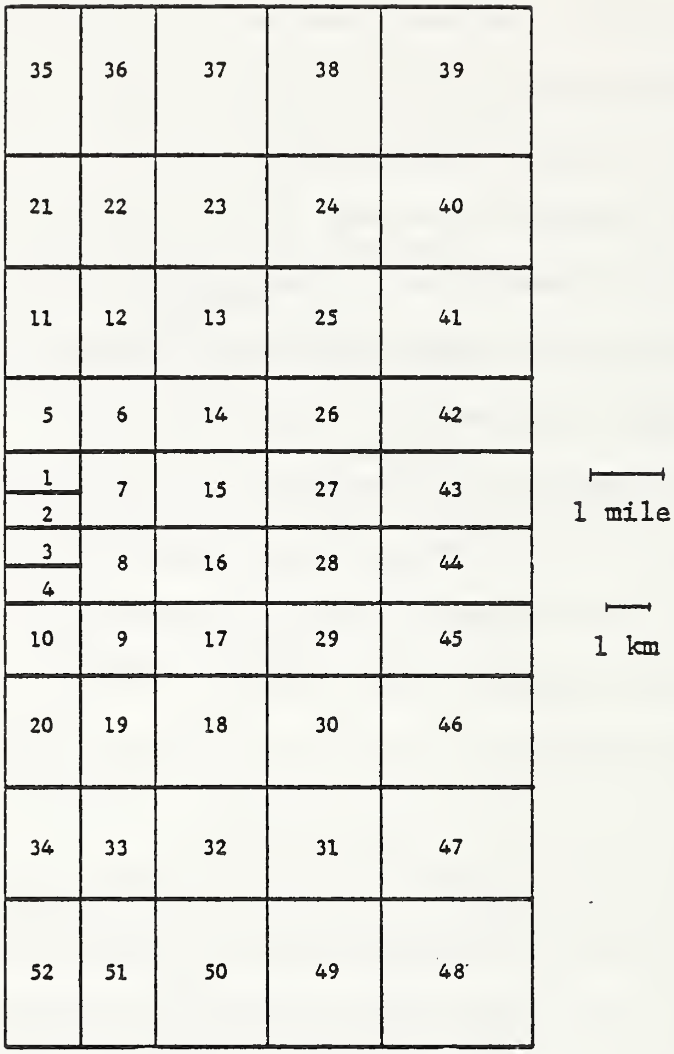


Transit Network

Figure 5-2. Transportation Networks in Concentric Ring City transportation studies. The total area is 100 square miles. All highways are assumed initially to be arterial streets. Local and collector-distributor streets are not depicted since they usually handle intrazonal trips which are largely ignored in the model (i.e., they are assigned to hypothetical intrazonal highway links). Freeways are omitted in the standard incremental run since, for cities of the size simulated, there are usually few, if any, freeway links used for intraurban travel.

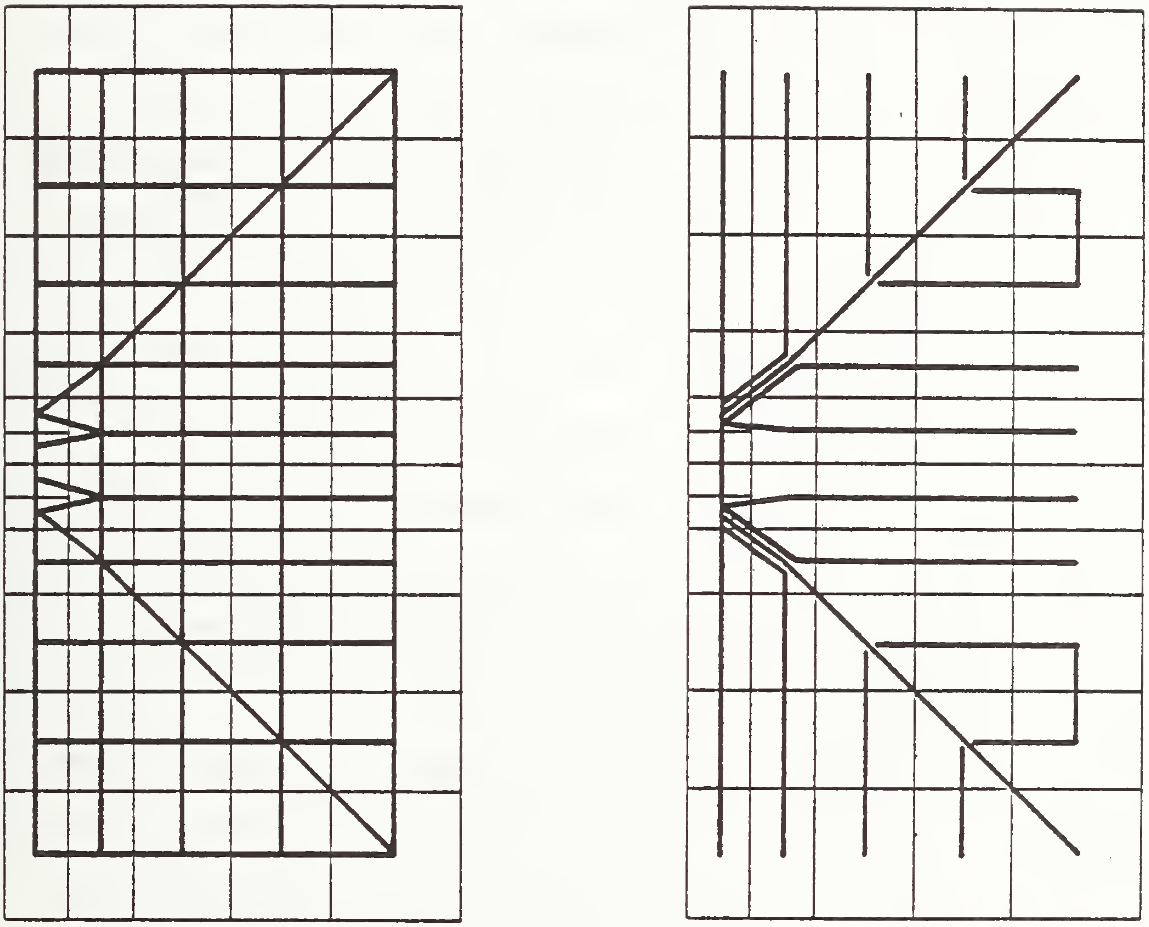
The transit network is representative of urban bus routes in typical U.S. cities in terms of route spacing, average link speeds, and frequency of service. The transit minimum time path algorithm in MOD3 is superimposed on the arterial street network. All routes begin and end at the city periphery and serve the CBD, as is common in many smaller U.S. cities.

The second test city, termed a one-sided city and shown in Figures 5-3 and 5-4, is essentially half of a larger concentric ring city and was selected to explore the relationship between transportation and land use in less symmetrical urban forms than the concentric ring city. This city contrasts with the concentric ring city in several ways. First, while the total area, 98 square miles, is similar, the CBD is twice as large, reflecting the tendency for dense growth in the central areas of coastal cities to sprawl along the coastline. Second, although the highway network is primarily a rectangular grid, there are two CBD-oriented diagonal arterial highways. Similar highways are found in representative U.S. cities. The overall similarity with the concentric ring city, in terms of zone sizes and general characteristics of the highway and transit networks, is intentional since the analysis is simplified if there is a high



		Basic Employment Density (employees per sq. mile)	
	Zones	Base Run	Standard Incremental Run
CBD:	1 - 4	1500	1000
Ring 1:	5 - 10	1000	292
Ring 2:	11 - 20	363	0
Ring 3:	21 - 34	0	0
Ring 4:	35 - 52	0	0

Figure 5-3. One-Sided City



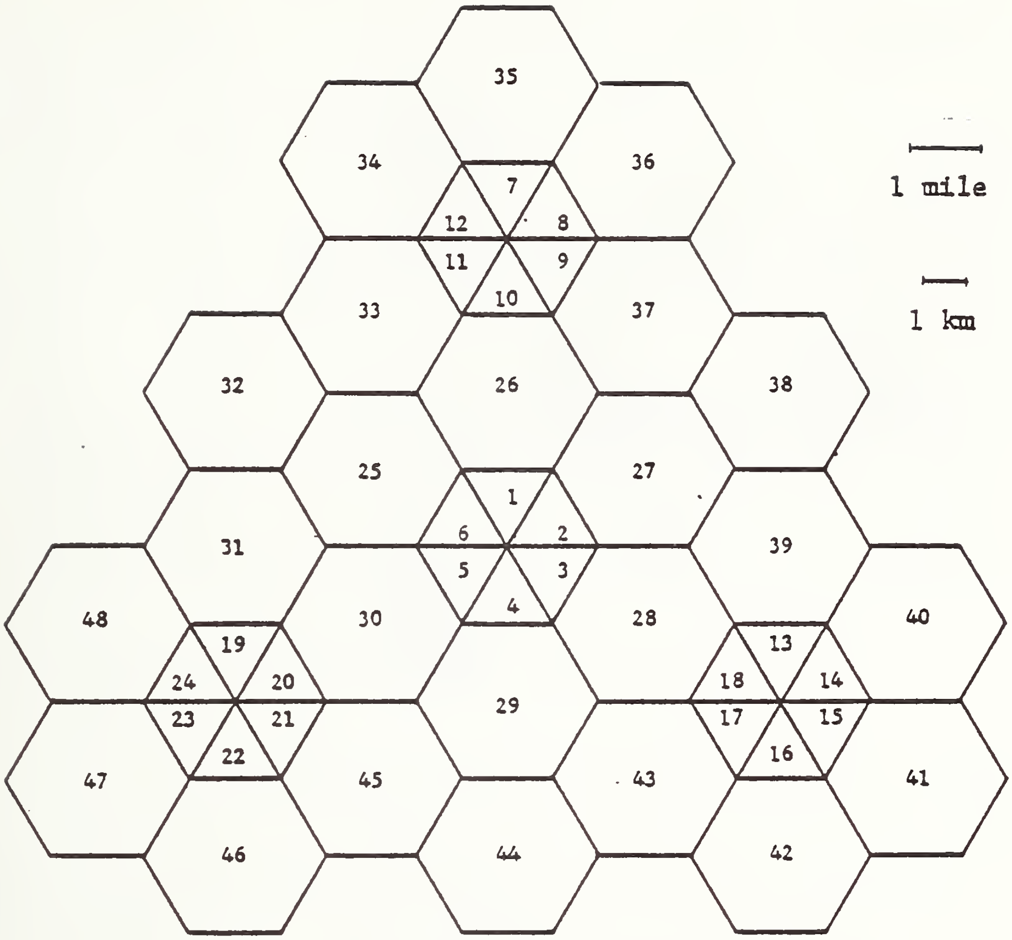
Highway Network

Transit Network

Figure 5-4. Transportation Networks in One-Sided City degree of structural comparability between the test cities.

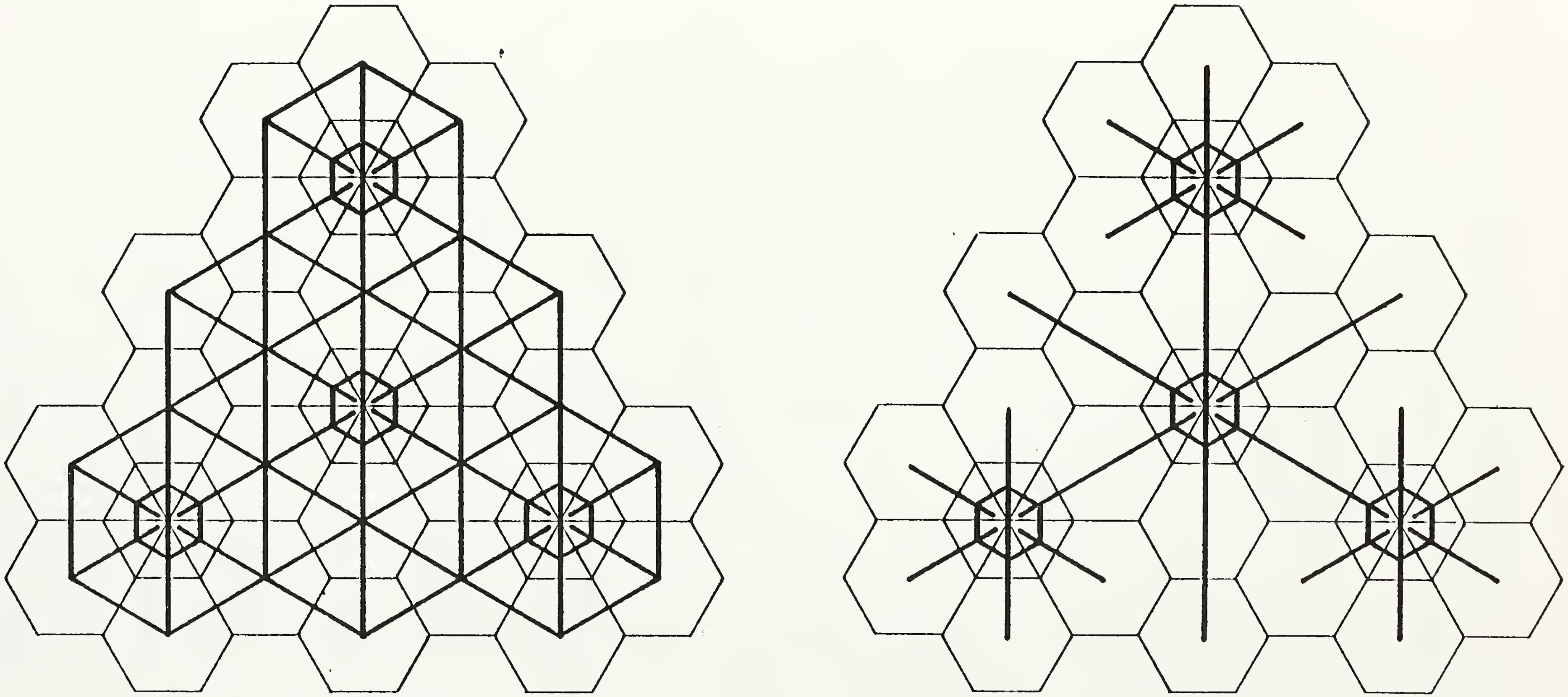
The design of the third test city was prompted more by the results of Edwards' research than by the frequency of its occurrence in the real world. This urban form is the polynucleated or multicentered city which was found to have the potential for great savings in transportation energy consumption. Aside from some of the new towns developed in the U.S. and Great Britain, there are no true multicentered cities of the size and degree considered in this research. It was hoped that further exploration of this urban form would increase the understanding of the relationship between transportation and land use.

Edwards' polynucleated and cruciform cities simply consisted of strings or fingers of zones radiating from a single zone or set of zones. With less than 25 zones, the degree of detail was quite limited. The polynucleated city simulated in this research, shown in Figures 5-5 and 5-6, consists of a more realistic set of three satellite subcenters about a central business district. Each of these nodes of development is composed of six zones. Surrounding the CBD and the subcenters are rings of larger zones which allow for sprawled development between the subcenters. There are only 48 zones, compared to 52 for the other two test cities, but the highway network is more complex due to the greater connectivity (as measured by the link to node ratio). This also resulted in more total roadway-miles of highways than the other two cities. These two measures are summarized for the test cities in Table 5-1. This lack of comparability resulted from the attempt to make the orientation of the triangular highway grid of the polynucleated city as similar as possible to the other cities by directing links toward the denser zones while, at the same time,



		Basic Employment Density (employees per sq. mile)	
	Zones	Base Run	Standard Incremental Run
CBD:	1 - 6	1283	521
CBD Ring:	25,27,29	53	0
	26,28,30	80	0
Subcenters:	7 - 12 13 - 18 19 - 24	107	0
Subcenter Rings:	33 - 37 39 - 43 45 - 48	27	0
Outlying:	32,38,44	0	0

Figure 5-5. Polynucleated City



Highway Network

Transit Network

Figure 5-6. Transportation Networks in Polynucleated City maintaining a similar city size. The area of the polynucleated city is 104.75 square miles.

Table 5-1. Total Roadway-Miles and Link-to-Node Ratio of Test Cities in Standard Incremental Run

City Type	Area (sq. mi.)	One-Way Roadway-Miles*	Link-to-Node Ratio*
Concentric Ring	100.00	232.640	3.538
One-Sided	98.00	264.472	3.731
Polynucleated	104.75	295.104	4.125

*Does not include intrazonal links

It would have been possible to design the cities so that total roadway-miles, roadway-miles per person, or roadway-miles per square mile was constant, but it is not clear how to construct such networks. Changes in the design would probably have given different numerical values in the experimental results, but not have changed the general conclusions.

Table 5-2 describes other structural, pricing, and behavior parameters that are uniform across all three hypothetical test cities in the standard incremental run.

C. Comparison of Results of Standard Incremental Runs Across Test Cities

As a basis for comparison in subsequent experiments, a standard incremental run was made for each of the test cities. A brief examination of some of the resulting characteristics, shown in Table 5-3, provides a starting point for the analysis. The first measure, and the most impor-

Table 5-2. Common Inputs for Standard Incremental Run for each Test City

Population	125,000 (25 percent increase from base run)
Location of Additional Basic Employment	53 percent in CBD, remainder in Ring 1 or subcenters
Gasoline Price	60 cents per gallon
Parking Cost	CBD: $2.50 per day for work trips $1.00 for non-work trips Ring 1 or Subcenters: half CBD rate Elsewhere: free
Transit Fare	35 cents with 10 cents transfer
Mode Split Model Coefficients (6)	calibrated for Pittsburgh
Base Travel Time Distributions (7)	from transportation study for Amarillo, Texas
Trip Generation Rates (8)	service type N: 0.2 non-home-based: 1.5 service type S: 0.3 social: 0.2 (one-way trips per household or employee)
Automobile Occupancy (9)	work: 1.2 non-home-based: 1.5 service: 1.6 social: 1.8

Table 5-3. Standard Incremental Run Outputs

	CITY TYPE		
Output	Concentric Ring	Polynucleated	One-Sided
Run Number	145	206	302
Total Energy Consumption (gallons/person)	1.083	0.466	0.837
Percent Total Energy Consumption by Transit	2.583	6.138	3.136
Work Trip Gasoline Consumption (gallons)	102,272	23,592	73,952
Work Trip Congestion Index	1.511	1.125	1.659
Total Automobile Vehicle-Miles Travelled	565,208	548,603	551,631
Average Auto Work Trip Length (miles)	2.837	1.993	2.583
Percent Work Trips by Transit	13.29	8.76	13.29
Second Moment of Population (person-miles^2)	116 x 10^4	249 x 10^4	183 x 10^4

tant for this research, is the total of automobile gasoline and transit fuel energy consumption converted to equivalent gallons of gasoline per person per day. This is computed using the following formulation:

$$\underset{\text{[gallons]}}{\text{total energy}} = \left(\underset{\text{[Btus]}}{\begin{matrix}\text{auto}\\ \text{gasoline}\end{matrix}} + \underset{\text{[Btus]}}{\begin{matrix}\text{transit}\\ \text{diesel fuel}\end{matrix}}\right)\left(\frac{\text{gallon}}{\text{125,000 Btus}}\right) \qquad (5\text{-}1)$$

It is immediately obvious that urban form is a vital factor since the concentric ring city consumes more than twice the energy of the polynucleated city. The difference between the two cities is even more distinct in terms of work automobile gasoline consumption. Part of the reason for this may be explained by the average automobile work trip congestion index, which is far higher in the case of the concentric ring city. Apparently, automobiles are travelling at faster, more energy-efficient speeds in the polynucleated city. It is important to note, however, that the energy costs for freight movement could be much higher in the polynucleated city. These costs are not considered in the analysis.

That the one-sided city is more energy-efficient than the concentric ring city is surprising since, intuitively, it would seem that it would be less efficient due to its asymmetrical spatial structure. The apparent reason for this is that the population density gradient is less steep for the one-sided city. It is interesting that the congestion index for the one-sided city is higher than that for the concentric ring city, especially since the average automobile trip length is shorter. Extremely high volumes on the highway links along the city "shoreline" connecting ring 2 to ring 3 are the reason for this.

The energy consumed by transit is a very small fraction of the total for automobile travel. Since it remains fixed in all experiments, except where transit service is altered, the influence of transit energy consumption is largely ignored in the rest of the analysis.

The total automobile vehicle-miles travelled (VMT) and percent of work trips by transit are similar for both the one-sided and concentric ring cities. This indicates that there is some degree of comparability between the transportation networks. The lower average automobile work trip length and work trip transit usage of the polynucleated city are probably due to its radically different spatial structure. Apparently, by location of basic employment in several clusters, rather than one, shorter work trips are possible since the model can allocate population closer to employment sites. The greater number of roadway-miles in the polynucleated city is another factor which can reduce congestion.

The second moment of population is presented because it will be used later in the analysis as a measure of spatial dispersion. Comparisons between test cities with this measure is difficult and perhaps misleading, however. While the centroid of population of the concentric ring city is very close to the geographic center, this is not the case for the one-sided city where the centroid is along the minor axis but not at the central business district. The second moment of population of the polynucleated city is much larger than those of the other two test cities due to the separation of the subcenters from the CBD.

This discussion is intended as a starting point for the analysis; as such, it provides some directions for further investigation of urban form. Most notable is the low transportation energy consumption of the polynucleated city. While there are no obvious representative cities of this form, the imposition of polynucleated <u>growth</u> on an existing urban form may be a promising possibility. Considering the broad range of values of the congestion index for work trips, it seems that some of the differences between urban forms may center on the structural characteristics of the highway networks. Later experiments investigate congestion effects, particularly in regard to highway network improvements, and alternative urban development patterns.

D. Ranking the Effectiveness of Alternative Policy Changes with Different Measures

The analysis of alternative policy actions begins with an examination of the effectiveness of a set of policy changes implemented in each of the test cities. Four different measures are used to rank the policies in terms of changes from the standard incremental run:

- total energy consumption
- average work trip congestion index
- total automobile vehicle-miles travelled
- average work trip opportunity cost.

Since the values of each of these measures are not uniform across the test cities in the standard incremental run, the percent change is used in the analysis.

Eight types of parameter changes, representative of possible actions that could be taken in the areas of encouraging changes in trend behavior, transportation network improvements, transportation pricing, and land use controls are examined individually in each of the test cities:

- increased work trip automobile occupancy = 1.8 (50 percent increase)
  = 2.4 (100 percent increase)
- increased gasoline price per gallon = $0.90 (50 percent increase)
  = 1.20 (100 percent increase)
  = 1.80 (200 percent increase)
- doubled work automobile parking cost
- free transit service
- elimination of transit service
- adding radial freeways from the CBD
- centralized growth at the CBD
- peripheral growth, in ring 2 of the concentric ring and one-sided cities, and in the subcenters of the polynucleated city.

