CHARACTERIZING THE EVOLUTION OF URBAN PATTERNS AND TRAFFIC NETWORK PERFORMANCE

by

Hani S. Mahmassani, Robert Herman, C. Michael Walton
M. Hadi Baaj, Shekhar Govind, Chee-Chung Tong
and James C. Williams

Research Report GM-1986-F

Conducted for the Operating Systems Research Department
General Motors Research Laboratories

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUTIN

November 1986

PREFACE

This report summarizes the results of an eight-month study, funded by the General Motors Research Laboratory, "The Future of Cities: The Role of the Automobile", aimed at exploring ways of characterizing the evolution of urban development patterns and their implications for personal transportation and mobility.

The authors are appreciative of the support, encouragement and technical advice of Mr. William Spreitzer and Dr. Richard Rothery, of the GM Research Laboratory's Operating Systems Research Department, throughout the duration of the study.

Several students and other administrative and technical staff members have participated in the conduct of this research and preparation of this report. In particular, the contribution of Oddvar Steinsholt, undergraduate research assistant, in digitizing the census maps and helping develop the database for the study of spatial density patterns is acknowledged. The help of Donna Ogle in final report preparation is also appreciated.

Naturally, the authors remain solely responsible for the contents of this report, which do not necessarily reflect the views or opinions of the project sponsors.

EXECUTIVE SUMMARY

This report summarizes the results of a study aimed at exploring approaches for the characterization of urban patterns, their evolution and interaction with and effect on personal mobility and transportation. This objective was pursued at three levels: 1) long term (since the turn of the century) evolution of various infrastructural attributes of cities, with a focus on fundamental mechanisms and underlying constants; 2) urban structure, in terms of the spatial patterns of population density and other variables, and its evolution; and 3) urban traffic network performance, in terms of quality of traffic service, and its dependence on the physical and operational features of the network and the associated land use. The three levels address important components in an integrated framework linking the long-term evolution of urban characteristics, the spatial distribution of these characteristics (location of residences and business activities) and the physical and operational features of the transport infrastructure to the flow patterns and resulting quality of service.

In the first activity, the evolution of several infrastructural attributes of two cities (Austin and San Antonio), were tracked over about 85 years, in an attempt to understand the mechanisms underlying the overall development of these areas. A subset of these variables was also tracked over a shorter time period for eleven other cities (Atlanta, Boston, Chicago, Cincinatti, Denver, Los Angeles, Miami, New York, Phoenix, Seattle and St. Louis), providing a means for comparing these cities. The results suggest several hypotheses about future development, and begin to point at useful ways of characterizing urban development patterns. This approach would benefit from further investigation using a larger sample of cities and different variables.

In the second level of the research, the spatial patterns of population density, household automobile ownership and other socio-demographic variables, as a function of distance from the central city core, were found to provide a useful characterization of urban structure, and of its evolution when taken at different time intervals. The principal substantive conclusions from the four case cities (Austin, Atlanta, Dallas, Phoenix) considered for 1960, 1970 and 1980, are: continuing overall dispersion away from the traditional central core, accompanied by the densification of formerly low-density suburbs, with implications for high congestion levels in the densifying "suburban" communities, comparable to those typically associated with the CBD. In addition, the analysis has captured the continuing growth of average household automobile ownership, in all parts of the urban area, and revealed a distinct spatial pattern that seems to be robust across the case areas considered, as well as within radial corridors in the one case that was so analyzed (Austin). This component of the research should, in future effort, consider the spatial patterns of the location of firms and businesses of various types, which could then be considered, along with the spatial distribution of residents (and related variables at the home end), in describing the resulting flow patterns. In addition, it would benefit from the consideration of a richer collection of urban areas. Other suggestions for useful extensions of the approach are discussed in chapter 3 of the present report.

Suburban networks generally exhibit somewhat different characteristics from CBD systems, in terms of physical features, traffic control and adjoining land use and its generation of traffic-interfering activities. The implications of these differences on the performance of the traffic system, in terms of congestion and the associated quality of traffic service, can be addressed using the results generated by the third component of this work. Two principal objectives were accomplished: 1) the development of a system of relations that comprehensively describe the joint behavior of traffic variables such as the average speed, flow, concentration, average fraction of vehicles stopped in the network, and the two-fluid stopped and running time variables; and 2) the investigation of the sensitivity of these relations and their parameters to the network's characteristics, particularly its topological features, prevailing control strategies and degree of interference from the adjoining land use. Methodologically, both objectives were supported by microscopic simulation experiments, which provided useful macroscopic insights into network traffic behavior. The most important conclusion is that it is possible to characterize traffic flow in urban street networks with relatively simple relations among the principal networkwide traffic variables, and that these relations closely parallel those that have been established at the individual facility level, despite the complex interactions that take place in a network.

The analysis presented in chapter 5 suggested that these relations and their parameters appear to follow systematic trends in response to the network features. On the basis of the limited simulation experiments conducted for this study, it appears that the network's physical features have a greater effect on its performance than traffic control through conventional signal timing. Nevertheless, meaningful improvements could be achieved in the concentration ranges under which most actual networks operate.Interesting insights were also obtained regarding the effect of traffic interfering activities (short term events) typically present in an urban setting.

A better understanding of these mechanisms would be useful in trying to understand and deal with the scenarios of deteriorating traffic conditions in densifying suburban communities. The private automobile has been an essential element in the development of these suburban development patterns, which initially seemed to offer congestion-free circulation. Rapid degradation of traffic conditions in these communities could have important consequences on the outcomes of the personal location, mobility and travel decisions of area residents, particularly with regard to automobile ownership and utilization.

Particularly promising opportunities for substantive and methodological contributions through additional research on the various approaches explored in the present study are discussed in the concluding chapter of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The future development of urban travel and associated car use patterns are intrinsically related to developments in city structure and the location of workplaces, activities and residences. Changes of this nature generally take place only over relatively long periods of time, as considerable inertia appears to be associated with the vast infrastructure already in place and with the lifestyle patterns acquired by residents over many years. At any given time, there are several forces and trends, associated with technological, economic, political and social phenomena, that shape such development. Recently, various indications seem to have generated concern among researchers and planners regarding the future development of urban systems and the potentially significant implications for personal transportation and mobility (Brotchie et al., 1985; Webster et al., 1985).

While the rate of change of urban patterns might seem "slow", it is probably greater than that required by the responsible agencies to plan and implement decisions aimed at the needs associated with the emerging patterns. Similarly, the lead times necessary for the conception, design, testing and production of transportation products and services adapted to the emerging urban patterns are also long compared to the time frames over which changes in these patterns might be taking place. It is thus desirable for the auto industry and other actors involved in urban transportation to characterize, understand and, to the extent possible, anticipate such development in order to provide valuable input to related decisions and actions.

While predicting the future undoubtedly involves a fair dose of speculation, exemplified by the recent collection of articles in Brotchie et al. (1985) or Lakshmanan and Chattergee (1986), understanding of the fundamental processes that have shaped past development provides an essential starting point and sound basis. Several studies have investigated the underlying structural mechanisms and phenomena shaping the evolution of urban systems, but these efforts have been fragmented, often along disciplinary lines, and rarely guided by a specific operational purpose. This is particularly true for those aspects that affect travel behavior and transportation system performance, and their interaction with the broader urban system. Many efforts, insightful in their own right, have been too microscopic in scope to usefully contribute to the macro-level characterization and understanding of complex urban systems.

This report presents the results of an eight-month effort directed at these complex questions. Naturally, it cannot claim to give all the answers, but rather indicates useful and promising directions for exploring, characterizing and understanding urban development patterns as they affect and interact with transport in cities. This work is pursued along three levels. The first, and broadest, level is an exploration of the long term (since the turn of the century) evolution of several infrastructural attributes of two cities (Austin and San Antonio), with a focus on the mechanisms underlying the overall development of these areas. A subset of these variables is also tracked over a shorter time period for eleven other cities (Atlanta, Boston, Chicago, Cincinatti, Denver, Los Angeles, Miami, New York, Phoenix, Seattle and St. Louis), providing a means for comparing these cities.

The second level is concerned with the combined effect of network shape and of the relative locations of activities, residences and workplaces on the characteristics of urban travel, particularly on average trip distances. Thus it incorporates a spatial dimension which is essential to the analysis of urban structure and travel interactions. The evolution of spatial density patterns over the past three decades is examined in four urban areas (Atlanta, Austin, Dallas and Phoenix). Comparisons over time and across cities are performed through the calibration of models of the spatial density as a function of distance from the traditional city centers, allowing the examination of hypotheses regarding suburbanization and spatial dispersion/concentration trends. In this report, only the spatial patterns of residential location and other residence-based variables are analyzed, primarily due to data availability and time limitations, though similar comparative analysis for the spatial density patterns of employment and business location would be particularly valuable to the description of the resulting intra-metropolitan flows.

At the third level, we focus on the characterization of traffic flow quality in urban networks, through the development of macroscopic network-level models relating the principal traffic flow variables in a simple and operationally useful manner. In particular, we examine, using extensive simulation experiments, the variation of the principal model parameters with the features of the network (network topology as well as traffic control), the associated trip patterns and a measure of urban activity. This work points to answers to questions such as: 1) What are the determinants of the quality of traffic service and congestion in an urban street network? 2) How can this quality of service can be influenced, and to what extent? 3) What is the "ultimate" service level that can be obtained in a particular network and urban environment?

The report is organized as follows. The next chapter presents the definition of and analysis of the historical data for about twenty variables for the cities of Austin and San Antonio (selected primarily on the basis of data accessibility to the reseach team), followed by the examination of several of these variables for a sample of eleven cities in the U.S. Chapter three presents the analysis of the spatial density patterns for the four initially selected urban areas: Austin, Dallas, Phoenix and Atlanta. Chapters four and five are devoted to the characterization of traffic service in urban street networks. Chapter four first presents the derivation, calibration, and comparative assessment of three interrelated sets of macroscopic network-level traffic models, while chapter five summarizes the results pertaining to the effect of various network features and urban characteristics on the model parameters (and consequently on traffic quality). The study's overall conclusions are summarized in Chapter six, along with suggestions for particularly promising further research.

CHAPTER 2

CHARACTERIZING THE EVOLUTION OF CITIES

2.1. INTRODUCTION

In a paper presented by John S. Adams (1986) at a workshop on The Future of Infrastructures sponsored by the National Academy of Engineering, the growth of the metropolitan framework is categorized into four eras or "epochs". The key feature that distinguishes between each "epoch" is the mode of transportation used ("Sail-Wagon", "Iron Horse", "Steel-Rail" and "Auto-Air..."). Each "epoch" sees unique metropolitan growth patterns being molded by the transportation available. Adams also speculates about the "epoch" yet to come :

> "Our current romance with computers and telecommunications prompts us to wonder about a fifth epoch, but their impact on the geography of metropolitan areas is still unclear."

One thing is clear. The automobile, like most new technology, brought about a virtual revolution in certain areas. In particular, it caused the spatial reorganization of human activities by redefining distances people could travel for their daily chores. By increasing personal mobility it also fostered the environment for the growth of the service sector - the popularity of the 'drive-in window service' is an excellent example of such a phenomenon.

For a peep into the crystal ball to examine the future of the automobile, we can hypothesize separately on two different time scales. Predictions can be made on a small time scale (roughly, the time to the implementation of the next new major substitute technology), or a much larger time scale (beyond the implementation of the next major substitute technology). Any attempts to predict the role of the automobile in society should be limited to the smaller of the two time scales. Perhaps, some day the automobile will go the way of the sailboat - from being a prime mover to being a pleasure craft. However, such conjectures about the distant future are akin to dabbling in science fiction.

Linked as it is to the spatial organization of the urban centers, the automobile's security in the short run depends primarily on the future of the metropolises and how they evolve. A number of pertinent questions can be asked in this regard. Will the metropolises continue to develop 'bedroom communities' necessitating a daily home-work-home trip of a considerable distance or will the communities reorganize and become self-sufficient in terms of providing adequate work opportunity (and space) at the local level? How will the home-market-home trip change over time? Will there be a conglomeration of a few large stores in key shopping areas removed from residential communities (such as seen in shopping malls and plazas) or will there be concentration of a number of small stores located much closer to the homes of the consumer (such as often seen in mixed development areas)? There are also some very interesting speculations about what telecommunications will do to the market for transportation and the extent to which "transportation" as we understand it today will be replaced by "communications".

For an urban center, any of these scenarios discussed in the previous paragraph could be equally likely. What eventually comes about will be due to the effects of a multitude of factors including economic, geographic, political, social and the infrastructural setup of the urban area. The automobile usage by the community would be different from one another as each area goes through diverse evolutionary patterns.

Consider the recent demographic shift towards cities. The bulk of the market for automobiles has been, is, and will continue to be, in the cities and urban areas. A study on the future of the automobile would have to be based on predictions about the future of the urban centers. One way to look at the future is to study the past in the hope that certain evolutionary trends may be established. Therefore, a look at the evolution of the metropolis during the "automobile...epoch" could not only provide valuable insights about how the automobile has shaped the growth of these cities, but also lead to predictions (for the time period left in this "epoch") about the future (usefulness) of the car in the urban context.

This study looks at historical data for variables that represent a few infrastructural attributes of two cities (Austin and San Antonio) and follow their evolutionary track from the turn of the century to the present. Similar variables are evaluated for eleven other cities (Atlanta, Boston, Chicago, Cincinnati, Denver, Los Angeles, Miami, New York, Phoenix, Seattle and St. Louis) over a shorter period of time. The data (on Austin and San Antonio) is initially viewed in the spirit that pictorial representations of data derived from a complex situation may provide insights into the mechanisms of the evolution of the system. An attempt is then made to characterize the evolution of these two cities by the use of "snow-flake diagrams" (a classification scheme introduced by Herman and Montroll (1972) for characterizing countries and representing them pictorially in the form of multi-axis phase diagrams). For the group of the eleven cities, similar diagrams are constructed for comparisons both across the cities and across time. Such an endeavor would allow us to examine how cities have evolved, and provide a basis for predicting the future of these cities.

2.2. DISCUSSION OF DATA

Acquisition of historical data is never an easy task. Even when data is available, there is virtually no means of checking its validity. It is not surprising therefore, that a large number of different publications had to be used to compile the data base for this study. As such, these sources can be divided into two distinctly different groups. The distinction between the types of sources depends on the fact that the first type of source provides disaggregate data where actual counts have to be made of the variables values while the second type of source has data already compiled in a format which can be used readily for analysis.

The first type of source consisted of the City Directories of Austin (1959 to 1985) and San Antonio (1900 to 1985). These directories are published each year and are available through the Public Library or the Chambers of Commerce of the two cities. These directories have a wealth of information for the cities in question and provide a fascinating glimpse into the antecedents of the modern metropolis, in terms of providing valuable (raw) statistical information and giving the researcher a panoramic view (across time) of changes in the city.

An actual count was made of all establishments and professions listed in the directories (e.g., the number of restaurants, number of doctors etc.). This data was complimented by using a number of sources of the second type. Data for the consumption for water and power were obtained from various publications of the respective city utility departments. Utility hookup data are listed in basic data sheets published by the city; for most years, these are also listed in the "City Directory". Street mileage was also obtained from the basic data sheets. For some years, when this data was not available, mileage of urban streets (on a county basis) was obtained from the Highway Department and reasonable adjustments were made to get data on the city level. A similar process was followed for years where data for the number of vehicles was available only on a county basis. Population and area estimates were found in census publications.

A major data source of the second type came from the Bureau of the Census in their publication "County and City Data Book" (1949-83). These volumes contain statistics on such varied items as vital statistics, housing, trade, manufacturing, crime, city government finances and even bond ratings. The drawbacks of using this source are that certain variables are not represented in each volume and that there are currently only seven published volumes (circa 1949, 1956, 1962, 1967, 1972, 1977 and 1983). Further complicating the issue is the fact that not all variables presented in any one volume are for a single common year. Despite these shortcomings, it remains the best single data source for a study of this nature. These seven volumes were utilized for building the data base for the group of the eleven cities mentioned earlier.

As can be seen from the preceding discussion, the sources that have been utilized in building the data base for this study are quite diverse. Not only does this raise the question of homogeneity of the data sources, but there is also the added problem of missing data for key variables for certain years. These features could reduce the confidence limits of the inferences drawn. However, in the view of the authors, the procedures being used in this study and the conclusions inferred, are well within the bounds of the limitations imposed by the use of this data set.

2.3. A TALE OF TWO CITIES

As noted in a previous section, we shall look at pictorial representations of the evolutionary path taken by some attributes of the city of Austin. Later in this section, similar aspects of the nature and growth of the city of San Antonio shall be presented. For a more detailed analysis of these two cities, the reader is referred to a publication by Ardekani, Dona, Govind and Herman (1986) for discussions on Austin and a paper by Govind, Herman and Walton (1986) for discussions pertaining to San Antonio. This section has been based in part on the aforementioned papers.

Comparisons, across both time and space, requires the use of data either normalized on some scale or reduced to a dimensionless quantity. It is a common practice to use population as a normalizing variable and represent attributes on a per capita (or its reciprocal) basis. Density functions in 2 dimensions (involving area) have also been used previously for normalizing. It would be worthwhile to investigate density functions formed in 1 dimension when normalization is done with respect to the total length of streets in a city. The following is a look at a partial history of Austin using the strategies outlined above.

Figures 2.1, 2.2 and 2.3 illustrate how the three basic variables population, area and street-miles, have changed over time. (It would be interesting to observe the changes in lane-miles rather than street-miles; unfortunately, such data are very difficult or impossible to obtain).

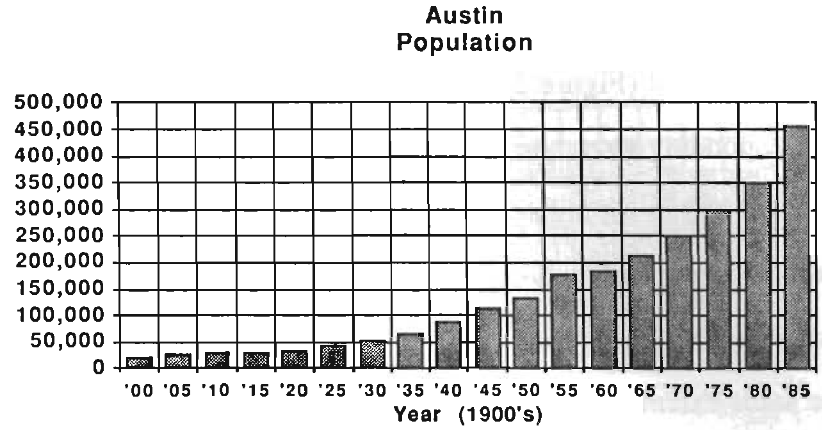


Figure 2.1

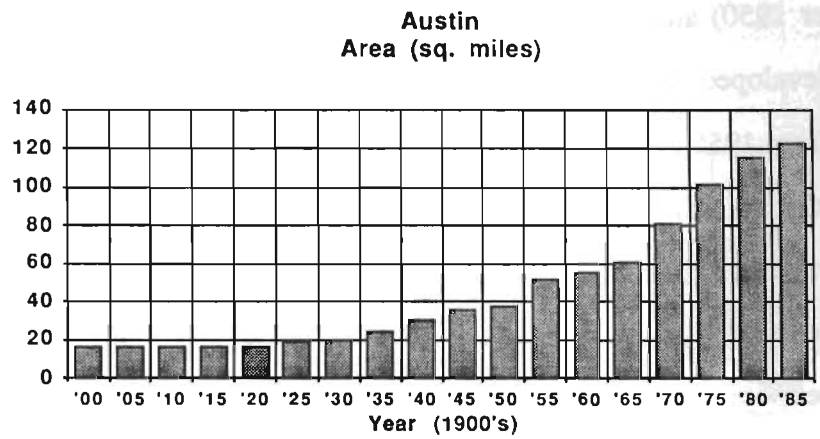


Figure 2.2

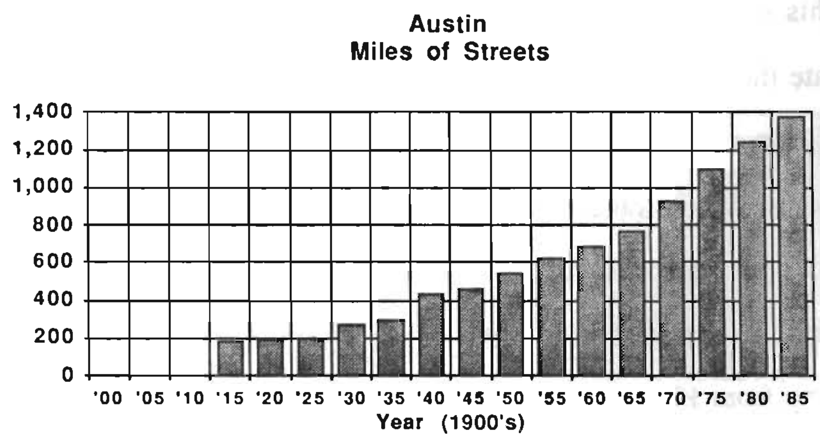


Figure 2.3

The next series of charts (Figures 2.4, 2.5 & 2.6), show how the basic variables change with respect to one another. The density of population shows an approximate linear increase from 1900 to 1950 (Figure 2.4). From 1950 to 1980, the growth in area was faster than the corresponding growth in population. The peak at 1985 represents the spurt of growth the city has had in the eighty's. The density of street-miles may give a general indication of the "efficiency" of land use (Figure 2.5). The decreasing trend from 1950 onwards suggests that even though the city did acquire more land, these have not been opened up to the same extent as land acquired previous to 1950. Another interpretation could be that the density of streets in the inner city (areas included in the city limits till 1950) may not be greater than the density of streets in the suburban areas adjoining the city (developed after 1950) and the decline comes simply from the inclusion of tracts of completely undeveloped land. The density of population on a street-mile basis remains fairly constant from 1955 to 1980 (Figure 2.6). This supports, though inconclusively, the latter argument that the inclusion of undeveloped land causes the decrease. One immediate conclusion drawn from Figure 2.6 is that the growth of streets in the city has lagged behind the growth in population over the last 70 years. This reflects a simple measure of the increasing number of people sharing the use of one unit of the transportation infrastructure.

