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AN URBAN AIR POLLUTION PREDICTION MODEL BASED ON DEMOGRAPHIC PARAMETERS

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AN URBAN AIR POLLUTION PREDICTION MODEL BASED ON DEMOGRAPHIC PARAMETERS

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DEDICATION

This work is dedicated
to my wife, Peg; my son,
John III: and to my
daughter, Nell

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ABSTRACT

The body of information presented in this paper is directed to those individuals concerned with future urban growth problems. The research uses the statistical correlations between the regression of demographic and emissions data to construct a model to predict future air pollution emissions, concentrations, and costs-to-control based upon demographic data inputs from a population model.

Correlations were run for 23 cities ranging in population from 100 thousand to 2 million. These correlations are between total pollutant emissions and the demographic factors of population, number of passenger vehicles registered in the county, and the percent of the work force employed in manufacturing. Land area is used to unitize the emissions on a ton per square mile per year basis. Using these correlations to describe cities of increasing size and age, a linear modeling technique is used to describe the future air pollution emissions in a growing city either on a geographical or a population-industrial growth pattern. Since the probability that the emissions of a growing city will fall precisely on the regression line is low, the model provides that measured emission values may

be substituted to establish a more representative regression for that city.

Reductions in emissions from mobile sources as a result of the requirements of the Air Quality Act of 1967 for the manufacture of reduced-population auto engines by 1975 - 1976 are predicted by a step-function.
Future concentrations of air pollution are predicted through the use of meteorological retention factors developed by George C. Holzworth. The amount of emissions in excess of the ambient air quality standards are predicted and the total cost-to-abate these excesses is calculated.

The model is validated against the measured emissions and concentrations of nine cities.

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CHAPTER I

INTRODUCTION

Many models have been developed to predict the location and amount of air pollution over urban areas. Most of these models disperse a known amount of pollutant from a point or line source into a specific volume of air through the use of mathematical equations representing the meteorological parameters of wind speed, depth of the vertical mixing layer, and distance from the source. These models have produced accurate estimates of pollution concentrations but are generally limited to predicting only the present where the emissions are known. A thorough understanding of present air pollution conditions and mechanics is critical to an effective abatement program. However, there is a need for a modeling technique that will provide for a prediction of future emissions of pollutants that might be expected in a city that is growing in size and complexity.

The purpose of this research was to develop a model which uses predicted demographic parameters as a driving force to predict future air pollution emissions, concentrations, and costs-to-abate for a typical contiguous United States city. This model was to have the capability of being manipulated by a computerized program, a desk calculator, or even with just paper and pencil in a reasonably short period of time. It was also to be applicable to geopolitical units ranging in size from a small city isolated by space from other cities to large metropolitan areas covering the largest portion of a county and including one or more suburban communities outside the main city limits.

The major problem in the model development was the procurement of current demographic parameters and emissions inventories for representative cities of various sizes in the contiguous United States. An important constraint in the model development was the differences in data gathering and reporting techniques used by the various states and their environmental control agencies. For example: Some cities reported emissions inventories representative of that city only, where others calculated their emissions inventories for the whole county or even for an Air Pollution Control Region involving several counties in more than one state. Due to the non-similarity of reported data, correlations between demographic parameters and pollutant emissions

were difficult to calculate. The development of emissions units on an amount per square mile basis aided in arriving at these correlations.

In the pollution concentration phase of the model, retention factors developed by George C. Holzworth (1971) were used to describe the meteorological transport mechanisms of the atmosphere. A step function was developed to predict the reduction in motor vehicle generated pollutants as an expected result of the Air Quality Act of 1967, United States Congress (Public Law 90-148) which requires new motor vehicles as of 1975 - 1976 to reduce these emissions by 90% of the 1971 vehicle model measured values.

An average abatement cost-per-ton was calculated from the results of a study by D. A. LeSourd, et. al. (1970) and is used to predict the future costs of an abatement program to maintain the state or Air Pollution Control Region concentration standards.

It is believed that this model will provide a means for predicting future air pollution conditions for a city where only demographic growth parameters are predicted and where there is insufficient historical or planning base for predicting future air polluting conditions.

CHAPTER II

LITERATURE REVIEW

The Air Pollution Problem

Although only recently recognized, air pollution has been a problem in the United States for several decades. The vast industrial complexes that developed in northeastern cities such as Pittsburgh and Detroit have produced large amounts of pollutants since early in this century. At first, this pollution was looked upon as only a smoke problem requiring more frequent cleaning of clothing and painting of buildings. Since World War II, increasing numbers of communities have experienced the adverse effects of atmospheric contamination. In an attempt to provide the basic data necessary to characterize the problem of air pollution, the Public Health Service in 1953 established an air sampling network.

Congress first voted to give the federal government a role in air quality management through the Federal Air Pollution Research and Technical Assistance Act of 1955 (Public Law 84-159). This act authorized the Public Health Service to conduct a program of research, technical

assistance to state and local governments, training of technical personnel, and dissemination of information. The federal government's role was limited to determining the nature of the problem with the primary responsibility for air quality management reserved to the state and local governments. The objectives of the National Air Sampling Network were: the determination of the extent and the nature of air pollution as well as the study of the trends in the levels of various atmospheric contaminants and the investigation of relationships between air pollution and socioeconomic, geographic, topographic, meteorological, and other factors.

By 1958 concern with air pollution had risen to the point that the Public Health Service sponsored a national conference in which sentiment was tested for possible next steps in attacking the problem. In 1960, the Surgeon General of the Public Health Service established the Division of Air Pollution, which gave significant organizational status to the program. Continued public and governmental concern for air pollution control led to the second National Air Pollution Conference in late 1960 (Hagevik 1970).

On February 7, 1963, President Kennedy sent a special message to Congress entitled "Improving America's Health," in which he called for new legislation to strengthen and intensify federal air pollution control efforts. Congress responded by passing the Clean Air Act of 1963 (Public Law 88-206).

In October, 1964, the Senate Special Subcommittee on Air and Water Pollution submitted the report "Steps Toward Cleaner Air," in which legislation was recommended to regulate emissions from gasoline-powered motor vehicles (Hagevik, 1970). In 1967 the President proposed sweeping new authority for the Department of Health, Education, and Welfare (HEW), including the establishment of national emission standards, whereby certain industries would be subject to uniform nation-wide controls regardless of plant location. The Air Quality Act of 1967, however, retained the state control of air pollution problems (Public Law 90-148). This act did establish federal emission standards for new motor vehicle engines effective in 1975.

As a result of this legislation a legal basis has been established for governmental establishment and enforcement of air quality standards in the United States.

Prediction Models

In an attempt to better understand the behavior of atmospheric pollutants, many models have been designed to predict where pollutants will go after being emitted to the atmosphere. A few models have been developed to affect either abatement or more rapid dispersion of pollutants. Most models are of sufficient complexity to require computer analysis (Martin and Tikvart, 1969).

According to Hilst (Stern, 1968) two approaches to mathematical models are available to us. Previous histories of air pollution sources, meteorological measurements, and ambient air quality may be used to construct statistical models of the air pollution system. Alternately, an understanding of the processes of atmospheric transport and diffusion coupled with knowledge of the time and space distributions of sources of pollution permits synthesis of a physical model of this system. Frequently, both methods, statistical and physical, are used concurrently, generally by way of combinations of the predictor variables which tend to linearize the statistical prediction system. Statistical models of air pollution behavior provide an increasingly valuable tool for dealing with management control decisions. Frequently, statistical methods of synthesizing complex interactions will be the only tools available. Whereas the statistical models of air pollution systems contain the variables of sources of pollutants, the reactions of the pollutants, and atmospheric processes only implicitly; physical models attempt to identify these component parts of the air pollution system explicitly. To the extent that such attempts are successful, the physical models have a significant advantage because they then provide the opportunity to simulate the consequences of discreet changes in any of the component parts of the system.

The earliest specific attempts to apply computer oriented systems analysis techniques to the planning and implementation of air pollution control appears to have emerged in the National Air Pollution Control Administration (NAPCA) in 1966 when an Aerospace Industry Task Group formulated a series of recommended "goals" in the application of aerospace technology to urban problems. An outgrowth of this was the solicitation by the Office of Program Development of NAPCA in 1967-68 of proposals for development of mathematical models for regional and national decision making on air pollution control when a three year contract was awarded to TRW-Systems Division (National Industrial Pollution Control Council, 1971). Also in 1967 a contract was let by the Health Program Analysis Group to Ernst and Ernst of Washington, D. C. to undertake a "Model City I" study. The objectives of the study were to demonstrate the value of systems analysis and simulation in cost effectiveness of air pollution and abatement strategies and to identify information needs for developing HEW policy. This study was limited to the abatement of sulfur dioxide (SO_2) from the combustion of fossil fuels (National Industrial Pollution Control Council, 1971).

Later in 1967 Ernst and Ernst performed a "Model City II" study to cover both SO_2 and particulates from fossil fuel and industrial sources and further developed the data base and automation of the simulation. In the "Model City II" study the

Ernst and Ernst approach utilized a mathematical model and computer program which, with inputs on (a) control alternatives and their costs on a source-by-source basis, (b) an emissions inventory on a source-by-source basis, and (c) appropriate meteorological parameters and diffusion models, could represent the spatial distribution of average annual concentrations of particulates and SO_2 for varying degrees of control and cost-to-control (National Industrial Pollution Control Council, 1971).

The TRW-Systems Division research produced two computer programs: Air Quality Display Model (AQDM) and Implementation Plans Program (IPP).

AQDM takes meteorological and emissions inventory data for a particular region and gives time average spatial distribution of specific pollutants of concern. The model allows examination of the effectiveness--but not cost--of various control strategies in reducing time-average spatial peak concentrations of pollutants of concern. AQDM is being utilized by the Bureau of Abatement and Control for evaluation of implementation plans submitted by states under the provisions of the Clean Air Act of 1967 (National Industrial Pollution Control Council, 1971).

IPP is an extension of AQDM which introduces cost-to-control into the analysis. It requires, in addition to the meteorological and emissions inventory inputs of AQDM, a

data base of control costs for the alternative control strategies. IPP is thus a cost-effectiveness model; one which relates direct costs-to-control to desired levels of air quality on a regional basis.

RAPA (Regional Air Pollution Analysis) which is the ultimate objective of the current TRW research, is a regional air pollution cost-benefit analysis. It is achieved by adding damage analysis to IPP. RAPA is a cost-benefit tool which will assist in identifying the level of air quality at which the cost is equal to the benefits (National Industrial Pollution Control Council, 1971).

Several models have been prepared to predict the future air pollution problems of specific cities. One of the most promising of these was prepared by Cohen and Norco (1971) of the Argonne National Laboratory. The methodology presented in their paper provides a means of evaluating future effectiveness of emission control regulations. Their system consists of three computerized sub-models: (1) a projection model which estimates future emissions based on current growth and fuel-use trends from stationary sources, (2) a statistical climatology model to analyze meteorological conditions based on historical data, and (3) a dispersion and display model for making air quality estimates via isopleth maps.

The projection model provides an emissions inventory for any specified year assuming an exponential growth

pattern which is assumed to be unaltered by a control regulation such as a sulfur content limit on fuels.

The climatology model uses historical weather bureau statistics to generate joint frequency distributions for given combinations of standard meteorological parameters such as wind speed, wind direction, stability class, and temperature.

The outputs of the projection and climatology models are utilized by a steady-state Gaussian plume dispersion model to obtain ground level estimates of pollutant concentrations.

The Cohen and Norco model requires an extensive historical data base and specific local meteorological parameters as inputs, whereas the model described in this paper was limited to census-generated demographic parameter inputs.