In addition, in the case of the concentric ring and polynucleated cities, two more policy changes are examined:

- adding express radial transit service to the CBD
- adding circumferential transit service, in rings 1, 2, and 3 of the concentric ring city and around the CBD and subcenters of the polynucleated city.

The following subsections explain the four measures used in the evaluation and compare the rankings across city types. Important changes in the order of rankings for the different measures are also noted. The primary purpose here is to be descriptive and identify promising policy changes areas for further investigation.

1. Effectiveness Ranking in Terms of Total Energy Consumption

The most important evaluation criterion in this research is the total energy consumption required for passenger travel. The effectiveness ranking shown in Figure 5-7 includes transit energy consumption which is fixed except in those experiments where transit service is augmented or eliminated. The most obvious finding is the similarity in the ordering of the effectiveness of the alternative policy changes across the three test cities. This is an indication that there is some comparability between the test cities and potential for robustness in the policy evaluation. The lower sensitivity of the polynucleated city to policy changes is probably due to its lower congestion index and/or shorter work trips. The similar magnitudes of impact in the concentric ring and one-sided cities is expected since the structure of these two cities is so similar.

Encouraging increased average work trip automobile occupancy (simulating commuter carpooling) is the most effective policy change in reducing

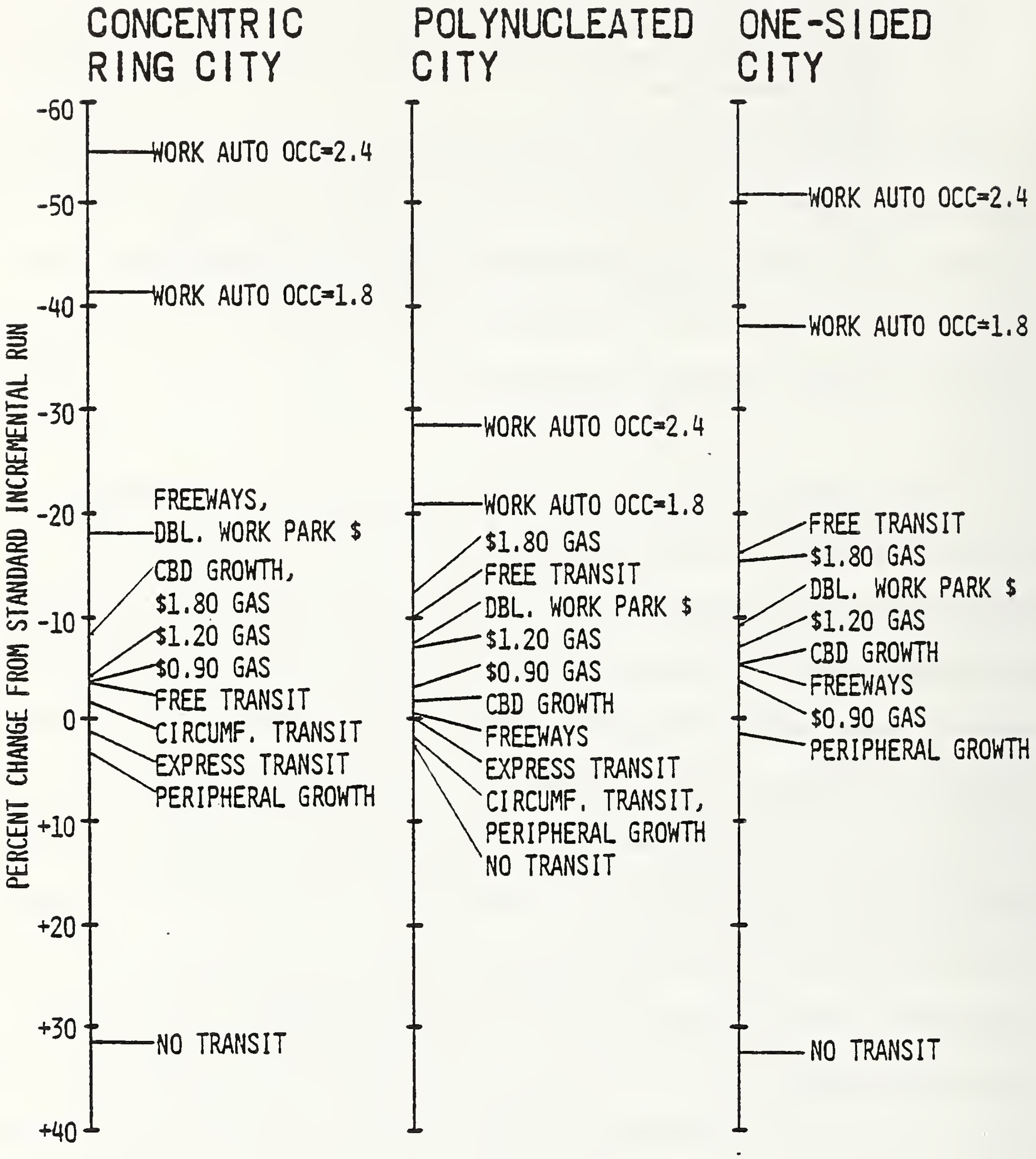


Figure 5-7. Effectiveness Ranking in terms of Total Energy Consumption

energy consumption. A principal reason for this is that, by reducing the total number of vehicles travelling, the average congestion on the highway network and vehicle-miles travelled are reduced. Surprisingly, eliminating transit as an alternative mode of travel resulted in the greatest increase in energy consumption. Apparently, this action forced onto the highway network many transit trips that were at or near the CBD, thereby aggravating the congestion problem on the most travelled portion of the highway network.

While removing transit greatly increased energy consumption, adding more transit service did little to improve transit usage and thus had little impact on improving energy consumption. In a few cases, the additional transit service actually resulted in a slight increase in total energy required for transportation. Adding radial freeways to the arterial highway network had very different impacts. Contrary to intuition, freeways seem to be a potentially important means of reducing energy consumption. Adding diagonal freeways to the rectangular grid network of the concentric ring city had the greatest impact. Replacing the already existing diagonal and left-side "shoreline" arterials of the one-sided city with freeway links was much less effective. Replacing radial arterials with freeways in the polynucleated city had nearly no impact. It thus appears that the structure of the highway network is most important in determining energy consumption. The precise nature of the difference between adding freeway links and replacing existing arterial links with freeways is an area for further analysis.

Experiments comparing the effects of CBD and peripheral growth show a small but potentially important tendency for CBD-oriented growth to reduce fuel consumption. This impact is most distinct in the concentric ring city which has the most clustered distribution of basic employment. In all cases, the peripheral growth pattern resulted in greater energy consumption than the standard incremental run.

In general, transportation pricing actions are not as effective as other policy changes that affected congestion more directly (such as carpooling, which reduced demand, or building freeways, which increased supply). Increases in the price of gasoline are not too influential until exceedingly high prices are reached. Doubling the commuter parking price is a generally more effective approach, particularly in the concentric ring city. This is because the increased parking costs produce a larger increase in the total trip cost than do higher gasoline prices. The impact of free transit service varies greatly across the three test cities. The reason for this policy action to be nearly four times as effective in the one-sided city than in the concentric ring city, even though transit usage is nearly identical in the standard incremental runs, seems to be the relative costs of highway travel near the CBD, the area where there is the most transit travel.

2. Effectiveness Ranking in Terms of the Highway Congestion Index

The importance of actions directly affecting the level of service on the highway network has been shown in the previous analyses. A convenient measure of level of service at the network level is the congestion index, the weighted average ratio (by link volume) of the actual to free-flow travel time for each link. This measure is used in the effectiveness ranking in Figure 5-8.

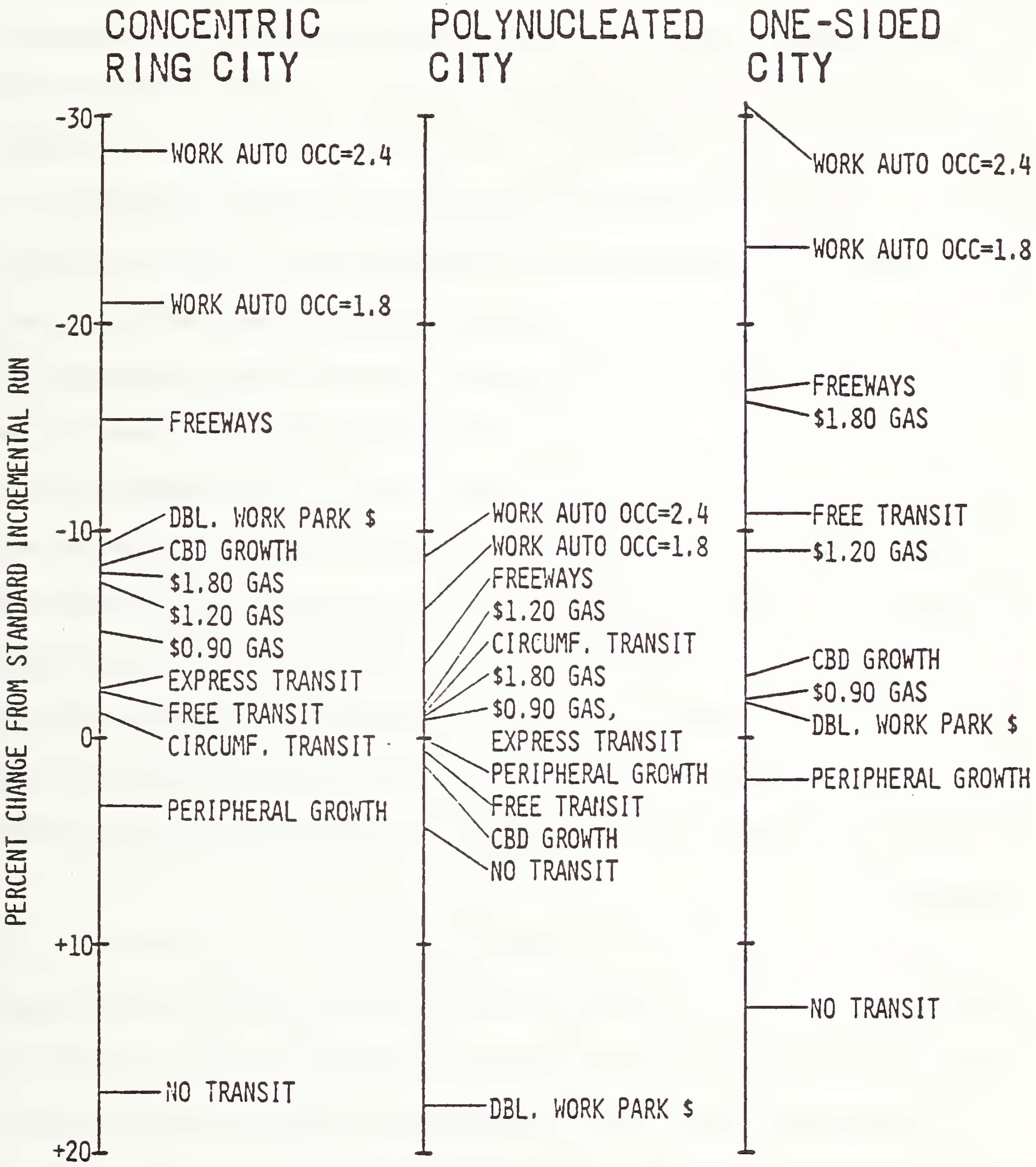


Figure 5-8. Effectiveness Ranking in terms of Work Trip Congestion Index

The most important observation is that the ordering of the ranking is almost identical to that in terms of total energy consumption. The one-sided and concentric ring cities, with similar rectangular grid highway networks, have very similar values for each policy action, except for increases in the price of gasoline, to which the one-sided city seems more sensitive. The major difference with the fuel consumption ranking is that the magnitudes of the impacts are much smaller. Part of the reason for this is that, although a strong relationship between energy consumption and highway congestion is beginning to emerge in the analysis, the relationship is indirect, both in the real world and in the model. Urban development tends to lag behind the construction of new highways in the real world. In time, this can result in greater congestion than before the highway improvement was made. In MOD3, the indirect relationship is due to the complex simulation framework and the characteristics of the highway assignment algorithm, notably the exponential congestion function. This is probably the reason for the lower sensitivity of the polynucleated city since it has a lower level of congestion in the standard incremental run.

There are two anomalies in the ranking for the polynucleated city that are of interest. The first is the apparent inversion of the order of the effectiveness of gasoline prices at $1.20 and $1.80 per gallon. A close examination shows that the values vary only by a fraction of a percent and are probably due to some oscillation in the highway assignment algorithm. The second anomaly is the large increase in congestion caused by doubling the commuter parking cost. A detailed examination of the highway link flows shows that the links leading in to the satellite subcenters from the CBD are heavily congested and account for the entire increase in the average congestion index for the network. This seems to be due, in part, to a 7 percent increase in population in each of the subcenters.

3. Effectiveness Ranking in Terms of Total Automobile VMT

Historically, automobile VMT has been an important aggregate measure of volume of travel. As such, it has been used as an indicator of fuel consumption in monitoring the impacts of various transportation policy changes. The major reason for this is the difficulty in obtaining accurate and timely gasoline sales data for a given urban area. The ranking of effectiveness of alternative policy actions in Figure 5-9 (when compared with Figure 5-7) shows that VMT may not be suitable as a surrogate of actual energy consumption. Measurement in terms of VMT exaggerates the impact of gasoline price changes and underestimates the impact of carpooling and increased commuter parking costs. In addition, this measure only shows that freeways increase total travel, but fails to show that they can, under some circumstances, encourage more energy-efficient travel. Further, measuring VMT fails to show the importance of maintaining the present level of transit service by underestimating the energy impact of eliminating transit service. These observations point out the importance of investigating the quality of highway travel (i.e., congestion) rather than simply the quantity of travel that takes place.

Some of the differences in the effectiveness rankings of the policy changes in terms of VMT compared to those in terms of total energy consumption and the work congestion index are due to the indirect relation-

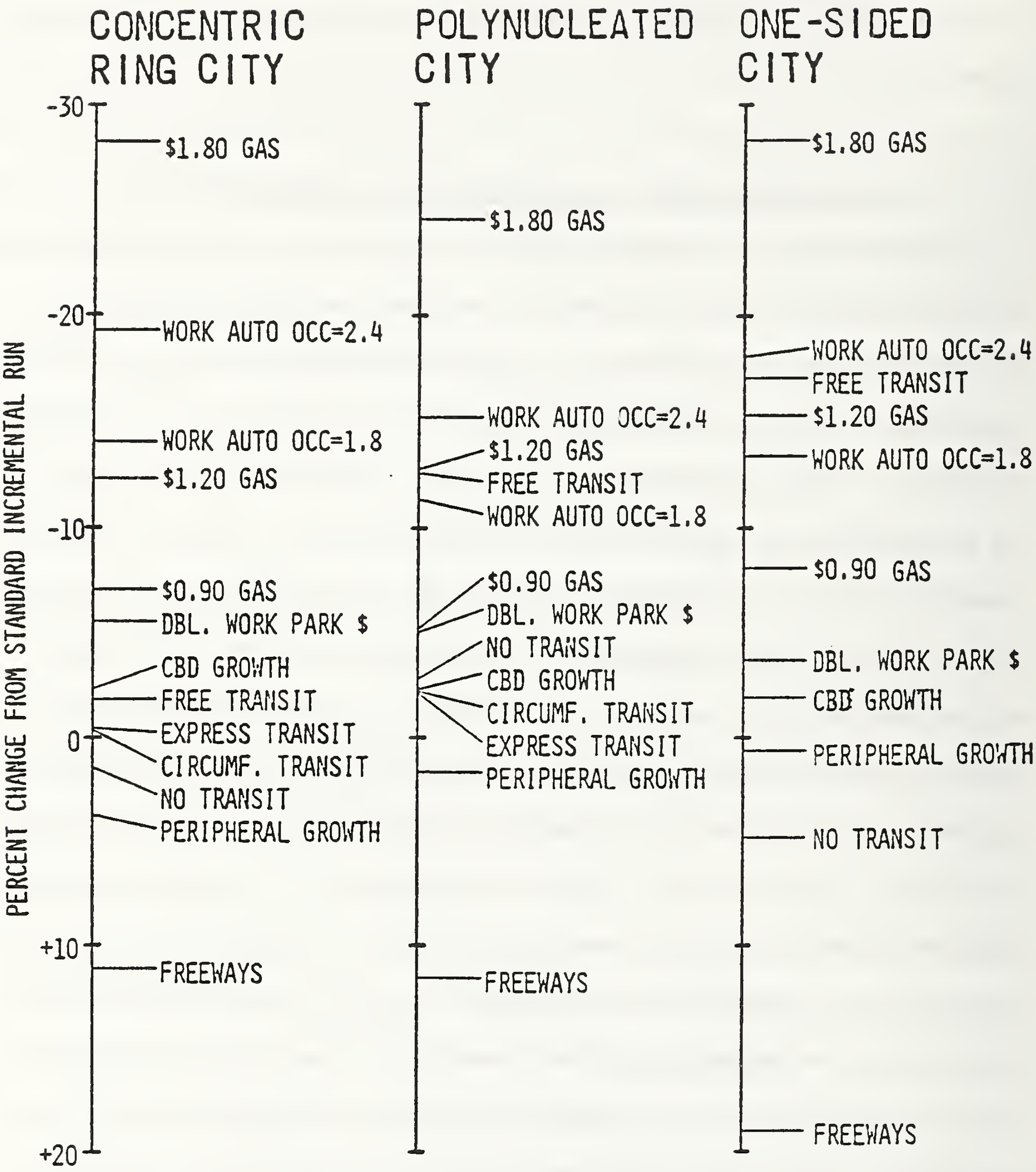


Figure 5-9. Effectiveness Ranking in terms of Total Automobile VMT

ships in the transportation/land use feedback and the non-linearity of the functions describing automobile gasoline consumption, highway congestion, mode split, and interzonal impedance to travel. Basically, this is an aggregation problem that can only be resolved with an analysis more detailed than possible for this research. VMT and the congestion index are descriptive of the highway network as a whole and do not accurately portray travel on the individual links, where the VMT/energy consumption relationship may be more straightforward.

4. Effectiveness Ranking in Terms of Average Work Opportunity Cost

The fourth measure used in ranking the effectiveness of the initial set of policy changes in the average generalized cost for all work trip linkages computed by a gravity model which ignores impedance to travel and bases accessibility solely on the relative number of destinations in each zone, i.e., the land use pattern determined by the model. The average value of this opportunity cost (10) distribution might be considered a quality of life measure in that it measures the cost separation of urban activity locations. It is potentially more useful than the regional accessibility value from the gravity model, in which impedance to travel is considered, since that measure depends directly on the exogenously specified travel time distribution of the base run.

The ranking shown in Figure 5-10 shows that policy changes which directly affect highway congestion result in the greatest reductions in work trip opportunity cost. This is important since two of these changes, increasing commuter carpooling and building freeways, are very effective actions in the energy consumption ranking discussed above. Policy changes

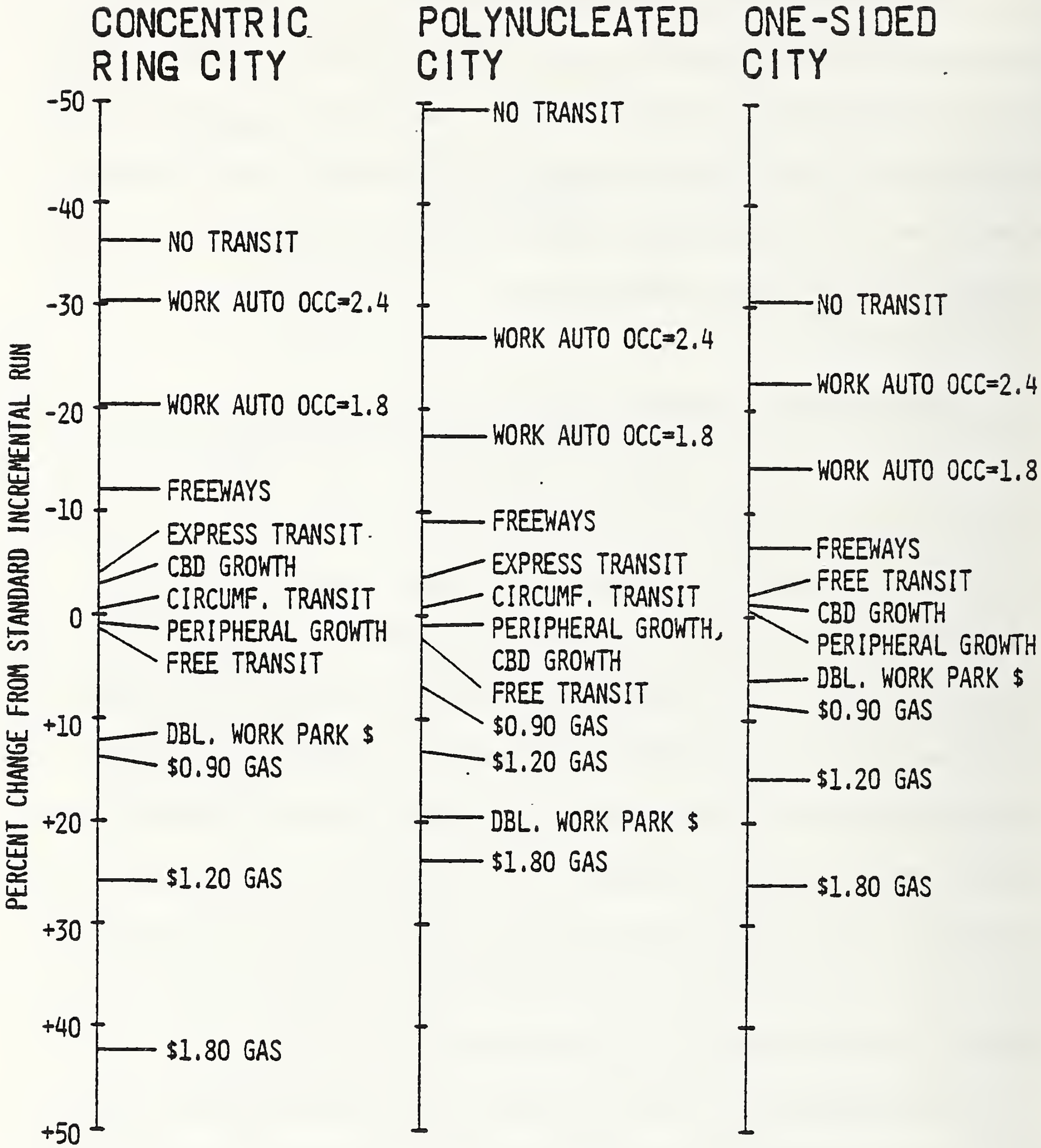


Figure 5-10. Effectiveness Ranking in terms of Average Work Opportunity Cost

which would tend to improve the quality of life as well as reduce energy consumption would probably gain public acceptance more easily. It is apparent though that part of the reduction in opportunity cost caused by carpooling is due to the sharing of costs rather than to the more energy-efficient speeds of automobiles.