An important variable to study with regard to this report would be the number of vehicles in a city. In the context of this study, the number of vehicles includes passenger vehicles, farm trucks, commercial trucks and motorcycles. The next four Figures 2.7 - 2.10 examine this variable. The total number of registered vehicles has grown at an "exponential" rate that is much faster than the growth in population (Figure 2.7). The number of vehicles per capita demonstrates this fact (Figure 2.8). As would be expected from the preceding discussions, both the number of vehicles per street-mile and the number of vehicles per square mile, have increased "exponentially" since 1950 (Figures 2.9 & 2.10). What is worthy of note is the fact that all the three charts have a similar characteristic hump from 1920 to 1945 and thereafter, from 1950, show an "exponential"

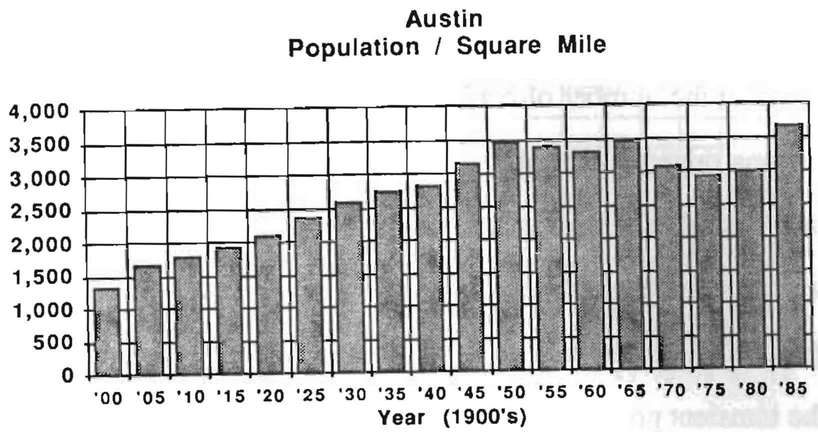


Figure 2.4

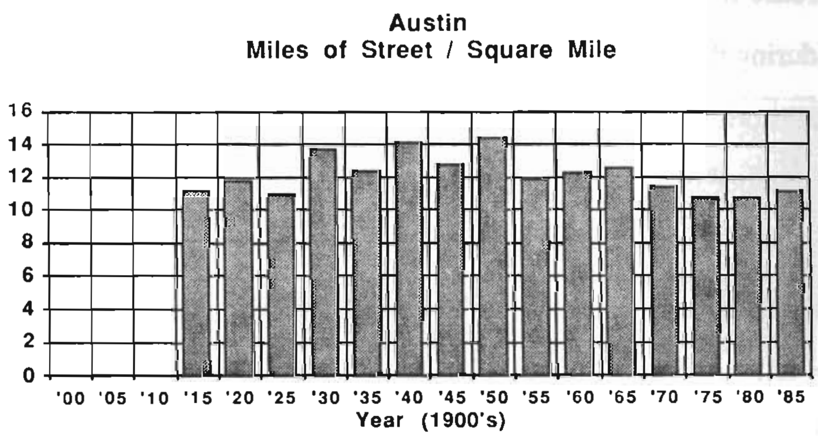


Figure 2.5

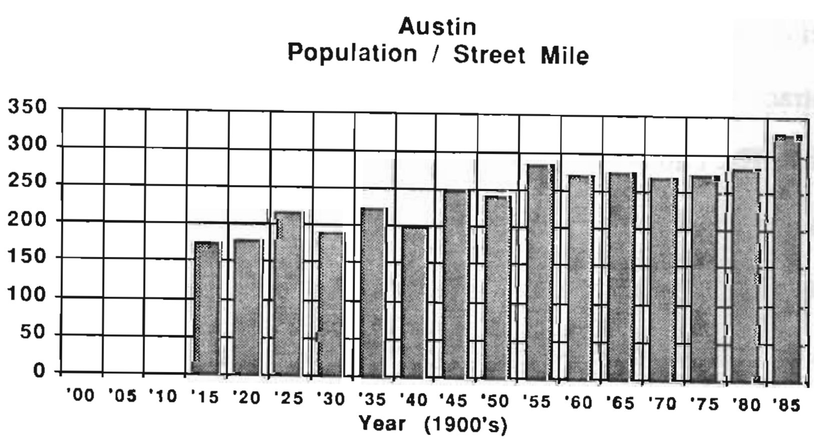


Figure 2.6

growth (Figures 2.8, 2.9, & 2.10). This phenomenon indicates that strong correlations may exist between the dependent variables.

When looking at the number of banks and hospitals (Figures 2.11 & 2.12), one of the pertinent questions raised is that of size. In the case of hospitals, data regarding the number of beds or the number of admissions may prove to be more revealing; similarly, for banks the number of customers or the net assets and liabilities may be more meaningful.

It is suggested that normalized variables derived from hotels/motels might give a fair measure of the transient population of a city (Figure 2.13). However, as in the case of the two previous charts, the question of size confounds the issue. A look at hotel revenues and the number of beds available may provide more definite answers. In terms of Figure 2.13, a sharp increase in the number of motels was noted after World War II while the number of hotels during the same period actually declined.

One of the more intriguing results to come out of this study involves different functions of the number of restaurants (Figures 2.14, 2.15 & 2.16). But for localized fluctuations, the number of people per restaurant has been remarkably steady from 1900 to 1985 (mean = 678, std. dev. = 159). Charts showing the number of restaurants normalized by area (mean = 4.2, std. dev. = 1.3) and street-miles (mean = 0.4, std. dev. = 0.1), also exhibit a similar consistency over the years (Figures 2.15 and 2.16). It would be interesting to compare these values for different cities assuming that other cities display such characteristic numbers as well.

The level of sharing of certain services - auto dealerships (Figure 2.17), doctors, lawyers and contractors (Figure 2.18) - by the population may represent key factors in the growth of the city. The number of doctors, which includes both physicians and dentists, indicates the level of health care available to the city. A lower population number per contractor will lead to the inference of a higher construction activity. Further, the number for law firms could indicate some essential aspects of the nature of the city and the type of activity it thrives on.

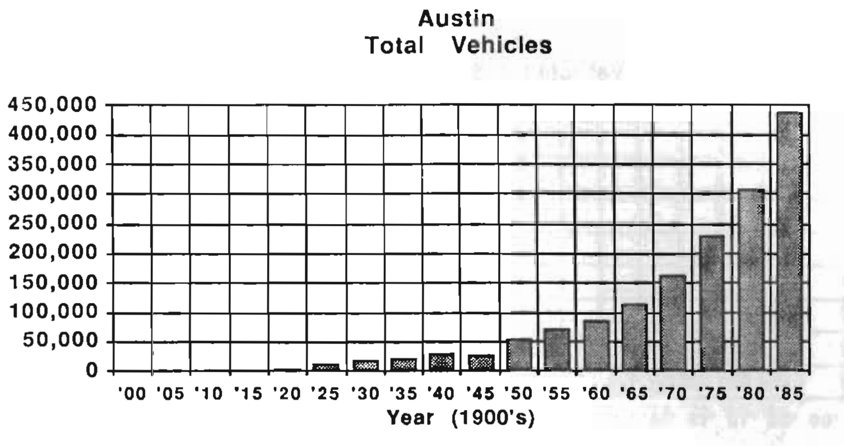


Figure 2.7

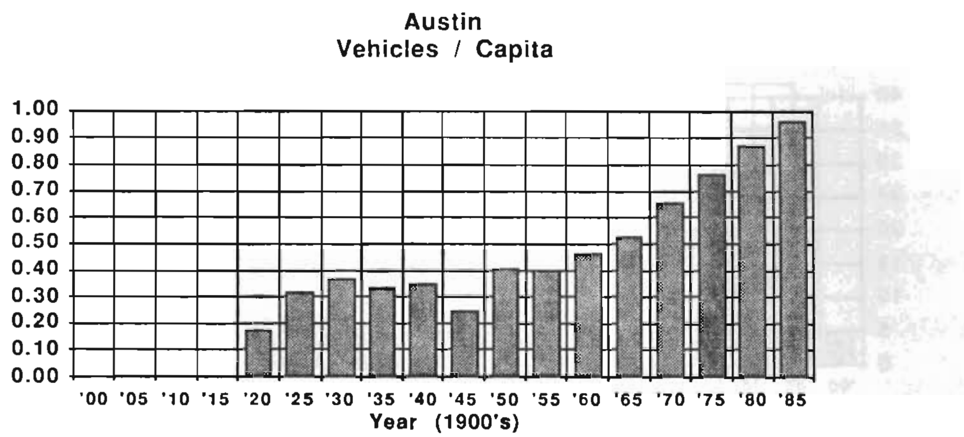


Figure 2.8

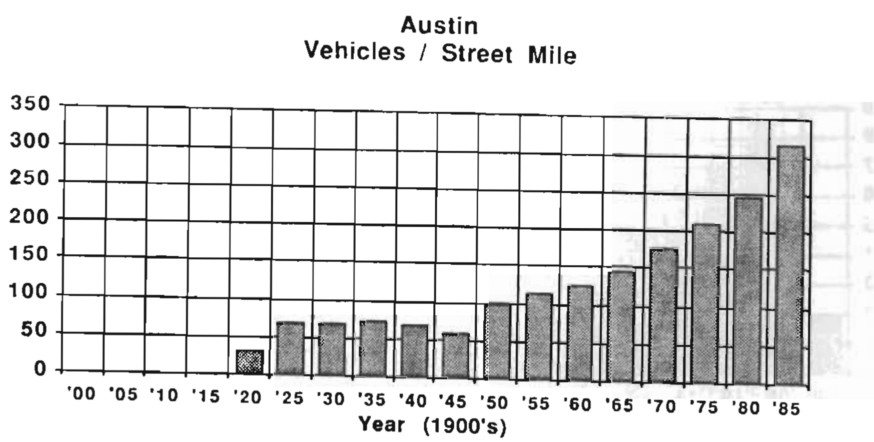


Figure 2.9

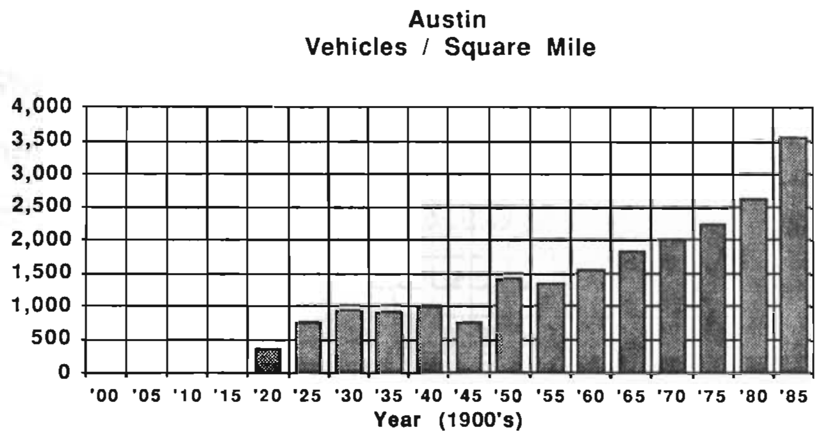


Figure 2.10

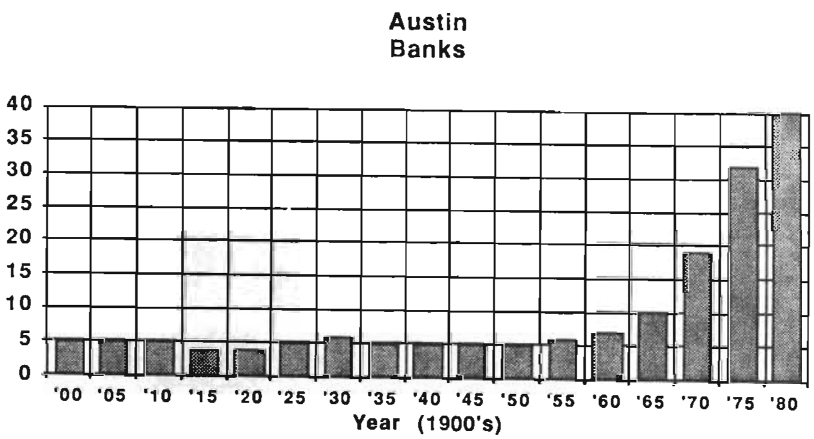


Figure 2.11

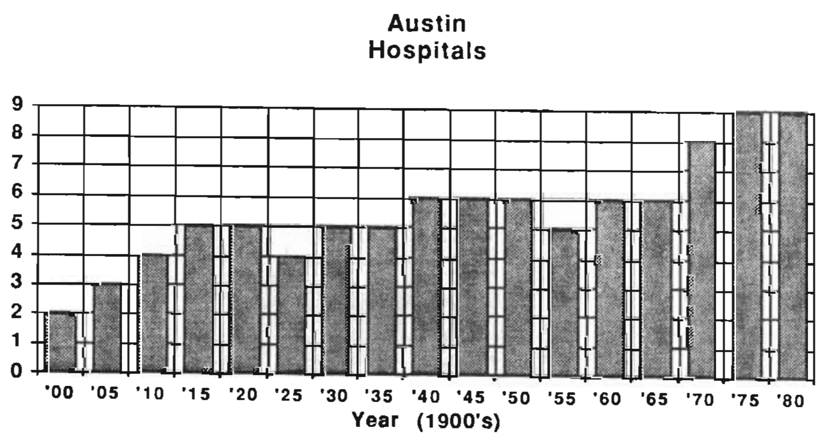


Figure 2.12

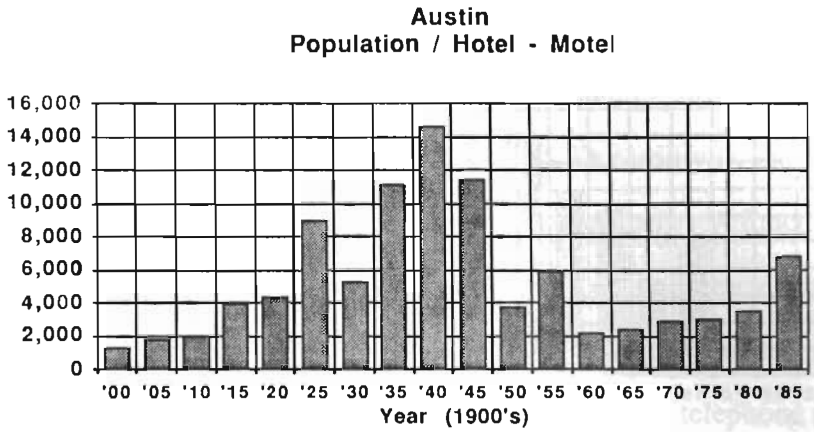


Figure 2.13

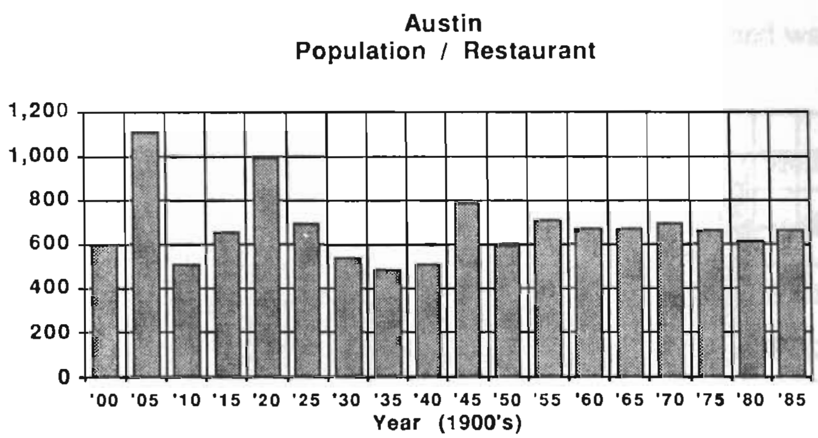


Figure 2.14

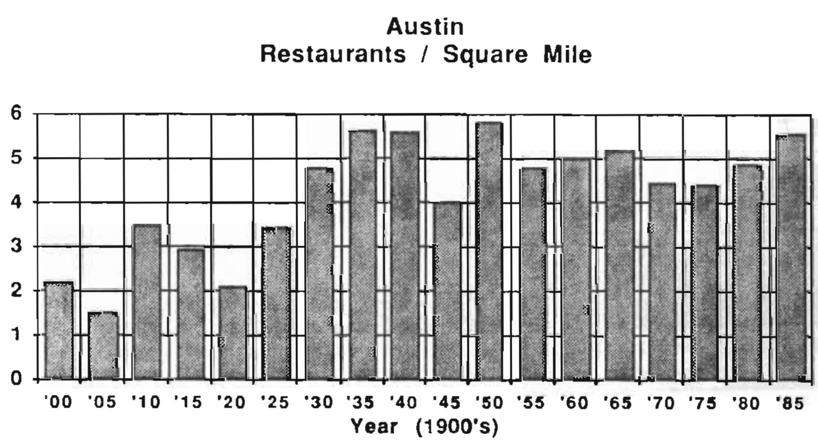


Figure 2.15

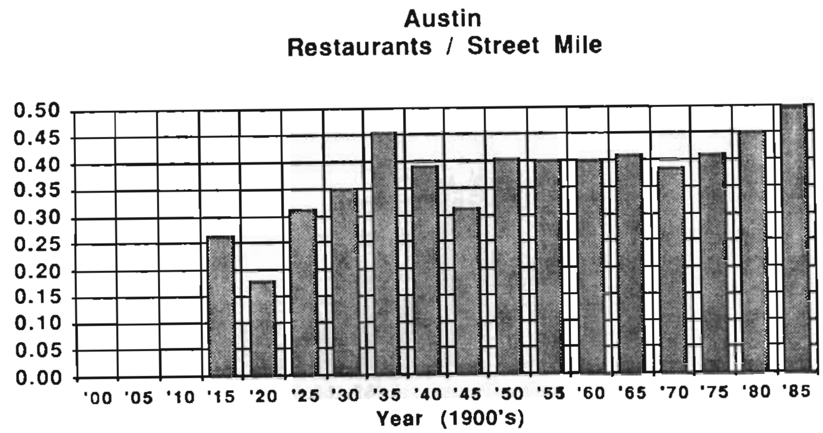


Figure 2.16

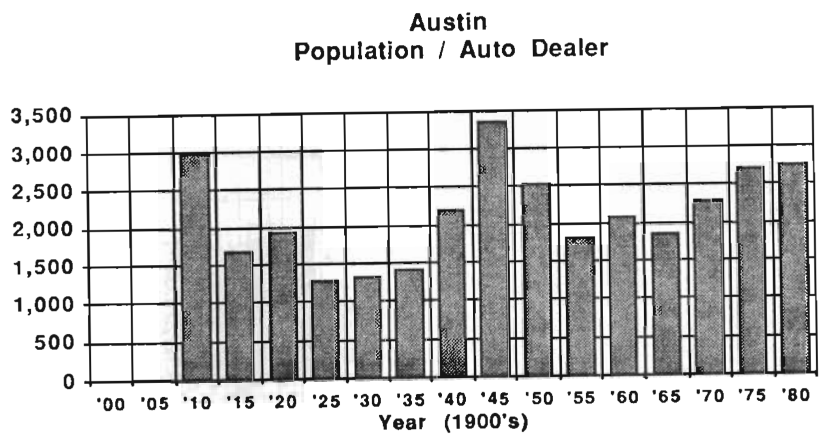


Figure 2.17

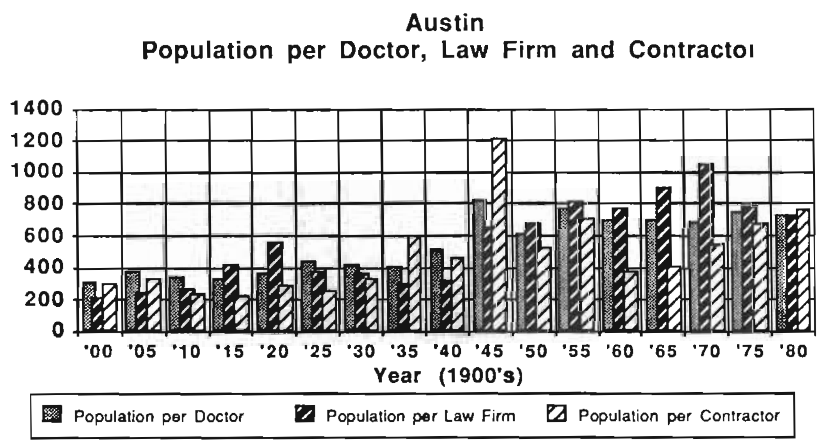


Figure 2.18

A number of conclusions may be drawn by looking at the utility hookups in a city (Figure 2.19 & 2.20). It can be reasoned that every dwelling unit would, most likely, have its own electric meter. However, in the case of almost all apartment complexes, the water meters are not uniquely assigned to each apartment. This utility is, mostly, charged for by a fixed rate (which may be included in the rent of the apartment). A function of the number of electric meters and water meters could, therefore, be used to characterize the composition of the housing market (Figure 2.19). The number of telephone numbers in use may be a reflection of not only the average family size (assuming one telephone number per family) but also the business activity of the city (Figure 2.20). Historical data on the number of business telephone lines would be interesting to look at. A spatial history of a city could also be captured by plotting miles of telephone lines, sewer lines and water pipe lines over time.