The team of Roberts, Croke, and Kennedy (1970) developed an urban atmospheric dispersion model for the Chicago Air Pollution Systems Analysis Program (CAPSAC), which is a multiple-source model programmed for the IBM 360-75 computer system. It is an "integrated puff" model providing a realistic physical simulation of the processes of smoke plume dispersion by providing for near-zero wind speed conditions, modeling three-dimensional wind vector variation and atmospheric diffusion, and permitting variations of stability and mixing layer depth with time. A

series of algorithms are assembled around a kernel that represents the transport and diffusion of pollutant species from point and area sources according to a Gaussian distribution in three dimensions. Present-day air quality only is determined by this model.

An air quality model for Knox County, Tennessee was prepared by Steven R. Hanna (1971) using the Atmospheric Turbulence and Diffusion Laboratory Model (ATDL) developed by Hanna and associates at the National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee. It calculates the surface concentrations of SO_2 and suspended particles for a variety of meteorological conditions. A detailed area and multiple point source inventory is used as input. Hanna found that low level sources (e.g., small industries and household and commercial heating units) contribute as much as tall point sources to total surface concentration of pollutants. This model can be used in the future to estimate the impact of changes in stack heights or patterns of emissions on patterns of surface concentrations.

A critical summary of air pollution modeling to date was prepared by Kenneth L. Calder (1970) in which he wrote, "The basic structure of many current urban pollution models is examined from the point of view of underlying assumptions and physical basis. Initial attempts to extend steady-state models to variable conditions and long-term predictions

are indicated, with a brief discussion of stochastic simulation of the concentration patterns and average seasonal and annual distributions." He further states, "At the present time, there appears to be a real need to study the sensitivity of the concentration predictions to variations in inputs to the models. In some cases large variations in input may have little effect on output. With others, the reverse may be true. ...some recently proposed models may already be over-complicated."

As Calder points out, models should be sensitive to input variations without becoming over-complicated. An attempt has been made in the model described in this paper to achieve sensitivity without sacrificing simplicity of manipulation.

Emissions Inventories

If the chicken who cried, "The sky is falling" had bothered to define the sky and then had differentiated between this sky and that which fell he probably would not have created such mass hysteria in the anthrophomorphic world of children's literature.

In much the same way, if research personnel bother to define the atmosphere in its natural state and differentiate between this natural state and that which constitutes air-pollution then a perfectly normal hazy day might not create mass hysteria among the general public.

It was early recognized that the amounts and types of pollutants emitted to the atmosphere in an area of concern must be known if a differentiation between the natural and the unnatural is to be made. Man-generated pollution emissions might be difficult and costly to control but the control of natural pollution emissions are even more difficult and costly and since nature has a way of arriving at a balanced state in its own inimitable way man is and should be reticent to disturb this natural balance.

Some of the earliest attempts to develop an inventory of the air pollutant emissions in an urban area were based upon the registration of the known sources. The Air Pollution Control Field Operations Manual published by the U. S. Department of HEW in 1962 presented guidelines for registration of pollution sources (Weisburd, 1962). This publication states, "The success of the control program depends on the accuracy and completeness of data concerning the air pollution potentials of each of the sources of air pollution. Without such information, the control program lacks direction and purpose, and the results of control activity are uncertainly verified. The registration process is intended to secure a detailed breakdown of the air pollution potentials." In securing this detailed breakdown of potentials the following data was to be compiled:

1. Corporate or individual ownership or responsibility.
2. Location of the equipment source.
3. Complete identification and description of the equipment, including all important constituents, appurtenances, and other conditions which affect the emission of contaminants.
4. All data relevent in demonstrating and expressing the air pollution potentials of the equipment. These data may include the nature of process, rates of emission based on size of outlet and flow rate of effluents, composition and description of effluent, etc.
5. Some record of status to indicate the degree of compliance with the air pollution laws.

It was recognized from past experiences that although the procurement of the needed data looked easy in print it was indeed a difficult task which prompted the writers (Weisburd, 1962) to state, "There is little disagreement among those interested or affected by air pollution control regarding the necessity for source registration, but there is considerable disagreement as to the methods by which the sources of air pollution should be registered. The conflict relates to the powers of the control agency to gather such data, and the rights of plant operators to secrecy. Depending on its control policy, a community may

provide for any one or combination of the following methods of registration:

1. Plant operator supplies information on a voluntary basis as conditions change in the plant.
2. Plant operator supplies information as authorized and required by law, but only upon formal request.
3. Plant operator supplies information under order of the control agency, and as required by law.
4. All data acquired by field inspection personnel, with the necessary authority."

In 1961, a pilot study of air pollution in Jacksonville, Florida was conducted (Sheehy, 1963). To better evaluate existing and potential area-wide air pollution problems in the Jacksonville area, an emission inventory was carried out. Approximately 50 of the largest industrial and municipal establishments were contacted by personal visits, questionnaires, and/or telephone. The following classification of sources was used:

Classification	Source type
Local sources	Power generation
	Incineration
	Water aeration -- (municipal plants for removal of hydrogen sulfide from well waters).
	Industrial combustion
Area sources	Commercial
	Domestic
	Transportation

The techniques used in the Jacksonville study were typical of the techniques used during that period but were not standardized.

A major advance in the evolution of the standardized emissions inventory techniques was the development and consequent publication in 1965 of a Compilation of Air Pollutant Emission Factors for Combustion Processes, Gasoline Evaporation, and Selected Industrial Processes by Martin Mayer (1965). **Emission factors, by type, were presented as the amount of pollutant emitted for a quantity of fuel consumed or material processed by a specific combustion or processing technique. The factors were compiled primarily for use in conducting an air pollutant**

emission inventory. Mayer stated, "Obviously, the best emission factor to use for any specific source of air pollution is that resulting from source tests of the specific source. Unfortunately, many urban areas are not equipped to conduct the numerous and expensive stack testing studies needed for an emission inventory. The purpose of this compilation of emission factors is to provide the best available substitute to air pollution control agencies unable to conduct extensive source test programs."

The Environmental Protection Agency (EPA) published a compilation of Air Pollutant Emission Factors in 1972 (AP -42, 1972) which expanded and updated Mayer's compilation to include the ten following major categories of emission sources:

1. Stationary combustion sources.
2. Solid waste disposal.
3. Mobile combustion sources.
4. Evaporation loss sources.
5. Chemical process industry.
6. Food and agriculture industry.
7. Metallurgical industry.
8. Mineral products industry.
9. Petroleum industry.
10. Wood processing.

These same categories are included in the emissions inventories which have been prepared according to a rapid survey technique developed by Ozolins and Smith (1966). An important feature of this method is the concept of reporting zones. Emissions are assigned to the general geographical localities where they occur, rather than reported as total values for the entire metropolitan area. In this manner, areas of high emission strengths are identified and the distribution patterns of the different pollutants within the study area may be estimated.

The method utilizes information readily available in most communities to provide reasonably accurate, yet rapid, estimates of the major air pollutant emissions of an urban area. The method does not require extensive plant surveys or source sampling procedures involving high levels of technical competence and large expenditures. It is presented in a step-wise format, including discussions of basic assumptions, aimed at guiding a person of moderate professional training. Field trials of the method in communities with 350,000 and 2,000,000 inhabitants required 3 and 6 weeks, respectively, for such a person to complete the survey and basic report.

Emissions inventories prepared prior to the development of the rapid survey technique in 1966 are difficult to compare since there was little standardization of procedures. Those prepared by the rapid survey techniques

can usually be compared on a categorical basis since they generally employ the same emission factors in their calculations.

Pollution Transport

Man-generated pollution obviously adds to the natural background pollution load of the earth's atmosphere and as such affects the whole world, however, concentrations sufficiently great to be immediately noticeable and hazardous to life are limited to the areas surrounding the points of pollution release. As the earth rotates, so does its atmosphere--grossly speaking. Actually there is some tendency for the atmosphere to lag behind the earth's rotation which aids in the movement of air masses from one area to another on the earth's surface. This movement is accelerated or modified by areas of high and low atmospheric pressure. The winds resulting from these mass air movements carry air pollutants away from the points of release. Due to the physical unevenness of the earth's surface and the tendency of various areas of the earth's surface to absorb or reflect solar heat at different rates a turbulence is generated in the atmospheric layer near this surface. Reynolds studied and described the laminar and turbulent flow characteristics of a fluid mass. These studies found that the areas of greatest turbulence are nearest the boundary with a solid mass and are expressed

in present day physics as Reynolds' numbers (Blackwood, 1965). The earth's surface is a solid mass that contributes to atmospheric turbulence, therefore, at an altitude of several hundred meters above the earth's surface, the atmosphere tends to move in a laminar flow. This tendency towards a laminar flow is aided by the lower layer of air responding immediately to decreases in the earth's surface temperature, resulting in a boundary layer between the lowest turbulent level of the atmosphere and the warmer, more stable, layer above it. There is very little interchange between these two layers which acts as a cap or inversion with the result of trapping surface released pollution below this inversion layer (Ledbetter, 1972).

The concentrations which air pollutants can maintain near the points of release are dependent upon the speed with which they are moved away from these release points and the speed with which they are mixed with the surrounding mass of air. These dilution mechanisms then require that certain parameters be known if pollution concentrations near the earth's surface are to be predicted. These parameters are wind speed, amount of turbulence, and height of the inversion layer (Ledbetter, 1972).

In 1961 Charles R. Hosler tabulated the frequency of inversion and/or isothermal conditions based below 500 feet for the contiguous United States (Hosler, 1961). Hosler stated that, "In essence the dilution efficiency of

the atmosphere depends on the wind and temperature gradients, both of which vary vertically, horizontally, and with time. Since the general spatial problems of slow atmospheric dispersion which affect large areas unquestionably arise at times when a stable stratified layer of air exists near the surface, a knowledge of the frequency of low-level stability for geographical and/or climatological areas will be helpful for assessing the potential for air pollution inherent to a given region." In this study, U.S. Weather Bureau radiosonde data from weather stations throughout the contiguous United States was used to tabulate the frequency of low-level inversions. The entire nocturnal period was considered stable if an inversion was observed at any time during the night, and the maximum percent frequency of inversions for any one observation time within a nocturnal period was assumed applicable to the entire nighttime period; and, conversely, the entire daytime period was assumed to be unstable, and low values of inversion frequencies occurring at observation times during the daytime heating period were not considered in computation of inversion frequency as a percent of total hours (Hosler, 1961).

In 1964, George C. Holzworth published Estimates of Mean Maximum Mixing Depths (MMD) in the Contiguous United States as a supplement to Hosler's work. Holzworth calculated and plotted these MMD's for areas of the United States

as exist during each of the twelve months of the year (Holzworth, 1964). This information led to a further study by Holzworth resulting in his presentation of An Atmospheric Diffusion Model for Metropolitan Areas to the 59th Annual Meeting, Air Pollution Control Association, June 1966. This model makes possible rough estimates of relative concentrations of pollutants at the usual times of maximum and minimum atmospheric dilution; these times are, respectively, mid-afternoon and early morning (Holzworth, 1966).

In April 1971, Holzworth presented A Review of Air Pollution Climatology and Forecasts to the conference on Air Pollution Meteorology of the American Meteorological Society at Raliegh, N. C. In this review he presented a series of air pollution retention factors for areas of the United States based upon meteorological transport mechanisms and city sizes (Holzworth, 1971). These retention factors are used in the model presented in this paper as part of the technique of determining the predicted concentrations of air pollutants.

Ambient Air Quality

When one begins to contemplate the goals of the so-called "Clean Air Acts" it becomes immediately apparent that a meaningful definition is difficult to formulate. Technical definitions of air have been published as a

result of accurate chemical analyses which describe the composition of Normal Ambient dry air. Table 1 (Ledbetter, 1972). Numerous physical studies have provided definitions so that the physical properties of air have also been described. Table 2 (Ledbetter, 1972).