Removal of transit, which was the worst policy change in terms of energy consumption, was the most effective means of reducing opportunity cost. Apparently, even though congestion increases greatly, the savings in travel time by those shifted from transit to automobile far exceeds the greater gasoline costs. It is possible this relationship could change, however, as the value of travel time changes.

The limited response to alternative urban growth policies is anticipated since the impact measured in the previous three rankings is small. That free transit service has no great impact on the average opportunity cost is explained by the generally low usage of transit and by the importance of the longer travel times by transit compared to those by automobile. The relatively large increase in opportunity cost caused by increased gasoline price is important since this action may be the only methodology, short of restricting supply through rationing, to directly control gasoline consumption. Further investigation of the price of gasoline is indicated.

5. Summary of Effectiveness Ranking Observations

The analysis thus far has indicated that policy actions which can directly affect the congestion on the highway network can be the most effective in reducing transportation energy consumption. This observation has been supported through confirming evaluations based on several interrelated measures. Three avenues of additional research have been identified. First is the simulation of alternative highway improvement policies. Constructing new freeways, as in the concentric ring city, would be a very expensive solution to reducing energy consumption. It is necessary to find out precisely what characteristics of such a network change are most important in reducing energy consumption. Second, it seems clear that shaping urban growth can be an effective means of reducing fuel consumption. Third, there appear to be some transportation pricing impacts whose exact nature have not been clearly defined in the effectiveness rankings. Changes in the price of gasoline warrant further investigation, if only because of the likelihood of price increases in the near future.

Beyond pointing the way for further analysis, the strong relationship between congestion and energy consumption in the effectiveness rankings indicated that the heart of the causal structure of the model, dealing with the transportation/land use feedback, is giving intuitively appeal-results. This provides some confidence in interpreting the results in the next part of the analysis.

E. Further Investigation of Promising Policy Changes

The general approach in the experimental program thus far has been to investigate briefly a broad array of policy actions in order to identify those which seem most promising. In this section, these policy actions are further investigated using two different approaches: policy excursions, successive experiments simulating a sequence of related policy actions, and in-depth study of some of the experiments briefly described in the effectiveness rankings. The transportation policy changes examined include alternative highway network improvements, further investigation of transit usage, pricing changes, and combinations of transportation policy actions. The land use policy changes concern the location of urban growth as determined by the exogenously specified placement of basic employment.

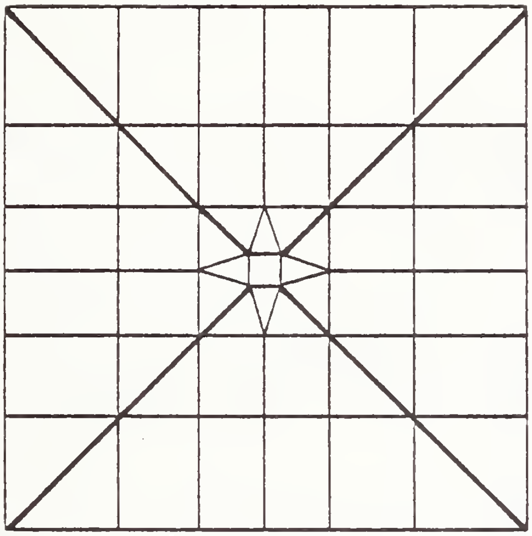
1. Highway Network Improvements

The rankings of effectiveness of policy changes reveal that there is considerable difference between test cities, especially the polynucleated city as compared to the concentric ring and one-sided cities, in the manner they respond to policy actions. This could be caused, in part, by differences in the arrangements of the respective highway networks. This could also explain the differences in the responses of the test cities when freeway links are added to the base arterial highway networks. Several policy excursions are analyzed in this subsection in terms of changes in energy consumption, automobile travel, and the land use pattern. It must be noted that the impacts that occur in these experiments are caused solely by the changes in the network structure. Trip generation rates for non-work trips are assumed to remain constant, even though relative interzonal accessibilities may increase dramatically in some cases. Further, it is assumed that population and services in the incremental layer of growth could not locate beyond the edge of the city defined in the base run. As seen later in the analysis, this may result in shorter trips than might be expected.

a. Freeways Added to the Concentric Ring City

The first policy excursion consists of two alternative arrangements of CBD-oriented freeways in the concentric ring city: adding diagonal freeway links to the arterial grid (experiment 149) and replacing axial arterials with freeway links (experiment 171). Figure 5-11 illustrated these alternatives and the experimental results shown in Table 5-4. While both network changes reduce energy consumption, the diagonal freeway is far superior, both in terms of work automobile gasoline consumption (reduced 25 percent) and total energy (reduced 17.9 percent). This increase in energy efficiency does not seem to be caused by an increase in transit utilization, but rather by a large (15 percent) reduction in congestion. Part of the reason the axial freeways result in greater average network congestion, and thus higher energy consumption, is that this arrangement adds fewer lane-miles to the highway network. Whereas the diagonal freeways provided 84.86 lane-miles of additional links, the axial freeways simply expanded already existing arterials in capacity, providing only 35 percent of the total lane-miles added by the diagonal freeways. The higher total fuel consumption in the case of the axial freeways is also explained by the 17.5 percent longer non-work automobile trips. Apparently, there are two processes at work here. One is the tendency for the network with the diagonal links to facilitate shorter trips. The other is that longer trips are being encouraged due to a diversion from the base arterial links to the faster freeway links. The diagonal freeways may be more energy-efficient because they combine the two processes, whereas the axial freeways induce only the second, detrimental process.

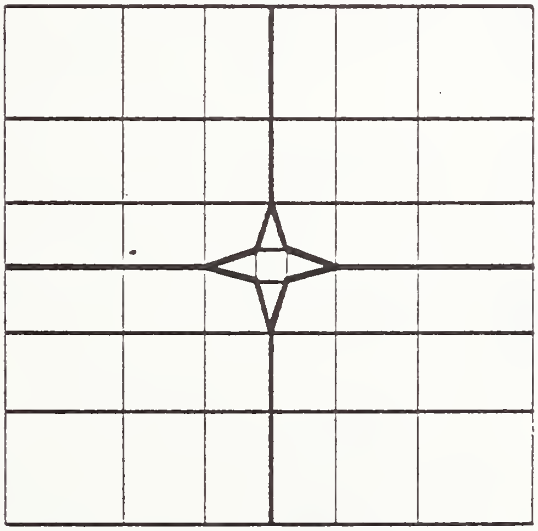
Experiment 149



Diagonal Freeways

(84.9 lane-miles added)

Experiment 171



Axial Freeways

(36.8 lane-miles added)

Figure 5-11. Alternative CBD-Oriented Freeway Additions to Concentric Ring City

Table 5-4. Impacts of Alternative CBD-Oriented Freeway Additions in Concentric Ring City

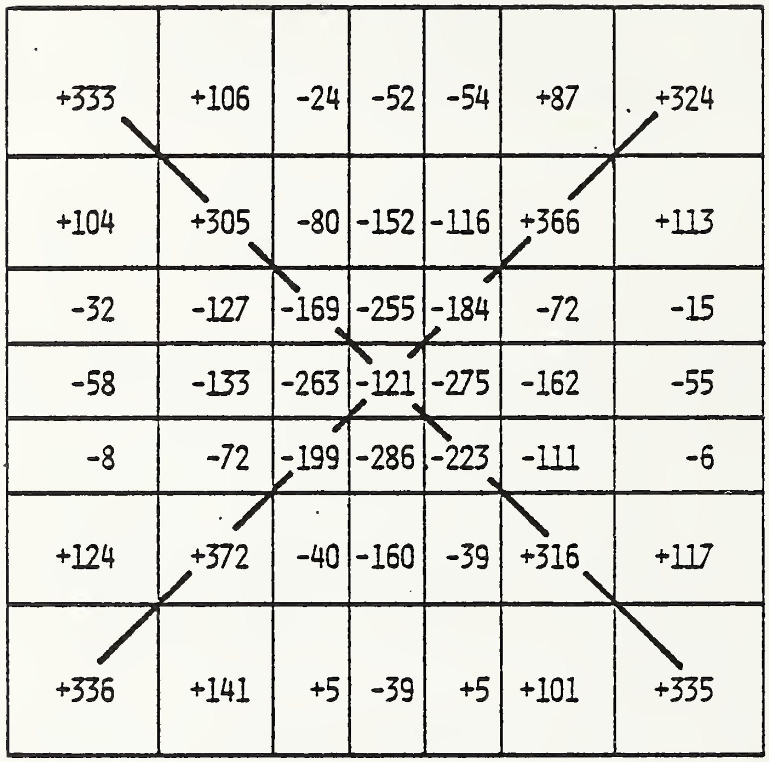
Run No.	Description	Total Energy $\left(\frac{\text{gallons}}{\text{person}}\right)$	Work Auto Energy (Btu $\times 10^6$)	Average Work Congestion Index	Average Auto Work Trip Length (miles)	Percent Work Trips by Transit	Average Non-Work Auto Trip Length (miles)	2nd Moment of Population (person-mi^2 $\times 10^2$)
145	Std. Incr. Run	1.083	12784	1.511	2.837	13.29	2.798	11608
149	Diagonal Freeways	0.889	9590	1.280	2.916	12.91	3.105	12206
191	Diagonal Arterials	0.905	10021	1.286	2.647	13.10	2.852	11942
171	Axial Freeways	1.072	12335	1.719	2.932	13.12	3.648	11770

Another explanation for the large differences between the effects of adding diagonal and axial freeways is the resulting allocation of added population. Figures 5-12 and 5-13 show the differences in population added per zone between the standard incremental run and the runs in which diagonal freeways and axial freeways are added, respectively. The diagonal freeways encourage growth along the diagonal route of the freeways in the outer two rings of zones with some spillover of growth to the adjacent zones in the outermost ring. Growth is discouraged in the CBD and the first ring.

The axial freeways induce a different type of growth. First of all, only 58 percent of the total number of people who are located in different zones by the diagonal freeways (compared to the standard incremental run) are located in different zones by this network change. Apparently, the axial freeways have a less powerful influence on urban growth. Second, while growth is encouraged along the route of the freeways in the outer two zones, there is no spillover into adjacent zones, as in the case of the diagonal freeways.

Since the network structure is very much altered by the addition of the diagonal freeway (increasing the link-to-node ratio from 3.54 to 4.00) and since the impacts of this change result in considerable energy savings, it seems reasonable to investigate the impacts of changes in structure alone (i.e., diagonal links imposed on a rectangular grid) as opposed to the impact caused by adding capacity and improving level of service on the existing links. In experiment 191 diagonal arterial links of lower capacity and free-flow speed than freeway, as described in Table 5-5, are added to the base highway network. The results of this experiment

Experiment 149



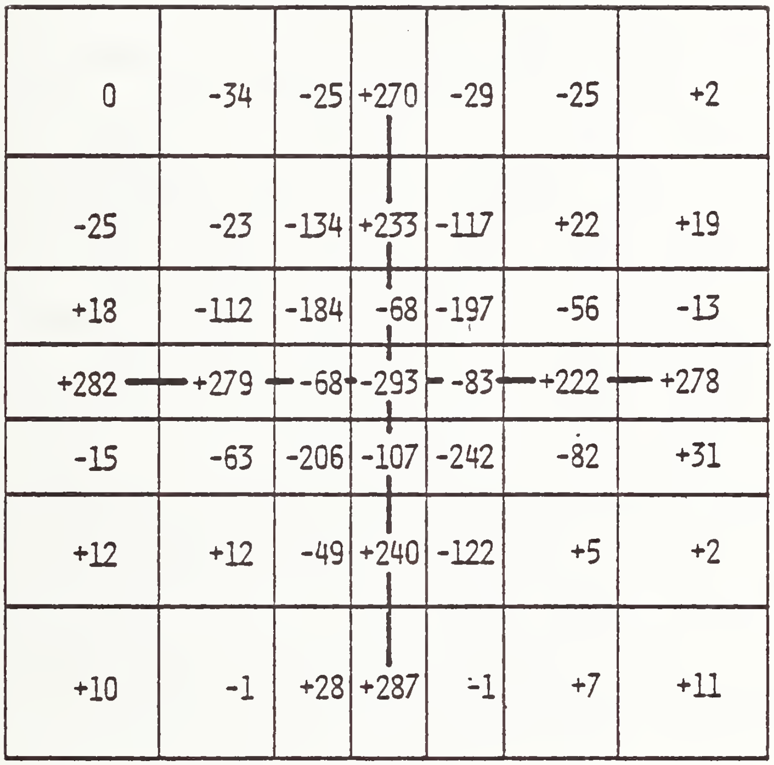
+333	+106	-24	-52	-54	+87	+324
+104	+305	-80	-152	-116	+366	+113
-32	-127	-169	-255	-184	-72	-15
-58	-133	-263	-121	-275	-162	-55
-8	-72	-199	-286	-223	-111	-6
+124	+372	-40	-160	-39	+316	+117
+336	+141	+5	-39	+5	+101	+335

values indicate change from standard incremental run

━━ denotes freeway route

Figure 5-12. Change in Population in Concentric Ring City due to Adding Diagonal Freeways

Experiment 171



0	-34	-25	+270	-29	-25	+2
-25	-23	-134	+233	-117	+22	+19
+18	-112	-184	-68	-197	-56	-13
+282	+279	-68	-293	-83	+222	+278
-15	-63	-206	-107	-242	-82	+31
+12	+12	-49	+240	-122	+5	+2
+10	-1	+28	+287	-1	+7	+11

values indicate change from standard incremental run

▬ denotes freeway route

Figure 5-13. Change in Population in Concentric Ring City due to Axial Freeways

Table 5-5. Characteristics of Additional or Improved Highway Links

Link	Free-Flow Speed (mph)	Free-Flow Capacity (one-way) (vehicles/hour)
Freeway	55	4000
Arterial	30	1000

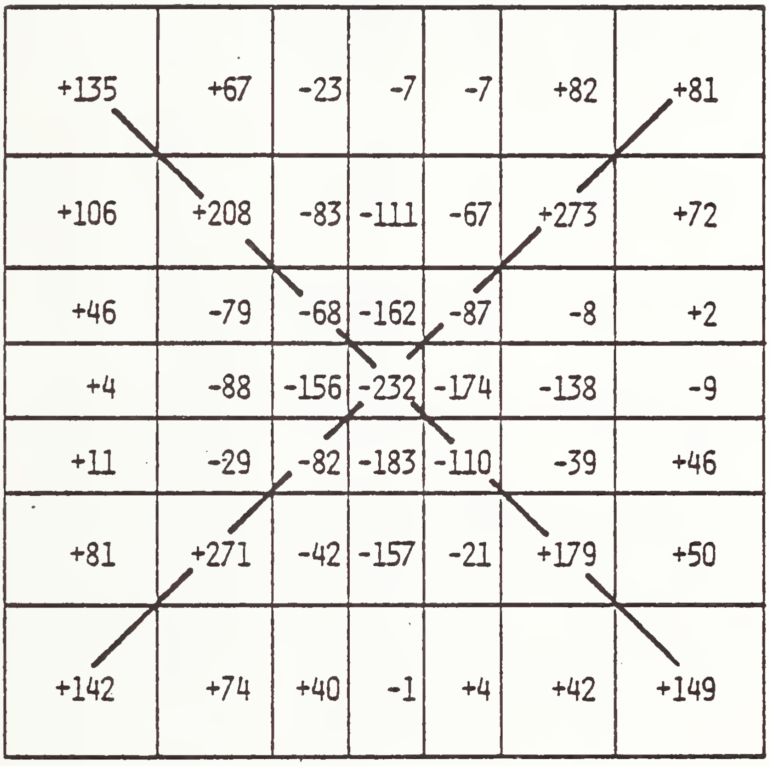
are also shown in Table 5-4. Energy consumption and congestion are both very similar to experiment 149 in which diagonal freeways are simulated. The major difference is that automobile trips are shorter with diagonal arterials. It seems clear that lower free-flow speeds of the diagonal arterials results in fewer trips being diverted from the rectangular grid arterials. This tends to offset the less energy-efficient speeds compared to the freeway links.

Diagonal arterials also result in a less dispersed layer of population growth. Figure 5-14 shows that, compared to diagonal freeways, less growth is encouraged at the periphery, especially at the extreme corners of the city, reflecting a greater relative accessibility of the CBD.

b. Freeways Added to the One-Sided City

The impact of diagonal highway links is further investigated by a series of experiments on the one-sided city, which includes two diagonal arterials along with the rectangular grid in the standard incremental run. Three alternative freeway patterns are shown in Figure 5-15 and the results of the experiments are shown in Table 5-6. In experiment 318, the left-side "shoreline" and diagonal arterials are replaced by

Experiment 191

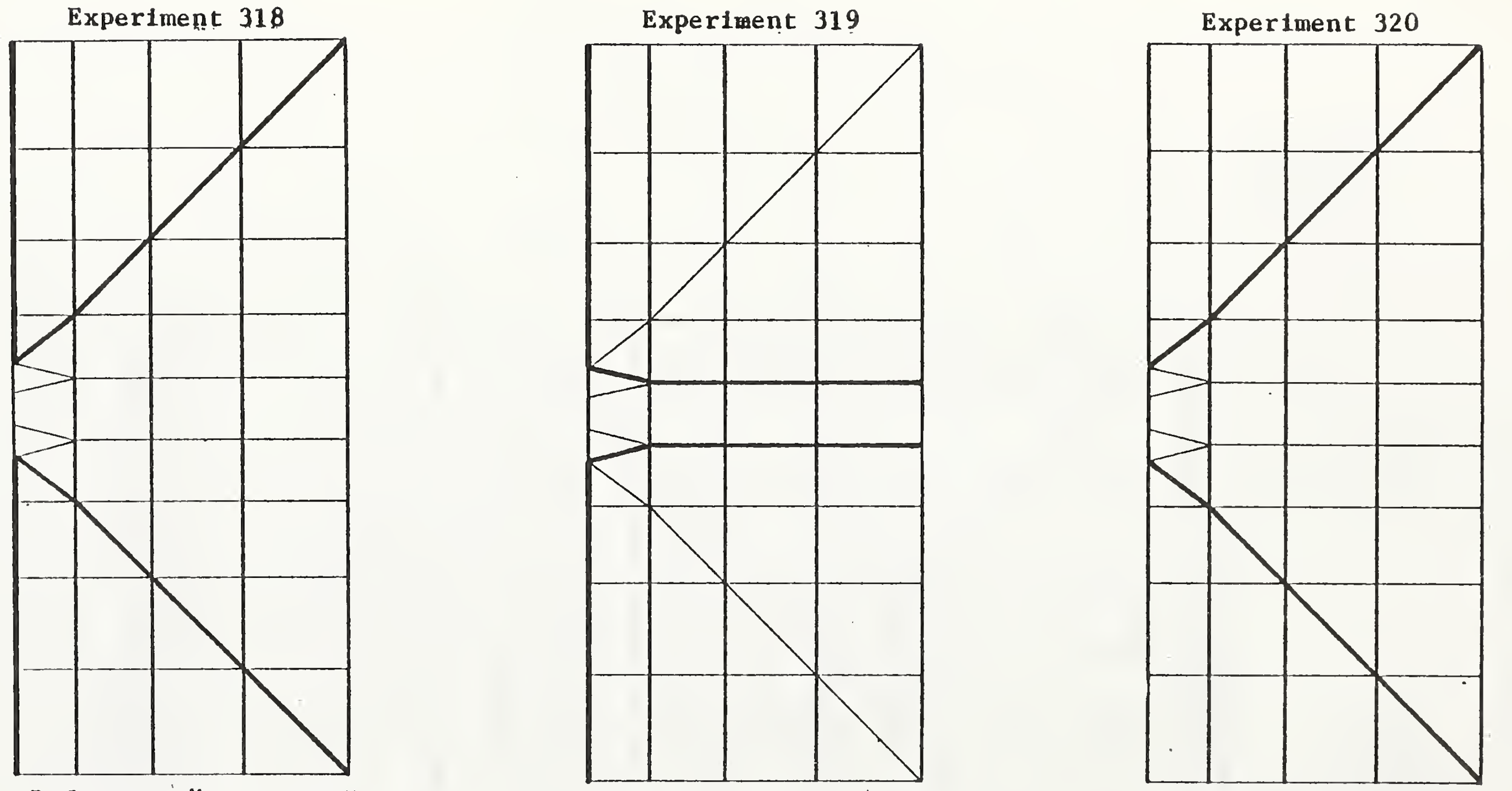


+135	+67	-23	-7	-7	+82	+81
+106	+208	-83	-111	-67	+273	+72
+46	-79	-68	-162	-87	-8	+2
+4	-88	-156	-232	-174	-138	-9
+11	-29	-82	-183	-110	-39	+46
+81	+271	-42	-157	-21	+179	+50
+142	+74	+40	-1	+4	+42	+149

values indicate change from standard incremental run

— denotes arterial highway route

Figure 5-14. Change in Population in Concentric Ring City due to Adding Diagonal Arterials.