The annual per capita water consumption appears to have been kept stable at the 70,000 gallons mark since 1970 and shows no signs of increasing (Figure 2.21). This variable could be used as an indicator of geographical and climatological differences between cities. Another excellent scale for the comparison of cities would be the per capita annual power consumption since it measures an infrastructural attribute which is often of prime concern (Figure 2.22). Cities that use electrical energy for transportation (from the urban/suburban rapid transit systems to quite simply the escalator and elevators in a city full of high-rise buildings) may show higher level of consumption than the other cities. Weather and industry, (among others) affect this variable as well. The 'exponential' rise in postal receipts (Figure 2.23) may not be so steep if this chart was further normalized by the corresponding year's postage rates and indexed for inflation. Current levels of postal revenues could be a strong indicator of the nature of the businesses of the city.

Since normalization can be done by a number of different variables (e.g. area, population, street miles etc.), it can be seen that an almost endless number of such functions can be derived and plotted over time to represent a city's evolution. For the sake

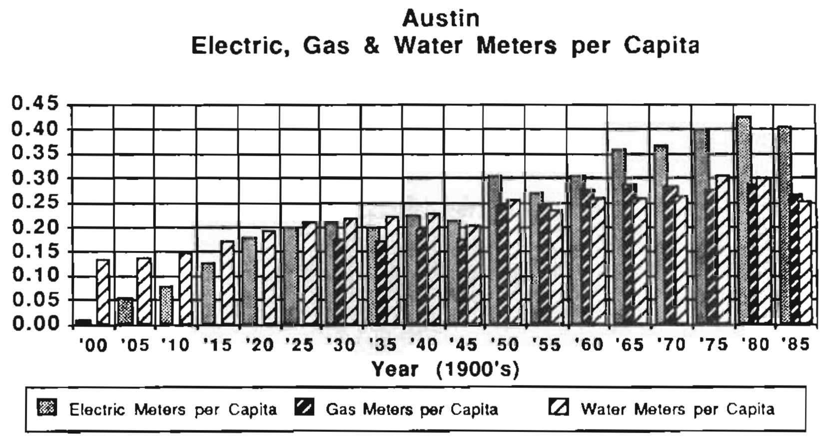


Figure 2.19

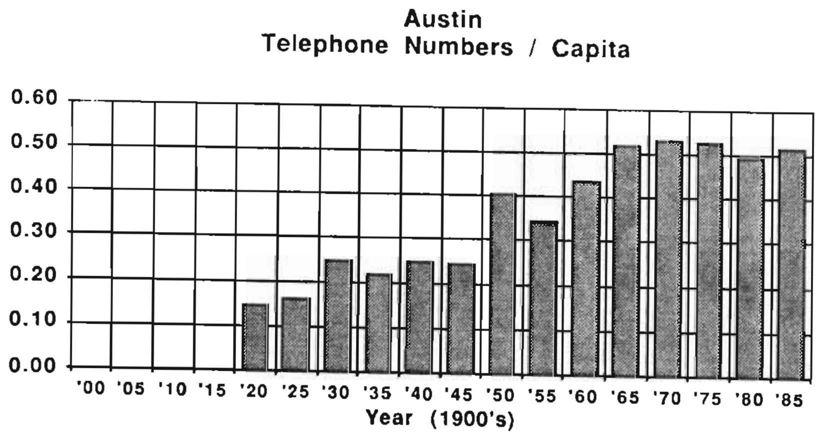


Figure 2.20

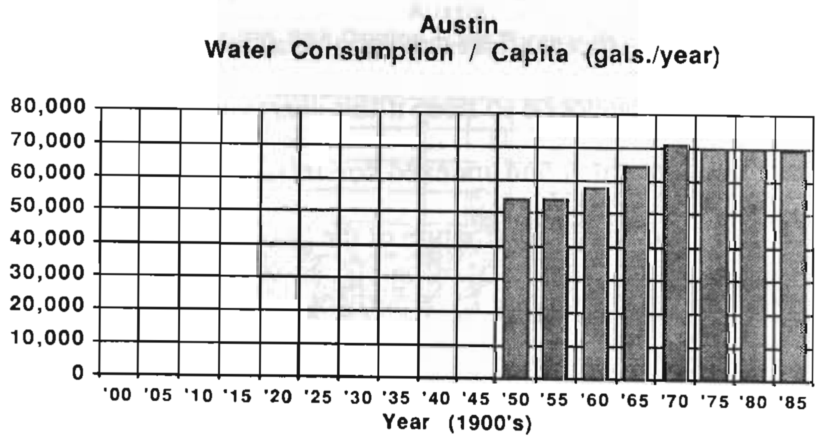


Figure 2.21

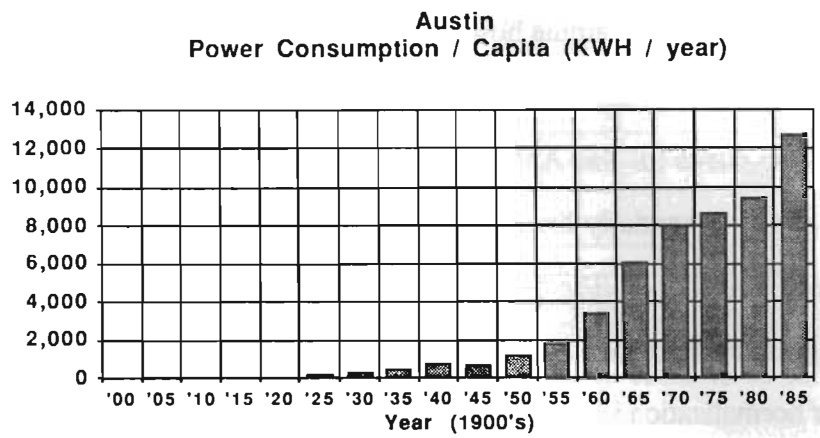


Figure 2.22

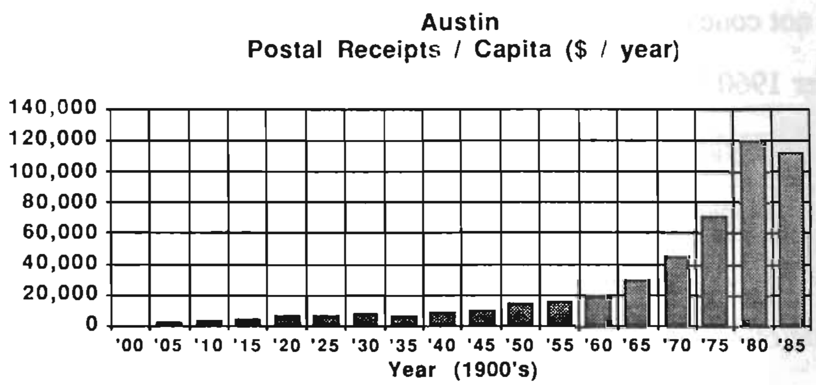


Figure 2.23

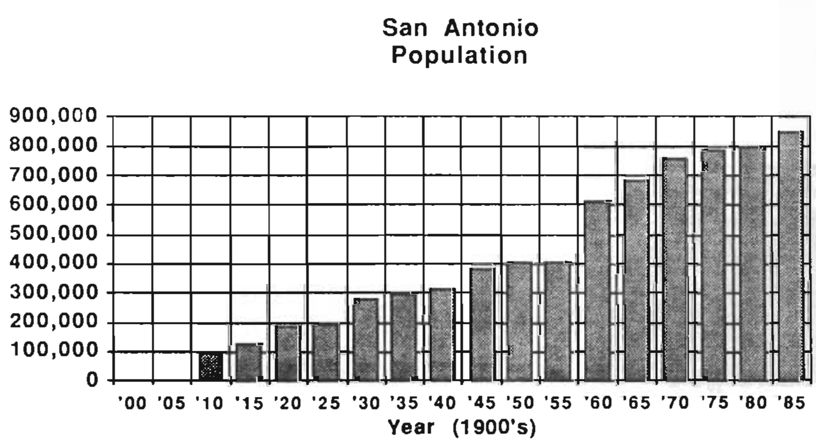


Figure 2.24

of brevity and conformity, we shall present the evolutionary track of only a few variables for the city of San Antonio, and examine how they appear when normalized by population alone.

The population curve for San Antonio (Figure 2.24) shows a distinct growth over time. The growth seems essentially linear in nature (unlike an "exponential" growth as seen for Austin - see Figure 2.1). The 50 % increase shown between the years 1955 and 1960 is a fairly high rate of growth and the effect of its presence in the charts where this variable is used for normalization is quite distinct.

Figure 2.25 is a plot of the number of vehicles in the city. The total number of registered vehicles has grown at an "exponential" rate. The number of vehicles per capita (Figure 2.26) does not conclusively establish a pattern. However, it may be said that the decline noticed after 1960 is simply due to the phenomenal growth in population noted earlier. The jump in vehicles per capita from 1975 to 1980 almost suggests an economic boom. It is interesting to speculate on the nature of the curve above a value of 1.

As in the case of Austin, one of the unresolved issues in Figure 2.27 (depicting hotels/motels) is that of size. It is suggested that World War II may be the cause of the fluctuation at the year 1940. The jump at 1960 is also observed here (see Figure 2.24). As in the case of Austin, a sharp increase in the number of motels was noted after the 1950's while the number of hotels started to decline. This effect could be attributed to a rise in the personal mobility brought about by the automobile. It would be worthwhile to plot gasoline sales revenue or airline activity versus the number of motels to see if any correlation exists among them.

The number of restaurants shows a period of stability sandwiched between two periods of growth (Figure 2.29). However, when normalized, the chart exhibits a tendency to be stable over fairly long periods (Figure 2.30). The year 1960 again provides a local anomaly. (Compare with Figure 2.14.)

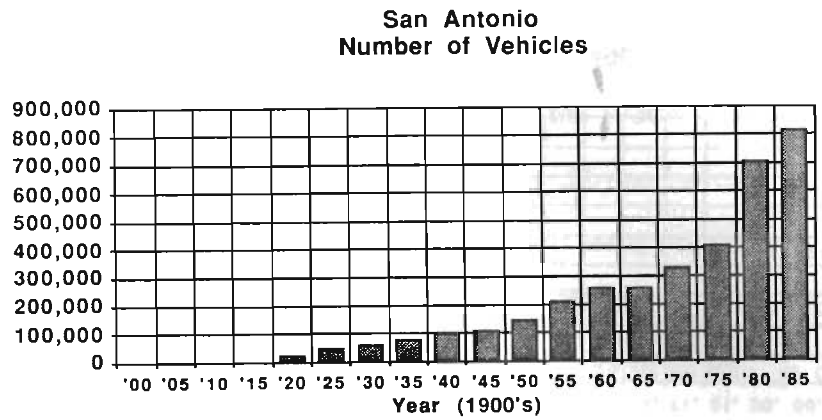


Figure 2.25

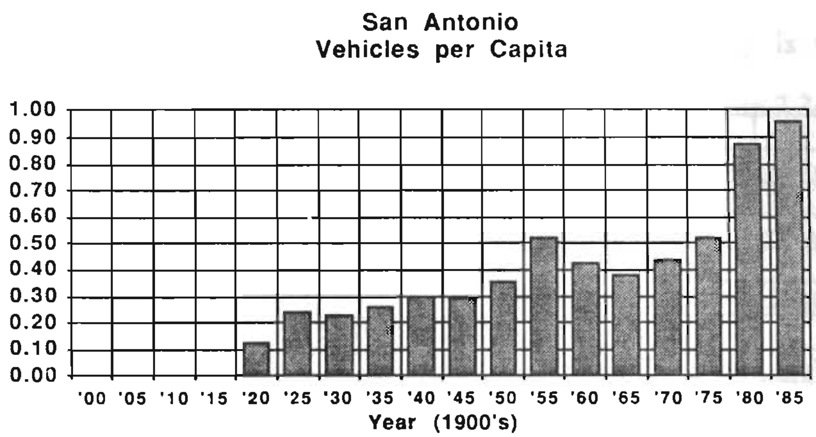


Figure 2.26

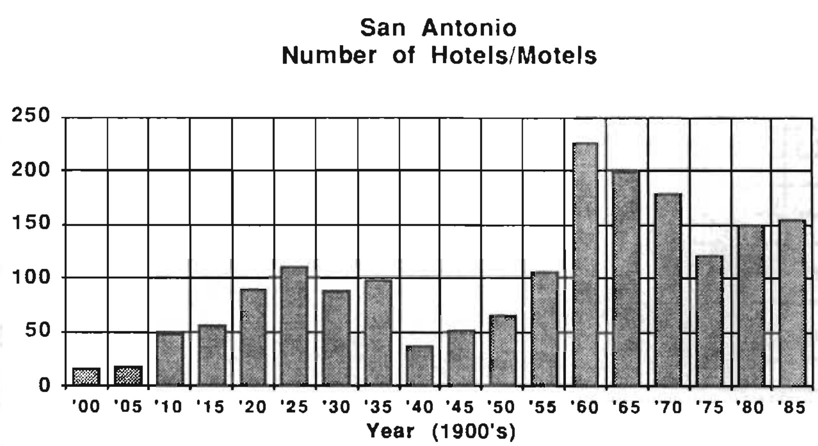


Figure 2.27

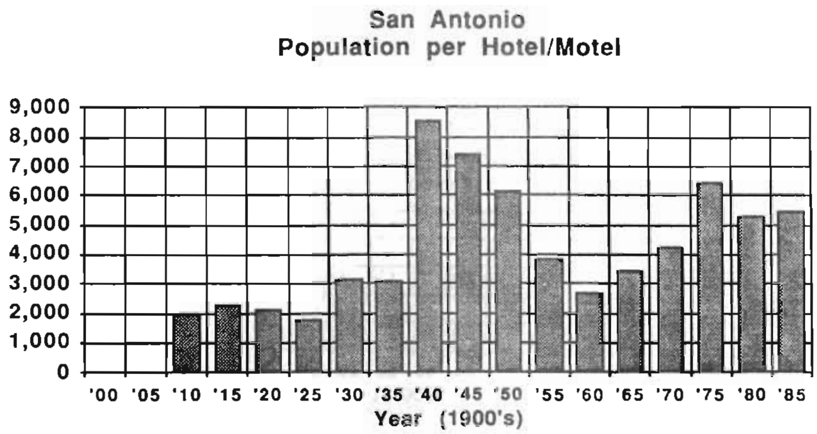


Figure 2.28

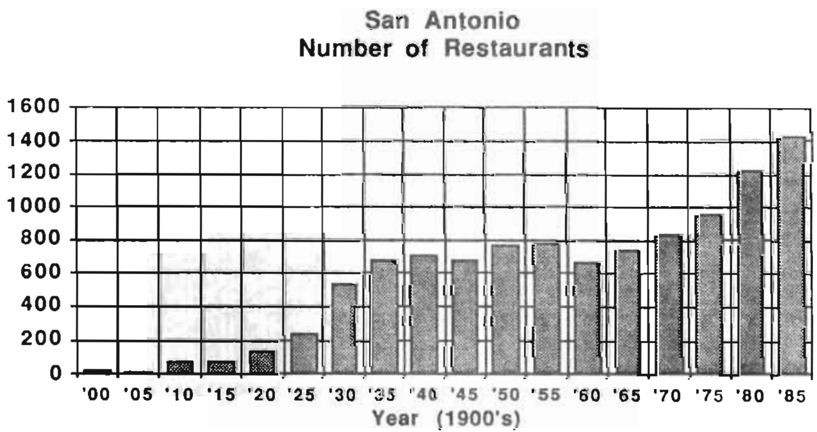


Figure 2.29

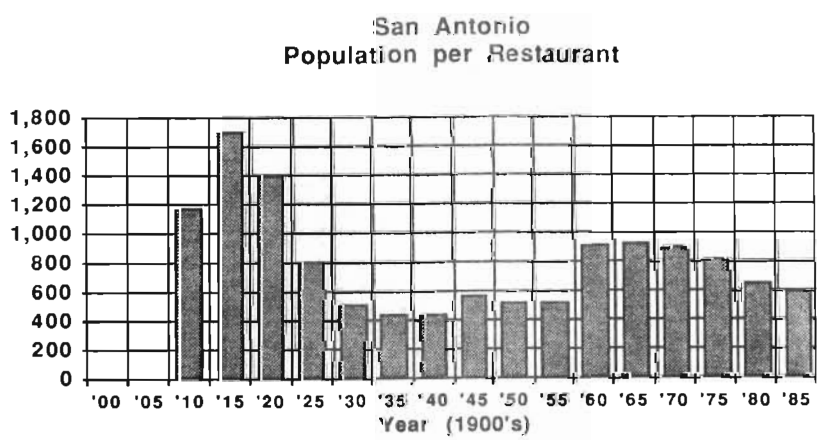


Figure 2.30

The history of auto dealerships (Figures 2.31 & 2.32) shows changes that can be reasoned in the following manner. With the advent of the automobile and its rise in popularity, the number of dealerships grew until the 1930's. The years of World War II saw a corresponding drop in their numbers followed by an increase in the post war years. A decline after 1950 can not be attributed to any one factor conclusively, though this could be resolved if the revenues from new cars sold was studied. A five fold increase in the number of auto dealerships in 1975 is most likely due to foreign car manufacturers competing successfully in a market dominated solely by domestic manufacturers until the 60's.

The number of doctors, lawyers and contractors seems to rise and fall (like a "wave") almost in unison (Figure 2.33). What is surprising is the fact that this phenomenon also evident when the variables are normalized (Figure 2.34).

For telephone numbers, an "exponential" growth is evident until 1980, both in Figure 2.35 and in Figure 2.36. This suggests that the increase in population is not the only factor responsible for the increase in the number of telephones. Historical data on the number of telephone lines for business establishments should provide more useful information.

As mentioned earlier, a function of the number of electric meters and water meters can be used to characterize the composition of the housing market (Figure 2.37). If Figure 2.38 were plotted only for residential connections, one could similarly derive data for the average occupancy of dwelling units.