Although accurate descriptions of air exist, it is not just air, as such, that must be defined but rather air as the atmosphere around the earth. Webster's unabridged dictionary defines atmosphere as: "The whole mass of aeroform fluid surrounding the earth" (Webster, 1956). According to Ledbetter (1972), the composition of air varies somewhat with local conditions; however, the average concentrations of the various components can be rather narrowly defined. This inconsistency in the local composition of air has been realized by man for many decades. William Ferrel wrote in 1889, "The constituents of the atmosphere are not chemically combined, but exist together as a mechanical mixture. If the atmosphere were perfectly at rest each constituent would assume the same status and distribution as it would if the others were not present. Each one, therefore, would form an atmosphere of itself, independent of, and unaffected by, the others. This arrangement of constituents is called Dalton's Law" (Ferrel, 1889). Our atmosphere, however, is not at rest but is in constant and continuous motion.

TABLE 1

COMPOSITION OF NORMAL AMBIENT AIR (DRY)

Component	By volume	By weight	Total Mass (gm X 10^{-20})
N_2	78.084 ± 0.0004 %	75.51 %	33.648
O_2	20.946 ± 0.0002 %	23.15 %	11.841
A	0.934 ± 0.0010 %	1.28 %	0.6355
CO_2	0.033 ± 0.0010 %	0.046%	0.0233
Ne	18.180 ± 0.040 ppm	12.50 ppm	6.36 X 10^{-4}
He	5.240 ± 0.004 ppm	0.72 ppm	3.70 X 10^{-5}
Kr	1.140 ± 0.010 ppm	2.90 ppm	1.46 X 10^{-4}
Xe	0.087 ± 0.001 ppm	0.36 ppm	1.80 X 10^{-5}
N_2O	0.500 ± 0.110 ppm	1.50 ppm	7.70 X 10^{-5}
CH_4	2 ppm	1.20 ppm	6.20 X 10^{-5}
H_2	0.5 ppm	0.03 ppm	2.00 X 10^{-6}
O_3	0.01 ppm	--	--
Rn	10^{-13} ppm	--	--

TABLE 2

PROPERTIES OF AIR

Property	Value	Units
Thermal conductivity	5.68×10^{-8}	$cal/cm^2\text{-}sec\text{-}^oC/cm$
Specific heat	0.24	$cal/^oC\text{-}gm$
Mole volume STP	22.4146	liters
Molecular weight	29.095	
Density (dry)	1.293	gm/liter
Dynamic viscosity	170.8	micropoise
Kinematic viscosity	13.2	centistokes
Velocity of sound	1087	feet/sec
Refractive index	1.00029	Sodium light (524 nm)

As the chemical composition of air is not precisely consistent throughout the entire atmosphere neither is the bedload of airborne materials consistent. Concentrations of airborne materials tend to be greatest near the points of entry into the atmosphere and progressively less as a function of distance from the points of entry. This distance relationship was early recognized by man as evidenced by the writings of Pouchet in 1873 when he wrote, "But so soon as we abandon the solitudes of the sea or the mountains, the nearer we approach populous cities, the more does the air become loaded with invisible particles. The catalogue of these is in reality only the summary of all that man makes use of for his wants or pleasures. We find atoms of food, of our clothes, of our furniture, and of our dwellings, everything in short is represented there," (Pouchet, 1873). Even though recognized a hundred years ago this inconsistency of distribution of airborne materials has only become of concern to man within the past two or three decades. McCormick writes, "On any map of air pollution distribution over a country which one might be able to construct, the data for urban areas would stand out as sharp peaks at levels up to one or even two orders of magnitude higher than surrounding background, or rural, levels," (Stern, 1968).

Along with a definition and description of air it is necessary that one include a definition of air pollution.

The Engineers Joint Council has arrived at the following definition: "Air pollution means the presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, gas, mist, odor, smoke, or vapor, in quantities, of characteristics, and/or duration such as to be injurious to human, plant or animal life or to property, or which unreasonably interfere with the comfortable enjoyment of life and property," (Ledbetter, 1972).

Air pollutants have also been classified. The American Society for Testing Materials (ASTM) defined common forms of air contaminants in 1936. These contaminants are:

Dusts: Solid particles generated by handling, crushing, grinding, rapid impact, detonation and decrepitation of organic or inorganic materials such as rock, ore, metal, coal, wood, grain, etc. Dusts do not tend to flocculate except under electrostatic forces; they do not diffuse in air but settle under the influence of gravity.

Fumes: Solid particles generated by condensation from the gaseous state, generally after volatilization from molten metals, etc., and often accompanied by a chemical reaction such as oxidation. Fumes flocculate and sometimes coalesce.

Mists: Suspended liquid droplets generated by condensation from the gaseous to the liquid state or by breaking up a liquid into a dispersed state, such as by splashing, foaming, and atomizing.

Gases: Normally formless fluids which occupy the space of enclosure and which can be changed to the liquid or solid state only by the combined effect of increased pressure and decreased temperature. Gases diffuse.

Vapors: The gaseous form of substances which are normally in the solid or liquid state and which can be changed to these states either by increasing the pressure or decreasing the temperature alone. Vapors diffuse (Ledbetter, 1972).

Several terms other than those defined above are needed to characterize air pollutants. Some of these in common use are:

Fly ash: Particles of ash which become entrained in combustion gases and are carried into the air.

Aerosols: An air or gas suspension of particles (usually less than 50 μm in diameter).

Fog: An aerosol of liquid droplets near the ground as distinct from clouds.

Smoke: Carbon or soot particles, often less than 0.1μ in diameter, that result from the incomplete combustion

of carbonaceous materials such as coal, oil, tar, and tobacco.

Haze: Suspension of small (fractional micrometer) particles in the air which makes distant, large objects indistinct.

Smaze: Mixture of smoke and haze. Suggested for photo-chemical smog but not widely used.

Radioactivity: The nuclear disintegrations atoms undergo in giving off ionizing radiations.

Radiation: Electromagnetic radiations plus those corpuscular emissions classed as "rays".

Noise: Unwanted sound. Sound is the effect that rapid, local fluctuations of the atmospheric pressure have on the ear (Ledbetter, 1972).

For use in the design of the model described in this paper only the following air pollutants will be considered:

Particulates

Sulfur Oxides (SO_x)

Carbon monoxide (CO)

Nitrogen Oxides (NO_x)

Hydrocarbons

The nationwide emissions of these pollutants in tons/year for 1968 are listed in Table 3 (AP-42, 1972).

It is evident that if man is to pursue his destiny on earth he will continue to generate air pollution. The question becomes, How much air pollution can man pump

TABLE 3

NATIONWIDE EMISSIONS FOR 1968

Source	Particulates 10^6 tons/yr.	Sulfur Oxides 10^6 tons/yr.	Carbon Monoxide 10^6 tons/yr.	Hydro Carbons 10^6 tons/yr.	Nitrogen Oxides 10^6 tons/yr.
Stationary combustion	8.9	24.4	1.9	0.7	10.0
Solid waste disposal	1.1	0.1	7.8	1.6	0.6
Mobile combustion	1.2	0.8	63.8	16.6	8.1
Industrial processes	7.5	7.3	9.7	4.6	0.2
Misc.	9.6	0.6	16.9	8.5	1.7
TOTAL	28.3	33.2	100.1	32.0	20.6

into the atmosphere and still maintain an acceptably healthy environment? The answer to this question dictates that some form of standards must be established which describe the allowable concentrations of air pollutants.

The Air Quality Act of 1967 has as one of its objectives the state control of air pollution problems, which is a reflection of a belief that federal control would not be desirable and that differences in controls in different regions taking into account varying atmospheric, topographic, industrial, and other conditions are at this time necessary. Pollution abatement activities are to be coordinated in air quality regions designated by HEW and will be guided by air quality criteria and recommended control techniques developed by HEW for specific pollution agents, and are to be in accord with air quality standards and enforcement plans developed by the states (Hagevik, 1970).

Although the Air Pollution Control Regions in the states will set their own ambient air quality standards, the Environmental Protection Agency (EPA) of the federal government has published National Primary and Secondary Ambient Air Quality Standards in the Federal Register of April 30, 1971.

The model described in this paper is designed to use the EPA approved ambient air quality standards of the individual air quality control regions.

Cost of Abatement

Probably the first specific attempt to develop a plan for predicting the cost of air pollution control was made in 1967 by Ernst and Ernst of Washington, D. C. in their "Model City I" study where they demonstrated the value of systems analysis and simulation in cost effectiveness of air pollution and abatement strategies **(National Industrial Pollution Control Council, 1971).**

In 1969 the TRW-Systems Division developed the Implementation Plans Program (IPP). IPP is an extension of a previously developed Air Quality Display Model (AQDM) which required meteorological and emissions inventory inputs. IPP added a data base of control costs.

Jackson, Wohlers, and DeCoursey developed a method for determining the costs of air pollution control within a metropolitan region which they published in 1969. Their systematic method of evaluating emission control costs is outlined in a series of six steps. Any metropolitan region could be considered for application of the procedure, which is briefly described as follows:

1. Examine present emission rates by source category and evaluate the existing degree of air pollution controls.
2. Evaluate regional trends and make future projections of controlled and uncontrolled emissions.

3. Evaluate emission control trends that have been established in the region or throughout the nation.

4. Examine alternate control schemes that may be feasible for application to each source category.

5. Determine emission control costs based on the best available data.

6. Evaluate optimum control effectiveness.

The Jackson technique is very flexible and can be tailored to fit the cost requirements for most any geo-political region, however, it is not mathematically stable enough to easily lend itself to a simple modelling scheme for broad application (Jackson, et. al., 1969).

In 1970 LeSourd and associates (LeSourd, et. al., 1970) published a Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Effects of Air Quality Standards. This study was prepared for the Environmental Protection Agency. The purpose of this research was to make estimates of the air pollution control costs and economic impact that will result from implementation of the Clean Air Acts and from the Air Quality Act of 1967. Air pollution control costs were estimated for each stationary source except residential heating plants that were operated during 1967 in 298 designated metropolitan areas

of the nation. In 1967, these areas contained 85 percent of the nation's population. Additionally, air pollution control costs that would be incurred by facilities built during the period 1968 through 1976 were estimated. These estimates are limited to stationary sources and to 298 selected metropolitan areas. Estimated costs for each source are aggregated for the metropolitan areas and are given in terms of total investment required as well as the total annual cost which can be expected by 1976. The emissions from solid waste disposal and stationary fuel combustion, as estimated with and without implementation of the Clean Air Act, are shown in Table 4.

The estimated 1976 industrial processes emissions levels and control costs for each pollutant by source are shown in Table 5.

The cost data developed by LeSourd, et. al. are used in the model described in this paper to predict an average cost-per-ton to abate emissions which create concentrations in excess of the ambient air standards.

TABLE 4

SOLID WASTE DISPOSAL AND STATIONARY FUEL COMBUSTION
ESTIMATES OF POTENTIAL AND REDUCED EMISSION LEVELS AND ASSOCIATED COSTS

Source	Year	Quantity of Emissions (Thousands of Tons Per Year) Part	SO_x	CO	HC	Control Costs (Dollars X 10^6) Initial	Annual
Solid Waste Disposal	FY76 W/O	1,500.0		3,450.0	2,020.0		
	FY76 W	185.0		414.0	293.0	201.0	113.0
Commercial Heating	FY76 W/O	152.0	1,440.0				
	FY76 W	135.0	1,440.0			41.7	25.1
Industrial Boilers	FY76 W/O	1,410.0	2,310.0				
	FY76 W	142.0	1,100.0			1,050.0	555.0
Residential Heating	FY76 W/O	120.0	597.0				
	FY76 W	120.0	597.0			0	0
Electric Power Plants	FY76 W/O	2,185.0	10,100.0				
	FY76 W	533.0	1,600.0			1,340.0	426.0

W/O - Without implementation of the Clean Air Act. (LeSourd, et. al., 1970)
W - With implementation of the Clean Air Act.