Experiment 318

Left-Side "Shoreline"
and Diagonal Freeways

(102.9 lane-miles added)

Experiment 319

Left-Side "Shoreline"
and East-West Freeways

(86.0 lane-miles added)

Experiment 320

Diagonal Freeways

(60.9 lane-miles added)

Figure 5-15. Alternative CBD-Oriented Freeway Additions to One-Sided City

Table 5-6. Impacts of Alternative CBD-Oriented Freeway Additions in One-Sided City

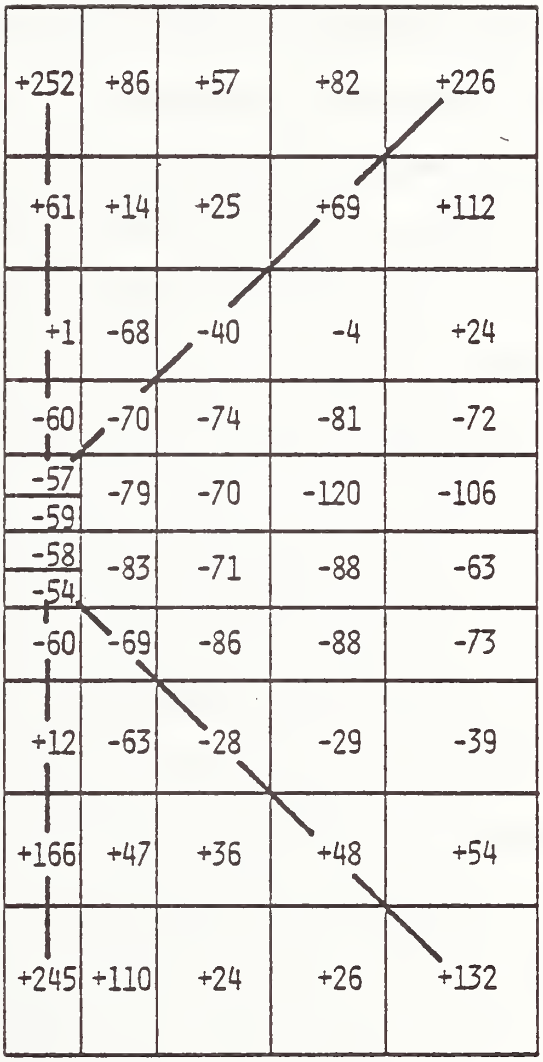
Run No.	Description	Total Energy (gallons/person)	Work Auto Energy (Btu x 10^6)	Average Work Congestion Index	Average Auto Work Trip Length (miles)	Percent Work Trips by Transit	Average Non-Work Auto Trip Length (miles)	2nd Moment of Population (person-mi^2 x 10^2)
302	Std. Incr. Run	0.837	9244	1.659	2.583	13.29	3.165	18324
318	Shoreline and Diagonal Freeways	0.793	8191	1.383	2.973	12.68	3.657	18876
319	Shoreline and East-West Fwy.	0.814	8455	1.385	2.894	12.67	3.889	18514
320	Diagonal Freeways	0.800	8452	1.477	2.769	12.97	3.389	18693

freeways. This is the freeway pattern in the effectiveness ranking analysis. Work trip congestion is reduced 16.6 percent, more than by experiment 149, in which four diagonal freeways are added to the concentric ring city. The reduction in energy consumption is not as drastic, however. Work gasoline consumption decreased 11.4 percent and total energy consumption dropped 5.3 percent compared to the standard incremental run. Even though this network change results in more energy-efficient travel, automobile work trips increased in length by 15.1 percent and non-work trips increased by 15.5 percent. Although the diagonal distance between zones is shorter than the rectilinear distance, trips normally taken on the rectangular grid are apparently being diverted along a longer path to the faster freeway links.

Longer trips may also be encouraged by the altered distribution of the incremental layer of population, shown in Figure 5-16. In a manner similar to the impact of the diagonal freeways in the concentric ring city, population is attracted along the route of the freeways in the outer two rings. Population is also attracted to the zones in the outer two rings between the "shoreline" and diagonal freeways, an area which apparently has a higher relative accessibility than the area between the diagonal freeways, which lost population compared to the standard incremental run.

The impact of diagonal freeways is further investigated in the next two experiments. In experiment 319, freeways replaced the "shoreline" and two east-west arterial routes radiating from the CBD. The intent is to simulate a purely rectangular grid freeway network yet keep the number of lane-miles improved as close as possible to experiment 318. While

Experiment 318



+252	+86	+57	+82	+226
+61	+14	+25	+69	+112
+1	-68	-40	-4	+24
-60	-70	-74	-81	-72
-57 -59	-79	-70	-120	-106
-58 -54	-83	-71	-88	-63
-60	-69	-86	-88	-73
+12	-63	-28	-29	-39
+166	+47	+36	+48	+54
+245	+110	+24	+26	+132

values indicate change from standard incremental run

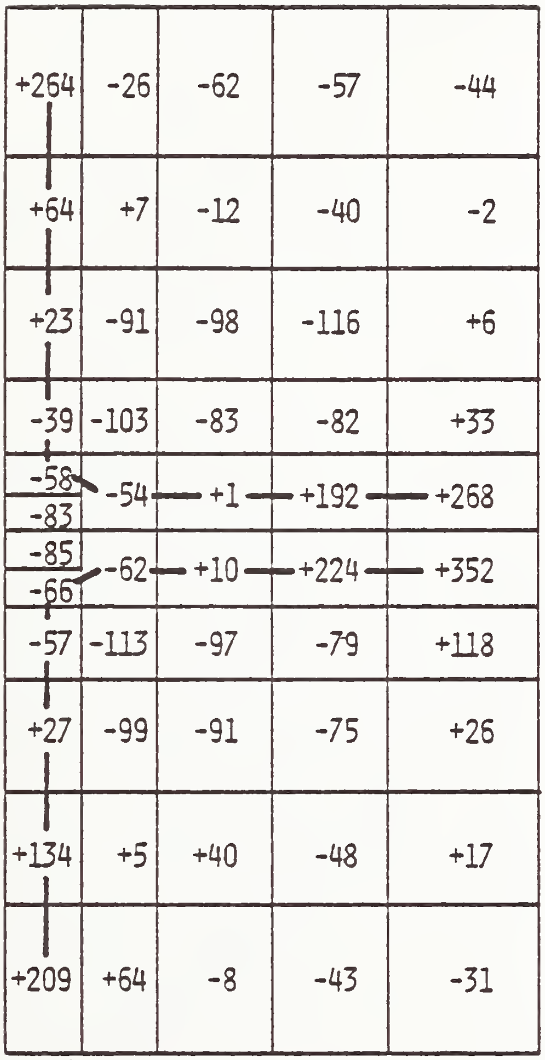
━ denotes freeway route

Figure 5-16. Change in Population in One-Sided City due to Left-Side "Shoreline" and Diagonal Freeways there is little change in congestion compared to the previous network, the resulting travel is not quite as energy-efficient. Although the average automobile work trip length decreases slightly, non-work trips are 6 percent longer. The change in population growth, shown in Figure 5-17, is mostly along the freeway routes, with only the slightest spillover to adjacent zones. Still, this freeway network shifts the location of 9 percent more persons than the network in experiment 318.

In experiment 320, freeways replace only the diagonal arterials. Compared to experiment 319, congestion is higher but the total fuel consumption remains the same. Automobile trips are 7 percent longer, however. It appears that the trend observed in the case of the concentric ring city regarding the impact of additional lane-miles on the highway network continues to hold in the case of the one-sided city. Experiment 320 adds only 59 percent of the number of lane-miles added in experiment 318 and only 71 percent of that added in experiment 319. This experiment also has the highest congestion in the series of experiments. Energy consumption in experiment 320 is similar to the standard incremental run primarily because of the allocation of the incremental layer of population. As shown in Figure 5-18, population shifts (compared to the standard incremental run) are along the route of the freeways with considerable spillover to adjacent zones in the outer two rings. The total number of persons shifted is only 63 percent of the total shifted in experiment 318, however. By shifting fewer persons and thus maintaining short trip lengths, the diagonal freeways keep energy consumption from increasing even though congestion does increase.

As with the concentric ring city, it appears that the arrangement of

Experiment 319



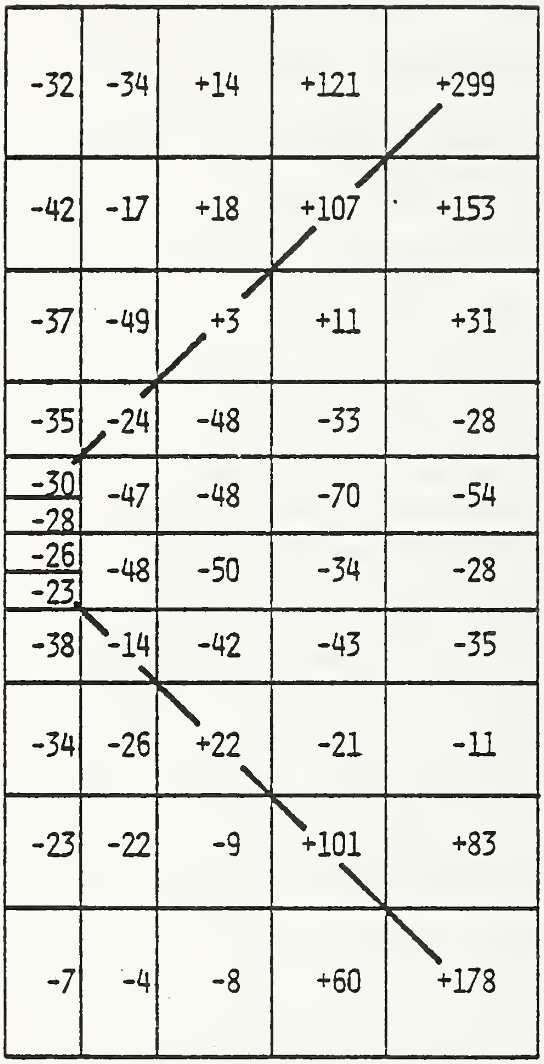
+264	-26	-62	-57	-44
+64	+7	-12	-40	-2
+23	-91	-98	-116	+6
-39	-103	-83	-82	+33
-58 -83	-54	+1	+192	+268
-85 -66	-62	+10	+224	+352
-57	-113	-97	-79	+118
+27	-99	-91	-75	+26
+134	+5	+40	-48	+17
+209	+64	-8	-43	-31

values indicate change from standard incremental run

—— denotes freeway route

Figure 5-17. Change in Population in One-Sided City due to Left-Side "Shoreline" and East-West Freeways

Experiment 320



-32	-34	+14	+121	+299
-42	-17	+18	+107	+153
-37	-49	+3	+11	+31
-35	-24	-48	-33	-28
-30 -28	-47	-48	-70	-54
-26 -23	-48	-50	-34	-28
-38	-14	-42	-43	-35
-34	-26	+22	-21	-11
-23	-22	-9	+101	+83
-7	-4	-8	+60	+178

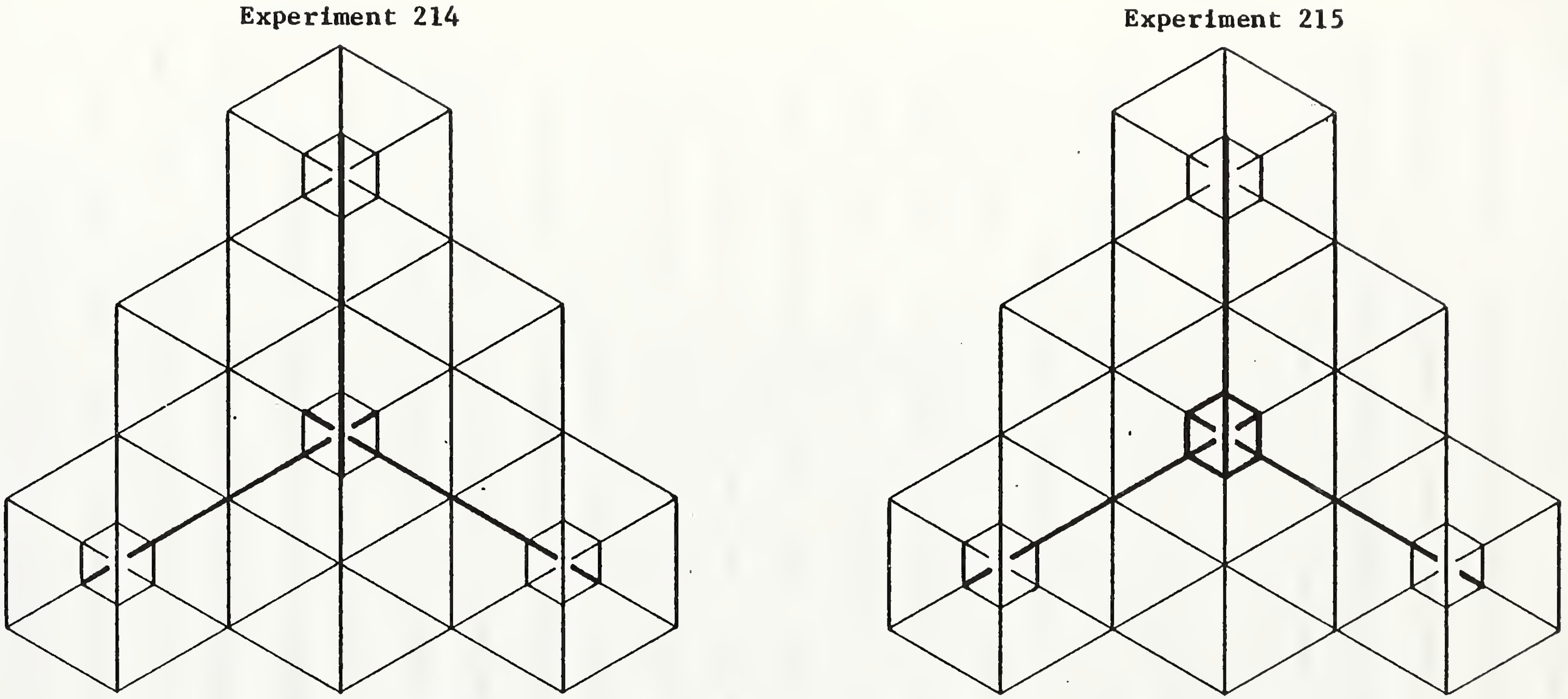
values indicate change from standard incremental run

▬ denotes freeway route

Figure 5-18. Change in Population in One-Sided City due to Diagonal Freeways highway improvements is more important than the total lane-miles of capacity added. Diagonal freeways imposed on a rectangular grid seem to be the best approach, especially in terms of cost-effectiveness. Further experiments with diagonal freeways of greater capacity than those in experiment 320 would probably have resulted in decreased energy consumption and only slight increases in trip length compared to the standard incremental run.

c. Freeways Added to the Polynucleated City

Further investigation of the freeway pattern imposed on the polynucleated city in the effectiveness rankings is warranted for two reasons. First, since freeways have been shown to reduce congestion, it would be interesting to observe the impact of freeways in a city where congestion is low in the standard incremental run. Second, the radial arrangement of subcenters might be an important factor in freeway use, particularly in light of the tendency for freeways to shift population away from the CBD in previous experiments. The freeway pattern originally simulated in the effectiveness rankings (experiment 214) is shown in Figure 5-19 along with a modification (experiment 215) in which the arterial ring in the CBD is converted to freeways. The results are summarized in Table 5-7. In experiment 214, congestion reduction was slight but gasoline consumption for work trips was reduced 8.7 percent. Total energy consumption remained the same as for the standard incremental run, due primarily to much longer non-work automobile trips. It must be noted that the decrease in automobile work trip length is opposite of the trend observed in the concentric ring and one-sided cities. This seems to be due to the shifted allocation of population, shown in Figure 5-20.



Experiment 214

Radial Freeways

(66.5 lane-miles added)

Experiment 215

Radial Freeways and
Circumferential Freeway in CBD

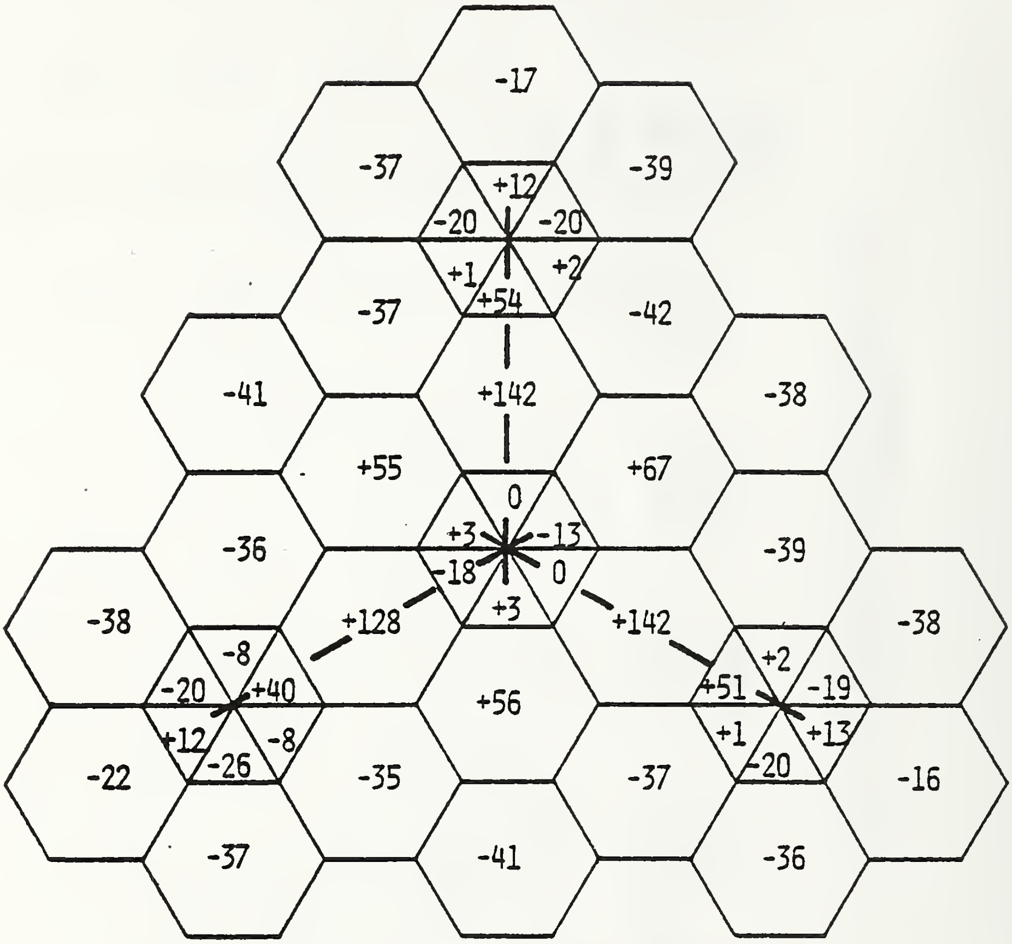
(83.2 lane-miles added)

Figure 5-19. Alternative CBD-Oriented Freeway Additions in Polynucleated City

Table 5-7. Impacts of Alternative CBD-Oriented Freeway Additions in Polynucleated City

Run No.	Description	Total Energy $\left(\frac{\text{gallons}}{\text{person}}\right)$	Work Auto Energy (Btu x 10^6)	Average Work Congestion Index	Average Auto Work Trip Length (miles)	Percent Work Trips by Transit	Average Non-Work Auto Trip Length (miles)	2nd Moment of Population (person-mi^2 x 10^2)
206	Std. Incr. Run	0.466	2949	1.125	1.993	8.37	3.001	24931
214	Radial Freeways	0.463	2692	1.085	1.809	8.63	3.486	24820
215	Radial and CBD Freeways	0.467	2725	1.112	1.710	8.71	3.677	24704

Experiment 214



values indicate change from standard incremental run

▬ denotes freeway route

Figure 5-20. Change in Population in Polynucleated City due to Radial Freeways

Population is attracted along the route of the freeways between the satellite subcenters and the CBD and to the ring of zones surrounding the CBD. The zones with the greatest change in population are thus the three between each of the subcenters and the CBD.

In experiment 215, with the additional ring of freeways around the CBD, there was a slight increase in fuel consumption, particularly work gasoline consumption. The most notable difference with experiment 214 is the longer average non-work automobile trip length. Like the other test cities, this is probably due to trips being diverted from the arterial highways to the faster freeway links.

d. Summary of Freeway Impacts

Providing diagonal freeways to a rectangular arterial highway grid seems to be the best highway improvement in terms of reducing total energy consumption. It seems clear though that adding highway capacity in this manner will result in some diversion of trips from shorter paths due to the faster travel times on the less congested freeway links. For these policies to have the maximum impact, it may be necessary to control the pattern of the resulting growth. The tendency for freeways to draw population away from the CBD may result in less energy-efficient travel beyond the planning horizon of this study. This is particularly true if some of the simplifying assumptions implicit in the model are relaxed. These include the assumption of a fixed boundary around the city and no change in the trip generation rates. The impact of imposing an "edge" to the city is discussed later in the analysis.

e. Further Investigation of Congestion Impacts

A sensitivity analysis on highway capacity was performed to confirm the important influence of congestion on transportation energy consumption. For both the concentric ring and polynucleated cities, all links in the highway network were reduced in free-flow capacity by 10 (polynucleated city only), 20, and 40 percent. The results are presented in Table 5-8 in terms of percent changes from the standard incremental run. The concentric ring city is more sensitive to capacity reductions in terms of increases in the congestion index and energy consumption. Surprisingly, the polynucleated city was more sensitive with regard to the average automobile trip length, principally because this is very short in the standard incremental run. Considering the exponential nature of the

Table 5-8. Sensitivity Analysis of Highway Network Capacity

		Percent Change from Standard Incremental Run				
Run No.	Description	Total Energy	Work Auto Energy	Average Work Congestion Index	Average Auto Work Trip Length	Total Auto VMT
Concentric Ring City						
403	Reduce Capacity 20 percent	+5.26	-7.03	+27.66	-2.40	-0.79
404	Reduce Capacity 40 percent	+15.05	-20.08	+100.07	-7.61	-3.03
Polynucleated City						
220	Reduce Capacity 10 percent	+0.86	+2.03	+4.08	-1.71	-0.45
221	Reduce Capacity 20 percent	-0.64	-1.29	+7.11	-4.87	-1.33
224	Reduce Capacity 40 percent	+0.64	+3.53	+29.87	-9.08	-2.55

congestion function, it is not surprising to note that the concentric ring city, with a fairly large congestion index in the standard incremental run, experiences relative changes in congestion larger than the relative changes in capacity reduction.

Figure 5-21 shows the total transportation energy consumption plotted as a function of the average work trip congestion index for all 111 experiments conducted in this research. The data points are clearly clustered by city type. The energy consumption of the concentric ring city seems most sensitive to congestion, with the data points falling on the steepest line. The polynucleated city is least sensitive, with points falling on a nearly flat line. This confirms observations made on a limited number of experiments earlier in the analysis.

Another representation of the importance of congestion is shown in Figure 5-22 which is a plot of percent changes in total energy consumption as a function of percent changes in congestion for the concentric ring and one-sided city experiments. The curve defined by the data points for both cities further confirms the strong relationship between congestion and energy consumption. Polynucleated city data points are not plotted due to large and misleading perturbations from the curve due primarily to insignificant changes from the already low congestion index values.