Power consumption data shows an increase of usage not only in absolute values (Figure 2.39), but also when normalized by population (Figure 2.40). It would seem reasonable to expect both these data to correlate well with variables denoting the sales of electric goods. Water pumped annually has grown steadily over the years as can be seen in Figure 2.41. The commissioning of new sources of water to be pumped is suggested in or before the year 1980. When normalized by population in Figure 2.42, it holds a steady

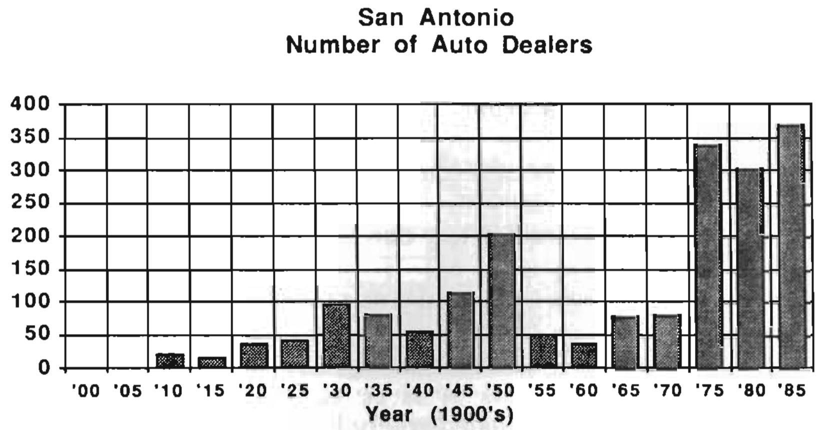


Figure 2.31

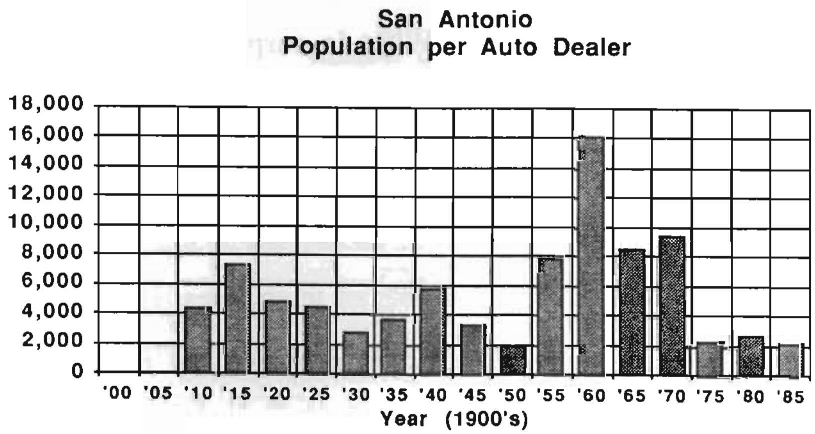


Figure 2.32

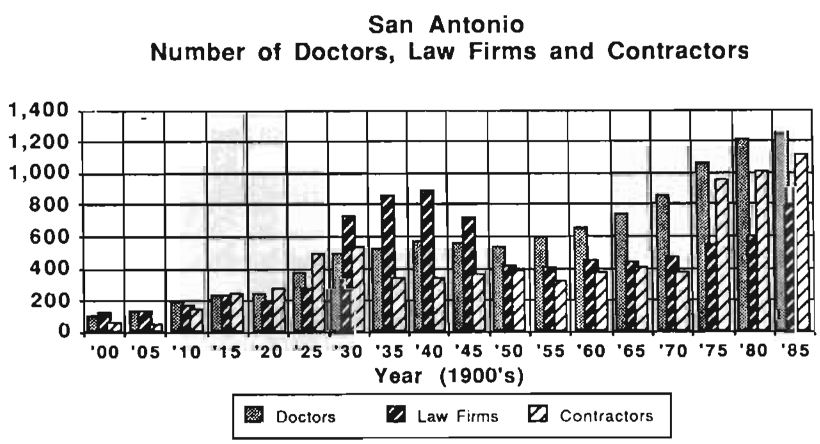


Figure 2.33

San Antonio
Population per Doctors, Law Firms and Contractors

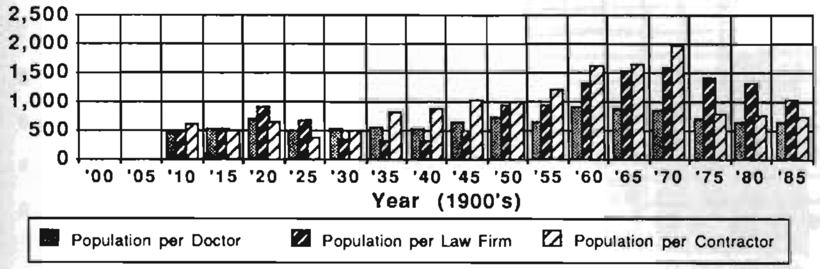


Figure 2.34

San Antonio
Number of Telephone Numbers

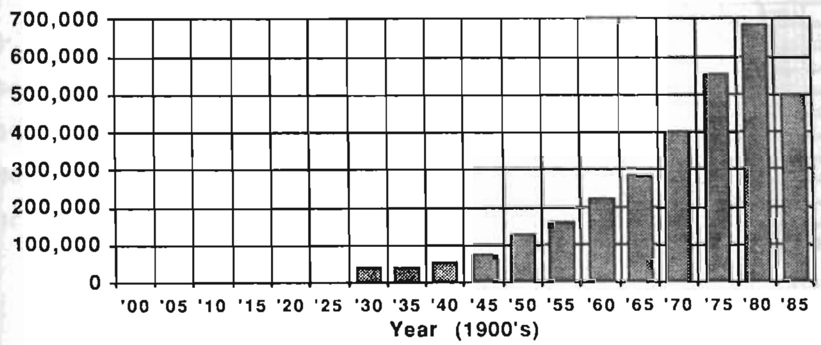


Figure 2.35

San Antonio
Telephone Numbers per Capita

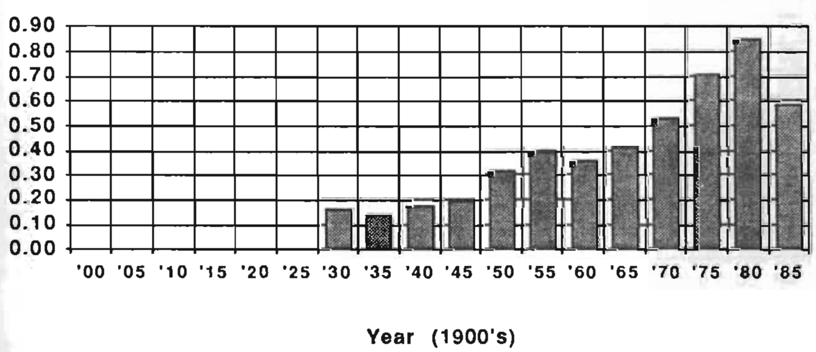


Figure 2.36

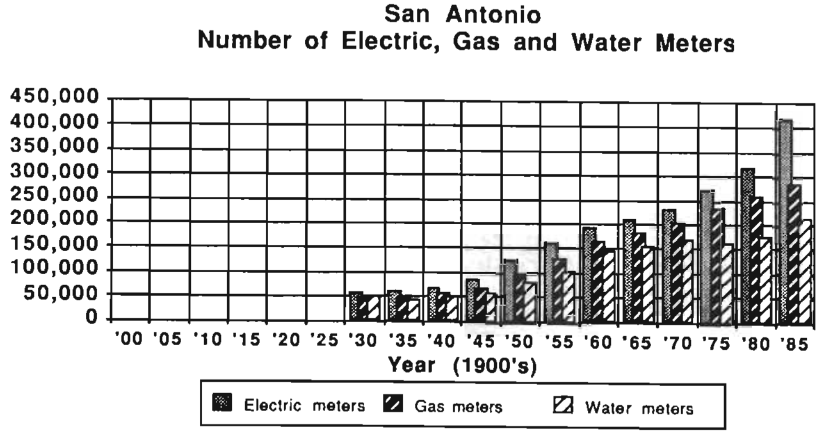


Figure 2.37

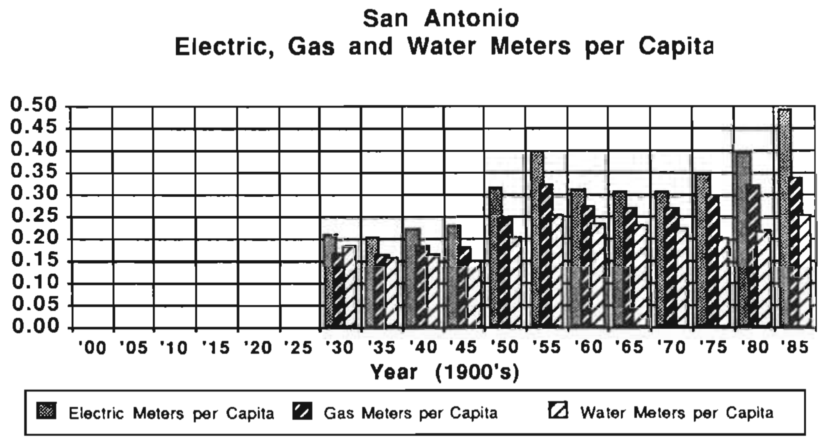


Figure 2.38

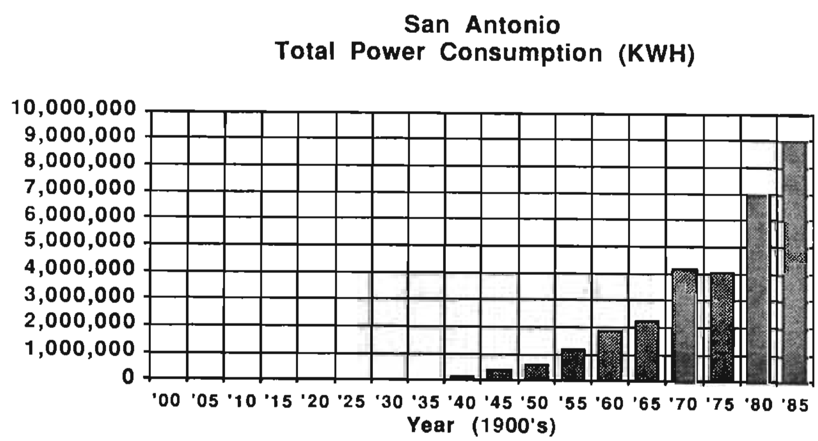


Figure 2.39

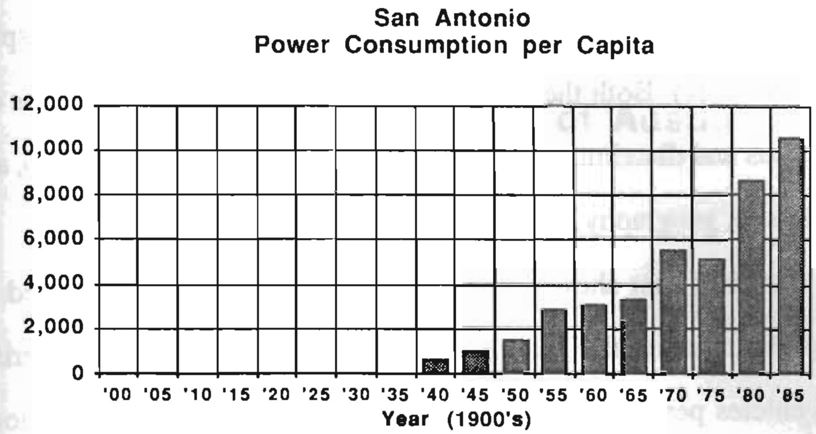


Figure 2.40

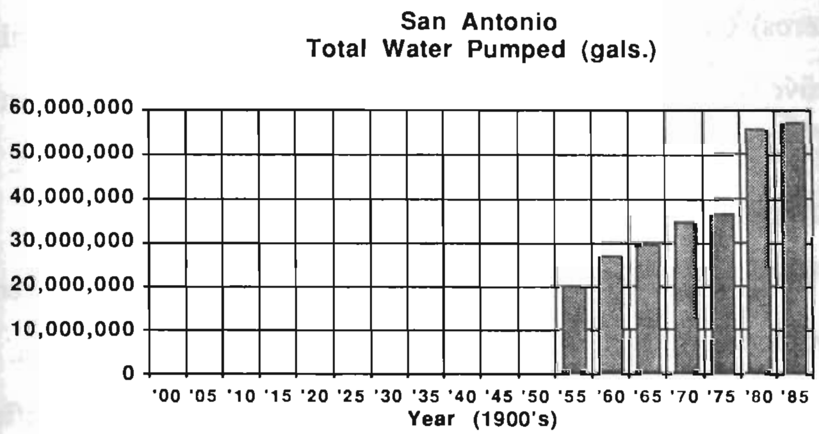


Figure 2.41

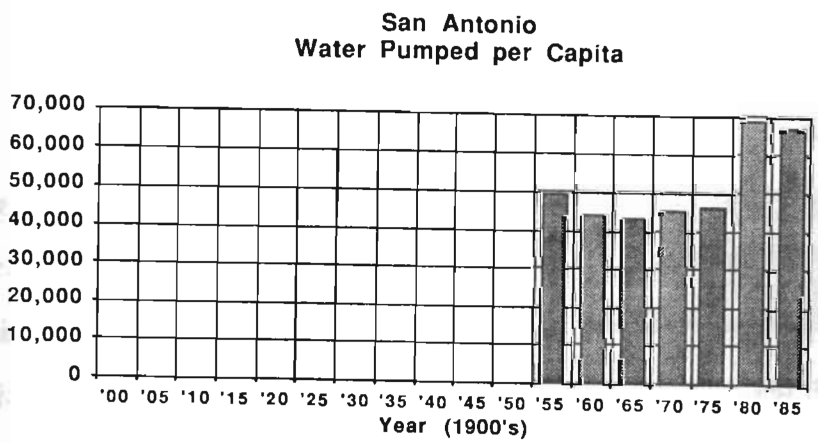


Figure 2.42

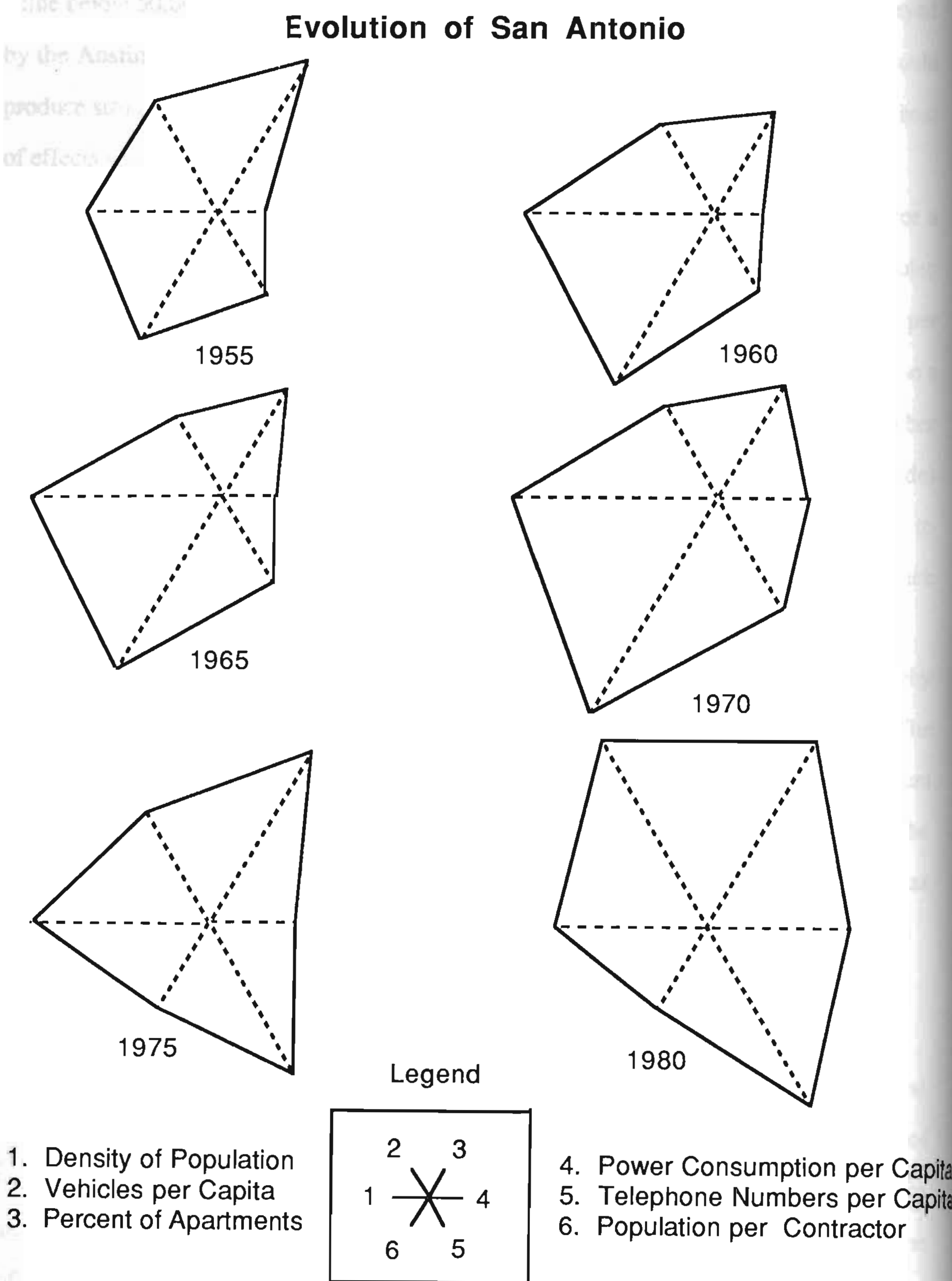

Evolution of San Antonio
1955
1960
1965
1970
1975
1980
Legend
1
2
3
4
5
6
1. Density of Population
2. Vehicles per Capita
3. Percent of Apartments
4. Power Consumption per Capita
5. Telephone Numbers per Capita
6. Population per Contractor

Figure 2.44

area bounded by the diagram. The aim, however, is not just to maximize information, but also to present it in such a manner that it can be easily assimilated by the reader. Situations where a large number variables are plotted on one diagram perhaps should be avoided. It is felt that four to six axes may be optimal for such representations in this study

The diagrams discussed in this section are scaled by a procedure similar to the one discussed in the previous section the values of the variable (for each of the eleven cities) on any one axis is divided by a round number marginally greater than the highest value among all cities attained by that variable for all the years under consideration. This insures that comparisons can be made across time for the cities as well as between cities (across space). Three sets of four-axis snow-flake diagrams are presented for discussion here.

Figure 2.45 shows a map of the U.S. with the locations of the cities being studied. Atlanta, Boston, Chicago, Cincinnati, Los Angeles, Miami, New York and Seattle - all are cities that fall in subdivisions created by Yeates (1976) for categorizing major urban areas on the continent. Denver, Phoenix and St. Louis are the only cities being studied here that are not located geographically in any of his regions. These three are included as being representative cities outside of the major urban areas.

The first set of diagrams for the evolution of the eleven cities is presented in Figures 2.46 through 2.50. The variables plotted on the four axes are - area, density of population, city budget per capita, and the city's highway department budget as a fraction of the total city budget. In addition to the information conveyed by the length of any one axis, it can be established that the space bounded by the axes area and density of population is proportional to the population of the city. Similarly, the space bounded by the axes density of population and city budget per capita would represent the city's budget per unit area and the space between the axes city budget per capita and the city's highway department budget as a fraction of the total city budget would indicate the amount spent by the highway department on a per capita basis.

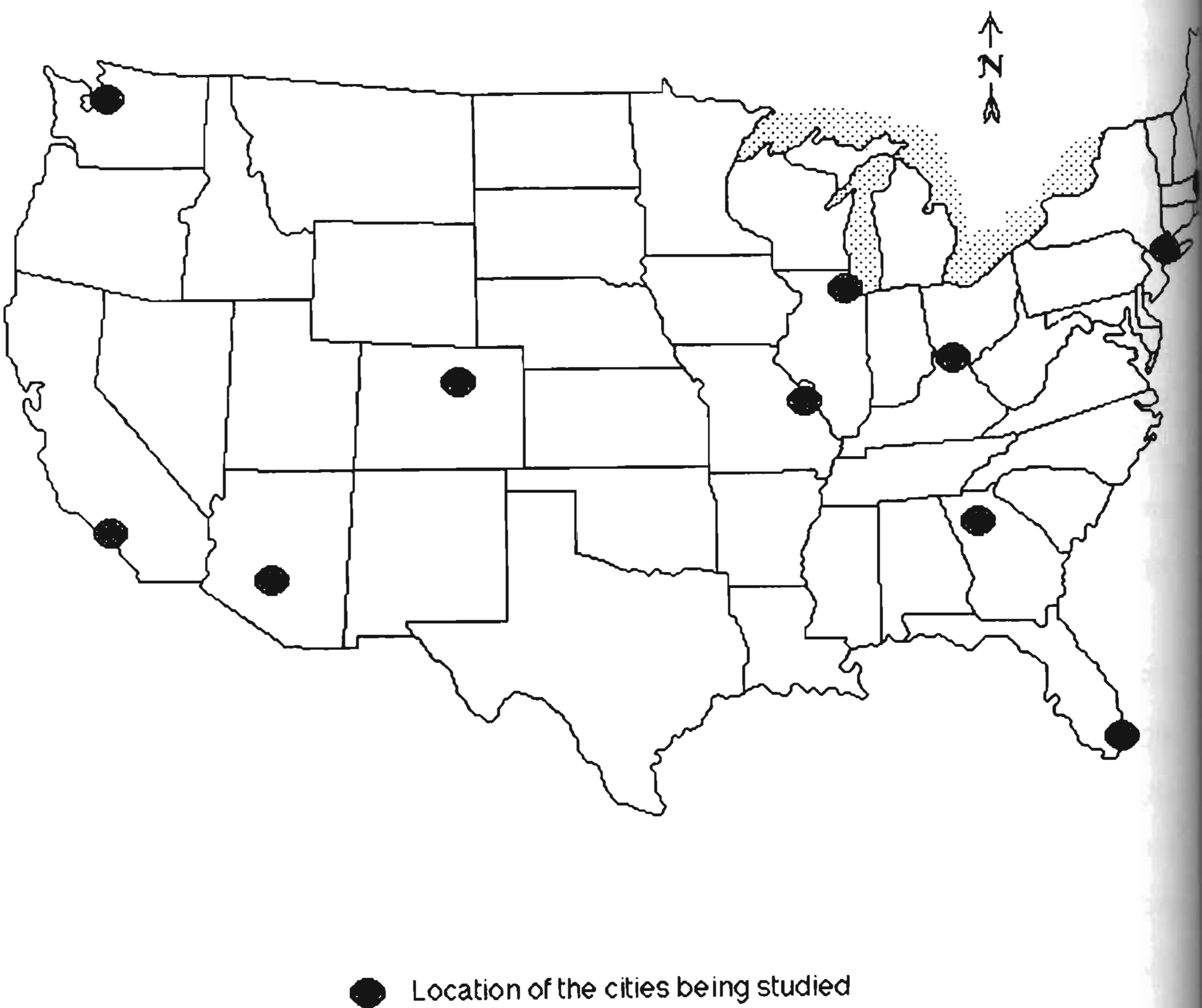


Figure 2.45

Figure 2.46 shows the situation existing in the year 1950. Cincinnati and Seattle are similar in all respects in this particular representation while Boston and St. Louis show similarities but for the fact that Boston's city budget per capita is almost three times that of St. Louis. New York, Chicago and Los Angeles stand out as being totally different from the rest of the cities. Among the three of them, while Los Angeles has the largest area, it has the smallest population. In fact, this is so disproportionate, that Los Angeles can be seen to have the lowest density of population among all the cities being studied. This is precisely what would be expected of a city of the "auto-air...epoch". This is brought home even more forcefully when Los Angeles is compared with older cities, like New York and Boston, both of which were thriving ports in the "sail-wagon epoch". Comparison with St. Louis and Chicago (both products of the "iron-horse epoch") also reinforces the differences. Even with no prior knowledge of the history and geography of these cities, the reader would still be able to deduce from the snow-flakes that the population was more dependant on the automobile for their mobility in Los Angeles than, say, in New York or Boston.