TABLE 5

INDUSTRIAL PROCESS SOURCES - ESTIMATES OF POTENTIAL AND REDUCED EMISSIONS LEVELS AND ASSOCIATED COSTS

Source	Year	Quantity of Emissions (Thousands of Tons Per Year) Part	SO_x	CO	HC	Control Costs (Dollars X 10^6) Initial	Annual
Asphalt Batching	FY76 W/O	571.0					
	FY76 W	37.8				15.4	12.3
Coal Cleaning	FY76 W/O	92.3					
	FY76 W	14.1				13.1	5.3
Cement Plants	FY76 W/O	280.0					
	FY76 W	16.1				110.0	29.6
Grain Handling	FY76 W/O	1,730.0					
	FY76 W	26.1				436.0	153.0
Grain Milling	FY76 W/O	347.0					
	FY76 W	5.4				27.4	11.0
Gray Iron Foundries	FY76 W/O	255.0		3,420.0			
	FY76 W	29.1		209.0		317.3	108.2
Iron & Steel	FY76 W/O	1,460.0					
	FY76 W	93.0				981.0	507.0

(LeSourd, et. al., 1970)

TABLE 5--Continued

Source	Year	Quantity of Emissions (Thousands of Tons Per Year) Part	SO_x	CO	HC	Control Costs ($Dollars \times 10^6$) Initial	Annual
Kraft	FY76 W/O	847.0					
Pulp	FY76 W	120.0				73.0	30.0
Lime	FY76 W/O	253.0					
		20.3				10.6	14.5
Petroleum	FY76 W/O				738.0		
Storage	FY76 W				320.0	1,080.0	0
Petroleum	FY76 W/O	98.4	2,150.0	6,620.0	996.0		
Refining	FY76 W	30.7	1,270.0	330.0	529.0	162.0	7.1
Primary Metallurgy							
Copper	FY76 W/O		2,380.0				
	FY76 W		227.0			87.0	42.0
Lead	FY76 W/O		269.5				
	FY76 W		17.2			16.2	7.1
Zinc	FY76 W/O		508.0				
	FY76 W		76.7			4.7	2.2
Secondary	FY76 W/O	14.8					
Metallurgy	FY76 W	2.9				61.9	21.8
Sulfuric	FY76 W/O	90.1	921.0				
Acid	FY76 W	35.1	129.0			176.0	4.08

CHAPTER III

PARAMETERS AND METHODS

Introduction

As any city grows, there should be trends in its demographic characteristics that are typical of other cities in the same stage of growth. At the same time, the growth of a city is generally accompanied by an increase in the amount of air pollutants emitted to the atmosphere. Whether these emissions become an air pollution problem or not is dependent upon the amounts and types of emissions and their retention time in sufficient concentrations in the human activities zone. If these generalizations be true, then there should exist a correlation between demographic characteristics and pollutant emissions that should show a positive progression as a city grows in size and industrial activities.

Models are in existence which are capable of predicting the demographic growth characteristics of cities based upon extrapolation of standard census data (Reid and Bollinger, 1969). There are also models which predict the air pollutant emissions increases that should accompany

urban growth (Cohen and Norco, 1971). The increases are predicted on the basis of industrial and transportation growth and development, modified by improved abatement and control techniques.

This research uses the correlations between the progression of demographic data and emissions data in order to construct a model that will predict the air pollution concentrations and costs-to-control based upon demographic data inputs alone from a population model.

Correlations were run for twenty-three cities ranging in size from less than 100,000 to approximately 2,000,000 population. These correlations are between total pollutant emissions and demographic factors such as population, number of passenger vehicles registered in the county, and the percent of the work force employed in manufacturing. Land area is used to unitize the emissions on a ton per square mile per year basis. Using these correlations to describe cities of increasing size and age, a linear modeling technique is used to describe the future air pollution emissions in a growing city either on a geographical growth pattern or a population-industrial growth pattern.

The possibility that the emissions as a function of demographic parameters for a growing city will fall precisely on the regression line is very rare. This model provides that the measured emission values for a city may

be substituted in the predicted emissions formulae to establish a more representative regression for that city.

Reductions in air pollution emissions from mobile sources as a result of the Clean Air Act's requirements for the manufacture of reduced-pollution engines by 1975 - 1976 are predicted by a step-function. It is estimated that a ten year period will be required for the eventual replacement of high pollution-potential engines.

Future concentrations of air pollution in a growing city are predicted through the use of meteorological retention factors developed by George C. Holzworth (1971). Holzworth's retention factors, presented as isopleth values are integrated in this model into zones with average retention factor values. This averaging is considered to be valid since Holzworth found that the progression of the values between isopleths was practically linear.

In order to compare the predicted air pollution concentrations and the limits of the existing legal standards, the difference between the predicted concentration and the standards is calculated. If the concentrations exceed the standards the amount of the excess is considered to be the amount that must be abated in the future.

The total costs-to-abate are predicted by the model by multiplying an average cost-per-ton to abate, developed

by D. A. LeSourd, et. al., by the number of tons in excess of the standards.

Previously developed and described air pollution models have depended heavily upon emission inventories and meteorological data to identify or predict zones of air pollution concentrations. The model described in this study uses a more devious, yet possibly a more meaningful, approach since it relates air pollution to people and uses people parameters as a driving force. This approach was necessary since this model is a part of a battery of six integrated models that comprises an Urban Systems Model (See Figure 1).

The Data Base

A data-gathering phase was begun with a search of published literature in an attempt to compile current values of air pollution emissions and demographic characteristics of representative cities in the contiguous United States. This literature search failed to produce either current data or complete data. As a result, it was determined that if this information was in existence it must be in the records of the local environmental agencies of the individual cities or Air Quality Control Regions. Reports for Consultation on the Metropolitan interstate/intrastate Air Quality Control Regions were requested by mail from 40 of these regions (See Figure 2). Twenty-two of these

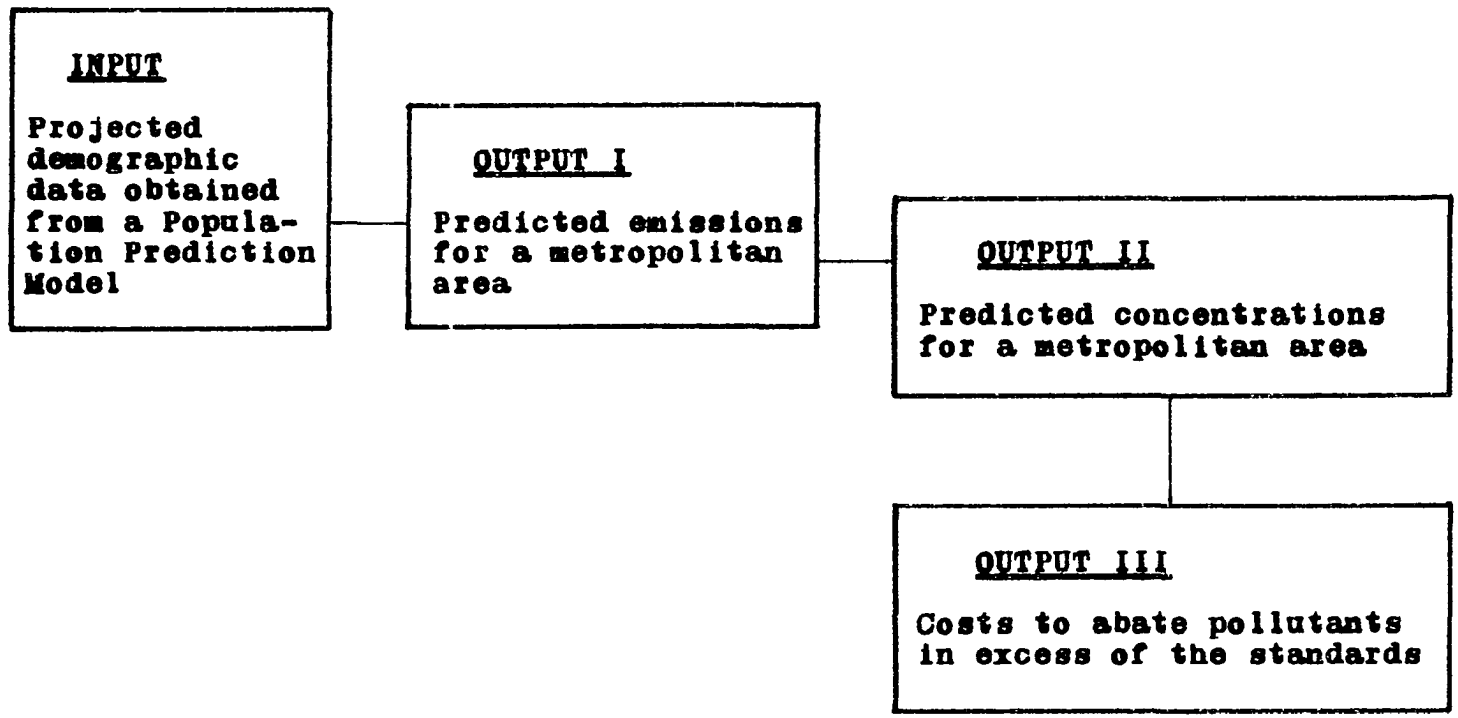

Fig. 1.--Logic diagram of the model objectives

Dear Sir:

We are presently engaged in the designing of an air pollution model to be used in conjunction with other environmental models to form an urban systems modeling scheme. Emission inventories for representative cities within the continental United States will provide the control data for this model.

We have an urgent need for Reports for Consultation on the Metropolitan Cities Intrastate Air Quality Control Regions, within your jurisdiction. These reports contain the precise information that is needed for our modeling program.

Any assistance that you might be able to give us in obtaining a copy of these reports will be greatly appreciated.

Sincerely yours,

Fig. 2.--Letter to Air Quality Control Regions

agencies responded, however, the inconsistency of data reporting techniques employed by these agencies rendered the data incomplete and inconclusive. Therefore, an information survey form was prepared and mailed to 100 individual city environmental agencies. This form (Figure 3) requested the following information:

Emissions Data (in tons/unit time)

- Particulates
- Sulfur Oxides
- Nitrogen Oxides
- Carbon monoxide
- Hydrocarbons

Demographic Data

- Land Area (total)
- Zoned: Industrial
  Commercial
  Residential
- Population
- Average Annual income per capita
- Percent of per capita income from manufacturing
- Percent of population employed in manufacturing

Spaces were provided on the form for the data to be entered and returned by mail. Of the forty-five cities responding to the survey only twenty-three cities provided complete

Dear Sir:

We are presently engaged in the designing of an air pollution model to be used in conjunction with other environmental models to form an urban systems modeling scheme.

There is an urgent need for both emissions data and demographic data from selected cities which will provide the control data for this model.

Any assistance that you might be able to give us in obtaining the following data concerning your city will be greatly appreciated.

Emissions Data (in tons/unit time)

Particulates _____

SO_2 _____

NO_x _____

CO _____

Hydrocarbons _____

Demographic Data

Land area (total) _____
Zoned: Industrial _____
Commercial _____
Residential _____

Population _____
Average annual income/capita _____
Percent of/capita income from MFG _____
Percent of Population employed in MFG _____

Fig. 3.--Letter to Environmental Agencies of cities

data in all categories.