Figure 5-23 is a plot of total energy consumption as a function of average automobile work trip length for all experiments. Work trip length alone is used since these trips are major consumers of energy in the experiments and are the basis for the transportation/land use feedback in the model. The relationship between fuel consumption and work

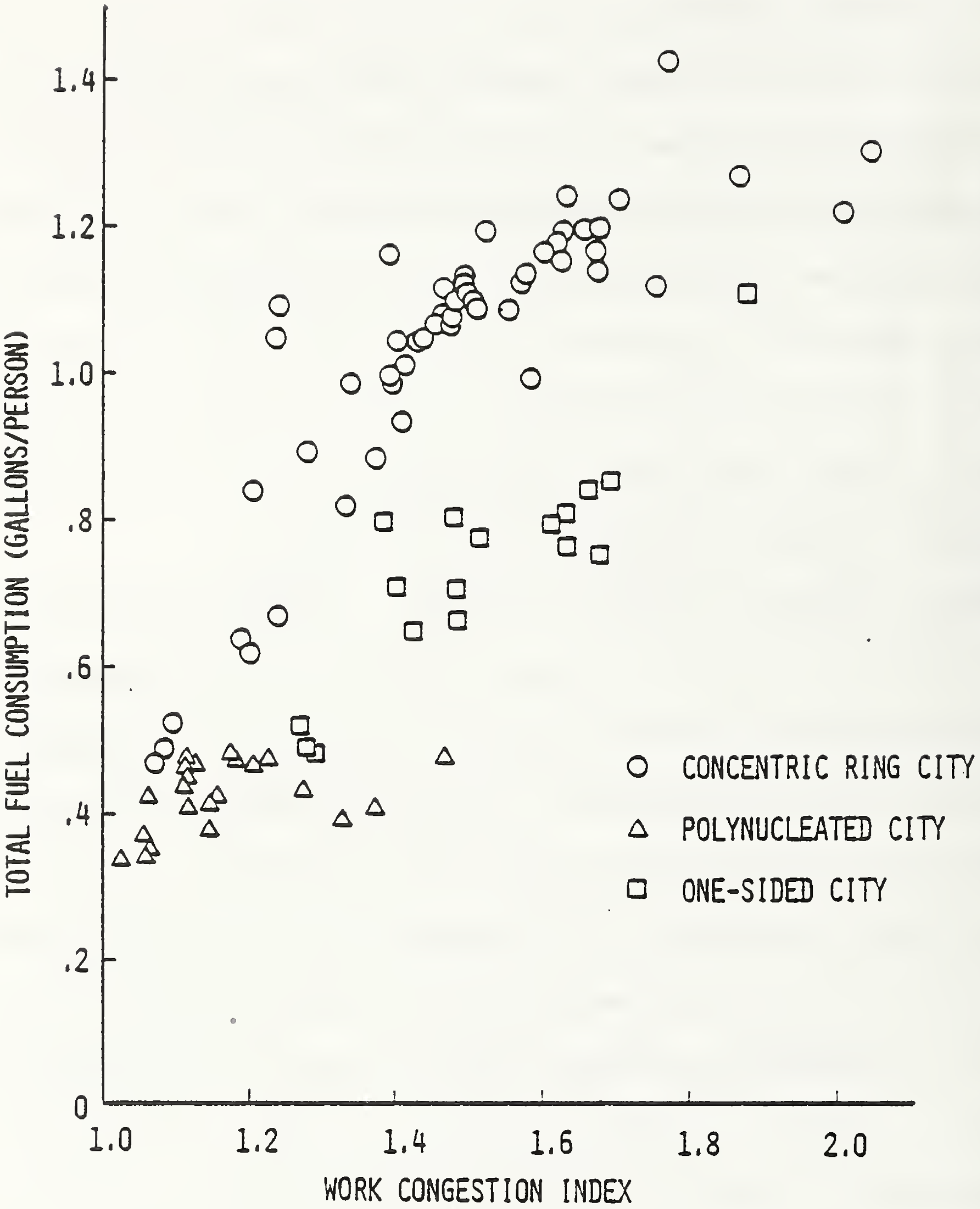


Figure 5-21. Effect of Work Trip Congestion Index on Total Energy Consumption

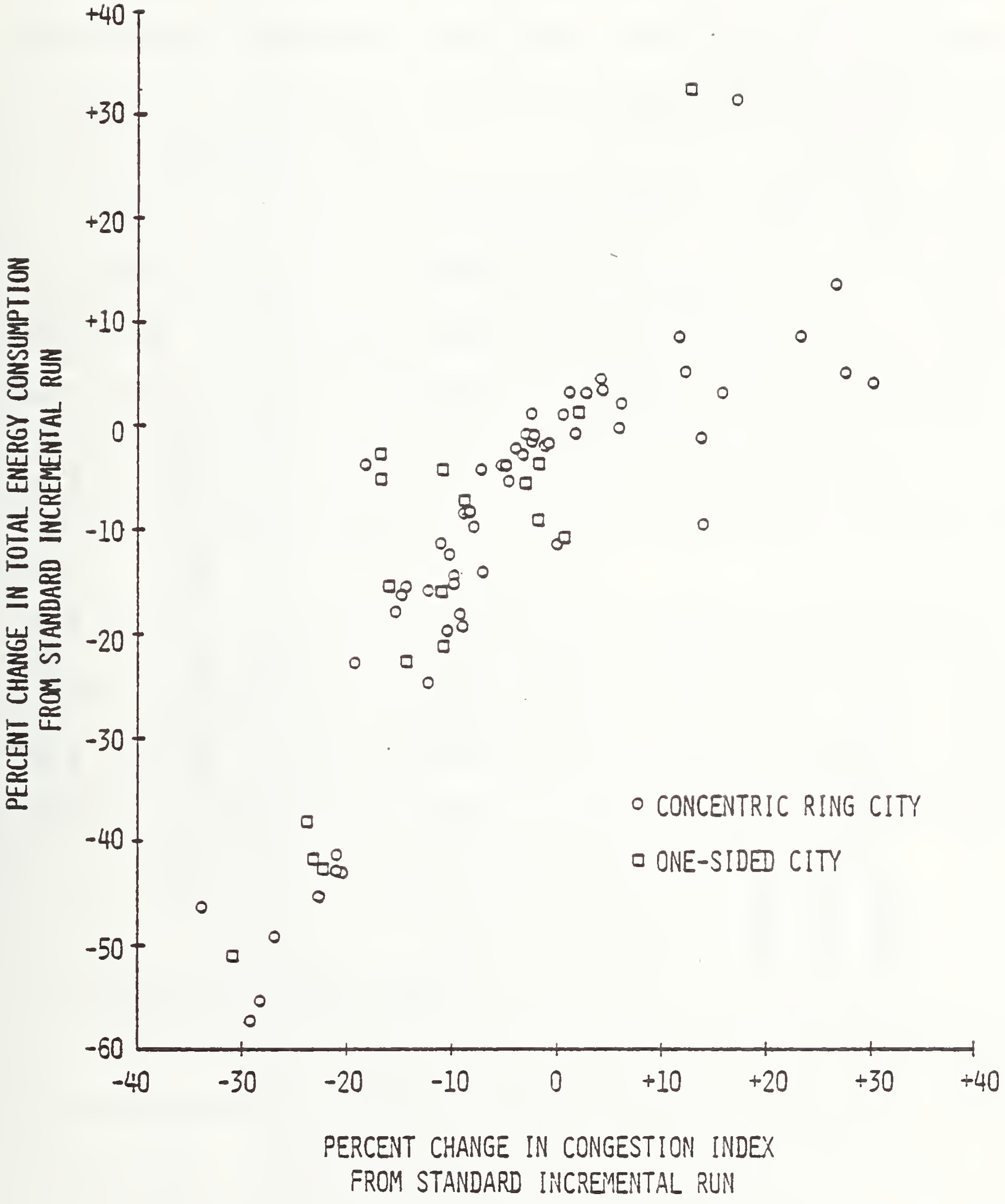


Figure 5-22. Effect of Change in Work Trip Congestion Index on Change in Total Energy Consumption

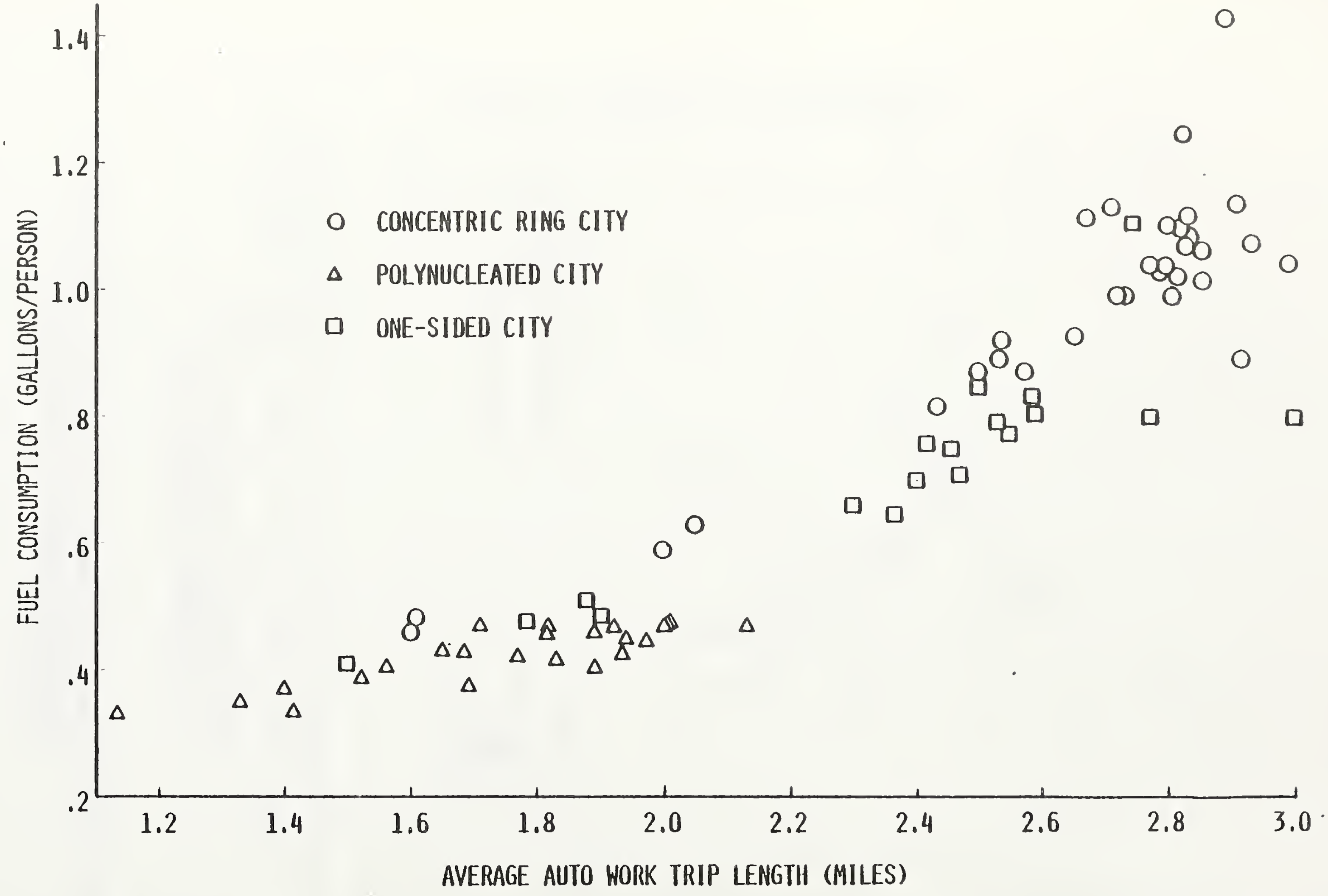


Figure 5-23. Effect of Automobile Work Trip Length on Total Energy Consumption

trip length is shown to be very strong and consistent across all city types. Average automobile work trip length thus seems to be a good indicator of energy consumption, even though total VMT can be misleading. The question must be raised at this point whether it is possible to get people to live closer to work.

Figure 5-24 combines the independent variables of the last two analyses, plotting the work trip congestion index as a function of work trip length for all experiments. There appears to be some indication that longer work trips result in greater congestion. This is intuitively appealing since longer trips mean more automobiles travelling on more links on the highway network, thus raising the congestion index on those links.

In summary, it has been shown that total energy consumption is a function of congestion which, in turn, is in part a function ot work trip length. The land use pattern is the major determinant of the length of work trips. Further investigation of urban development policies which can direct urban growth is discussed in a later subsection.

2. Impact of Transit Service

Two alternative improvements in transit service, express radial and circumferential routes, were included in the effectiveness rankings discussed above. These significant additions in the level of service are not effective in reducing energy consumption. This is the case despite the fact that the existing transit service in the standard incremental run is very important since it reduces congestion near the CBD. Additional experiments in which express radial transit service at greater

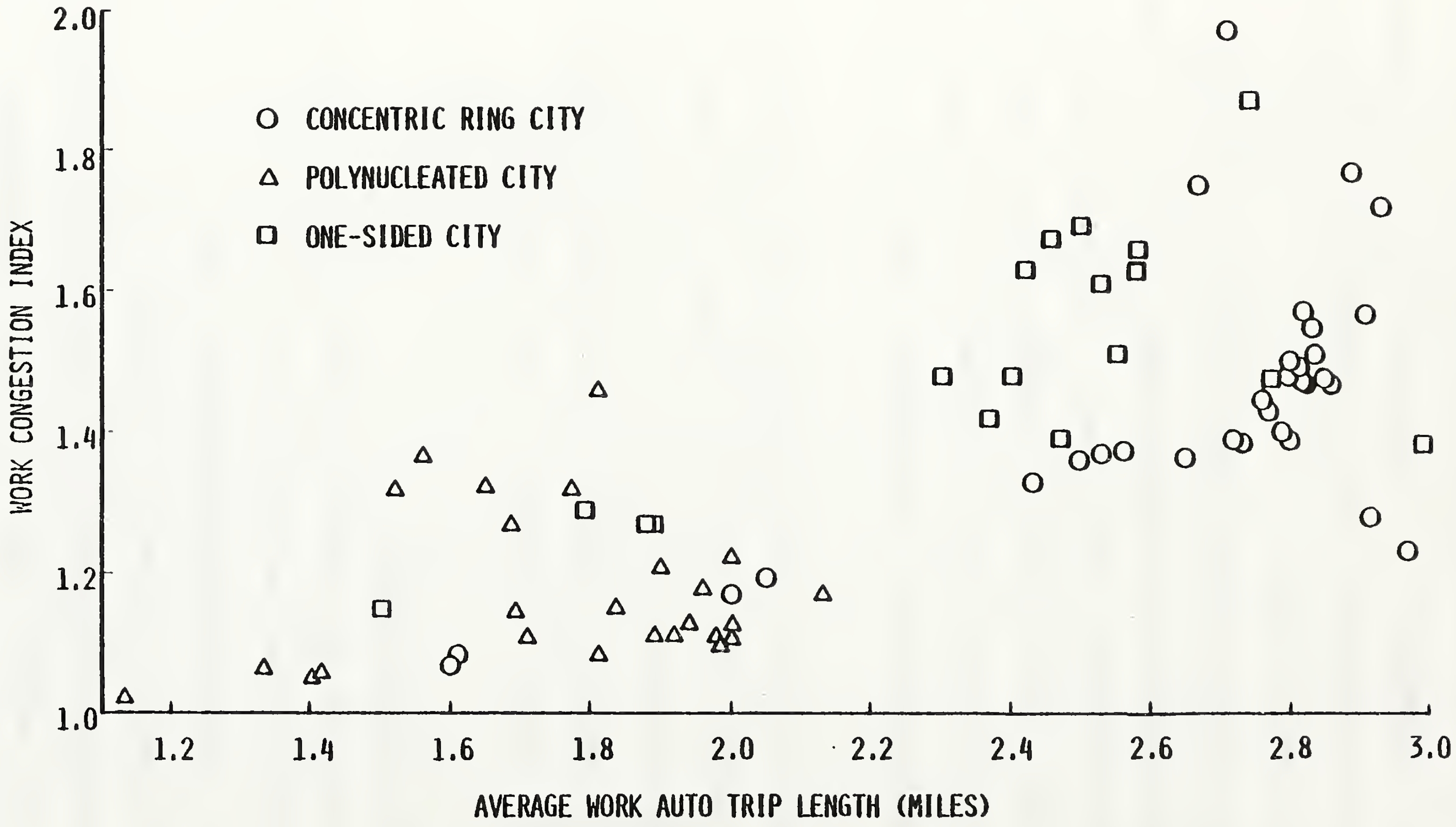


Figure 5-24. Effect of Automobile Work Trip Length on Work Trip Congestion Index

frequencies were simulated showed that improvements in existing service would be difficult to justify in terms of energy conservation.

An examination of the percentage of work trips by transit for all concentric ring city experiments reveals a strong relationship to the spatial dispersion of population, as measured by the second moment about the centroid of population. This is shown graphically in Figure 5-25. Since the transit network in the concentric ring city is oriented toward the CBD and since zones in or near the CBD are better served (in terms of frequency of service and walk distances to routes in other zones), it seems reasonable to expect that those cities with more population clustered around the CBD would have more trips by transit. While this analysis could have been continued for the other two test cities, the use of the second moment of population would not have sufficed as the measure of population dispersion since the population centroids would have coincided with the geographic centers, and thus would have been misleading. It must also be noted that these results are sensitive to the mode split model used in this research. It is possible this model is not perfect in predicting modal shares in the case of the hypothetical cities even though geographic transferability of disaggregate models has been demonstrated (11).

3. Transportation Pricing Changes

Most of the transportation network improvements discussed above are capital-intensive policy alternatives. Changes in transportation pricing can be much less expensive to implement and, as shown below, can achieve large reductions in automobile travel. There are three model

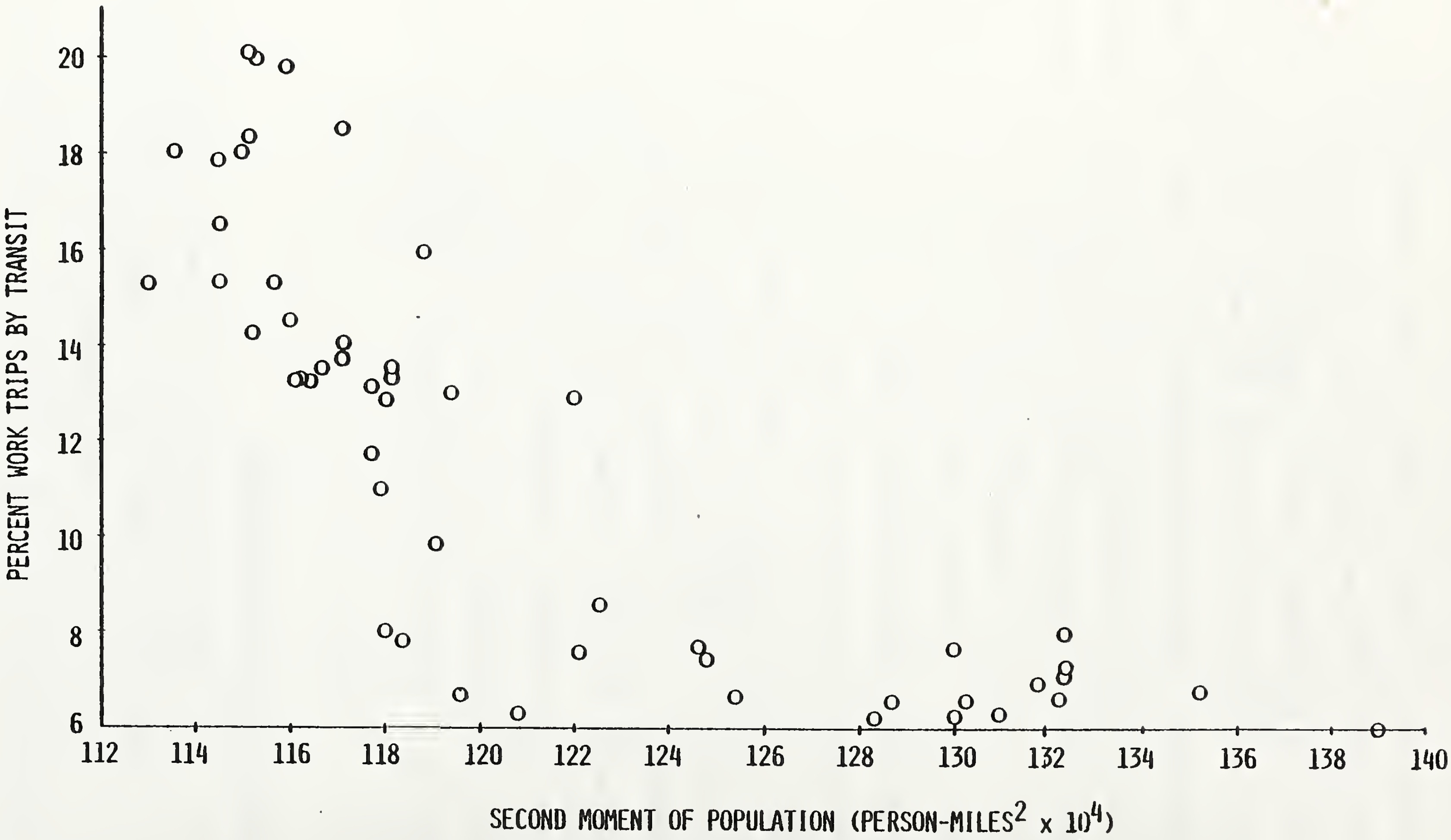


Figure 5-25. Effect of Spatial Dispersion of Population on Work Trip Transit Usage

inputs related to pricing: the price of gasoline, the cost of parking, and the transit fare and transfer cost.

a. Gasoline Price Changes

Exploration of the sensitivity of model outputs to changes in gasoline prices is useful to develop an understanding of model behavior; to compare this sensitivity to price elasticities derived in other work; and, pending the outcome of the first two issues, to speculate on the true price elasticity. It is important to note that sensitivity patterns reflect derived values, based on the assumptions, structure, and inputs for each component model and for the modeling system as a whole. In effect, the price elasticities reported here are implicitly specified in the modeling system, and their validity is clearly subject to question. Still, the derived elasticities have research interest because they are the product of an integrated modeling system.

Figure 5-26 presents the relationship between gasoline price and per-capita consumption for work and non-work automobile trips for the three test cities. The prices range from the mid-1976 average of 60 cents per gallon to $1.80 per gallon. Apparently, gasoline consumption is very insensitive to price. The large difference between test cities for work trips seems to be due primarily to congestion on the highway network. The concentric-ring city, with the greatest congestion, has the highest gasoline consumption. The poly-nucleated city, which has a congestion index close to 1.0 in the standard incremental run, has the lowest gasoline consumption; indeed, its work-trip consumption is almost identical to the consumption for the non-work trips for all of the test cities, which were assigned to the highway network using a free-flow algorithm ignoring congestion.