Phoenix, which we know to be another "auto-air....epoch" city, has undergone a drastic change in ten year from 1950 to 1960 (Figure 2.47). The area increases almost ten fold during this period, and the density of population in 1960 drops almost to a third of the 1950 value. Both the city budget and the fraction appropriated for the highway department increase. At this stage, Phoenix looks like a smaller version of Los Angeles. Miami has lowered the fraction spent on the highway department. However, an increase in its city budget per capita, with more or less the 1950 levels of area and population, now has this city spending a lot more on its highways per capita. New York, Chicago St. Louis and Seattle have increased not only their city budget per capita, but have also increased the fraction spent on the highway department. Atlanta too, has increased this fraction in a big way. At the same time, it also seems to have almost quadrupled its area without a corresponding rise in population. Boston, Cincinnati and Denver appear to have retained their character since 1950, only increasing their city budgets.

The 1970 diagrams are shown in Figure 2.48. New York, Chicago, Atlanta and St. Louis have actually decreased the fraction of the city's budget appropriated for the highway department. However, an increase in their city budget per capita (while the population and area remain a constant) offsets this decrease in terms of highway department dollars spent per capita. Boston and Cincinnati have increased both the city budget per capita and the fraction thereof spent on the highway department. Los Angeles and Phoenix seem to be travelling on the same evolutionary path, the current difference between these two being one of scale. Miami, Seattle and Denver have managed to retain the basic shape of their snow-flake diagram from 1960, while showing increases in their city budget per capita.

Figure 2.49, which is for the year 1975, has been presented here to show the state of the cities at the mid-point of the decade 1970 - 1980 in which all cities show a remarkable amount of change in terms of this snow-flake representation. All eleven cities show large increases in their city budgets per capita, while the other variables are more or less at the 1970 level. While some cities (e.g. Los Angeles, Seattle and Cincinnati) do show a decrease in their highway department budget as a fraction of the city budget, the highway department budget per unit area remains the same.

Before an an actual discussion of Figure 2.50 is presented, it wold be worthwhile to go back to Figure 2.46 and see what the cities 'looked like' at the beginning of the study period and what they 'look like' in Figure 2.50 - a time span of thirty years. Now consider the changes that are evident from 1975 to 1980. All cities except for Los Angeles, New York and Cincinnati, show significant increases in their city budget per capita. Atlanta, Los Angeles and Chicago show a decline in the highway department budget as a fraction of the city budget. Phoenix and Seattle are the only cities that show a considerable growth in area. Similarities between Los Angeles and Phoenix are no longer seen. In fact, Denver and

Cincinnati are the only two cities that have consistently seemed to have a basic similarity of shape over the study period.

The next set of variables discussed are number of manufacturing units, number of wholesale establishments, number of retail establishments and revenues from retail sales. These are presented in Figures 2.51 through 2.54 for the years 1948, 1958, 1967 and 1977 respectively. Due to the disproportionate sizes of the diagrams of some cities, the cities of Chicago, New York and Los Angeles have been reduced by a factor of 4 of their actual size. This means, for example, that when Chicago and St. Louis appear to be of the same size and shape in Figure 2.51, it actually implies that the values of the variables for Chicago are four times larger than those for St. Louis.

The change in these variables over time could indicate how the cities have evolved in terms of their manufacturing and trade characteristic. When taken in conjunction with the previous set of snow-flake diagrams (especially the variables that deal with area and population), trends could be established about the movement towards (or away from) large centralized establishments replacing smaller establishments. This could indicate an increase (or decrease) in the dependance on the automobile by the residents of the city.

The state of the cities in 1948 is shown in Figure 2.51. New York dominates in the size of the snow-flake, having more manufacturing units, more wholesale establishments and more retail establishments than any of other cities. In Figure 2.46, we have seen that the area of New York is actually smaller than that of Los Angeles. This implies that New York has a very high density of manufacturing units, wholesale establishments and retail establishments per unit area when compared with Los Angeles. St. Louis and Chicago are similar to each other in form (though in scale, Chicago is four times the size of St. Louis) in Figure 2.51. (Such a similarity, with difference in scale, is also evident in Figure 2.46). Similarities also exist between Denver and Seattle and between Miami and Phoenix in both the figures.

In the next ten years (ending 1958), the cities that show significant growth for these variables are Atlanta, Los Angeles, Miami and Phoenix (Figure 2.52). Further, with the exception of Los Angeles, they also show a corresponding growth in area and population (Figure 2.46 & 2.47). These cities can be identified as those of the "auto-air...epoch". St. Louis shows a decline in the number of manufacturing units. All cities show increases in retail revenues. Boston, Seattle, Cincinnati and Chicago remain stable for this decade. New York shows fewer manufacturing, wholesale and retail establishments with an increase in retail revenues. This may be representative of a trend moving away from small local units towards larger centralized establishments.

This trend is evident for New York in Figure 2.53 as well. By 1967, there is a marked decline in manufacturing, wholesale and retail establishments for Chicago, Boston and New York, while there is a definite increase in the retail revenues of these cities. Cincinnati and St. Louis too, have fewer retail stores in 1967 than in 1958. St. Louis, however, has an increased number of manufacturing units. Phoenix and Atlanta are the only cities that show increases in all four variables over this period.

Looking at Figure 2.54, one is stuck by the apparent similarity in the form of the snow-flakes for the various cities. What is it that causes these eleven diverse cities (that did not 'look alike' in 1948) to be so 'similar' to one another in 1977 ? There seem to be correlations that exist between the four variables (across the eleven cities) that gives each city a similar (kite-like) shape. Looking back at the snow-flakes for 1948 (Figure 2.51), we can see that Boston, Cincinnati, Chicago and St. Louis have 'shrunk' in terms of the number of manufacturing, wholesale and retail establishments. Over the same period (1950 to 1980), these cities do not show appreciable changes either in area or in population (Figures 2.46 & 2.50). Miami, and Phoenix show the most growth from 1948 to 1977 (Figures 2.51 & 2.54). Atlanta and Denver have evolved form a fairly similar state in 1948 to a point where they still resemble each other in 1977.

Figures 2.55 through 2.59 depict a new set of four variables number of hospital beds, revenues from new auto sales, revenues from gas stations, and revenues from restaurant and bar sales. While the grouping of these variables may seem unrelated at first glance, there is a common thread of information inherent in these four variables. One would expect that the slope of the line joining the auto sales and gas station sales would be a constant for all cities for a given year (if there are correlations between these two variable). If the slopes differ, it could indicate different auto usage patterns. The restaurant/bar sales and the number of hospital beds are indicators of differences between cities. When studied in conjunction with other variables, they can provide insights about the level of services available, which might lead to certain conclusions about the mobility of the population of these cities. As with the previous set of snow-flake diagrams, Chicago, New York and Los Angeles have been scaled down by a factor of 4 due to disproportionate sizes of the diagrams for the various cities.

Boston, Cincinnati and St. Louis show similarities both in the size and the shape of these diagrams in Figure 2.55. Seattle and Denver are also similar to each other for the year 1954. When looking at the other variables in the same general time span (1950 to 1960), we can see that Seattle and Denver have the same area and population (Figures 2.46 & 2.47). Boston and St. Louis also resembled each other in terms of area and population during the 1950's. The suggestion is almost as though the cities that developed during one era, did so with a remarkable similarity to each other in their ground plans.

Over the next four years, little seems to have changed for individual cities (Figure 2.56 for the year 1958). This may be due to the fact that only four years separate the two sets of data. Also, the variables under study here are expected to be fairly constant; after all it would be unreasonable to expect the number of hospital beds or the restaurant/bar sales to change drastically over such a short period of time. Despite these arguments, Atlanta, Phoenix, Los Angeles and Miami show distinct increases in each of these four variables.

As noted earlier, these are the cities of the "auto-air...epoch" and their rapid growth is hardly surprising.

Comparing the cities in 1963 (Figure 2.57) with their corresponding state in 1954 (Figure 2.55), we see that Boston, Chicago, Cincinnati, New York and St. Louis are more or less at their original (1954) levels. Atlanta, Los Angeles and Phoenix have all grown at a very rapid rate, while Denver, Miami and Seattle have grown at a slower pace. Figure 2.58 presents the snow-flakes for the year 1967. While changes are apparent in a few cities, no discussions will be presented here because of the small time span between this and the previous set of diagrams.

Looking at the changes that came about over twenty years is very revealing (Figures 2.59 & 2.55). Atlanta, Miami and Phoenix, the cities with the three smallest snow-flakes in 1954, are the three with the largest snow-flakes (excluding the scaled down heavy weights Chicago, Los Angeles and New York) in 1972. In terms of auto usage, we can see that even though the population of Los Angeles is about one third of the population of New York in 1970 (Figure 2.48), the revenues from auto sales and gas sales in these two cities are about equal in 1972. Among the cities drawn to its scale, Atlanta has the highest level of auto and gas station sales in 1972; in terms of population it is the third lowest ahead only of Miami and Cincinnati. An exact opposite is the case of Boston which has the lowest level of auto and gas station sales, yet has the largest population (excluding Chicago, Los Angeles and New York, the cities not in its scale).

rowth is

in 1954

ire more

own at a

ure 2.58

ities, no

and the

(Figures

lakes in

weights

see that

of New

o cities

level of

only of

st level

go, Los

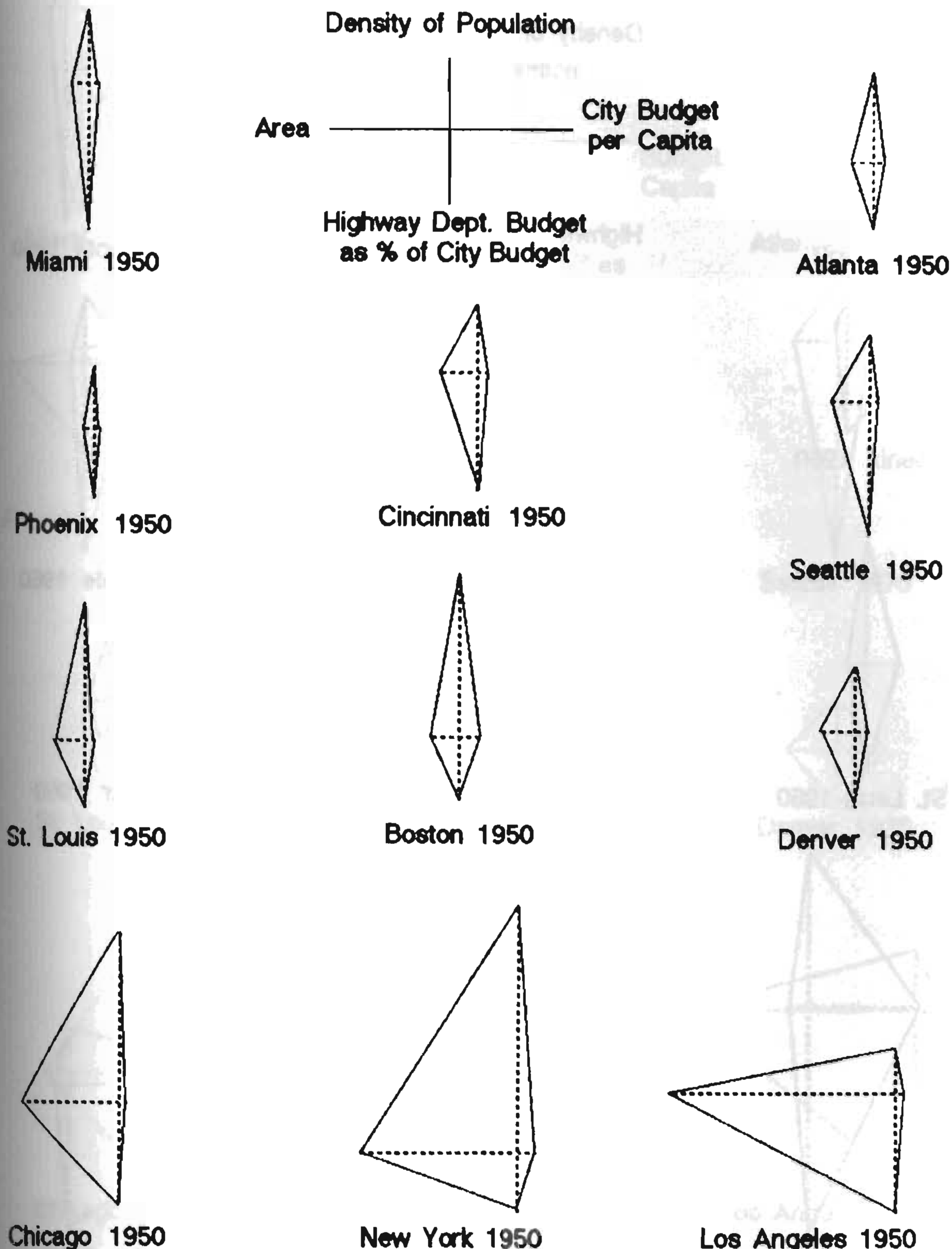


Figure 2.46

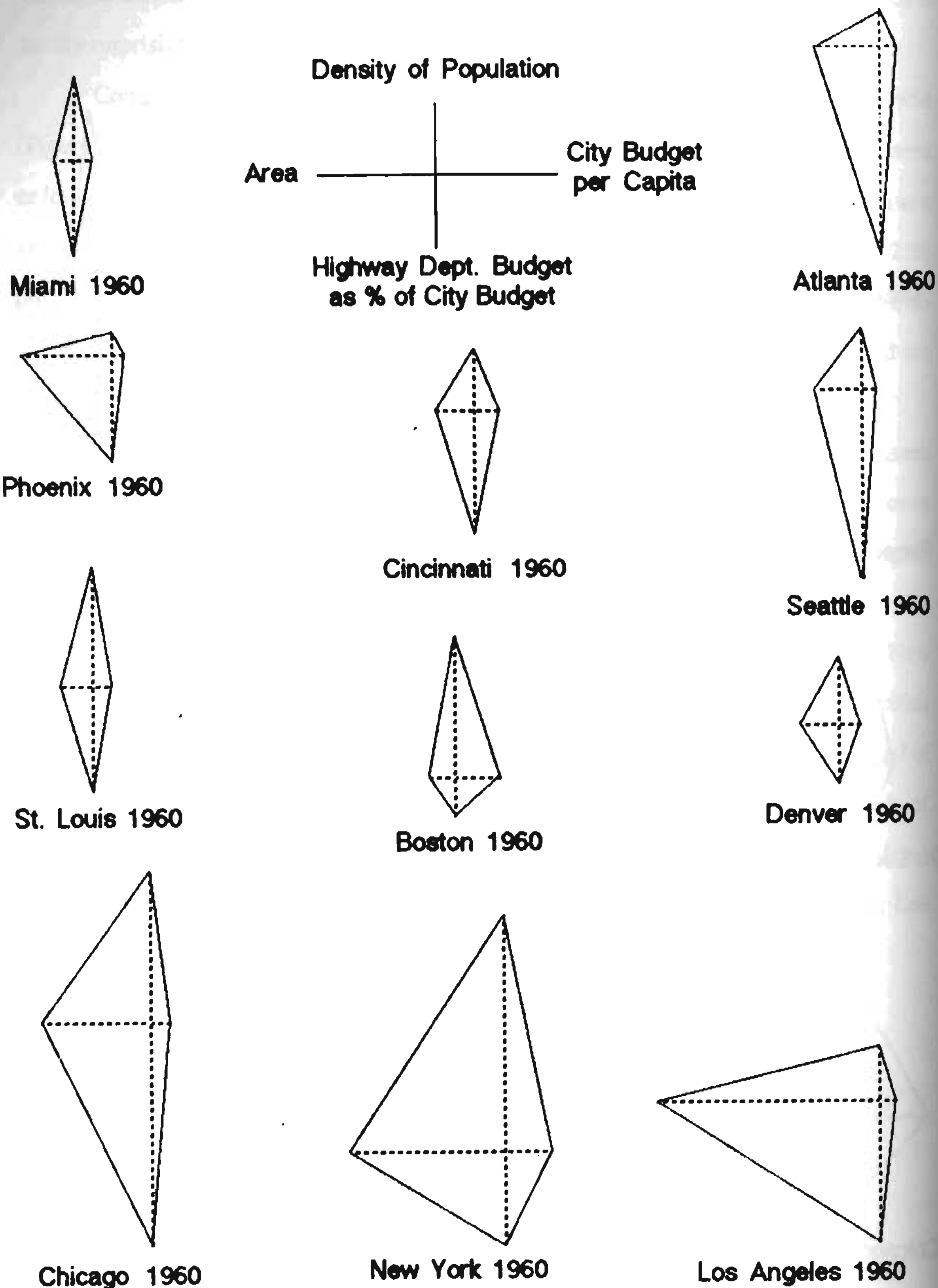
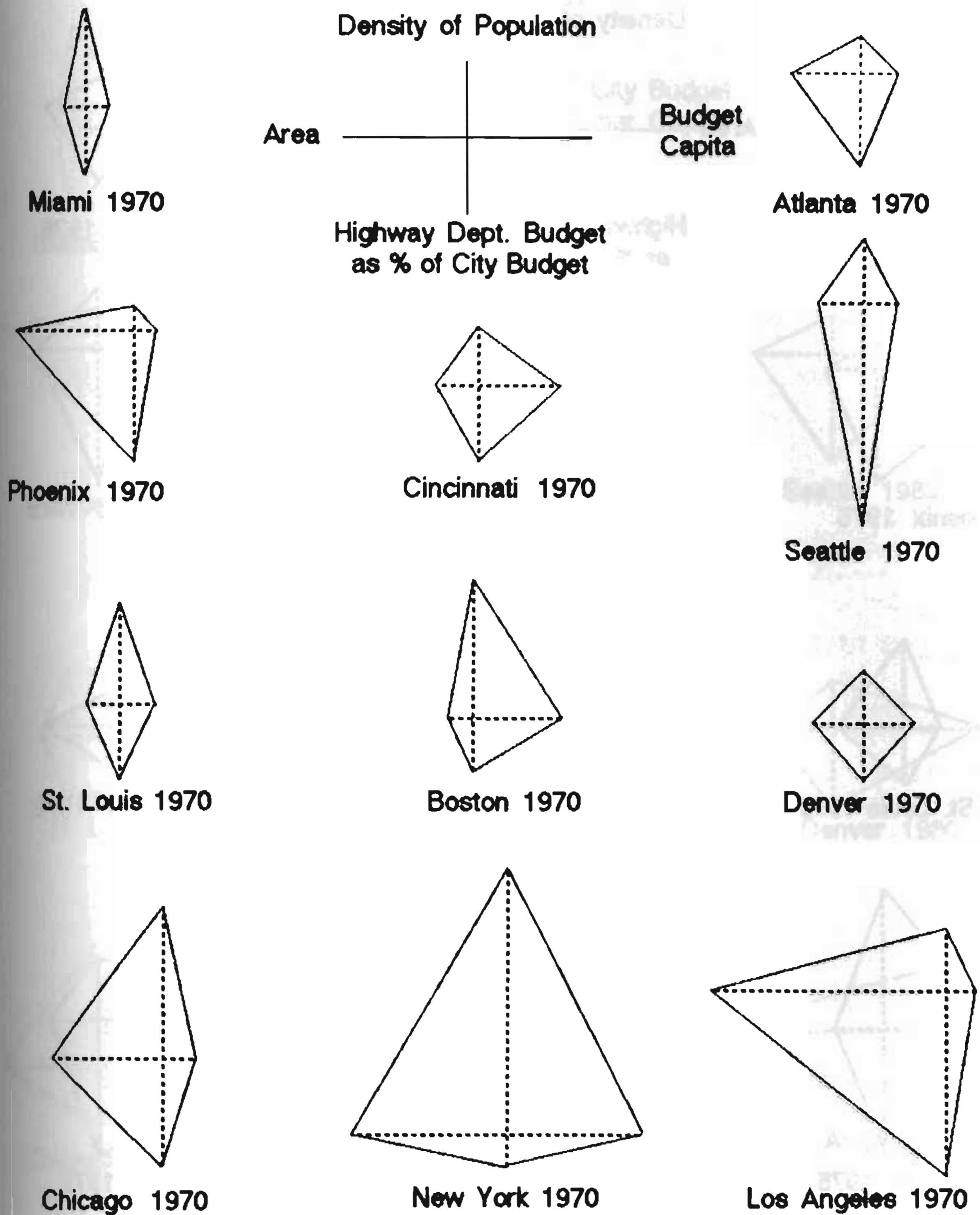