In an attempt to verify and further complete the demographic data from those 45 cities responding to the first survey, a survey form was mailed to the Chambers of Commerce of those cities (See Figure 4) of the same format as the previous survey except for the omission of emissions data.

Scatter diagrams were prepared to plot particulate emissions as a function of land area, annual per capita income, population, and percent of the work force employed in manufacturing (Figures 37, 38, 39, and 40 of the Appendix). These plots show that there is no observable linear correlation between emissions and annual per capita income. An erratic, yet obvious, correlation is indicated between emissions and land area, population, and percent of the work force employed in manufacturing.

Valid census data was available for population and percent of the work force employed in manufacturing but it was determined that the number of registered vehicles in the state should be replaced with the number of passenger vehicles registered in the county. Requests were mailed to highway departments of 22 states for which emissions and demographic data was available. All 22 states responded (Table 6).

Emissions were plotted as a function of the number of registered vehicles in the county (Figure 41 of the Appendix) which also indicates an erratic, yet discernable, linear trend.

Gentlemen:

We are presently engaged in the designing of an air pollution model to be used in conjunction with other environmental models to form an urban systems modeling scheme.

There is an urgent need for demographic data from selected cities which will provide the control data for this model.

Any assistance that you might be able to give us in obtaining the following data concerning your city will be greatly appreciated:

Land Area (Total) _____
Zoned: Industrial _____
Commercial _____
Residential _____

Population _____
Annual Average Income per Capita _____
Percent of Wage Income from MFG. _____
Percent of Population Employed in MFG. _____

Fig. 4.--Letter to Chambers of Commerce

TABLE 6

DEMOGRAPHIC DATA FOR CITIES USED IN STATISTICAL ANALYSIS

Nr.	CITY	WF IN MFG $X_1(\%X10^2)$	VEHICLES $X_2(X10^6)$	POPULATION $X_3(X10^6)$	LAND AREA (Mi^2)
1	DALLAS	.238	.704	.844	295
2	SAN ANTONIO	.133	.367	.654	198
3	MEMPHIS	.219	.278	.624	755
4	ST LOUIS	.305	.435	.622	497
5	SEATTLE	.249	.514	.531	213
6	JACKSONVILLE	.130	.252	.529	777
7	DENVER	.178	.273	.515	104
8	KANSAS CITY	.248	.288	.507	316
9	ATLANTA	.198	.287	.497	523
10	NASHVILLE	.277	.204	.448	200
11	PORTLAND	.225	.331	.381	102
12	LOUISVILLE	.348	.336	.689	375
13	TAMPA	.176	.251	.278	1,040
14	SACRAMENTO	.084	.328	.254	94
15	NEW HAVEN	.269	.263	.138	48
16	BALTIMORE	.242	.324	.906	272
17	OKLA. CITY	.148	.251	.369	308
18	PHILADELPHIA	.305	.845	1.950	128
19	PITTSBURGH	.318	.696	1.610	728
20	DETROIT	.370	1.179	1.513	623
21	HOUSTON	.192	.885	1.233	447
22	TOLEDO	.333	.241	.384	184
23	CHATTANOOGA	.411	.110	.119	135

In attempting to plot emissions inventories of the twenty-three base cities as a function of the demographic parameters, it was found that total emissions for some cities were actually representative of the county or air pollution control region. It became apparent that emissions must be expressed as an amount per unit area per unit time in order to standardize the emissions units between various cities. Since emissions were reported in the total tons per year, they need only to be divided by the total land area to unitize them into tons per square mile per year (Table 7).

$$\frac{\text{Emissions (tons/Yr)}}{\text{Land Area (Mi}^2\text{)}} = \text{Emissions (tons/Mi}^2\text{/yr)}$$

Although cities seem to be alike in many ways, they are different in more ways than they are alike. The total population figures for a city of paupers is the same as those for a city of the same size boasting a high percentage of middle income families. A small land-area eastern city may not have the total miles of vehicle travel per year as a sprawling western city even though they have the same number of registered vehicles. These differences in emissions for cities of equal demographic parameters make it difficult to obtain linear plots for a group of cities. However, when several parameters are added together, they tend to balance each other and a more linear plot is obtained.

TABLE 7

EMISSIONS DATA FOR CITIES USED IN STATISTICAL ANALYSIS

Nr.	CITY	EMISSIONS (TONS/Mi² /Yr)X10³ (Y_1)PART	(Y_2)SO	(Y_3)NO	(Y_4)CO	(Y_5)HC
1	DALLAS	.149	.050	.284	3.416	.586
2	SAN ANTONIO	.116	.015	.338	3.131	.601
3	MEMPHIS	.035	.123	.045	.321	.070
4	ST. LOUIS	.064	.072	.080	.759	.201
5	SEATTLE	.085	.070	.413	3.488	.254
6	JACKSONVILLE	.171	.060	.059	.416	.110
7	DENVER	.057	.057	.173	3.240	.413
8	KANSAS CITY	.060	.158	.164	.674	.167
9	ATLANTA	.038	.017	.103	.942	.183
10	NASHVILLE	.130	.110	.220	1.380	.345
11	PORTLAND	.088	.088	.245	2.245	.343
12	LOUISVILLE	.099	.643	.155	1.165	.261
13	TAMPA	.041	.291	.089	.306	.135
14	SACRAMENTO	.117	.333	.394	3.298	.777
15	NEW HAVEN	.063	.458	.167	.542	.083
16	BALTIMORE	.139	.444	.216	1.180	.422
17	OKLA. CITY	.019	.003	.074	.863	.149
18	PHILADELPHIA	.312	1.094	.703	4.688	.781
19	PITTSBURGH	.157	.350	.385	2.005	.243
20	DETROIT	.168	.780	.309	1.754	.483
21	HOUSTON	.053	.062	.279	1.767	.525
22	TOLEDO	.120	.707	.207	1.446	.489
23	CHATTANOOGA	.110	.077	.226	1.168	.200

The 3 parameters of percent of work force employed in manufacturing (X_1), passenger vehicles registered in the county (X_2), and population (X_3) were added together after their means had been normalized to 0.680 which was the mean of the population (Table 8). This was accomplished by adding .437 to each value of percent of work force in manufacturing, and adding .261 to each value of the passenger vehicles registered in the county.

The air pollution emissions (Y_i) of particulates (Y_1), SO_2 (Y_2), CO (Y_3), NO_x (Y_4), and hydrocarbons (Y_5) were plotted on scatter diagrams as a function of the sum of the 3 demographic parameters (ΣX_i). Statistical sample regressions were calculated for these plots and although definite linear progression trends were indicated the data was so widely scattered around the regression line that any prediction made from the data would have such a large margin of error as to render it highly inaccurate (Figures 5, 6, 7, 8, and 9). For calculations see Tables 9, 10, and 11.

In order to make the data display more linear and, therefore, more predictive of city growth it was determined that a data-shift technique might be employed. A method of moving the data points vertically towards the regression line was first investigated. This, of course, was based upon the assumption that the sum of the demographic parameters was precisely typical of the growth characteristics of the cities represented. Upon reflection, it becomes

TABLE 8

DEMOGRAPHIC PARAMETERS NORMALIZATION TO MEAN 0.680

CITY Nr.	BEFORE NORMALIZATION X_1	X_2	X_3	AFTER NORMALIZATION $X_1 + .437$	$X_2 + .261$	ΣX_i
1	.238	.704	.844	.625	.965	2.484
2	.133	.367	.654	.570	.628	1.852
3	.219	.278	.624	.656	.539	1.819
4	.305	.435	.622	.742	.696	2.060
5	.249	.514	.531	.686	.775	1.992
6	.130	.252	.529	.567	.513	1.609
7	.178	.273	.515	.615	.534	1.664
8	.248	.288	.507	.685	.549	1.741
9	.198	.287	.497	.635	.548	1.680
10	.277	.204	.448	.714	.465	1.627
11	.225	.331	.381	.662	.592	1.635
12	.348	.336	.689	.785	.597	2.071
13	.176	.251	.278	.613	.512	1.403
14	.084	.328	.254	.521	.589	1.364
15	.269	.263	.138	.706	.524	1.368
16	.242	.324	.906	.679	.585	2.170
17	.148	.251	.369	.585	.512	1.466
18	.305	.845	1.950	.742	1.106	3.798
19	.318	.696	1.610	.755	.957	3.322
20	.370	1.179	1.513	.807	1.440	3.760
21	.192	.885	1.233	.629	1.146	3.008
22	.333	.241	.384	.770	.520	1.656
23	.411	.110	.119	.948	.371	1.338
$\overline{X_i}$ =	.243	.419	.680	.680	.680	$\overline{\Sigma X_i}$ = 2.039

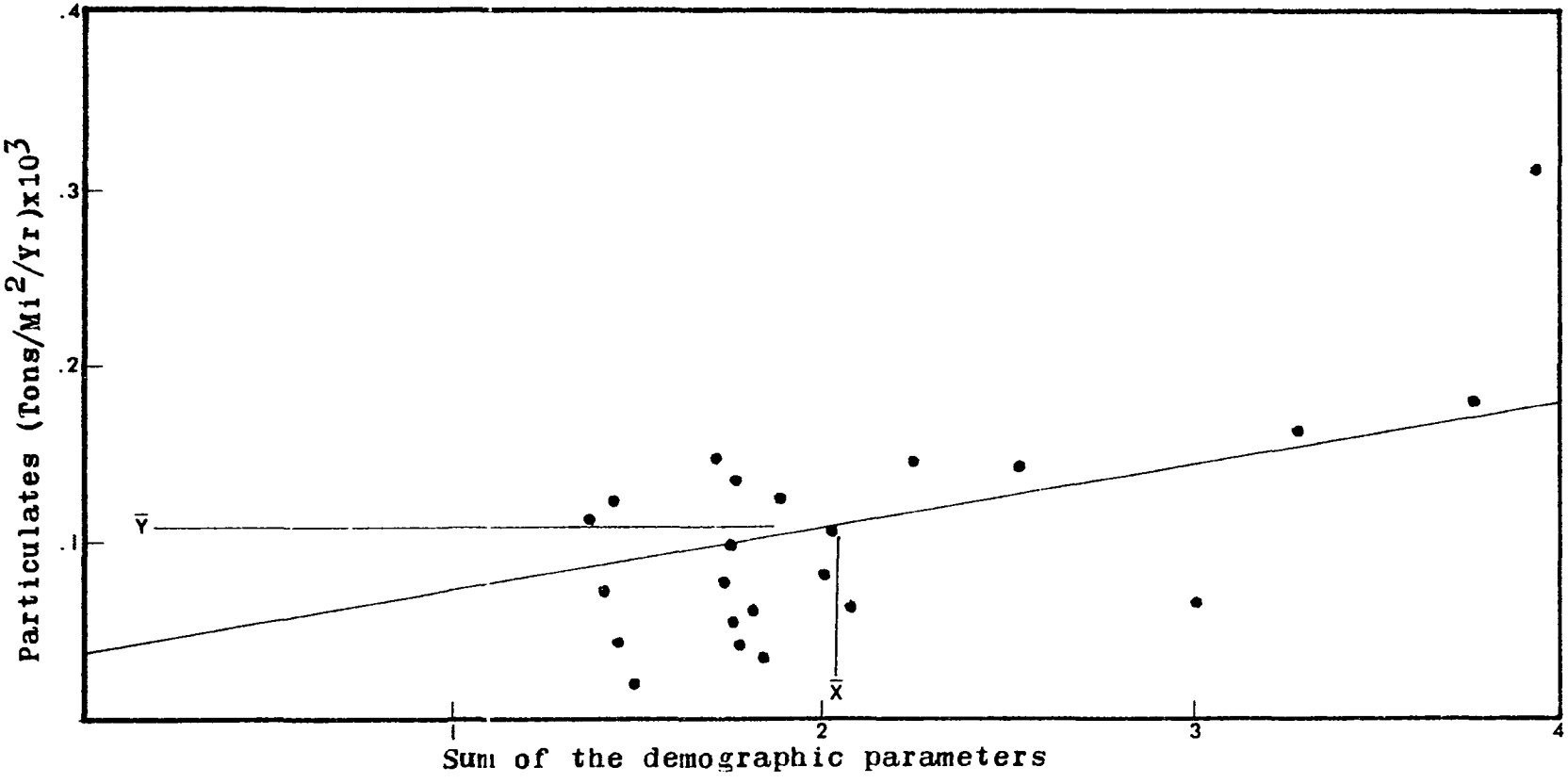

Fig. 5.--Regression of Particulate emissions on the sum of the demographic parameters.