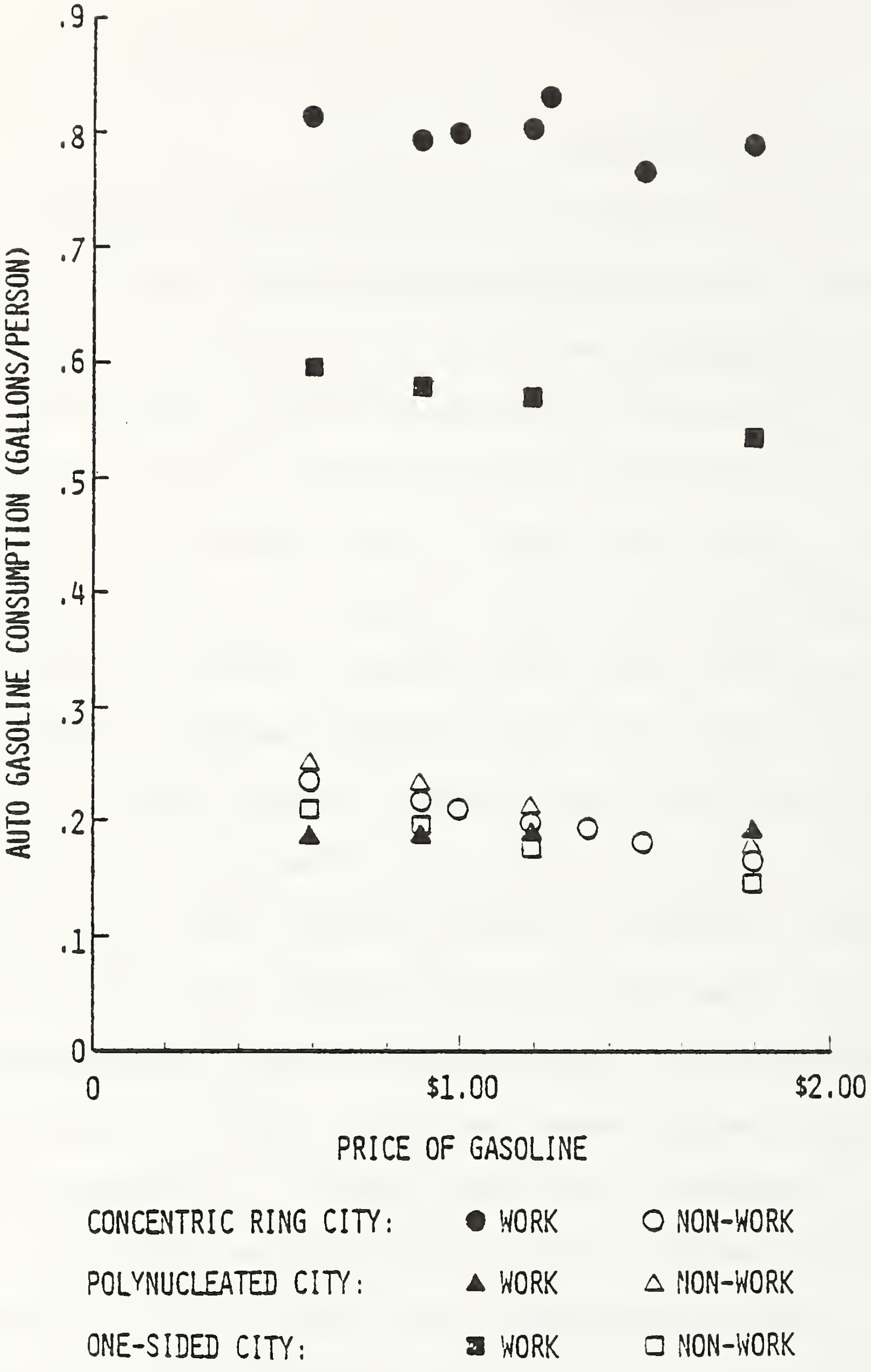


Figure 5-26. Effect of Price on Gasoline Consumption

Table 5-9. Price Elasticity of Gasoline Demand

Price Interval	Total Trips	Work Trips
Concentric Ring City		
$0.60 - 0.90	-.078	-.054
0.90 - 1.20	-.012	+.049
1.20 - 1.80	-.089	-.037
1.80 - 5.00	-.165	-.163
Polynucleated City		
$0.60 - 0.90	-.073	.000
0.90 - 1.20	-.128	+.016
1.20 - 1.80	-.139	+.063
One-Sided City		
$0.60 - 0.90	-.079	-.034
0.90 - 1.20	-.108	-.052
1.20 - 1.80	-.184	-.126

The slightly decreasing trend in gasoline consumption as price increases can be seen in the interval price elasticities of gasoline demand in Table 5-9. It appears that gasoline demand is highly price-inelastic, particularly for the lower price increases. The values of the 90 cents - $1.20 price interval of approximately -0.08 for all automobile trips are in agreement with short-range values cited in the recent economic literature (12, 13), and in a detailed study of the impacts of the 1973-74 gasoline shortage (14). It is interesting to note that the price elasticity for work trips alone is much closer to zero. This is important since it has been shown in this analysis that the effect of congestion on work trips plays an important role in determining gasoline consumption. If work trips are insensitive to gasoline price changes, then some other action to control gasoline consumption may be needed in the future if long-range impacts are considered important.

A further investigation of the sensitivity of the model to gasoline price concerns the effect on vehicle-miles travelled. Figure 5-27 shows that the total automobile VMT is almost a linear function of gasoline price. There is apparently a high degree of comparability between the test cities in this regard since the data points for each price are so close. It was noted above in the effectiveness ranking analysis that measurement of VMT as a surrogate for gasoline consumption could be misleading policy evaluation. An examination of the gasoline price elasticity of VMT in Table 5-10 shows that this continues to be the case, with VMT elasticities in general having a greater magnitude than the demand elasticities shown in Table 5-9. These values are also confirmed by the economic literature (15). It would be important to recognize that VMT is more sensitive to price than is total consumption when developing a monitoring program when implementing price changes.

It is important to recognize that the mechanism by which the model responds to policy changes varies both in regard to policy type and trip category. Gasoline price increases result in greater reductions in energy consumption and VMT for non-work trips, where congestion is not a consideration, than for work trips. This is accomplished with relatively small changes in the land use pattern. Policy changes which more directly relate to congestion, such as encouraging carpooling, result in a greater

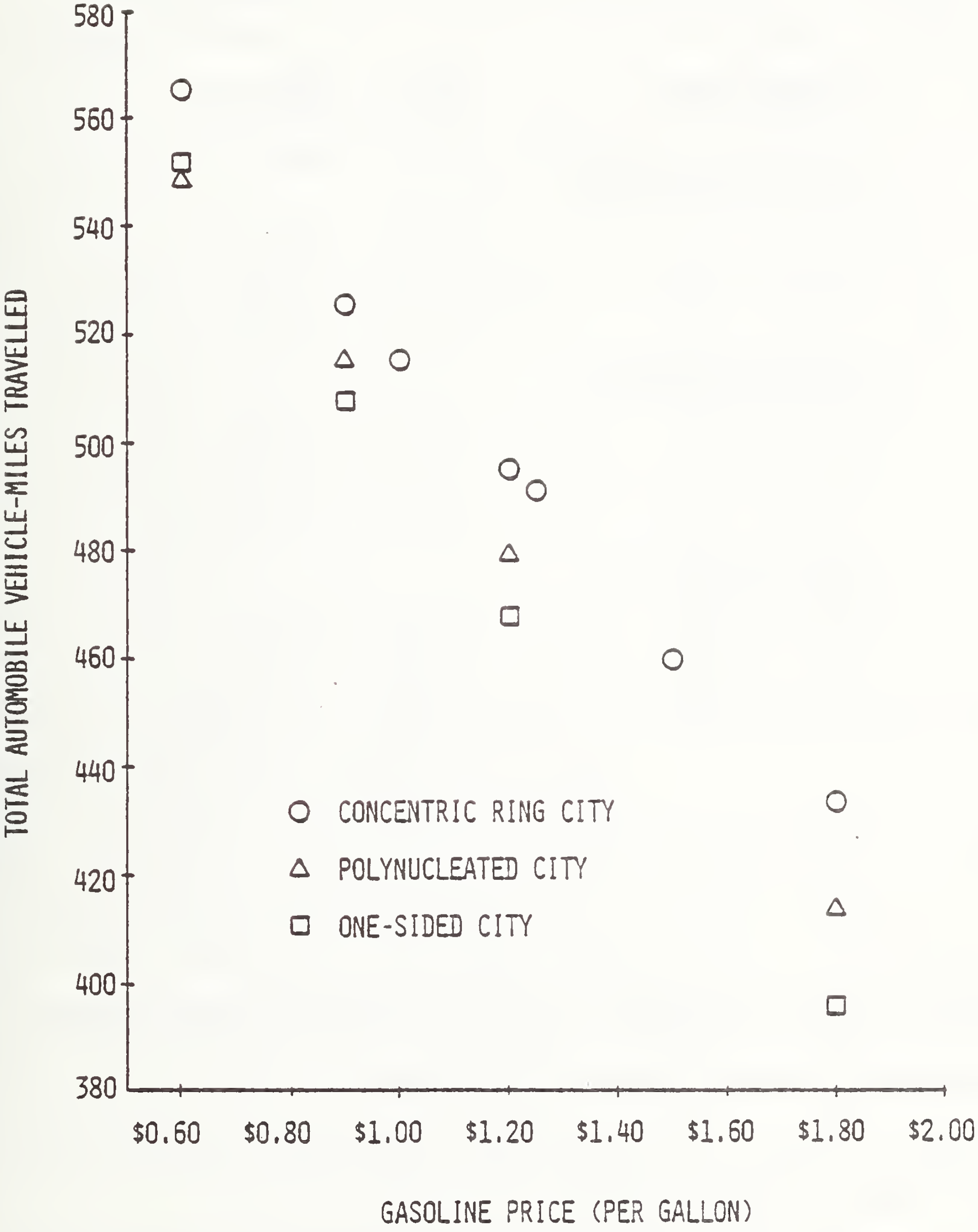


Figure 5-27. Effect of Gasoline Price on Total Automobile VMT

Table 5-10. Gasoline Price Elasticity of Automobile VMT

Gasoline Price Interval	Total Trips	Work Trips
Concentric Ring City		
$0.60 - 0.90	-.140	-.076
0.90 - 1.20	-.173	-.024
1.20 - 1.80	-.249	-.117
Polynucleated City		
$0.60 - 0.90	-.122	-.049
0.90 - 1.20	-.207	-.080
1.20 - 1.80	-.274	-.087
One-Sided City		
$0.60 - 0.90	-.159	-.043
0.90 - 1.20	-.236	-.105
1.20 - 1.80	-.308	-.147

sensitivity in energy consumption and VMT for work trips than for non-work trips and much larger shifts in land use.

b. Other Pricing Actions

Parking cost excursions were tested for work trips since increased commuter parking charges is a potential transportation system management (TSM) action and, in the context of this research, could be considered as a simulation of an area licensing scheme since the parking cost increase is limited to the CBD. In the effectiveness rankings, increased commuter parking costs were most effective in reducing energy consumption in the concentric ring city, which has the densest CBD. The concentric ring city also experienced the greatest reduction in congestion of the three test cities due to this action. These two impacts, combined with the fact that transit usage increased 34 percent, indicates that in those cases where congestion is a problem, increased commuter parking costs may be very effective in reducing energy consumption. The apparent reason is that trips near the CBD are diverted to transit, thereby reducing the level of congestion for those trips which are longer. It should be noted that increased parking costs for shoppers could push retail employment away from the CBD in real world applications. Such a dispersed distribution of employment sites could encourage increased energy consumption if population remains centered in the CBD.

The elimination of transit fares and transfer costs result in very small changes in the effectiveness rankings in Figures 5-7 to 5-10. The apparent reason for this is that transit trips are fairly short and not affected to a large extent by the generally slow travel times. Simply reducing the dollar cost for longer transit trips does not alter the mode split due to the very large travel times compared to those of automobile travel.

4. Increased Automobile Occupancy

In the effectiveness rankings it is shown that increasing the occupancy of automobiles for work trips was the most effective policy change in terms of reducing energy consumption and congestion. This action was surpassed only by extremely high gasoline prices in reducing automobile VMT. It seems apparent that congestion is the most important factor here. One problem in interpreting these results, however, is that the automobile occupancy is exogenously specified. The base value is the national average for cities of the size being simulated. Increased automobile occupancy cannot be viewed as the direct simulation of a policy change. Rather, it should be viewed as the result of some other action, possibly the provision of exclusive highway lanes or parking privileges for carpools. An increase of 50 percent in the work trip occupancy rate would be the result of an extremely successful carpooling program. A 100 percent increase is unrealistic, useful only for bounding the outcome space. Since there appear to be decreasing returns to scale with regard to increases in automobile occupancy in the effectiveness rankings in Figures 5-7 to 5-10, it appears that even a modest increase of 25 percent would still result in very favorable impacts.

Further examination of the effectiveness rankings shows some decreasing returns as the automobile occupancy approaches higher values. This appears to be continuing the trend observed in the sensitivity analysis on highway network capacity, in which increases in energy consumption occurred at a greater rate than the rate of capacity decrease.

5. Combining Transportation Policy Changes

Since it would be unrealistic to assume that any one of the policy actions simulated will be implemented individually in the future, a set of experiments was conducted on all of the test cities in which pairs of policy changes were simulated simultaneously. The analysis consists of adding the individual impacts of two separate actions and comparing this with the impact of implementing the two policy actions in the same experiment. Only a limited number of experiments were performed, dealing with typical TSM actions (16,17): transportation pricing and carpooling. The results are presented in the bar graph in Figure 5-28.

The first two sets of experiments are combinations of a transit incentive (free transit service) and an automobile disincentive (doubled gasoline price or doubled work parking cost). These were the only experiments where the effect of combining policy actions reduced energy consumption to a greater degree than implementing the policy actions individually. It must be noted that this was not the case for the one-sided city nor for the polynucleated city in the case of the doubled parking cost. Combining the two automobile disincentives together or combining them individually with carpooling never resulted in a fuel consumption reduction greater than the combined impacts of the individually implemented policies.

These results indicate that decision makers should be careful when developing a program of actions to reduce energy consumption. The interactions between the impacts can be hidden and result in an outcome not the linear sum of the independent effects. That combining an automobile disincentive with a transit incentive reduced energy consumption the best is intuitively appealing, especially since it is in the direction pointed out by recent federal policy (18).

6. Land Use Changes

The encouragement of alternative urban growth patterns might be

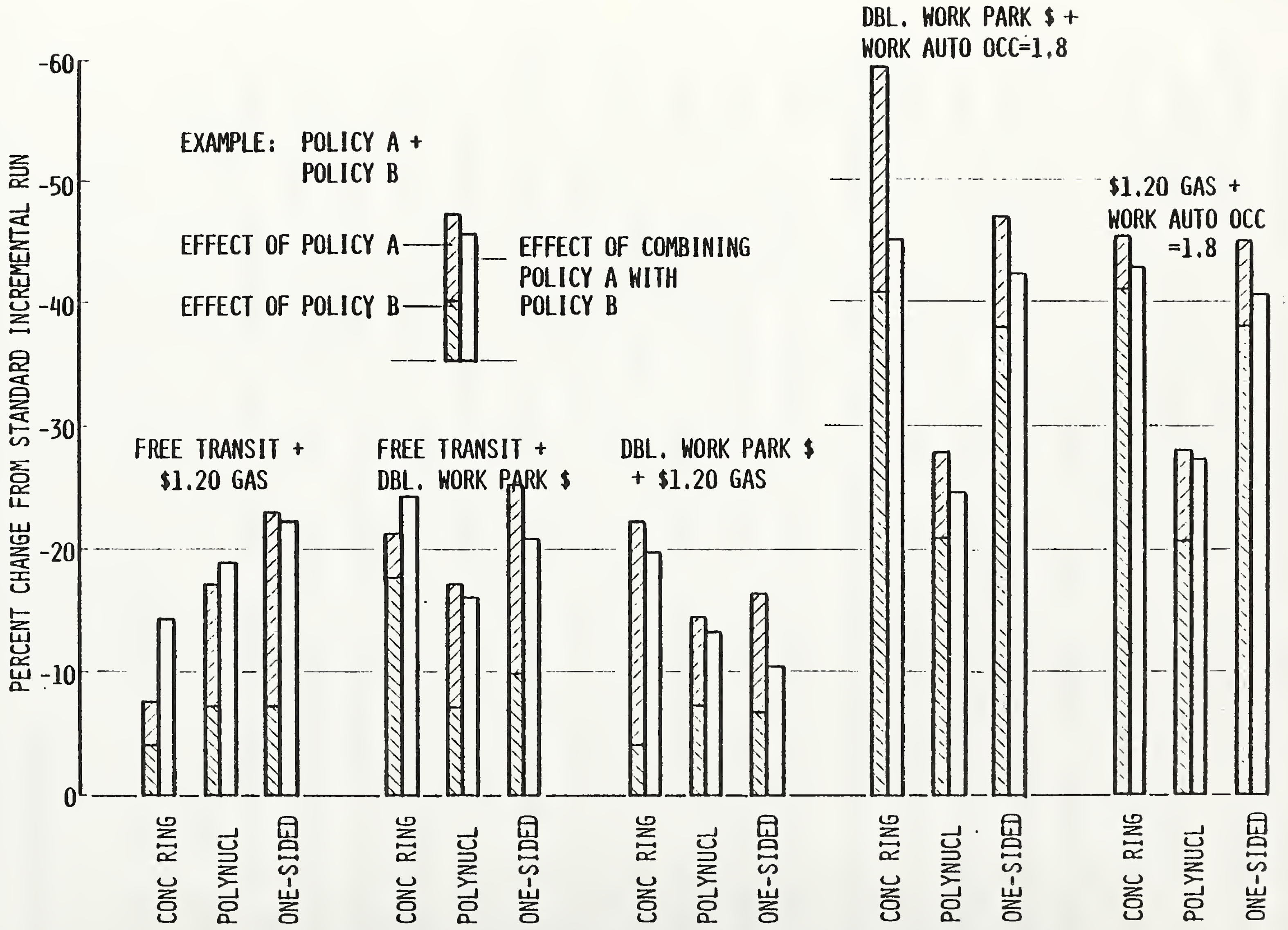


Figure 5-28. Effect of Combining Transportation Policy Changes on Total Energy Consumption

accomplished by the appropriate application of zoning ordinances, sewer connection permits, tax incentives, or federal redevelopment funds. In the model, the most direct control of land use allocation is through the exogenously specified location of the 3750 additional basic employees in the incremental runs. The effectiveness ranking analysis indicated the desirability of CBD-oriented growth. In this subsection, centralized growth is compared against sprawled growth. Then two approaches for directed growth, nodal and corridor development are explored.

a. Centralized versus Sprawled Urban Growth

The first land use policy excursion is a comparison of the impacts of locating all of the incremental basic employment in the CBD and spreading it uniformly throughout all the zones. Table 5-11 presents the results of this series of experiments on the concentric ring city. The decreased energy consumption, compared to the standard incremental run, associated with CBD growth seems to be due to reduced congestion, shorter work trips, and increased transit usage. By locating basic employment in the CBD, where the transit level of service is the highest, not only are work trips shorter, but many are diverted to transit, thus reducing traffic volume on the CBD links and allowing the longer automobile trips from the outer zones to travel on less congested, and thus more energy-efficient, links. The uniform distribution of basic employment encourages growth in zones not well served by transit, resulting in more and longer automobile trips on a more congested network.

The favorable impacts of CBD growth are reinforced when combined with the imposition of diagonal freeways. Indeed, even uniform growth becomes

Table 5-11. Comparison of Centralized versus Sprawled Urban Growth for Concentric Ring City

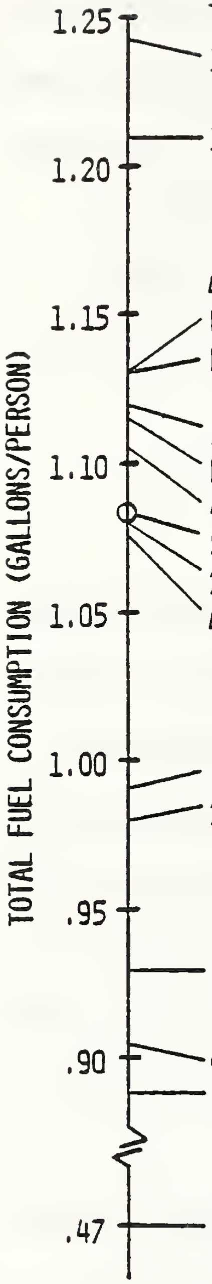
Run No.	Description	Total Energy $\left(\frac{\text{gallons}}{\text{person}}\right)$	Work Auto Energy (Btu x 10^6)	Average Work Congestion Index	Average Auto Work Trip Length (miles)	Percent Work Trips by Transit	Average Non-Work Auto Trip Length (miles)	2nd Moment of Population (person-mi^2 x 10^2)
145	Std. Incr. Run	1.083	12784	1.511	2.837	13.29	2.798	11608
149	Diagonal Freeways	0.889	9590	1.280	2.916	12.91	3.105	12206
154	CBD Growth	0.993	11413	1.386	2.803	16.49	2.800	11451
193	CBD Growth with Diagonal Freeways	0.834	8763	1.221	2.758	15.95	3.088	11886
189	Uniform Growth	1.131	13431	1.574	2.908	7.69	2.868	13012
194	Uniform Growth with Diagonal Freeways	0.915	9904	1.291	2.872	8.04	3.160	13227

much more energy-efficient when such a network improvement is added. One adverse impact is that the increased dispersion of population that occurs when diagonal freeways are added alone is also observed when combined with different orientations of directed urban growth. There is a large increase in total automobile VMT whenever diagonal freeways are added. This seems to be due principally to longer non-work automobile trips. There is clearly a need to investigate alternatives for directed urban growth which can both control sprawl and shorten the distance between home and work.

b. Nodal Growth Imposed on the Concentric Ring City

A series of experiments were conducted in which nodal growth patterns were imposed on the concentric ring city in an attempt to imitate some of the characteristics of the energy-efficient polynucleated city in a more realistic framework. The concentric ring city was selected as the test bed for this excursion since it is most representative of real cities. The results can be extended to one-sided cities since they are, in a sense, "half" of a concentric ring city and since both of these urban forms were shown to respond similarly to policy changes earlier in the analysis.