Density of Population
Area
City Budget per Capita
Highway Dept. Budget as % of City Budget
Miami 1960
Atlanta 1960
Phoenix 1960
Cincinnati 1960
Seattle 1960
St. Louis 1960
Boston 1960
Denver 1960
Chicago 1960
New York 1960
Los Angeles 1960

Figure 2.47



Density of Population
Area
Budget Capita
Highway Dept. Budget as % of City Budget
Miami 1970
Atlanta 1970
Phoenix 1970
Cincinnati 1970
Seattle 1970
St. Louis 1970
Boston 1970
Denver 1970
Chicago 1970
New York 1970
Los Angeles 1970

Figure 2.48

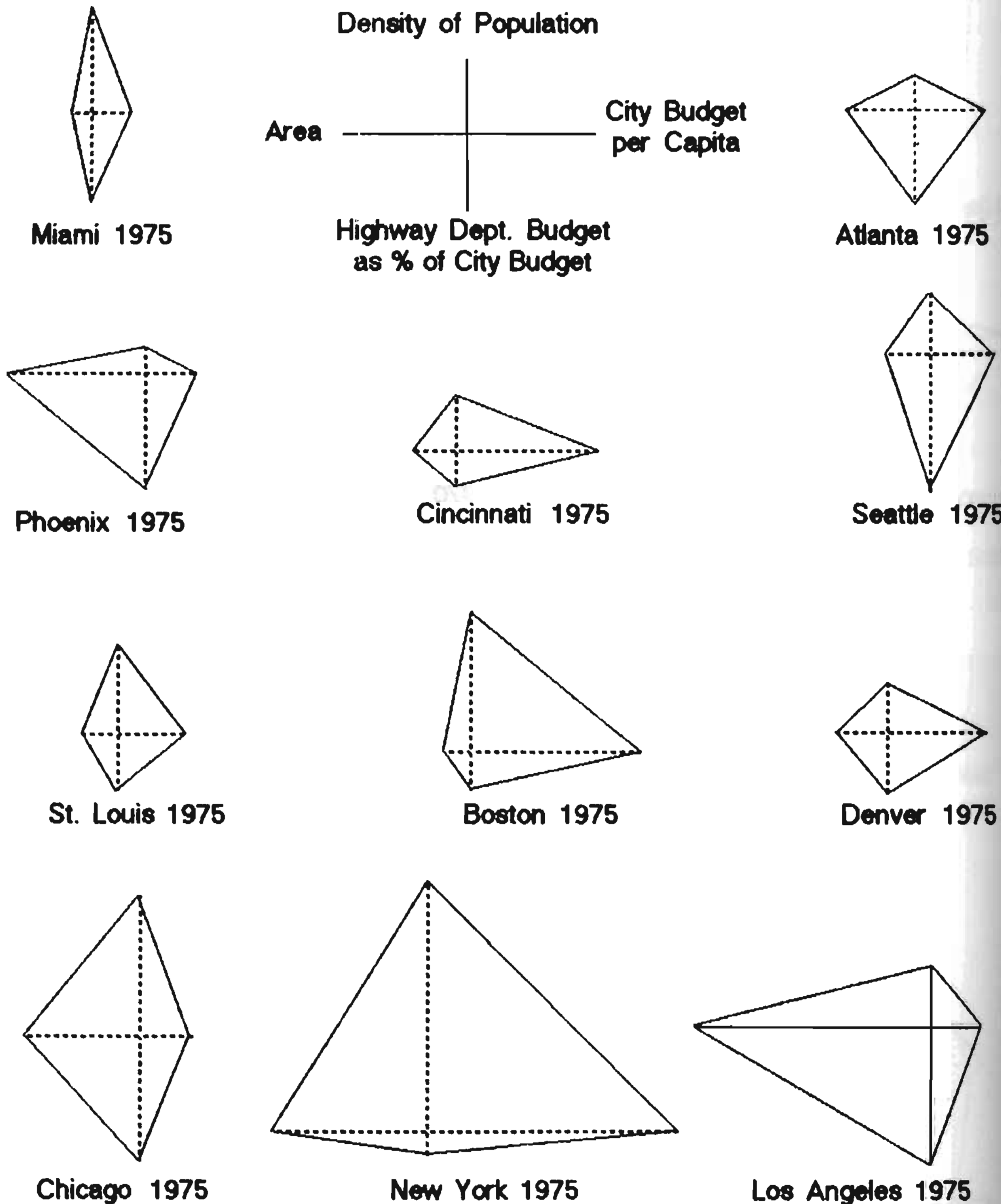

Density of Population
Area
City Budget per Capita
Highway Dept. Budget as % of City Budget
Miami 1975
Atlanta 1975
Phoenix 1975
Cincinnati 1975
Seattle 1975
St. Louis 1975
Boston 1975
Denver 1975
Chicago 1975
New York 1975
Los Angeles 1975

Figure 2.49

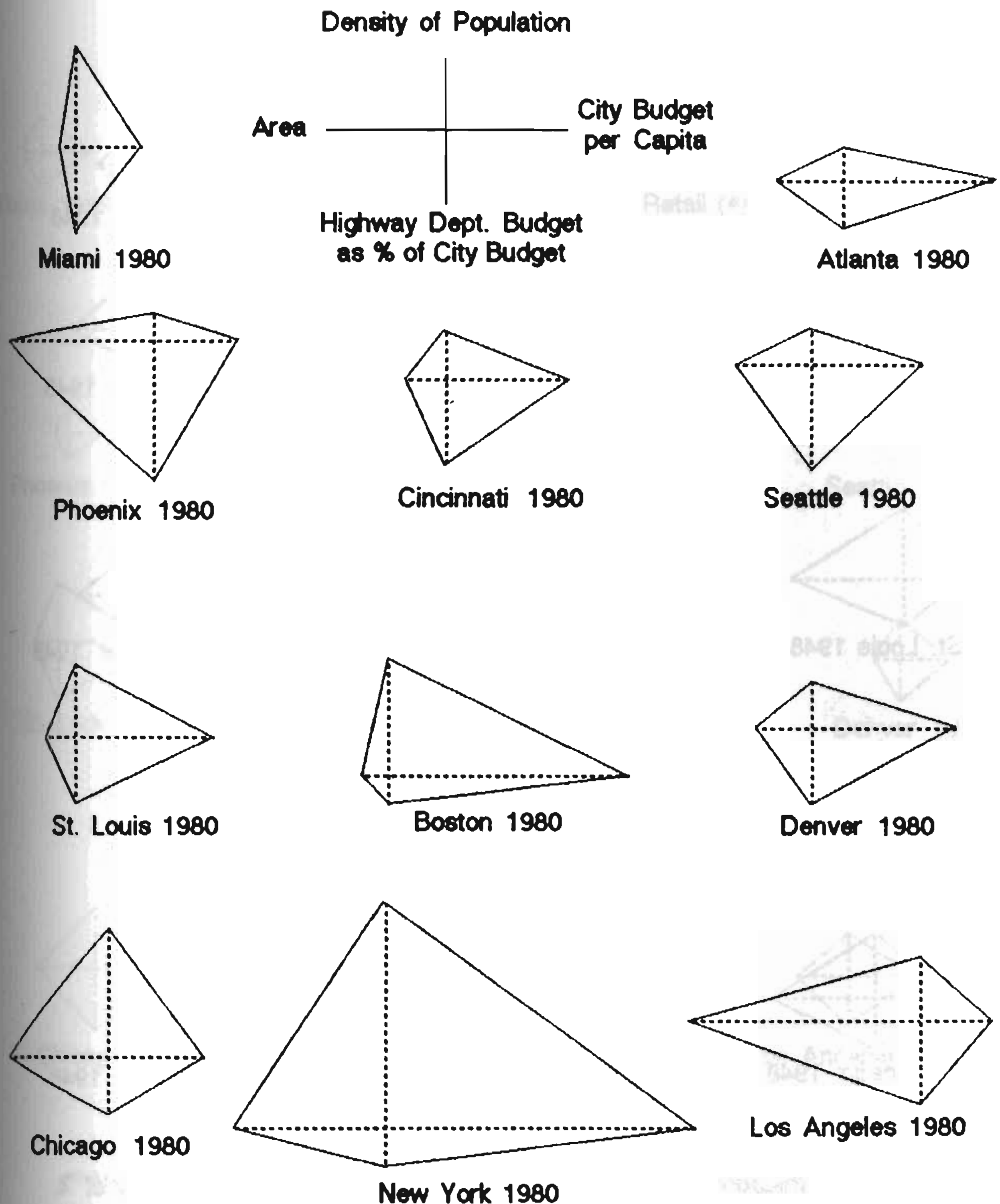
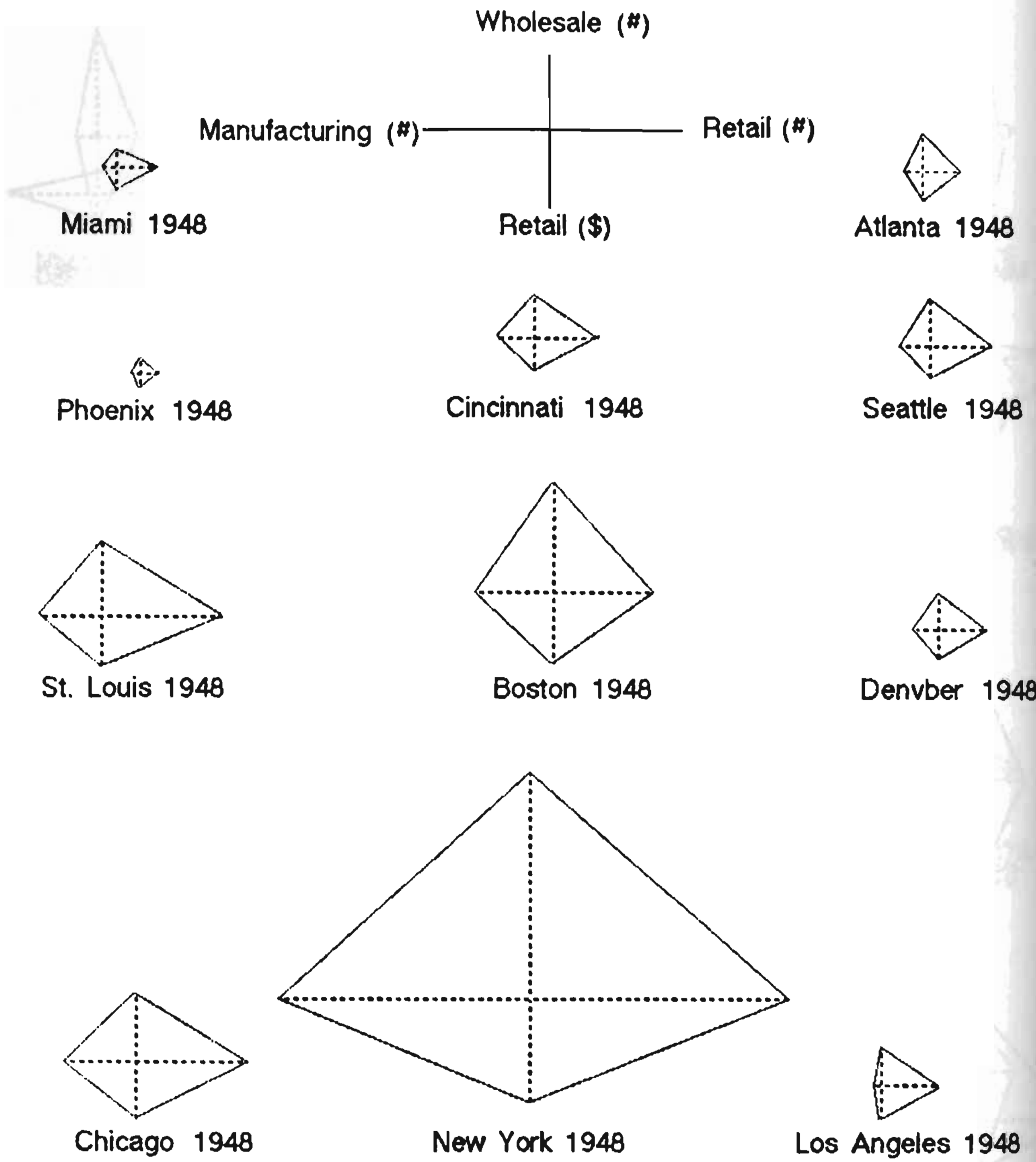
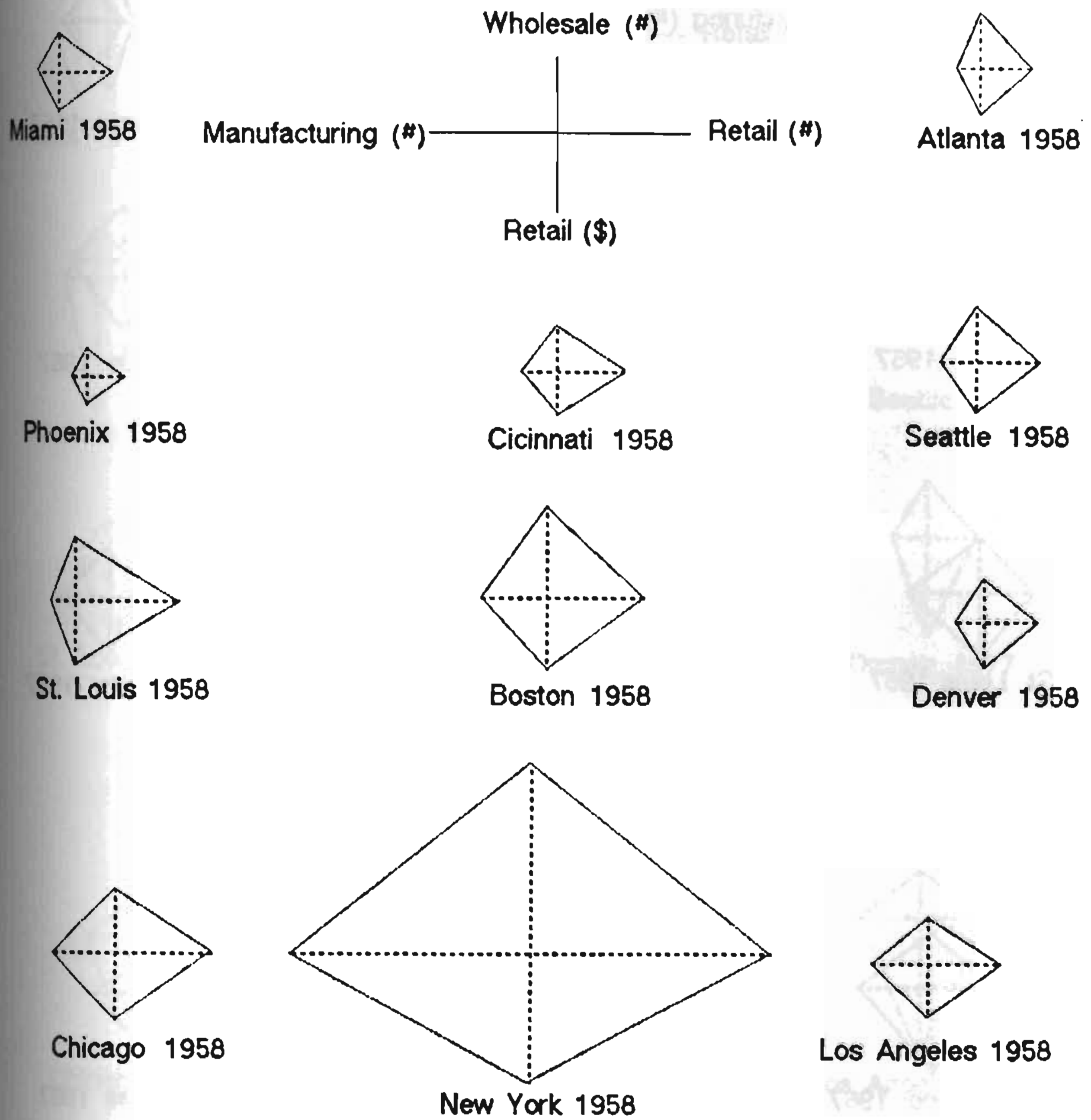

Density of Population
Area
City Budget per Capita
Highway Dept. Budget as % of City Budget
Miami 1980
Atlanta 1980
Phoenix 1980
Cincinnati 1980
Seattle 1980
St. Louis 1980
Boston 1980
Denver 1980
Chicago 1980
New York 1980
Los Angeles 1980

Figure 2.50



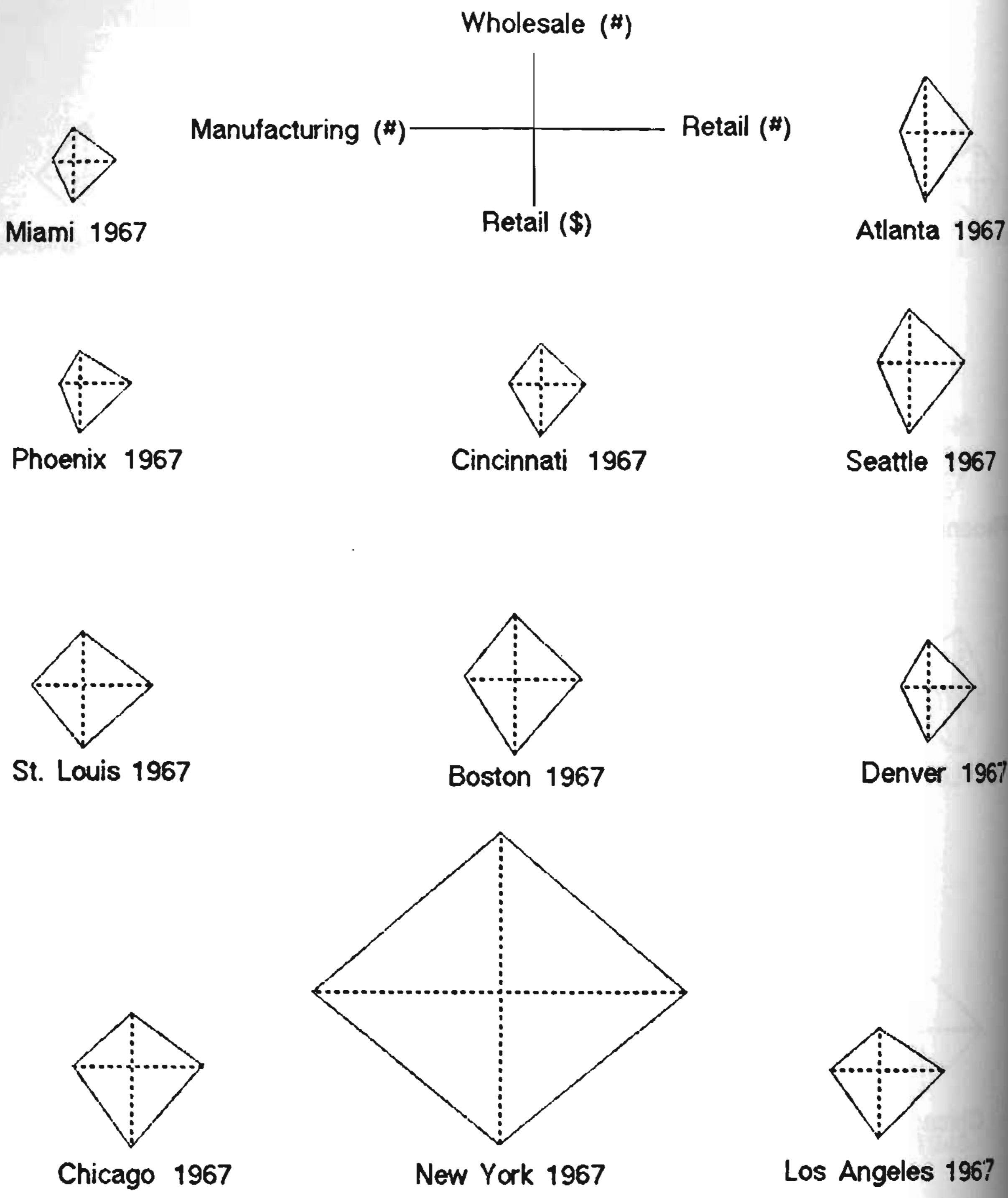
** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.51