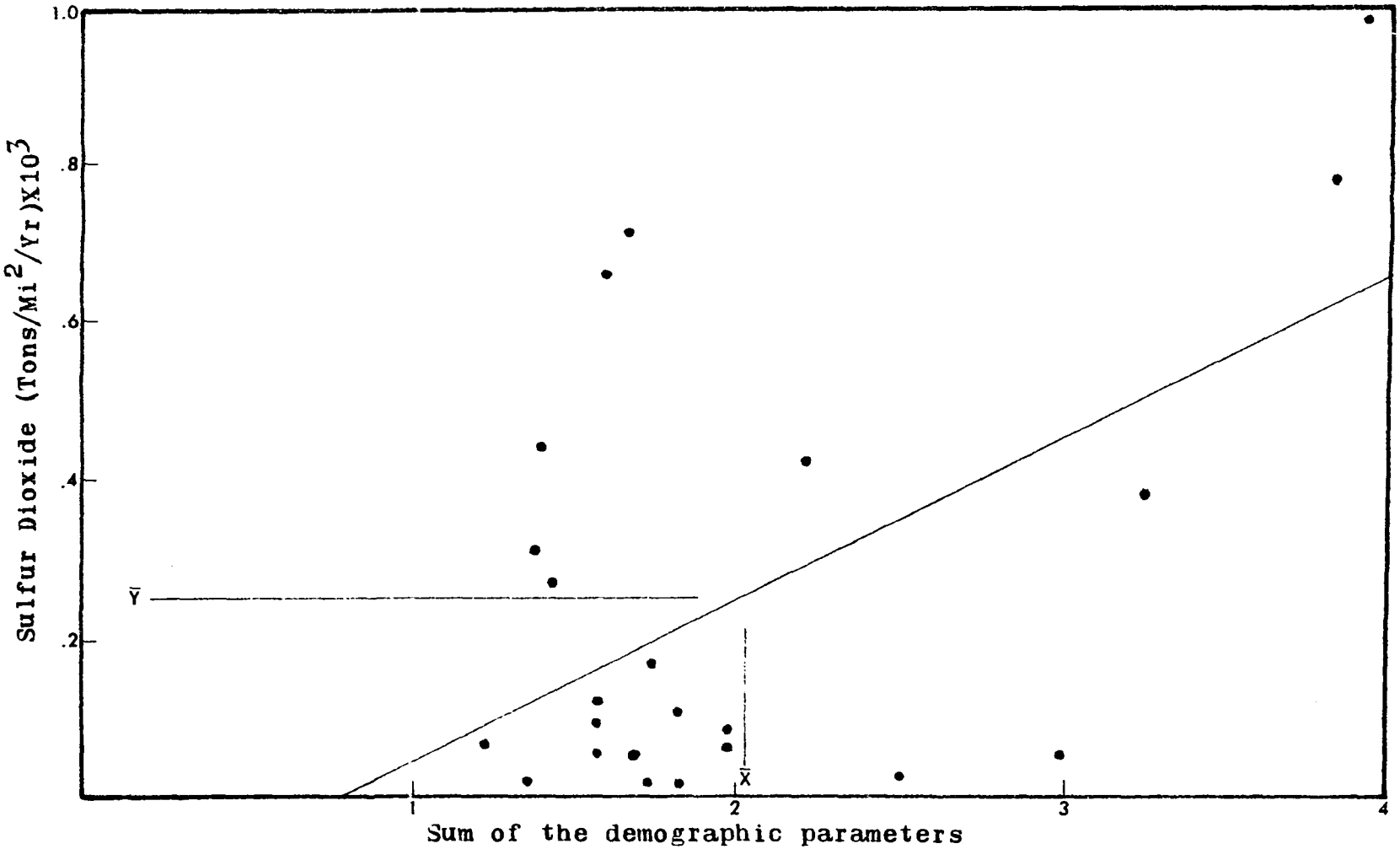

Fig. 6.--Regression of Sulfur Dioxide emissions on the sum of the demographic parameters.

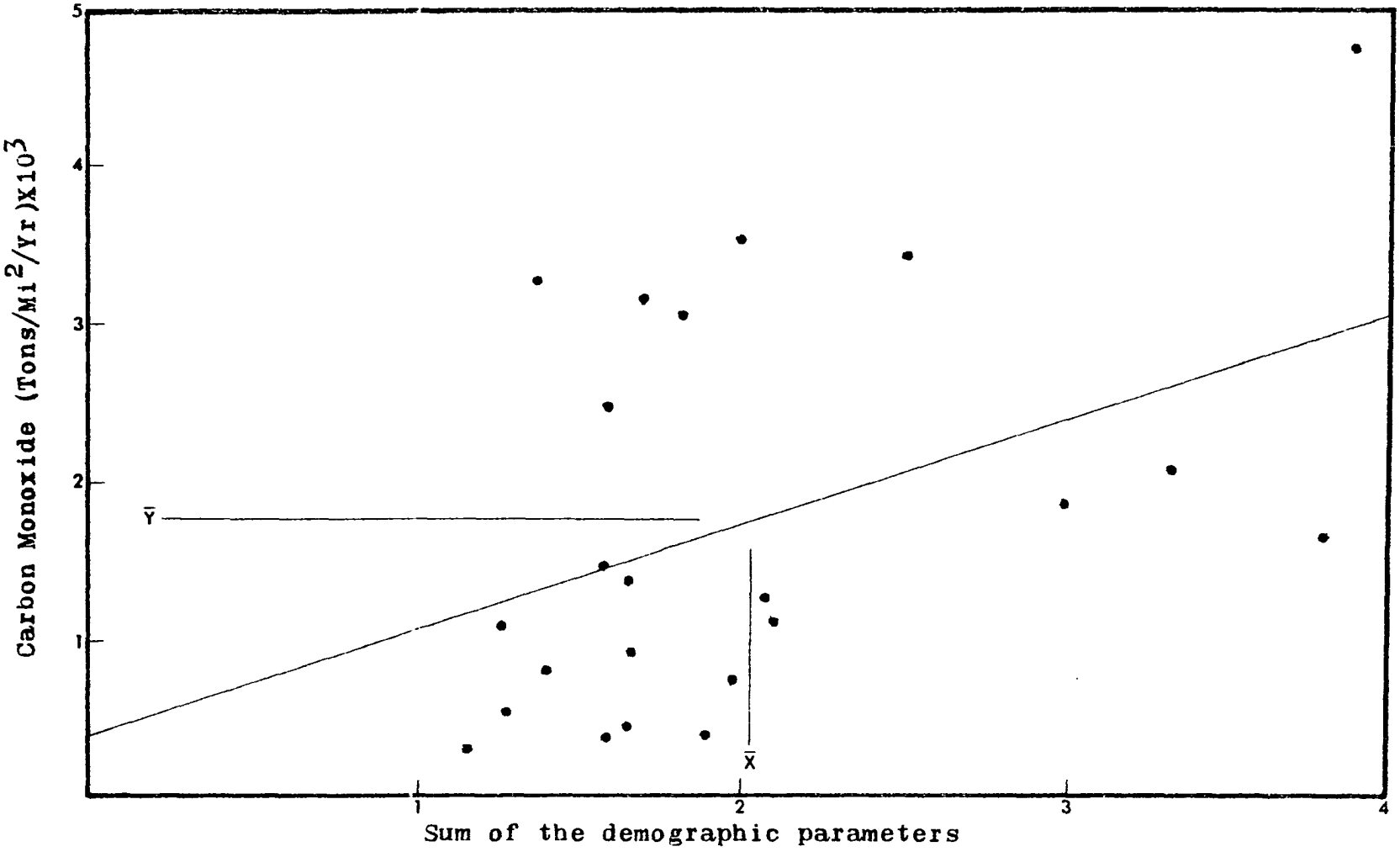

Fig. 7.--Regression of Carbon Monoxide emissions on the sum of the demographic parameters.

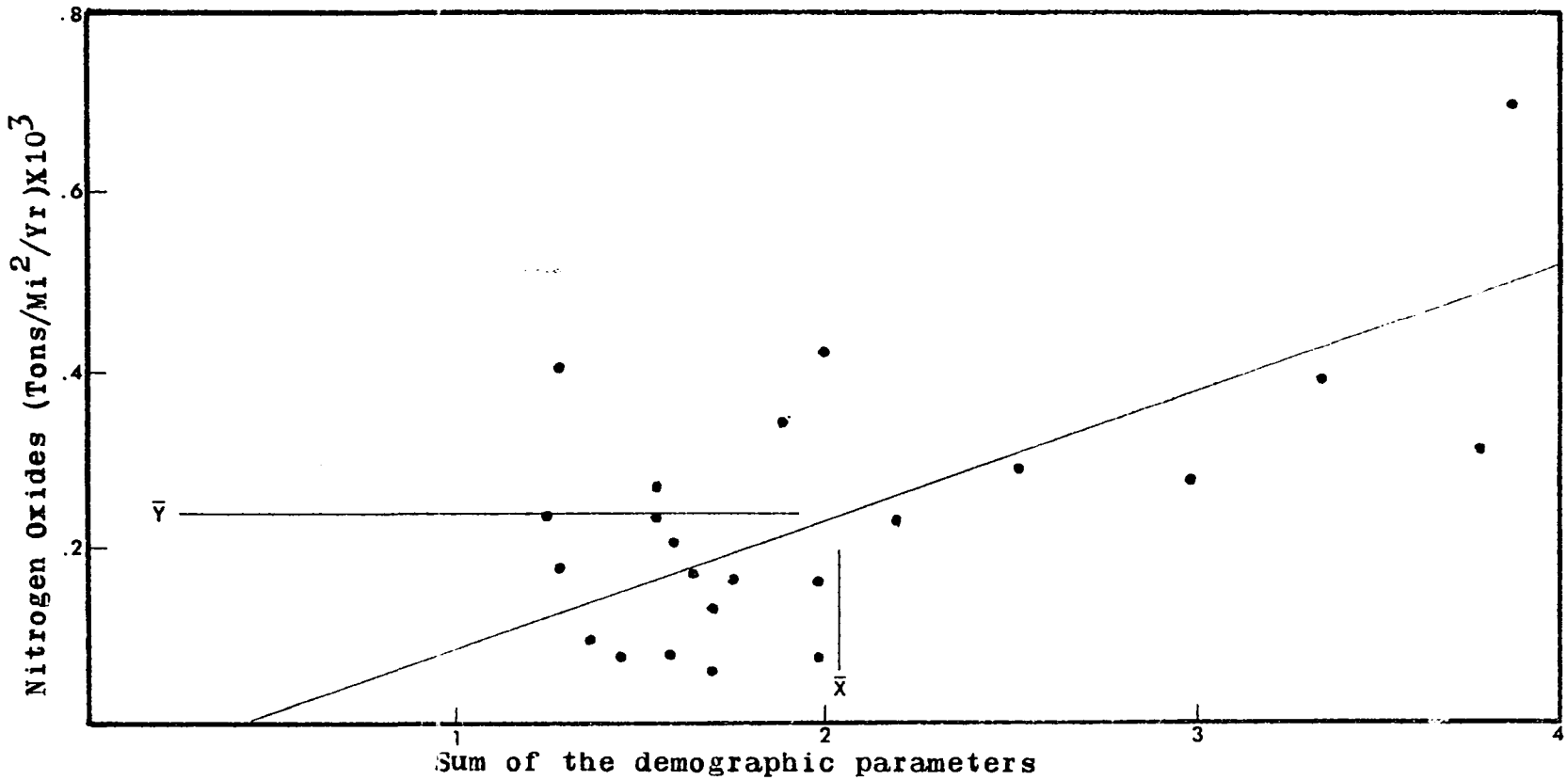

Fig. 8.--Regression of Nitrogen Oxide emissions on the sum of the demographic parameters.