Figure 5-29 is a ranking of several alternative nodal growth patterns in terms of total energy consumption. Also presented, for comparison, are several of the other growth patterns described above. The first major finding is the apparent need to limit high density development to those areas where the transportation network can accommodate greatly increased traffic volumes. The most energy-intensive growth pattern is in experiment



DESCRIPTION	CONGESTION INDEX	WORK AUTO GASOLINE (GALLONS)	WORK AUTO TRIP LENGTH (MILES)	RUN NO.
1 NODE ON DIAGONAL	2.915	121488	2.823	185
1 NODE ON DIAGONAL WITH FREEWAY TO CBD	2.498	116168	3.319	186
4 NODES ON AXES	1.698	109096	2.738	192
UNIFORM GROWTH	1.574	107448	2.980	189
EDGE GROWTH NODES WITH TRANSIT	1.970	106088	2.712	170
RING 2 GROWTH	1.574	106496	2.818	155
EDGE GROWTH NODES	1.749	105736	2.670	161
4 NODES ON DIAGONAL	1.603	104206	2.694	178
STANDARD INCR. RUN	1.511	102272	2.837	145
2 NODES ON DIAGONAL	1.599	101192	2.670	176
4 NODES ON DIAGONAL WITH IMPROVED ARTERIALS	1.538	102000	2.905	401
CBD GROWTH	1.386	91304	2.803	154
2 NODES ON DIAGONAL WITH FREEWAYS	1.725	87408	3.147	177
4 NODES ON DIAGONAL WITH FREEWAYS	1.405	81056	3.144	179
4 DIAGONAL ARTERIALS	1.286	80168	2.647	191
4 DIAGONAL FREEWAYS	1.280	76720	2.916	149
STANDARD INCR. RUN POLYNUCLEATED CITY	1.125	23592	1.993	206

Figure 5-29. Effectiveness Ranking of Alternative Nodal Growth Patterns Imposed on Concentric Ring City

185 in which all of the incremental basic employment is placed in a single on-diagonal zone in ring 2. The tremendous increase in the congestion index is due to overloading most of the arterial highway links near that zone. Adding a single freeway to the CBD in experiment 186 did much to reduce congestion and resulted in a decrease in energy consumption compared to experiment 185.

Experiment 161 is an alternative single growth node approach in which incremental basic employment is located east of the CBD, spread in three zones in the outer ring. The resulting "edge" growth node has much more energy-efficient travel than the single growth node in experiment 185 but the congestion index is still high, even though the growth pattern does permit many of the existing arterial highways to serve as direct routes to the CBD. Surprisingly, providing better transit service to the edge growth node, in experiment 170, resulted in more congestion in the adjacent highway links, primarily because this action concentrated more growth in the node. This is the sole case of improved transit service affecting land use to a large degree in this research.

It appears that more than one growth node is required if energy consumption is to drop below that of the standard incremental run. Dividing the incremental basic employment between two opposite zones on the diagonal in ring 2 in experiment 176 achieved this goal, although just barely. Maintaining this growth pattern and adding four diagonal freeways, in experiment 177, resulted in a large energy savings. Most of this seems to be due to a shifting of population to zones near the freeways, even to the two not running through the growth nodes.

Continuing this excursion, in experiment 178 the incremental basic employment is split into four diagonal zones in ring 2. While this resulted in an increase in energy consumption, compared to the standard incremental run, the increase is only half as large as when basic employment is uniformly added to all zones in ring (experiment 155). Again, the reason for this increase in energy consumption is the overloading of arterial links near the growth nodes. In experiment 179, the four diagonal growth nodes are paired with four diagonal freeways resulting in the lowest energy consumption of any nodal growth pattern simulated: While the average congestion index was reduced, the now familiar increase in the automobile trip length is observed, however.

Improved grid arterials replaced the freeways in experiment 401 to assess the degree to which the higher level of service and potentially shorter paths offered by the diagonal freeways influenced the energy consumption of the four diagonal node growth pattern. The energy consumption was only slightly better than the standard incremental run, primarily because the arterials could not reduce congestion as much as the freeways which had higher free flow capacities.

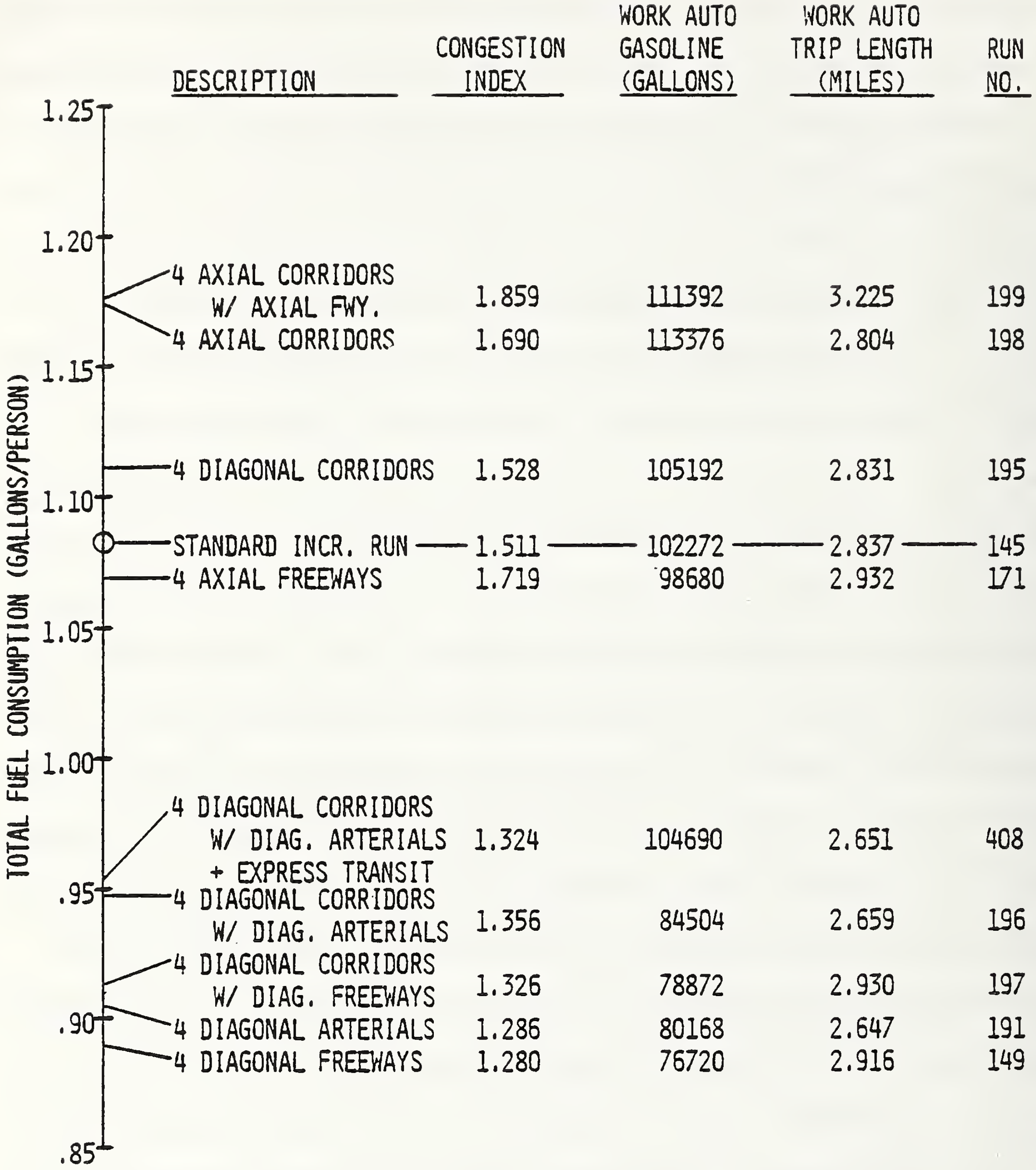
The placement of all incremental basic employment in the four axial nodes in ring 2 (experiment 192) results in a large increase in energy consumption. In this case, congestion is raised by vehicles being forced onto the single arterial routes connecting the growth nodes to the CBD. The diagonal growth node arrangement (experiment 178) seems to allow two rectilinear paths to be chosen to the CBD for each node and results in lower congestion.

The basic conclusion from this series of experiments is that it is desirable to cluster growth, although not so much as to overload the arterial street network. Clustering land use alone, however, is shown not to be a sufficient action to result in any truly meaningful reduction in energy consumption. It is only through the coordinated implementation of directed growth and improvements in the highway network that large energy saving result.

c. Corridor Growth Imposed on the Concentric Ring City

The encouragement of corridors of urban development radiating from the CBD, with complementary improvements in highway and transit facilities, would seem to be a reasonable approach to reduce energy consumption since it would direct growth across many zones and perhaps avoid the problem of overloading local highway links. Since the establishment of four diagonal growth nodes combined with diagonal freeways seems so promising, a series of experiments conducted to explore the impacts of establishing corridors of growth along these diagonals is presented in this subsection. Instead of just placing the incremental basic employment in the diagonal zones of ring 2, it is placed uniformly in the diagonal zones in rings 1, 2, and 3 of the concentric ring city. Alternatively, growth is encouraged in four axial corridors in a similar manner. Figure 5-30 shows a ranking of these experiments in terms of total energy consumption.

The establishment of four diagonal corridors alone (experiment 195) results in slightly higher energy consumption than the standard incremental run. In a manner similar to imposing four diagonal growth nodes, this is due to increased congestion caused by overloading highway links near the corridors. An examination of the change in population allocated



DESCRIPTION	CONGESTION INDEX	WORK AUTO GASOLINE (GALLONS)	WORK AUTO TRIP LENGTH (MILES)	RUN NO.
4 AXIAL CORRIDORS W/ AXIAL FWY.	1.859	111392	3.225	199
4 AXIAL CORRIDORS	1.690	113376	2.804	198
4 DIAGONAL CORRIDORS	1.528	105192	2.831	195
STANDARD INCR. RUN	1.511	102272	2.837	145
4 AXIAL FREEWAYS	1.719	98680	2.932	171
4 DIAGONAL CORRIDORS W/ DIAG. ARTERIALS + EXPRESS TRANSIT	1.324	104690	2.651	408
4 DIAGONAL CORRIDORS W/ DIAG. ARTERIALS	1.356	84504	2.659	196
4 DIAGONAL CORRIDORS W/ DIAG. FREEWAYS	1.326	78872	2.930	197
4 DIAGONAL ARTERIALS	1.286	80168	2.647	191
4 DIAGONAL FREEWAYS	1.280	76720	2.916	149

Figure 5-30. Effectiveness Ranking of Alternative Corridor Growth Patterns Imposed on Concentric Ring City

per zone (compared to the standard incremental run), shown in Figure 5-31, indicates a strong shift in growth toward the outer two rings, particularly in the diagonal corridor zones. This population shift is similar to that caused by diagonal freeways alone, although the spread of growth to adjacent, off-diagonal zones is larger. In experiment 196, diagonal arterials are added to the highway network. This would be expected to define the corridors more sharply and result in a decrease in energy consumption. While the energy savings does occur, due primarily to a decrease in congestion, the population shift away from three of the four extreme corners and into the CBD and ring 1 zones, shown in Figure 5-32, is not anticipated. Apparently, the accessibility of the CBD is greatly increased by this action.

Experiment 197 continues this excursion by replacing the diagonal arterials with diagonal freeways. This results in slightly less congestion and lower energy consumption. While this action does more strongly define the corridors, as shown in Figure 5-33, it forces more persons toward the extreme corners of the city. This may explain why the average automobile work trip length increases while the congestion index remains the same as in experiment 196. This indicates that while it may be beneficial to coordinate corridor growth with a spinal arrangement of freeways, there is a need to avoid providing extremely high level of service radial highways.

To determine if this consideration extends to transit, diagonal corridor growth is combined with diagonal arterials and diagonal express transit service in experiment 408. While the energy consumption is no better than in experiment 196, population growth in the corridor is more

Experiment 195

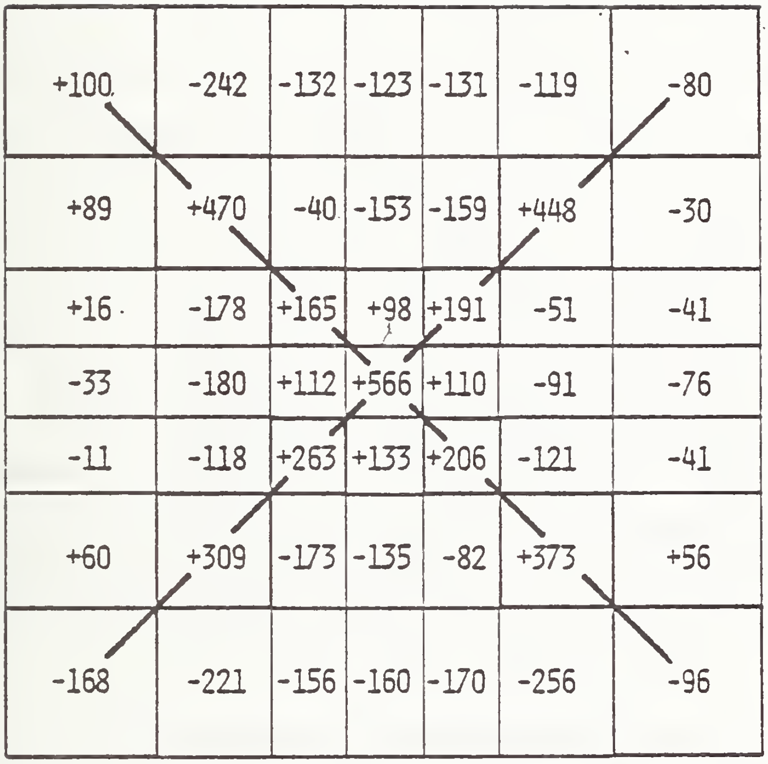
+522	+421	+186	+149	+225	+373	+668
+293	+126	+33	+86	+334	+216	+281
+171	+304	-266	-790	-306	+101	+159
+107	+117	-798	-5716	-818	-12	+96
+168	+129	-342	-844	-352	+298	+183
+218	+494	+200	-30	+109	+237	+270
+735	+500	+268	+170	+230	+385	+711

values indicate change from standard incremental run

zones with bold outline denote corridor

Figure 5-31. Change in Population in Concentric Ring City due to Diagonal Corridor Growth

Experiment 196



+100	-242	-132	-123	-131	-119	-80
+89	+470	-40	-153	-159	+448	-30
+16	-178	+165	+98	+191	-51	-41
-33	-180	+112	+566	+110	-91	-76
-11	-118	+263	+133	+206	-121	-41
+60	+309	-173	-135	-82	+373	+56
-168	-221	-156	-160	-170	-256	-96

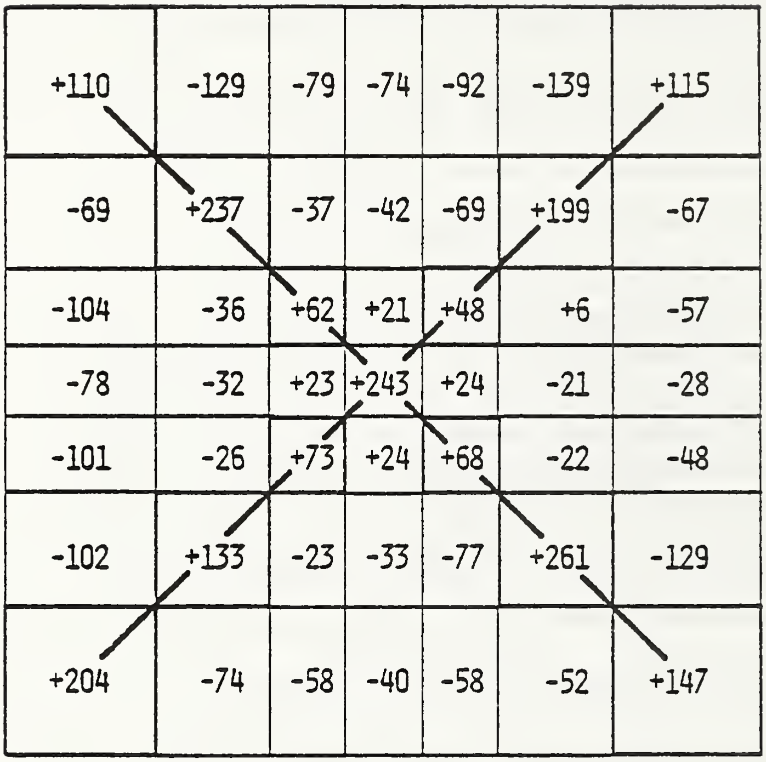
values indicate change from experiment 195
(diagonal corridor alone)

zones with bold outline denote corridor

— denotes arterial highway route

Figure 5-32. Change in Population in Concentric Ring City due to Diagonal Corridor Growth and Adding Diagonal Arterials

Experiment 197



+110	-129	-79	-74	-92	-139	+115
-69	+237	-37	-42	-69	+199	-67
-104	-36	+62	+21	+48	+6	-57
-78	-32	+23	+243	+24	-21	-28
-101	-26	+73	+24	+68	-22	-48
-102	+133	-23	-33	-77	+261	-129
+204	-74	-58	-40	-58	-52	+147

values indicate change from experiment 196
(diagonal corridors and diagonal arterials)

zones with bold outline denote corridor

▬ denotes arterial highway route

Figure 5-33. Change in Population in Concentric Ring City due to Diagonal Corridor Growth and Adding Diagonal Freeways sharply defined. Apparently, corridor growth coordinated with both improved transit and highway service is advantageous.

The simulation of axial corridors in experiment 198 results in increased congestion and fuel consumption compared to the standard incremental run. The population shift, shown in Figure 5-34, seems to indicate that the sprawl would continue past the edge of the city if another ring of zones were available for development. Replacing the axial arterials with freeways in experiment 199 does not change energy consumption and actually increases congestion by diverting trips from zones adjacent to the corridors, encouraging longer trips. Figure 5-35 shows a strong shift in population back to the CBD compared to experiment 198. This is opposite of the trend observed when diagonal freeways are added to diagonal corridors. The reason for this difference seems to be due to the structure of the highway network. Diagonal corridors seem to allow for more paths of lower travel time to the CBD than the axial corridors, which force most trips to follow the axial arterials to the CBD.

d. Investigation of Peripheral Growth

Experiments with diagonal freeways on the concentric ring city show a tendency for the incremental layer of population to locate toward the corners of the city. It is unknown how much further out population would be allocated if the boundaries of the city were more spread out from the CBD. The addition of another ring of zones in the concentric ring city is precluded by computer storage limitations, however. A substitute approach is used in which the incremental basic employment is located in the zones of ring 2 in the concentric ring and one-sided cities

Experiment 198

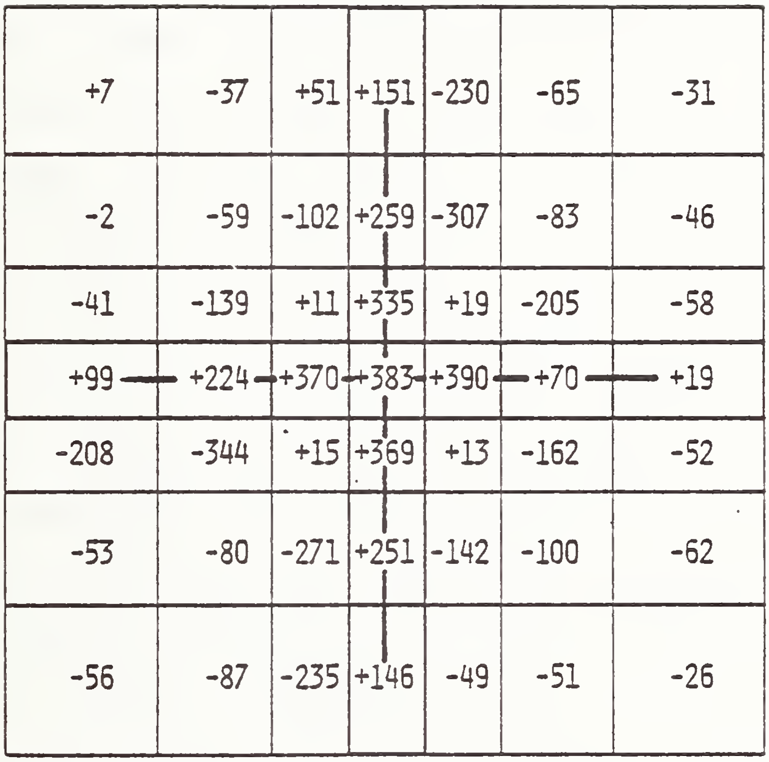
+9	+30	-46	+575	+234	+56	+39
-5	-39	-17	+488	+239	+49	+56
+87	+56	-315	-317	-345	+181	+105
+668	+585	-342	-4937	-359	-654	+706
+254	+267	-350	-376	-363	+151	+102
+41	+26	+199	+523	+98	+15	+49
+53	+77	+273	+636	+130	+60	+41

values indicate change from standard incremental run

zones with bold outline denote corridor

Figure 5-34. Change in Population in Concentric Ring City due to Axial Corridor Growth

Experiment 199



+7	-37	+51	+151	-230	-65	-31
-2	-59	-102	+259	-307	-83	-46
-41	-139	+11	+335	+19	-205	-58
+99	+224	+370	+383	+390	+70	+19
-208	-344	+15	+369	+13	-162	-52
-53	-80	-271	+251	-142	-100	-62
-56	-87	-235	+146	-49	-51	-26

values indicate change from experiment 198
(axial corridor alone)

zones with bold outline denote corridor

▬ denotes freeway route

Figure 5-35. Change in Population in Concentric Ring City due to Axial Corridor Growth and Axial Freeways to determine what population changes occur at the periphery when the "seed" basic employment is located closer to the city edge than in the standard incremental run.

In the case of the concentric ring city, a total of 8426 persons (one-third of the population added in the incremental run) are shifted in location compared to the standard incremental run. The pattern is shown in Figure 5-36. Ring 2 gains 68 percent while ring 3 gains 32 percent. Both the CBD and ring 1 lose population. It seems that population would continue to locate further away from the CBD if additional rings were available in this test city. To test this notion, the allocation of incremental population in the one-sided city, when basic employment is added to ring 2, is examined in Figure 5-37. The primary reason for this analysis is that this city has two rings of zones outside ring 2, whereas the concentric ring city has only one. Only 4929 persons are shifted in location compared to the standard incremental run. This is just 58 percent of the number shifted in the concentric ring city. Almost all of the shift is limited to increased population in ring 2. Surprisingly, there is a marked decrease in population in ring 3 and only some of the zones in ring 4 show a small increase. This indicates that past a certain point, which may vary from one city to another, the relative accessibility of the peripheral zones begins to decrease rapidly. In the case of the concentric ring city that point seems to be the outermost ring. In the case of the one-sided city, it seems to be much closer in, occurring in the second ring.