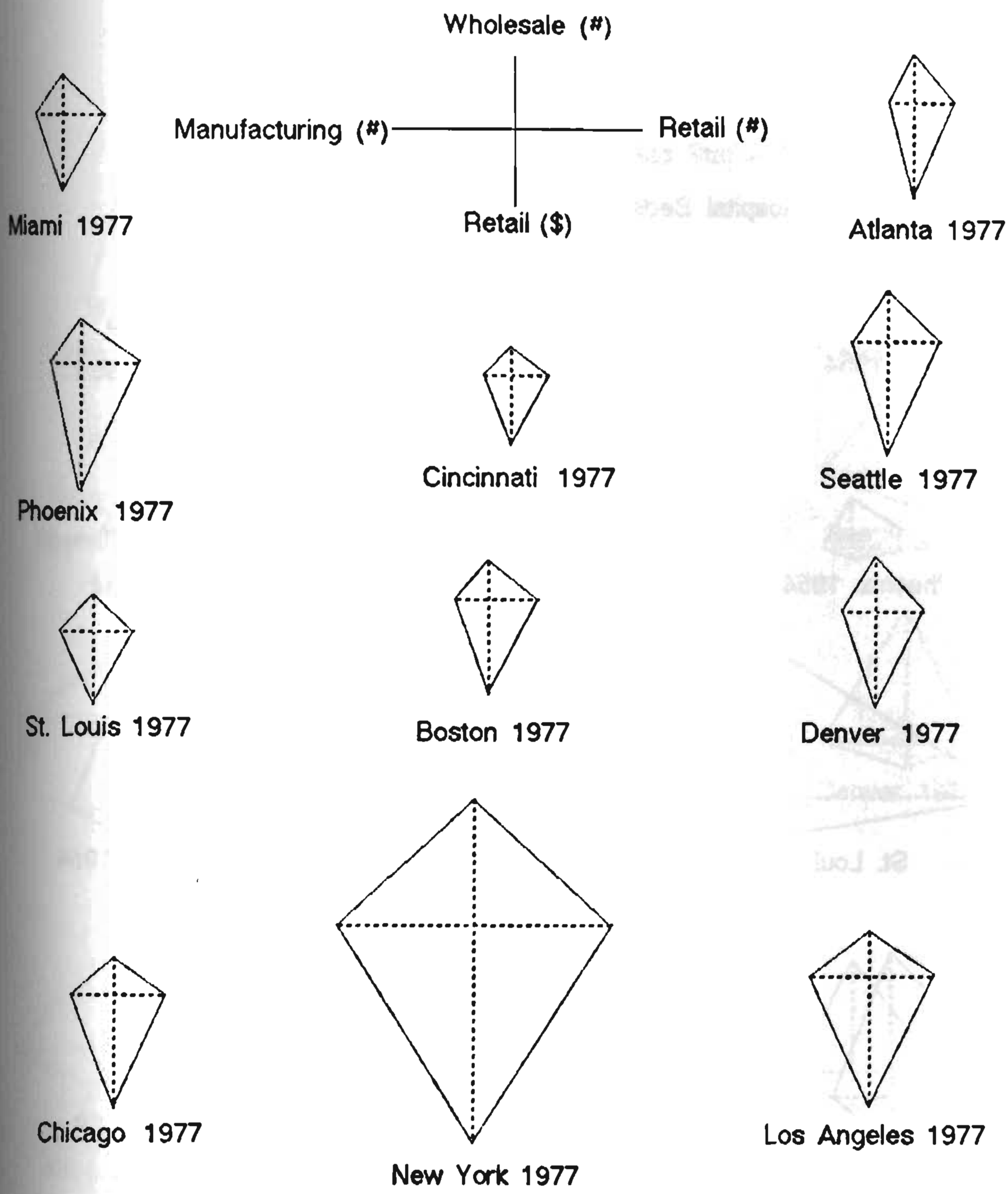
** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.52



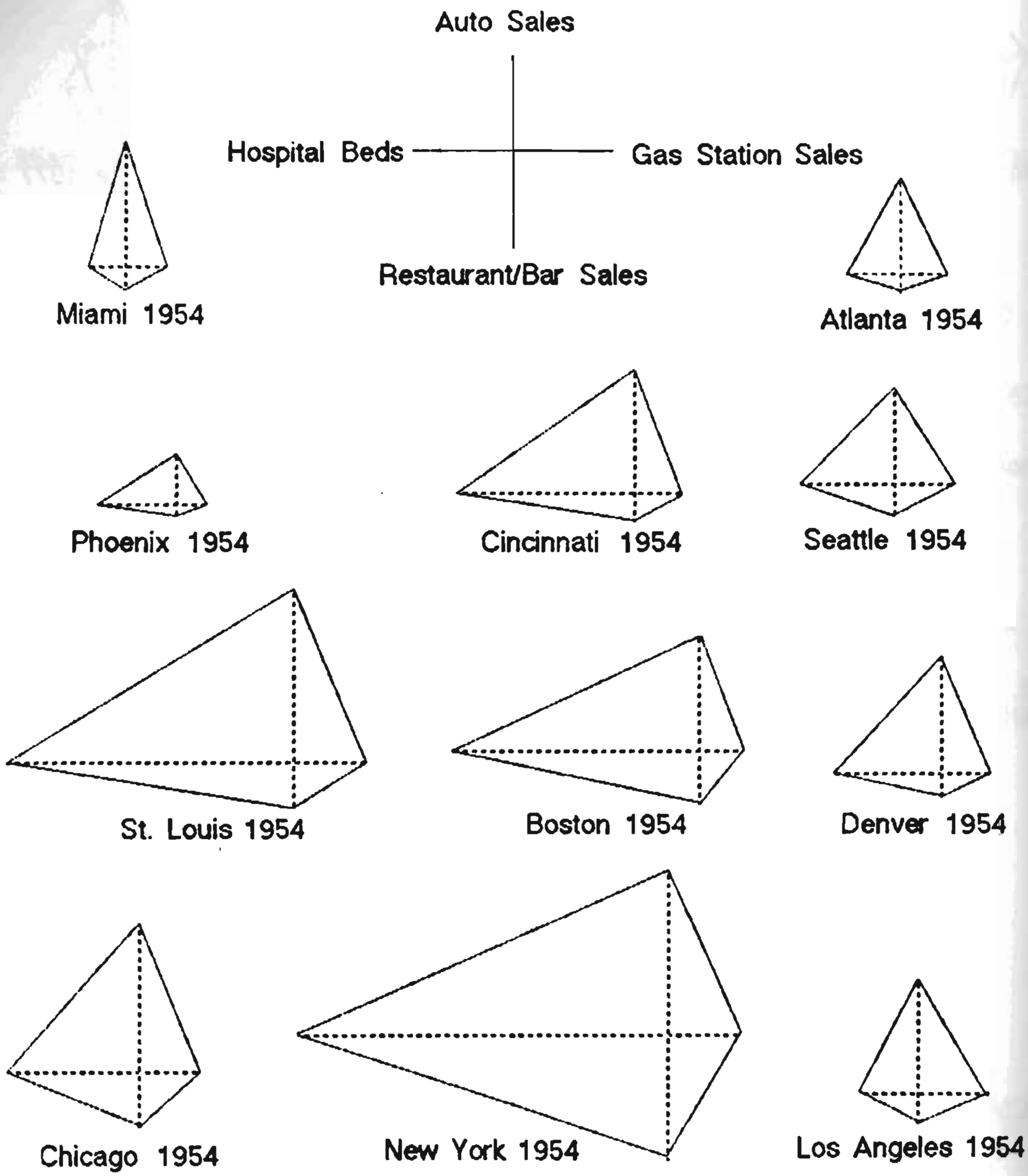
** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.53



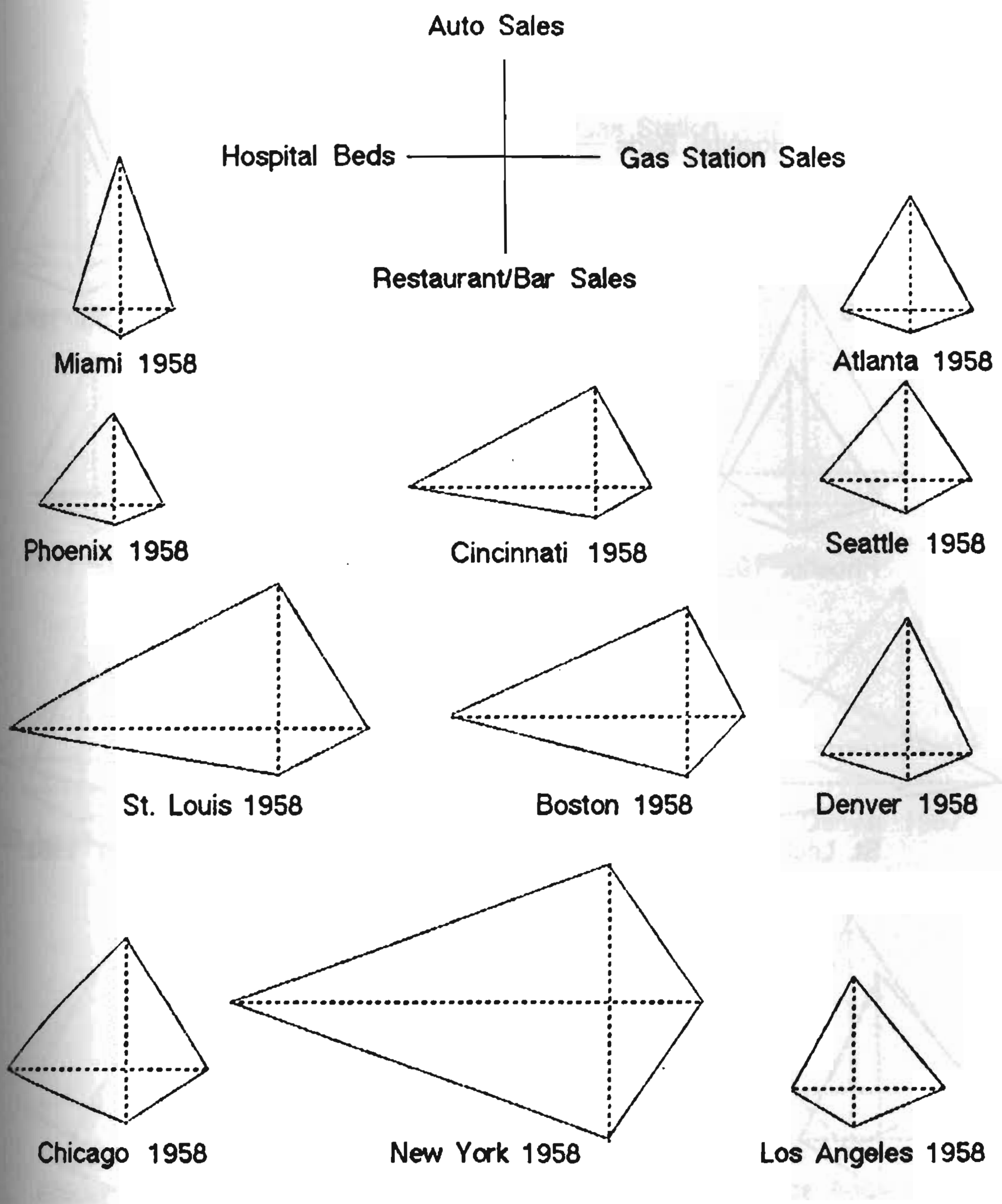
** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.54



** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.55



** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.56

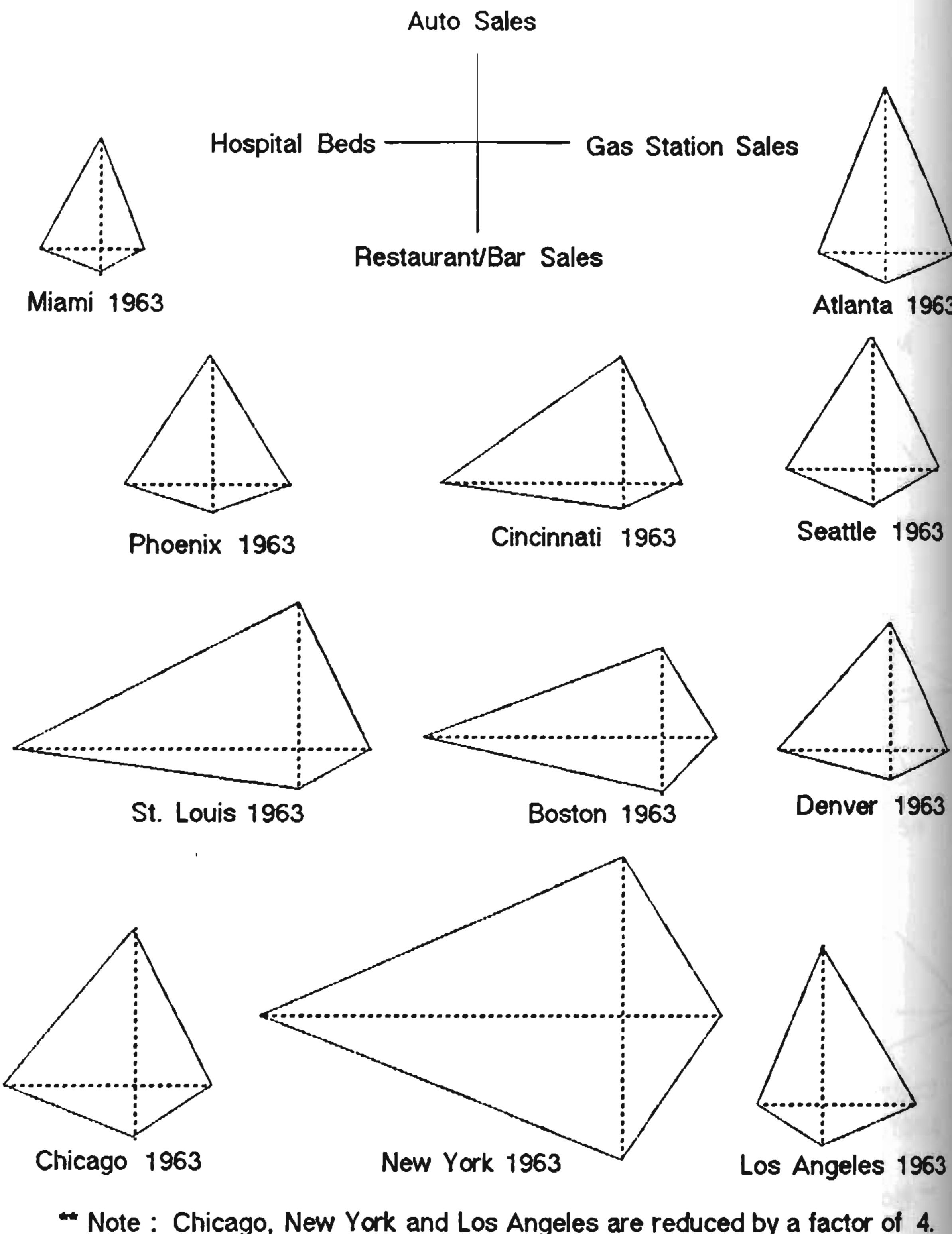
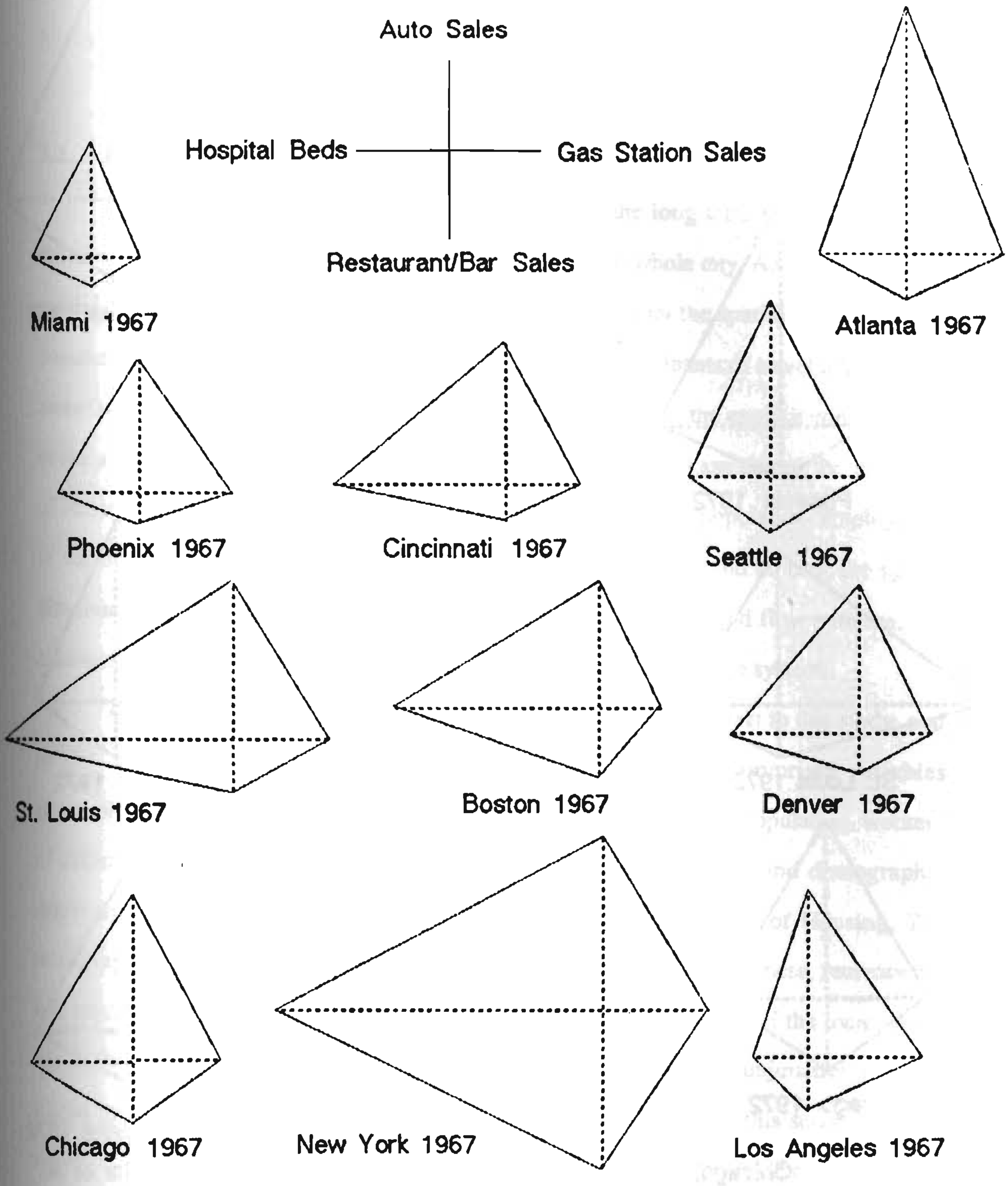
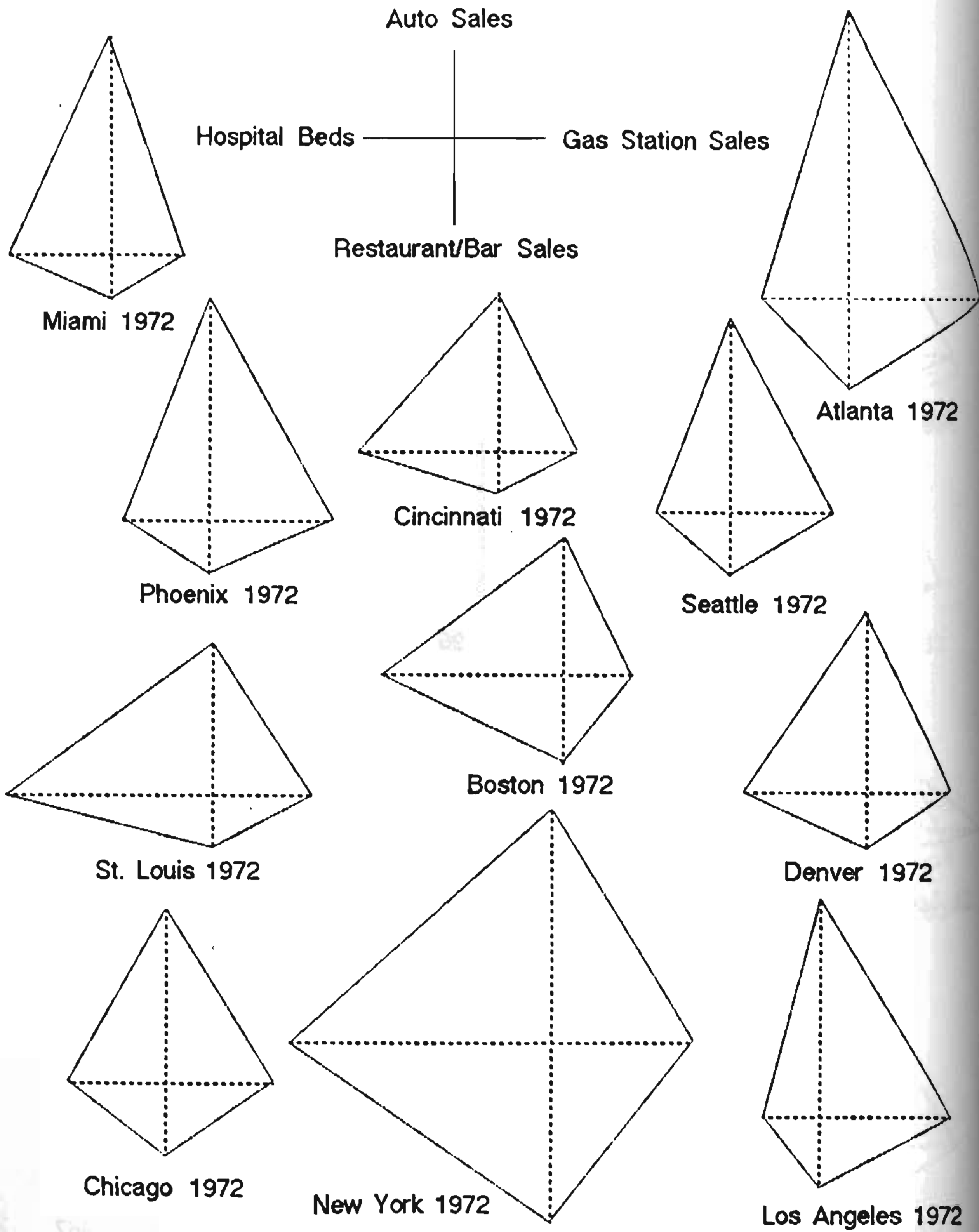