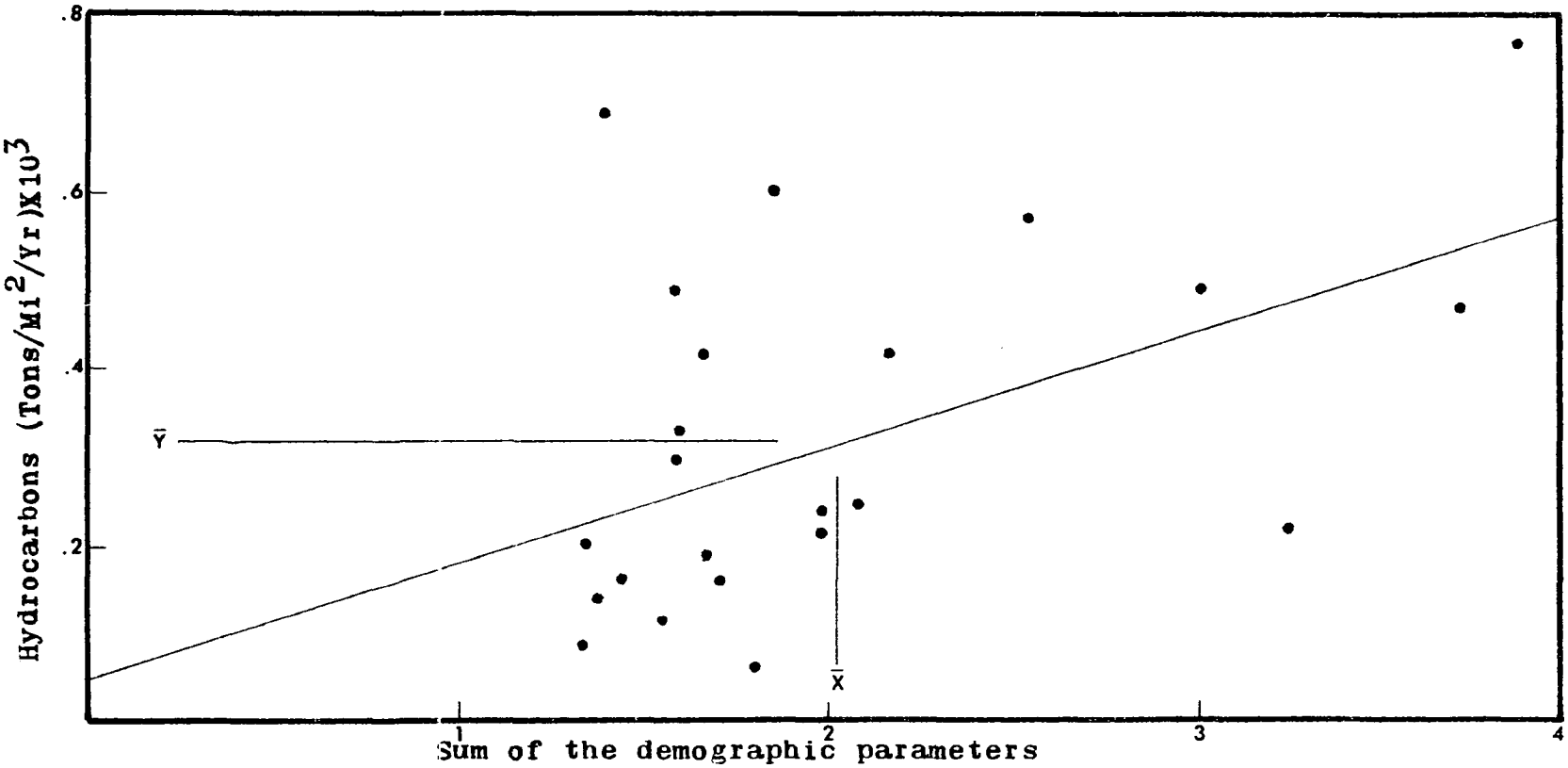

Fig. 9.--Regression of Hydrocarbon emissions on the sum of the demographic parameters.

TABLE 9

REGRESSION CALCULATIONS FOR THE SUM OF THE DEMOGRAPHIC PARAMETERS

CITY Nr.	ΣX_i	$\Sigma X_i - \overline{\Sigma X_i} = x_i$	x_i^2
1	2.484	.445	.1980
2	1.852	.187	.0350
3	1.819	.220	.0484
4	2.060	.021	.0004
5	1.992	.047	.0027
6	1.609	.430	.1849
7	1.664	.375	.1406
8	1.741	.298	.0888
9	1.680	.359	.1289
10	1.627	.412	.1697
11	1.635	.404	.1632
12	2.071	.032	.0010
13	1.403	.636	.4045
14	1.364	.675	.4556
15	1.368	.671	.4502
16	2.170	.131	.0172
17	1.466	.573	.3283
18	3.798	1.759	3.0941
19	3.322	1.283	1.6461
20	3.760	1.721	2.9608
21	3.008	.969	.9390
22	1.656	.383	.1467
23	1.338	.701	.4914
	$\Sigma\Sigma X_i$ = 46.887		Σx_i^2 = 12.0950
	$\overline{\Sigma X_i}$ = 2.039		

TABLE 10

REGRESSION CALCULATIONS FOR EMISSIONS DATA

CITY Nr.	Y_1	$\Sigma X_i Y_1$	Y_2	$\Sigma X_i Y_2$	Y_3	$\Sigma X_i Y_3$	Y_4	$\Sigma X_i Y_4$	Y_5	$\Sigma X_i Y_5$
1	.150	.3726	.050	.1242	3.416	8.485	.284	0.705	.586	1.456
2	.115	.2130	.015	.0278	3.131	5.799	.338	.626	.601	1.113
3	.035	.0637	.125	.2274	.321	.584	.045	.082	.070	.127
4	.065	.1339	.070	.1442	.759	1.564	.080	.165	.201	.414
5	.085	.1693	.070	.1394	3.488	6.948	.413	.823	.254	.506
6	.070	.1126	.060	.0965	.416	.469	.059	.095	.110	.177
7	.055	.0915	.055	.0915	3.240	5.391	.173	.288	.413	.687
8	.060	.1045	.160	.2786	.674	1.173	.164	.286	.167	.291
9	.040	.0672	.015	.0252	.942	1.583	.103	.173	.183	.307
10	.130	.2115	.110	.1790	1.380	2.245	.220	.358	.345	.561
11	.090	.1472	.090	.1472	2.245	3.671	.245	.400	.343	.561
12	.100	.2071	.645	1.3358	1.165	2.413	.155	.321	.261	.541
13	.040	.0561	.290	.4069	.306	.429	.089	.125	.135	.189
14	.115	.1569	.335	.4569	3.298	4.498	.394	.537	.777	1.060
15	.065	.0889	.460	.6293	.542	.741	.167	.228	.083	.114
16	.140	.3038	.445	.9657	1.180	2.561	.216	.469	.422	.916
17	.020	.0293	.005	.0073	.863	1.265	.074	.108	.149	.218
18	.310	1.1774	1.095	4.1588	4.688	17.805	.703	2.670	.781	2.966
19	.155	.5149	.350	1.1627	2.005	6.661	.385	1.279	.243	.807
20	.170	.6392	.780	2.9328	1.754	6.595	.309	1.162	.483	1.816
21	.055	.1654	.060	.1805	1.767	5.315	.279	.839	.525	1.579
22	.120	.1987	.705	1.1675	1.446	2.395	.207	.343	.489	.810
23	.110	.1472	.075	.1004	1.168	1.563	.226	.302	.200	.265
ΣY_i =	2.400		6.065		40.194		5.228		7.721	
$\overline{Y_i}$ =	.104		.264		1.748		.227		.336	
$\Sigma(\Sigma X_i Y_i)$ =		5.2746		14.9856		90.353		12.384		17.484

TABLE 11

REGRESSION ANALYSIS OF EMISSIONS AS A FUNCTION OF THE SUM OF THE DEMOGRAPHIC PARAMETERS

TYPE OF EMISSION	Σxy / $(\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n})$	SLOPE (β) $\frac{\Sigma xv}{\Sigma x}$
PARTICULATES	.3821	.0316
SULFUR DIOXIDE	2.6217	.2168
CARBON MONOXIDE	8.415	.6957
OXIDES OF NITROGEN	1.726	.1427
HYDROCARBONS	1.744	.1440

obvious that there are innumerable characteristics of city growth so that the 3 parameters represented in this analysis could scarcely be expected to be exactly statistically linear. This revelation led to a scrutiny of the representation of the air pollution emissions as a function of city growth. Since it was not necessarily the demographic parameters that must show a linear progression but rather the emissions data, the feasibility of a horizontal data-shift of the demographic parameters was studied. If a constant function could be found to treat all of the data points equally and, likewise, to treat all of the information to be plotted against this regression in the application of the model a more linear regression might be achieved. Such a function was developed (K) so that a different numerical constant for each of the 5 types of pollutants would move the data points to near the regression line. This was accomplished by moving the data points various distances until the most linear configuration was obtained. The statistical linearity of the relationships is not changed appreciably by this treatment but the optical linearity is greatly improved since it drastically narrows the distribution of the data points around the regression line. All of the data points above $\bar{Y}$ (mean of the Y data) are moved to the right and those below $\bar{Y}$ are moved to the left by the formula

$$\Sigma X_i' = \Sigma X_i + K(Y-\bar{Y})$$

where: ΣX_i = sum of the normalized demographic parameters.

$\Sigma X_i'$ = corrected sum of the normalized demographic parameters

For calculations see Tables 12, 13, 14, 15, 16 and the corrected statistical plots are displayed in Figures 10, 11, 12, 13, and 14.

Due to the general prediction capability of the model, a prediction that falls within one standard deviation of the regression line might be considered as useable to anyone applying the model. The statistical technique for calculating standard deviations (σ) utilizes the following formula:

$$\sigma = \sqrt{\frac{(Y - \bar{Y})^2}{n - 1}}$$

Where: σ = standard deviation

$\bar{Y}$ = mean of the Y values

Y = sample value

n = number of samples

To calculate the variance around a regression line which has a constant value change rather than a mean value the Y value of the regression line point representing each data point is substituted for $\bar{Y}$ and is designated as Y'. This results in the standard deviation around the regression line being calculated by

$$\sigma = \sqrt{\frac{(Y - Y')^2}{n - 1}}$$

For the calculations of the statistical variances, see Tables 17, 18, 19, 20, and 21.