Experiment 155

+68	+110	+73	+97	+81	+124	+45
+131	+288	+291	+483	+380	+348	+109
+167	+345	-307	-621	-299	+406	+100
+124	+419	-632	-3489	-615	+278	+42
+143	+297	-312	-667	-331	+368	+101
+122	+312	+491	+374	+391	+280	+116
+72	+173	+209	+147	+146	+119	+56

values indicate change from standard incremental run

zones with bold outline denote Ring 2

Figure 5-36. Change in Population in Concentric Ring City due to Ring 2 Growth

Experiment 317

-28	-6	+13	+12	+15
-96	-64	-9	-32	-32
+439	+531	+737	-72	+18
-217	-183	+471	-97	-9
-602 -740	-145	+419	-170	-40
-733 -581	-141	+398	-129	-4
-187	-157	+495	-158	-38
+286	+501	+652	-42	-21
-193	-96	-19	-80	+19
-24	+33	+24	+9	-5

values indicate change from standard incremental run

zones with bold outline denote Ring 2

Figure 5-37. Change in Population in One-Sided City due to Ring 2 Growth

e. General Impacts of Freeways on Urban Growth

Figure 5-38 explores the relationship between regional accessibility (as measured by the average work trip opportunity cost) and total energy consumption for many of the alternative growth patterns discussed above, both with and without additions to the highway networks, in the context of the concentric ring city. It is interesting to note that the general trajectory is similar whenever diagonal highways (either arterials or freeways) are added to the rectangular grid network. Apparently, as far as benefits to travellers are concerned, significant structural changes in the highway network, both in terms of free-flow capacity and level of service, have similar impacts, no matter what the form of land use controls. The exception to this is the addition of axial freeways which only reduce opportunity cost. The reason for this seems to be that network connectivity is not increased and the number of lane-miles added is far smaller than when adding diagonal links.

F. Some Observations on the Value of Travel Time

Since the impedance to travel is a function of the exogenously specified value of travel time in the model, it seems necessary to determine how sensitive the model results are to this value. Table 5-12 presents a summary of four experiments in which many values of travel time, representative of the range of values cited in the literature (19,20), are simulated in the concentric city. It should be noted that, in the standard incremental run and all other experiments, the average representative value of travel time is $5.00 per hour for work trips and $2.50 per hour for non-work trips. In the four experiments described below, the same

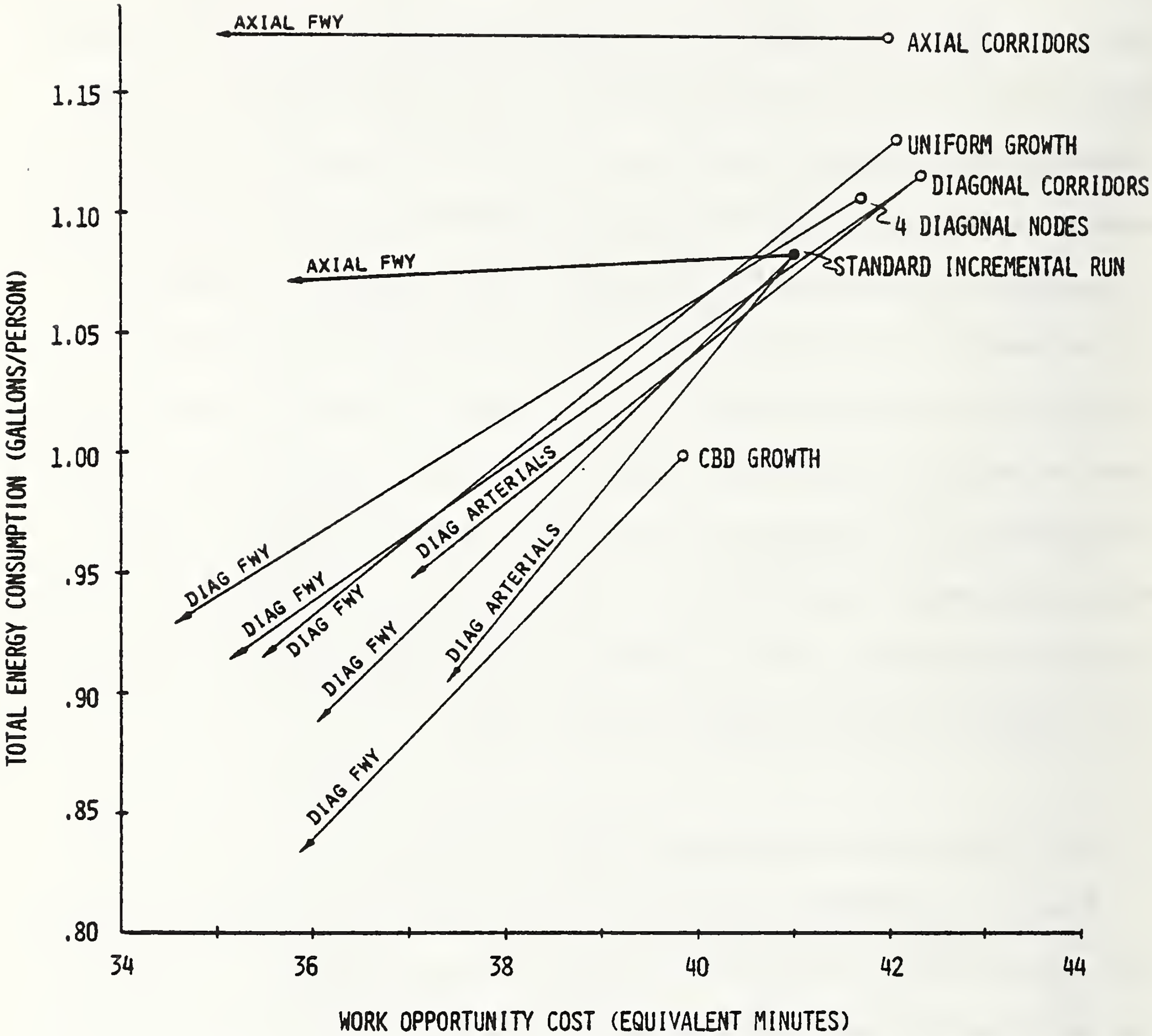


Figure 5-38. Impact of Freeways on Work Trip Opportunity Cost and Energy Consumption

Table 5-12. Impact of Altering the Assumed Value of Travel Time in Concentric Ring City

Run No.	Value of Travel Time (per hour)	Total Energy $\left(\frac{\text{gallons}}{\text{person}}\right)$	Work Auto Energy (Btu x 10^6)	Average Work Congestion Index	Average Auto Work Trip Length (miles)	Percent Work Trips by Transit	2nd Mom. of Population (person-mi^2 x 10^3)	Average Work Trip Opportunity Cost (minutes)
145	Std. Incr. Run $5.00/$2.50	1.083	12784	1.511	2.837	13.29	1161	40.98
181	$1.69	1.191	13059	1.517	2.895	15.29	1130	64.54
180	$3.62	1.111	14552	1.463	2.877	13.47	1167	45.88
190	$5.00	1.095	12978	1.519	2.877	12.83	1180	41.06
407	$10.00	1.037	12066	1.473	2.815	11.76	1177	34.53

value is used for both work and non-work trips for the sake of simplicity.

Generally, this sensitivity analysis of the model shows that, as the value of travel time increases, energy consumption falls slightly. This seems to be due to shortening in work-trip lengths, which also brings about reductions in congestion. Transit usage falls because transit travel times are larger than those for the auto.

The major outputs of the model do not appear strongly sensitive to shifts in the value of time. The use of a middle-range value ($5.00/hour for work, $2.50/hour for non-work) in most of the experiments seems to have been reasonable, given this low sensitivity and the fact that the middle value produces middle-range values for the other key output measures.

Further research is needed to determine the true validity of model predictions of responses to value-of-time shifts in terms of both location and travel behavior.

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CHAPTER SIX

CONCLUSION

A. Contributions of This Research

1. General Conclusions

Using land use and transportation modelling algorithms, previously developed and proven, an inexpensive and simple-to-operate model, specifically designed for testing alternative transportation energy conservation policies, has been built and applied in this study. The model explicitly considers relationships between transportation and land use with regard to the energy costs of travel. An extensive series of experiments was run, simulating a broad range of transportation network and pricing, urban development, and urban travel behavior changes. Many interesting results regarding the relative energy efficiency of policy actions, and the sensitivity of various travel, land use, and energy consumption measures, were generated. Most of these correlated strongly with intuition and logic, thus supporting their validity and that of the model. The model was particularly useful in that it provided measures of urban development and travel to explain changes in energy consumption that occurred as alternative policy actions were simulated. The model, and generally the simulation approach used to model transportation/land use interactions, has been shown to be a potentially valuable analytical tool for aiding planners and decision makers in developing transportation energy conservation policy.

2. Policy Guidelines

General guidelines for policy development that can be drawn from the experimental program center on three major areas of interest: alternative urban development patterns, transportation network structure considerations, and transportation system management actions. It must be noted that the conclusions presented should be considered as tentative. They are based on a limited number of experiments on representative, hypothetical cities, greatly simplified in structure compared to real cities. As shown in Chapter Four, the simulation system contains some assumptions and simplifications which may influence the experimental results in an adverse manner. These limitations are acknowledged. The strengths of these findings, in terms of their logic and intuitive appeal, seems to indicate, though, that they are not generally due to biases built into the model.

One final caveat regarding the conclusions in this research is that it was concerned only with energy requirements for urban passenger travel and ignored changes in consumption in the residential, commercial, and industrial sectors which might result when urban growth is altered. While a more comprehensive approach has been used in some analytic (1) and empirical (2) studies, this was avoided in this research in order to reduce computational complexity. Instead, this research concentrated on the transportation sector alone, examining a large set of specific policy actions.

a. Directed Urban Growth

Particularly when coordinated with the existing transportation network or improvements to that network, directed urban growth can result in more energy-efficient urban forms than sprawled development. It was shown that the polynucleated city was the most efficient due to the close proximity of homes to work locations. While such radically multi-centered cities do not exist, the imposition of nodal or corridor growth policies on existing urban forms seems a very real possibility. The desirability, from an energy perspective, to encourage people to live closer to work was thus demonstrated. The most appropriate manner in which to accomplish this goal was not identified but it may lie in the realm of tax incentives, zoning ordinances, the appropriate application of federal urban development funds, and broadly focused efforts to educate people regarding the true cost of transportation.

The potential energy saving benefits of social and physical redevelopment programs for inner city areas is also implied by the results. If older, more central residential locations, now made unattractive by urban blight, could once again become prime residential areas, significant savings in work trip energy consumption might result. Furthermore, persons living in medium to high density areas could be offered better quality transit service more easily, further reducing transportation energy consumption. Such urban development must be coordinated with programs to encourage employers to locate in the CBD, however. Simply locating more population in the central city may actually increase energy costs if future employment centers locate in the suburbs.

Care must be taken not to overload existing adjacent highway links when implementing directed urban growth, since the resulting congestion could significantly increase energy consumption. Directed urban development balanced with transportation network capacity, perhaps through improved or additional links, can result in lower energy consumption. For example, corridor growth, when combined with diagonal arterial or freeway links on a rectangular highway network, was shown to be among the most favorable of the alternative development patterns simulated.

In summary, this research has shown the value of comprehensive land use-transportation planning in energy conservation. Piecemeal, incremental urban development is not nearly as energy-efficient and could result in land use patterns with adverse transportation energy consumption characteristics. Analytic tools need to be developed to assess the regional and subregional transportation network and energy impacts of medium and large scale development proposals. This research has shown that this can be done with a minimum of theoretical model development.

b. Highway Network Improvements

The degree of congestion on the highway network was shown to be the most important factor influencing the transportation energy consumption in an urban area. Policy changes which could directly affect congestion were thus found to be the most effective in reducing energy consumption. Further, it was shown that improving the connectivity of the highway network could be more important, or at least more cost-effective, than adding capacity to the existing network. The addition of diagonal arterial highways to the rectangular highway grid of the concentric ring city resulted in greatly reduced congestion and energy consumption. The increased level of service provided by diagonal freeways, in terms of higher capacities and free-flow speeds, resulted in only marginal improvement in these measures.

The construction of radial freeways was shown to have a potentially adverse influence on urban growth, pulling population away from the CBD toward the periphery. If implemented without coordinated urban land use planning actions, potentially energy-intensive sprawled urban growth could result in the future. Due to their greater free-flow speeds, freeways tended to divert many trips from shorter, but slower arterial paths, resulting in greater volume on the freeways. It may be necessary to preserve the high level of service on new freeways through ramp metering in order to maintain the energy efficiency of trips which take place on them.

c. Transit Network Improvements

Providing additional circumferential or express radial transit routes did not seem to be very effective methods to reduce energy consumption in the cities tested, primarily because most transit trips were fairly short and occurred in or near the CBD. Maintaining the existing peak-period transit services was shown to be essential, however, since these carried trips that would cause congestion on the highway network if forced into automobiles.

d. Transportation Systems Management Actions

The findings of this research become more important when considered in light of the recent federal policy regarding the consideration of less capital-intensive transportation projects in the urban transportation planning process (3,4). Transportation system management (TSM) actions include several of the more easily implemented transportation policy changes that were simulated. Encouraging increased commuter carpooling was the most effective of these actions, reducing fuel consumption most directly by reducing the number of vehicle-trips. In so doing, congestion on the highway network was reduced, resulting in travel at more energy-efficient speeds, and in shorter trips, due to less diversion to avoid slower, congested links. There were some adverse effects resulting from carpooling, however. By increasing the level of service on the highway network, transit utilization decreased and there was a tendency for population to locate further away from the CBD. These are characteristics similar to the effects of adding freeway links. They may not be very likely in reality, however, as low density development probably diminishes the ease of carpooling.

Transportation pricing actions are a second type of TSM action tested here. Of the three pricing alternatives simulated, increased commuter parking charges were found to be the most effective. This is an action that is simple to implement, assuming the political objections can be met. When implemented through an area licensing scheme, wherein a premium price is charged for entering the CBD during peak period(s), such a transportation pricing action has been found (5) to be effective in reducing congestion, especially when applied in a comprehensive transportation improvement program including the provision of additional transit service. The economic impacts of such a policy action, which were not modelled, could be adverse, however.

Other transportation pricing actions were found to be less effective in this research. Increased gasoline prices resulted in only small reductions in gasoline consumption until extremely high prices, approaching $2.00 per gallon, were reached. Comparisons with real experience in the U.S. are difficult since the recent increases in gasoline price were accompanied by a restriction in supply (6,7). The elimination of transit fares resulted in no meaningful change in energy consumption. Indeed, this action hardly increased transit utilization. Apparently, the much greater travel times of transit compared to automobile were the reason for this. It must be noted that these price-related findings are weaker than those in many studies in the economic literature due to the untested generalized cost formulation and the uncertainty of the correctness of the mode split model used.

Several combinations of TSM actions were simulated since it is unlikely that single policy changes will be implemented in the future. Rather, policy packages will most likely be developed with the intent of coordinating the impacts across all the modes of travel. It was intuitively appealing to observe that combining transit incentives (e.g., free transit) and automobile disincentives (e.g., increased gasoline price and commuter parking charges) resulted in greater reduction in energy consumption when combined than when implemented individually and their impacts summed together (8).

e. Measures of Effectiveness

It was noted in the analysis that the use of total automobile vehicle-miles travelled may be a poor measure to use to assess the effectiveness of alternative transportation energy policy actions. Measurements of VMT may exaggerate the impact of increased gasoline prices, underestimate the impact of carpooling and increased commuter parking charges, and fail to show that certain freeways can lead to more energy-efficient travel even though trip length may increase. VMT has been used in the past as a measure of effectiveness simply because it has been more accessible than gasoline sales figures for a given urban area. The basic problem with VMT is that it is an aggregate measure and does not reflect the non-linear nature of the relationship between speed and fuel consumption.

An important implication of this observation is that VMT may not be an appropriate measure to use when monitoring the impact of implemented transportation energy conservation policies in the real world. Accurate and timely gasoline sales data for specific metropolitan areas need to be accessible to planners and decision makers in order for them to be certain that the policy actions they take are having favorable impacts.

The use of the highway congestion index (the weighted average, by volume, ratio of actual link travel time to free-flow travel time) could be valuable in further (simulation) studies. Congestion was shown to be most important in the relationship between transportation and land use and the congestion index helped to explain many of the experimental results that were not intuitively obvious.

B. Directions for Further Study

1. Further Interpretation of Experimental Results

Much could be learned by submitting the results of the experimental program to practitioners in the transportation planning profession for their comment. It would be interesting to discover what such individuals, with considerable experience in designing and implementing transportation policy changes, perceive as important in the results. The degree to which their intuitive assessment of the results support the conclusions of this study should help increase their validity.

2. Comparisons of Results Using a Different Theoretical Base

Recognizing the need to validate the model, a second avenue of further research would be to encourage others to pursue similar findings using a different theoretical base. If the findings presented above can be supported through the replication of the experimental results by alternative simulation or analytical approaches or case studies, planners and decision makers could be more confident in using MOD3 for policy analysis. Possible approaches include the application of Putman's (10) Lowry model-based algorithm for simulating urban growth in an incremental manner, more aggregate urban development models intended for sketch planning such as CAPM (11), or more disaggregate procedures such as those developed by Charles River Associates (12).

3. New Applications of MOD3

Many additional experiments were identified in the experimental program of this research that could be conducted in the future. It should be noted that in interpreting the results of such experiments, the researcher must be aware of the limitations in MOD3 and how they may affect the results. An early subject for further study would be a more detailed exploration of the more promising policy changes found in this research. These might include additional simulations of urban growth policies, freeways, and combined TSM actions. Such experiments could include sensitivity analyses and the use of hypothetical cities with more and smaller zones.

A second approach for using MOD3 would be to simulate policy changes in real cities and discuss the results with the planners and decision makers in those cities. This is similar to the approach described above in which the results of the experiments on the hypothetical cities would be brought to practicing planners. The advantage in simulating real cities is that local officials would probably be able to interpret the results more easily and accurately in this context.

The third area inviting further experimentation deals with the technology assumed to characterize the automobile fleet. The speed versus gasoline consumption relationship for automobiles used in this research was representative of the average automobile in 1969 (13) and does not reflect the trend toward more energy-efficient and smaller automobiles in recent years. More recent data are needed to provide more timely results. Related to this is the desirability to simulate the introduction of a new technology to the automobile fleet, particularly since recent federal emphasis has been in this direction. Recent research quantifying the relationship of fuel consumption to level of service (14, 15) is beginning to provide the data for such experiments.

Repeating some experiments using different representative behavioral parameters is the fourth area of further experimentation. It would be enlightening to determine if trip time distributions from transportation studies of many different cities provide similar results. If they do, then the general applicability of the experimental results presented here can be supported. The use of constants and coefficients of the node split model calibrated for different cities would also help to achieve this goal.

The fifth and final area for further research using MOD3 deals with the operation and application of the model, particularly the iterative nature of the solution. Throughout the analysis it was noted that some oscillation about the optimum solution in the capacity-restrained equilibrium assignment may have resulted in some slightly counter-intuitive results. In addition, it was not clear how the subset sizes of basic employment may have affected the degree to which relative interzonal accessibility values converge. Additional experiments in which the number of iterations in the assignment algorithm and the number and sizes of basic employment subsets are varied may clarify these issues.

4. Modifications to MOD3

The realism of MOD3 could be improved by adding capabilities while preserving the general simulation framework. Most of these changes involve eliminating some of the assumptions and simplifications implicit in the model. It would be highly desirable to internalize the determination of automobile occupancy. The values for each trip type are currently exogenously specified. Recent research has demonstrated that these values can change as gasoline and parking costs increase (16). It should be possible to include this computation just prior to the assignment of automobile trips to the highway network.

The second area in need of improvement is the capability to model more than one transit mode. Currently, only a single mode (bus or rail transit) can be modelled. It would be desirable to be able to simulate a more realistic transit system in order to apply the model more easily to larger cities. Related to this is the need to include a transit assignment algorithm. While transit usage is fairly low for the cities of the size simulated in this research, it is possible that transit routes could be overloaded in simulating larger cities. Even in those cases where this may not be a problem, a more detailed description of the transit travel may aid in the interpretation of the results.

There is also the need to model the level of service interaction between automobile and transit. Currently, MOD3 ignores the effect of buses, especially their entering and leaving the traffic stream, on highway congestion. Further, the impact of congestion on transit travel times is considered only through the exogenous specification of average urban speeds for buses. A more realistic simulation would, at least, consider the presence of buses in the capacity-restrained assignment of automobiles and redefine transit travel times to account for congestion on the highways.

There are several features of the land use submodel which could use further development. These include allowing households to relocate over time (i.e., change location between the base and incremental runs) and for work trip zonal interchanges to change. This was not done in MOD3 because it was unclear exactly how to determine accurately which households and which trips would shift. Also, in regard to the land use submodel, it would be desirable to insure that interzonal accessibility values are indeed converging. This could involve simply printing some aggregate measure of convergence after each iteration (say, the sum of the difference in interzonal accessibility values of all zone pairs for consecutive iterations) or requiring some built-in check of convergence within the model.

A final consideration is the desirability to model other environmental factors affected by transportation, notably air pollution. Ingram (17) discusses a procedure which could be compatible with the type of model developed in this research. Lieberman and Cohen (18) describe a model which may be useful, although possibly only at a more detailed level, in which more complete and realistic highway networks are simulated.

5. New Modelling Approach

For all its simplicity in structure, the Lowry-type model as used in this research does have two operational limitations which make it expensive to incorporate in a policy simulation model. The matrix inversion in the land use allocation process requires exceedingly long computational time as the number of zones becomes large. Related to this is the computation of interzonal accessibility which requires an assignment of automobiles to the highway network. This is also an expensive algorithm to run when the number of zones becomes large. The use of alternative urban development models which do not require such computations may be desirable since they could allow the computational time required per experiment to decrease. One such model is the Community Aggregate Planning Model (CAPM) (19). A problem with CAPM is that it relies on total VMT to allocate land uses. This aggregate measure was shown to be inappropriate for energy policy research in the analysis above.

It must be recognized that many of the policies that need to be simulated must be modelled at a fairly disaggregate level. There may be no way of avoiding the need to specify highway networks with a large number of links and nodes if the analysis is to provide realistic and accurate information.

A very different approach, which could be relevant should energy supplies for transportation again become restricted, would be to employ an optimizing methodology to the land use allocation process. By attempting to minimize energy consumption, instead of or in addition to travel time, models like TOPAZ (20) could be used to identify promising energy conservation policies.

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