Auto Sales
Hospital Beds
Gas Station Sales
Restaurant/Bar Sales
Miami 1963
Atlanta 1963
Phoenix 1963
Cincinnati 1963
Seattle 1963
St. Louis 1963
Boston 1963
Denver 1963
Chicago 1963
New York 1963
Los Angeles 1963
** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.57



** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.58



** Note : Chicago, New York and Los Angeles are reduced by a factor of 4.

Figure 2.59

CHAPTER 3

SPATIAL DENSITY PATTERNS

3.1. INTRODUCTION

In the previous chapter, the characterization of the long term evolution of cities relied on variables defined as aggregate quantities over the whole city. As such, no explicit spatial dimension was included in the analysis. It is clear that the spatial distributions of population, employment and other activities are critical determinants of travel intensity and associated flow patterns in the urban system. In our framework, the explicit consideration of the urban area's spatial characteristics provides an essential linkage among the evolution of variables such as those considered in the previous chapter (e.g. population, employment in various sectors, quantity of infrastructure of different types, and so on), the spatial distribution of these variables, the resulting travel characteristics and flow patterns, and ultimately the associated service levels experienced in the transportation system.

The spatial distributions of two types of variables are of interest to this study, and to any analysis of transport in an urban area. The first type comprises variables geographically identified by the dwellers' residential location, such as population, workers of different types, auto ownership, and many other socio-economic and demographic characteristics of households, typically provided by the U.S. Census of Housing. The second type consists of variables describing various employment, business, recreational and other activities in which residents engage; the spatial distribution of the locations at which these activities take place is the desired end result, for use in conjunction with the spatial patterns of the first type of variables. Unfortunately, data on this second type of variables at the desired spatial detail is not readily available, and requires the combination of information from several sources, such as various directories for each city. In this study, we focus on the first type of variables, primarily because the needed data gathering effort was more compatible with the study's time frame. This serves as an illustration of a general approach to examine and characterize the spatial patterns of interest, which could subsequently be extended to include other variables, and provides an initial indication of the changes in urban structure taking place over the past three decades.

The changing structure of cities and their transportation systems can be well illustrated by density functions. Population density functions, which capture the population density as a function of distance from the CBD, provide a good summary of the urban structure, and, when taken at different time periods, reveal the intervening changes in the urban landscape. In this chapter, the population density patterns of four urban areas (Atlanta, Austin, Dallas and Phoenix) are examined using the 1960, 1970 and 1980 U.S. Census data. Density functions are calibrated for these cities, using a cubic spline regression approach (recently suggested by Anderson [1985] for this type of application), providing a quantitative tool for the comparisons over time and across cities. The spatial patterns of the densities of other residence-based variables particularly relevant to passenger transport are also examined. For instance, we consider the density patterns of commuters by different transport modes, as well as the number of autos per square mile and per household, thereby capturing the variability of auto ownership with time and over space for a given city. In addition to overall density functions, specific directional density functions (i.e. within specific sectors or corridors) are important in revealing effects that may be unique to particular subareas within the city.

In the next section, we present the methodological aspects of the work presented in this chapter, including the background pertinent to urban density functions and the use of cubic spline regression models for this purpose, as well as the data sources and reduction procedures. This is followed by a discussion of the estimation results and the general trends in the evolution of the structure of each of the study areas. The examination of areawide density functions is followed in Section 3.5 by directional density functions for one of the study areas (Austin). Concluding comments are presented in section 3.6.

3.2. METHODOLOGICAL BACKGROUND

3.2.1. Density Functions and Their Estimation Using Cubic Splines

Population density functions are widely used to describe the changing structure of cities. Clark's (1951) pioneering work on the subject led to the early use of the negative exponential density function to represent urban structure, as follows:

$$Y_t = \alpha \exp[-\gamma X_t] \qquad (1)$$

where Y_t is the gross population density in census tract t, X_t is the distance in miles from the center of tract t to the CBD, α is a parameter representing the central business district (CBD) density, and γ a parameter known as the "density gradient", which reflects the degree of suburbanization.

The above form provides the classical mononucleated model of urban structure, with a smoothly decaying density from an urban area's CBD. However, as urban areas evolve, and suburbs continue their transformation from low-density bedroom communities for central city workers to active centers of retail, professional services and increasingly industrial activities, the negative exponential model's realism becomes questionable. Considerable empirical work has addressed the above functional form, such as Muth's (1969) investigation of its appropriateness for 46 cities. McDonald and Bowman (1976) tested 10 different functional forms, including the negative exponential, quadratic, and higher order polynomials, and evaluated their performance on several criteria, concluding that other forms outperformed the negative exponential in describing the urban density patterns in several cities. Recently, Anderson (1985) illustrated the use of cubic splines to the study of urban population density functions by applying the method to data from the Detroit metropolitan area. The presentation of the approach hereafter closely follows Anderson's paper (1985).

Cubic spline estimation is a procedure for estimating a relationship in several pieces (third-degree polynomials) in such a way that the pieces fit together smoothly (Poirier, 1973). This method involves dividing the x-axis (distance axis) into several segments, with latter type of information, i.e. to incorporate some feature of the area's transportation system into the spatial density function. The areas of the census tracts were obtained for this study from maps using a CAD automated planimeter system composed of an HP 1000 central processing unit, a CALCOMP 9000 digitizer (input device) and an HP2623A Graphics display (output display) unit.

In what follows, parameter estimates for the model of Eq. (4) are given only for the population density function. Graphical representations are given for the remaining variables; these graphs were generated using a cubic spline routine in the SAS statistical package.

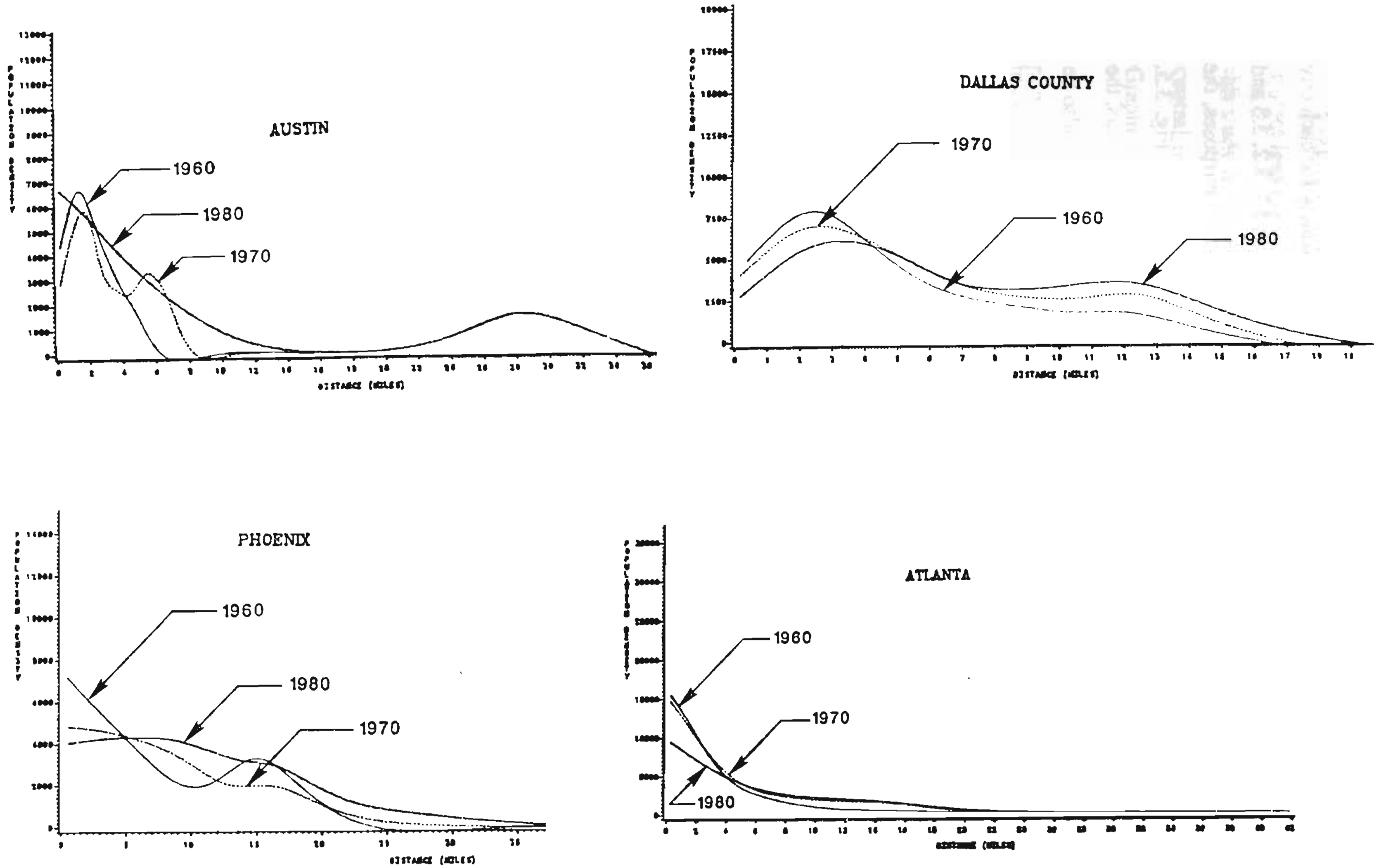
3.3. POPULATION DENSITY FUNCTIONS: ESTIMATION RESULTS

Figure 3.1 presents the fitted population density patterns in each of the four cities for 1960, 1970, and 1980, providing a graphical illustration of the evolution of urban structure in these cities. In all cases, there is a marked decrease over time in residential density in the core area, within 5 miles from the CBD, though not so evident in Austin, as discussed later. This is accompanied by an overall densification and "filling in" in the suburbs, whereby previous "troughs" between the highly peaked CBD and the much smaller outer peak in 1960 are being replaced a more uniform pattern of higher density. Also notable is the progressive "fattening" of the tail, away from the CBD, indicating the continuing move beyond the suburbs into the exurbs. Given the consistency of the patterns observed over the past three decades, these trends can be expected to continue, with formerly low-density suburbs reaching density and activity levels comparable to those previously associated with CBD's, and undoubtedly resulting in traffic congestion levels previously thought to be the exclusive domain of downtown streets.

However, while these general trends seem present in all four case areas, there are marked differences among these areas in terms of their evolution pattern and their current state along that process. These differences are more clearly visible in the parameter estimates for Eq. (4) than in the graphs. Estimation was performed separately for each city for each of the three time periods. Estimation results are shown in Tables 3.1, 3.2, 3.3 and 3.4 for Atlanta, Dallas, Austin and Phoenix, respectively. For comparison purposes, the results from a similar analysis for Detroit (Anderson, 1985) are reported in Fig. 3.5. Except for Austin, which has seen a dramatic growth in population in the past 10 years, the intercept a_1, interpreted as the density in the CBD, has decreased over time. It can also be noted that the magnitudes of the estimated coefficients corresponding to the most distant points (d_3-d_2) are smaller than those corresponding to closer points ([d_2 - d_1] or d_1).

Perhaps the most interesting indication in these estimates is the type of evolutionary pattern followed by each city, and, to some degree, its maturity. In particular, the results for Atlanta and Dallas exhibit clear trends which are consistent over time. For instance, all the signs of any given parameter behave consistently over time, and so do their magnitudes. This may be interpreted that the growth of these cities follows more stable patterns than those of either Phoenix or Austin. The results for the latter reveal the major structural change taking place in Austin and its transformation over the past decade. Similarly, while Phoenix shows consistent signs for the parameters of the lower degree terms (i.e. b_1 and c_1), the parameters of the higher degree terms (i.e. d_1, d_2-d_1 and d_3-d_2) exhibit fluctuating signs, unlike those of Atlanta, Dallas, or Detroit. The increased densification of the closer suburbs are evident through the decreasing magnitude of the parameters b_1 and c_1 over time, particularly apparent for Atlanta and Dallas, indicating the slower rate at which density decays away from the downtown. It would be useful to examine parameter estimates for a wider cross-section of cities, particularly in order to identify evolutionary paths that might provide a robust categorization of cities.

Another interesting set of quantities associated with the cubic splines consists of the location of the knots separating the various intervals, and the outward drift (away from the CBD) of these knots over time, reflecting the increased spatial dispersion and overall growth of the SMSA's over time.



POPULATION DENSITY PATTERN

Figure 3.1

Table 3.1 Estimated Coefficients for Austin Density Functions*

Year	$\hat{a}_1$	$\hat{b}_1$	$\hat{c}_1$	$\hat{d}_1$	d_2^d_1	d_3^d_2	Knots	R^2
1960**	3363.23 (3150.64)	6223.10 (5604.23)	-4691.05 (3147.75)	895.07 (574.51)	-904.73 (575.51)	- -	(0.16, 2.00, 15.47)	0.748
1970	2006.85 (3552.10)	9834.14 (5683.03)	-6340.18 (2861.44)	1031.61 (444.19)	-1129.61 (479.19)	97.00 (53.30)	(0.16, 2.50, 5.50, 12.75)	0.651
1980***	6066.40 (597.08)	-1154.78 (169.09)	72.38 (13.70)	-1.48 (0.33)	1.57 (0.47)	- -	(0.14, 17.00, 36.13)	0.583

* Estimated standard errors of coefficients are given in parentheses

** Due to insufficient data, only three knots were selected; hence, there is no estimate of (d_3 - d_2).

*** For 1980 data, three knots provided the best fit to the data.

Table 3.2 Estimated Coefficients for Phoenix Density Functions*

Year	$\hat{a}_1$	$\hat{b}_1$	$\hat{c}_1$	$\hat{d}_1$	d_2^d_1	d_3^d_2	Knots	R^2
1960	6264.55 (1215.64)	-1097.83 (658.72)	58.03 (104.66)	-0.69 (5.06)	-1.09 (5.54)	1.79 (0.61)	(0.43, 8.00, 16.00, 52.50)	0.505
1970	5172.48 (980.15)	-625.35 (476.83)	10.49 (68.66)	0.79 (3.00)	-2.02 (3.36)	1.22 (0.43)	(0.56, 9.00, 17.00, 55.68)	0.460
1980	4955.99 (902.50)	-1219.74 (334.68)	132.54 (37.36)	-4.62 (1.27)	6.18 (1.63)	-1.66 (0.43)	(0.56, 12.00, 19.00, 55.68)	0.378

* Estimated standard errors of coefficients are given in parentheses

Table 3.3 Estimated Coefficients for Atlanta Density Functions*

Year	$\hat{a}_1$	$\hat{b}_1$	$\hat{c}_1$	$\hat{d}_1$	d_2^d_1	d_3^d_2	Knots	R^2
1960	18867.75 (1599.27)	-7164.68 (1255.23)	1077.10 (289.30)	-59.95 (20.38)	51.35 (22.70)	8.42 (2.94)	(0.27, 5.50, 10.50, 32.85)	0.747
1970	11275.65 (776.52)	-2591.88 (348.74)	236.61 (46.16)	-7.65 (1.83)	9.43 (3.13)	-2.22 (1.60)	(0.27, 11.00, 15.50, 33.47)	0.773
1980	7786.83 (697.82)	-1517.37 (274.52)	130.54 (31.96)	-4.04 (1.12)	5.42 (1.77)	-1.60 (0.77)	(0.27, 12.00, 17.00, 41.84)	0.696

* Estimated standard errors of coefficients are given in parentheses

Table 3.4 Estimated Coefficients for Dallas Density Functions*

Year	$\hat{a}_1$	$\hat{b}_1$	$\hat{c}_1$	$\hat{d}_1$	d_2^d_1	d_3^d_2	Knots	R^2
1960	2805.15 (1611.52)	4672.63 (1617.84)	-1760.11 (483.84)	165.31 (43.86)	-185.93 (49.08)	30.10 (2.53)	(0.38, 4.50, 10.00, 16.68)	0.647
1970	2577.32 (1927.67)	3941.30 (1658.05)	-1285.71 (428.00)	105.66 (33.59)	-126.82 (39.47)	28.57 (11.00)	(0.15, 5.00, 10.00, 17.68)	0.611
1980	2375.23 (1489.30)	2699.41 (1223.98)	-833.53 (302.64)	65.61 (22.67)	-81.20 (26.85)	25.29 (8.68)	(0.16, 5.50, 11.00, 19.34)	0.602

* Estimated standard errors of coefficients are given in parentheses

TABLE 3.5 Estimated Coefficients for Detroit Density Functions*

Year	$\hat{a}_1$	$\hat{b}_1$	$\hat{c}_1$	$\hat{d}_1$	$\widehat{(d_2 - d_1)}$	$\widehat{(d_3 - d_2)}$	Knots	n	SE
1960	8401.05 (2896.32)	9776.91 (2888.60)	−2913.15 (844.44)	228.95 (73.86)	−226.01 (96.88)	−77.46 (85.76)	[0.10, 4.68, 9.26, 13.84]	484	3521.36
1970	3671.13 (2846.68)	7780.76 (2833.13)	−1790.37 (830.22)	120.76 (72.94)	−91.07 (96.36)	−102.47 (88.90)	[0.05, 4.62, 9.20, 13.77]	420	3122.82
1980	4572.69 (1702.09)	3148.62 (1860.03)	−615.98 (595.36)	40.79 (55.95)	−41.33 (77.54)	27.25 (85.73)	[0.38, 4.79, 9.21, 13.63]	343	2538.31

*Estimated standard errors of coefficients are given in parentheses.

Source: Anderson (1985)

Finally, the R^2 values for the regressions are quite reasonable in all cases, with the possible exception of Phoenix, where R^2 values ranged from 0.51 to 0.38. This underscores an important conceptual difficulty associated with this model's assumption of isotropic urban development, that can be explained exclusively by distance from the CBD. In actuality, asymmetries exist, with certain sectors or corridors experiencing greater densities than others, for a given distance from the center. For this reason, Anderson (1985) suggested the examination of "directional" density functions, taken only along one dimension of development away from the CBD. This type of directional analysis can reveal more about an urban area's spatial development patterns than areawide undifferentiated functions of the kind discussed in this section. For instance, the significance of an emerging relatively high-density non-downtown activity center would be more readily visible at the corridor or sector level than an areawide analysis, in which this center might be masked by the majority of less dense tracts located at the same distance from the CBD. A directional analysis of several corridors in the Austin area further illustrates this point in section 3.5. However, we first examine the spatial density patterns of the remaining residence-based variables, other than population, that have particular relevance to transport.

3.4. EVOLUTION OF URBAN STRUCTURE: OTHER VARIABLES

In this section, we continue the examination of the evolution of the spatial distribution of several demographic and transport related variables, geographically identified by residential location, for the four case areas. In particular, we consider the spatial density of workers, the density of private auto and carpooling commuters, the density of public transit users, the average number of autos per household, and the density of autos (measured as the number of autos in a given tract divided by the tract's area), all as a function of the distance from the CBD. The results of this analysis are in general fairly predictable given the above population density patterns, because most of these variables