TABLE 12

REGRESSION CALCULATIONS OF PARTICULATE EMISSIONS WITH DATA-SHIFT

CITY Nr.	ΣX_i	Y_1	y_1 $(Y_1-\bar{Y}_1)$	$18y_1$	$\Sigma X_i'$	x_1 $(\Sigma X_i'-\bar{\Sigma X_i'})$	x_i^2	$\Sigma X_i' Y_1$
1	2.484	.150	.046	.828	3.312	1.399	1.957	.4968
2	1.852	.115	.011	.198	2.050	.137	.088	.2358
3	1.819	.035	-.069	-1.242	.577	1.336	1.785	.0202
4	2.060	.065	-.039	-.702	1.358	.555	.308	.0883
5	1.992	.085	-.019	-.342	1.650	.263	.069	.1403
6	1.609	.070	-.034	-.612	.997	.916	.839	.0698
7	1.664	.055	-.049	-.882	.782	1.131	1.279	.0430
8	1.741	.060	-.044	-.792	.949	.964	.929	.0569
9	1.680	.040	-.064	-1.152	.528	1.385	1.918	.0211
10	1.627	.130	.026	.468	2.095	.182	.033	.2724
11	1.635	.090	-.014	-.252	1.383	.530	.281	.1245
12	2.071	.100	-.004	-.072	1.999	.086	.077	.1999
13	1.403	.040	-.064	-1.152	.251	1.662	2.762	.0100
14	1.364	.115	.011	.198	1.562	.351	.123	.1796
15	1.368	.065	-.039	-.702	.666	1.247	1.555	.0433
16	2.170	.140	.036	.648	2.818	.905	.819	.3945
17	1.466	.020	-.084	-1.512	-.046	1.867	3.486	.0009
18	3.798	.310	.206	3.708	7.506	5.593	31.282	2.3269
19	3.322	.155	.051	.918	4.240	2.327	5.415	.6572
20	3.760	.170	.066	1.188	4.948	3.035	9.211	.8412
21	3.008	.055	-.049	-.882	.882	1.031	1.063	.0485
22	1.1656	.120	.016	.288	1.944	.031	.001	.2333
23	1.338	.110	.006	.108	1.446	.467	.218	.1591
SUMS =	46.887	2.400			43.989		65.428	6.8290
MEANS =	2.039	.104			1.913			

$$\Sigma x_i y_1 = \Sigma X_i Y_1 - \frac{(\Sigma X_i')(\Sigma Y_1)}{n} = 2.2389$$

$$\text{SLOPE } (\beta) = \frac{\Sigma x_i y_1}{\Sigma x_i^2} = .0342$$

TABLE 13

REGRESSION CALCULATIONS OF SULFUR DIOXIDE EMISSIONS WITH DATA-SHIFT

CITY Nr.	ΣX_i	Y_2	y_2 $(Y_2-\bar{Y}_2)$	$8y_2$	$\Sigma X_i'$	x_1 $(\Sigma X_i'-\overline{\Sigma X_i'})$	x_i^2	$\Sigma X_i' Y_2$
1	2.484	.050	-.214	-1.712	.772	1.394	1.943	.0386
2	1.852	.015	-.249	-1.992	-.140	2.026	4.105	.0021
3	1.819	.125	-.139	-1.112	.707	1.459	2.129	.0884
4	2.060	.070	-.194	-1.552	.508	1.658	2.749	.0356
5	1.992	.070	-.194	-1.552	.440	1.726	2.979	.0308
6	1.609	.060	-.204	-1.632	-.023	2.143	4.592	.0014
7	1.664	.055	-.209	-1.672	-.008	2.158	4.657	.0004
8	1.741	.160	-.104	-.832	.909	1.257	1.580	.1454
9	1.680	.015	-.249	-1.992	-.312	1.854	3.437	.0047
10	1.627	.110	-.154	-1.232	.395	1.771	3.136	.0435
11	1.635	.090	-.174	-1.392	.243	1.923	3.698	.0219
12	2.071	.645	.381	3.048	5.119	2.953	8.720	3.3017
13	1.403	.290	.026	.208	1.611	.555	.380	.4672
14	1.364	.335	.071	.568	1.932	.234	.054	.6472
15	1.368	.460	.196	1.568	2.936	.770	.593	1.3506
16	2.170	.445	.181	1.448	3.618	1.452	2.108	1.6100
17	1.466	.005	-.259	-2.072	-.606	1.560	2.434	.0030
18	3.798	1.095	.831	6.648	10.446	8.280	68.558	11.4384
19	3.322	.350	.086	.688	4.010	1.834	3.366	1.4035
20	3.760	.780	.516	4.128	7.888	5.722	32.741	6.1526
21	3.008	.060	-.204	-1.632	1.376	.790	.624	.0826
22	1.656	.705	.441	3.528	5.184	3.018	9.108	3.6547
23	1.338	.075	-.189	-.712	.626	1.540	2.372	.0469
SUMS =	46.887	6.065			49.818		165.991	30.1507
MEANS=	2.039	.264			2.166			

$$\Sigma x_i y_2 = \Sigma X_i' Y_2 - \frac{(\Sigma X_i')(\Sigma Y_2)}{n} = 17.0139$$

$$\text{SLOPE } (\beta) = \frac{\Sigma x_i y_2}{\Sigma x_i^2} = .1025$$

TABLE 14

REGRESSION CALCULATIONS OF CARBON MONOXIDE EMISSIONS WITH DATA-SHIFT

CITY Nr.	Σx_i	Y_3	y_3 $(Y_3-\bar{Y}_3)$	$1.5y_3$	$\Sigma x_i'$	x_i $(\Sigma x_i'-\bar{\Sigma x_i'})$	x_i^2	$\Sigma x_i' Y_3$
1	2.484	3.416	1.668	2.502	4.986	2.782	7.740	17.032
2	1.852	3.131	1.383	2.075	3.917	1.723	2.969	12.295
3	1.819	.321	-1.427	-2.141	-.322	1.882	3.542	.103
4	2.060	.759	-.989	-1.484	.576	1.628	2.650	.437
5	1.992	3.488	1.740	2.610	4.602	2.398	5.750	16.052
6	1.609	.416	-1.332	-1.998	-.389	1.815	3.294	.162
7	1.664	3.240	1.492	2.238	3.902	1.698	2.883	12.642
8	1.741	.674	-1.074	-1.611	.130	2.074	4.301	.088
9	1.680	.942	-.806	-1.209	.471	1.733	3.003	.444
10	1.627	1.380	-.368	-.552	1.075	1.129	1.275	1.484
11	1.635	2.245	.497	.746	2.381	.177	.031	5.345
12	2.071	1.165	-.583	-.875	1.196	1.008	1.016	1.393
13	1.403	.306	-1.442	-2.163	-.760	1.444	2.085	.233
14	1.364	3.298	1.550	2.325	3.689	1.485	2.205	12.166
15	1.368	.542	-1.206	-1.809	-.441	1.763	3.108	.239
16	2.170	1.180	-.568	-.852	1.318	.886	.785	1.555
17	1.466	.863	-.885	-1.328	.138	2.066	4.268	.119
18	3.798	4.688	2.940	4.410	8.208	6.004	36.048	38.479
19	3.322	2.005	.257	.386	3.708	1.504	2.262	7.435
20	3.760	1.754	.006	.009	3.769	1.565	2.449	6.611
21	3.008	1.767	.019	.029	3.037	.833	.694	5.366
22	1.656	1.446	-.302	-.453	1.203	1.001	1.002	1.740
23	1.338	1.168	-.580	-.870	.468	1.736	3.014	.547
SUMS =	46.887	40.194			50.696		96.374	141.967
MEANS=	2.039	1.748			2.204			

$$\Sigma x_i y_3 = \Sigma x_i' Y_3 - \frac{(\Sigma x_i')(\Sigma Y_3)}{n} = 53.372$$

$$\text{SLOPE } (\beta) = \frac{\Sigma x_i y_3}{\Sigma x_i^2} = .554$$

TABLE 15

REGRESSION CALCULATIONS OF NITROGEN OXIDE EMISSIONS WITH DATA-SHIFT

CITY Nr.	Σx_i	Y_4	y_4 $(Y_4-\bar{Y}_4)$	$7y_4$	$\Sigma x_i'$	x_i $(\Sigma x_i'-\overline{\Sigma x_i'})$	x_i^2	$\Sigma x_i' Y_4$
1	2.484	.284	.257	1.799	4.283	2.181	4.757	1.216
2	1.852	.338	.111	.777	2.629	.527	.278	.889
3	1.819	.045	-.182	-1.274	.545	1.557	2.424	.025
4	2.060	.080	-.147	-1.029	1.031	1.071	1.147	.082
5	1.992	.413	.186	1.302	3.294	1.192	1.421	1.360
6	1.609	.059	-.168	-1.176	.433	1.669	2.786	.026
7	1.664	.173	-.054	-.378	1.286	.816	.666	.222
8	1.741	.164	-.063	-.441	1.300	.802	.643	.213
9	1.680	.103	-.124	-.868	.812	1.290	1.664	.084
10	1.627	.220	-.007	-.049	1.578	.524	.275	.347
11	1.635	.245	.018	.126	1.761	.341	.116	.431
12	2.071	.155	-.072	-.504	1.567	.535	.286	.243
13	1.403	.089	-.138	-.966	.437	1.665	2.772	.039
14	1.364	.394	.167	1.169	2.533	.431	.186	.998
15	1.368	.167	-.060	-.420	.948	1.154	1.332	.064
16	2.170	.216	-.011	-.077	2.093	.009	.000	.452
17	1.466	.074	-.153	-1.071	.375	1.707	2.914	.029
18	3.798	.703	.476	3.332	7.130	5.028	25.281	5.012
19	3.322	.385	.158	.406	3.728	1.626	2.644	1.435
20	3.760	.309	.082	.574	4.334	2.232	4.982	1.339
21	3.008	.279	.052	.364	3.372	1.270	1.613	.941
22	1.656	.207	-.020	-.140	1.516	.586	.344	.314
23	1.338	.226	-.001	-.007	1.331	.771	.594	.301
SUMS =	46.887	5.228			48.336		59.125	17.497
MEANS=	2.039	.227			2.102			

$$\Sigma x_i y_4 = \Sigma x_i' Y_4 - \frac{(\Sigma x_i')(\Sigma Y_4)}{n} = 6.510$$

$$\text{SLOPE } (\beta) = \frac{\Sigma x_i y_4}{\Sigma x_i^2} = .1101$$

TABLE 16

REGRESSION CALCULATIONS OF HYDROCARBON EMISSIONS WITH DATA-SHIFT

CITY Nr.	Σx_i	Y_5	$(Y_5-\bar{Y}_5)$	$6y_5$	$\Sigma x_i'$	$(\Sigma x_i'-\bar{\Sigma x_i'})$	x_i^2	$\Sigma x_i' Y_5$
1	2.484	.586	.250	1.500	3.984	1.908	3.640	2.335
2	1.852	.601	.265	1.590	3.442	1.366	1.866	2.069
3	1.819	.070	-.266	-1.596	.223	1.853	3.434	.016
4	2.060	.201	-.135	-.810	1.250	.826	.682	.251
5	1.992	.254	-.082	-.492	1.500	.576	.332	.381
6	1.609	.110	-.226	-1.356	.253	1.823	3.323	.028
7	1.664	.413	.077	.462	2.126	.050	.003	.878
8	1.741	.167	-.169	-1.014	.727	1.349	1.820	.121
9	1.680	.183	-.153	-.918	.762	1.314	1.727	.139
10	1.627	.345	.009	.054	1.681	.395	.156	.580
11	1.635	.343	.007	.042	1.677	.399	.159	.575
12	2.071	.261	-.075	-.450	1.621	.455	.207	.423
13	1.403	.135	-.201	-1.206	.197	1.879	3.531	.027
14	1.364	.777	.441	2.646	4.010	1.934	3.740	3.116
15	1.368	.083	-.253	-1.518	.150	1.926	3.709	.012
16	2.170	.422	.086	.516	2.686	.610	.372	.257
17	1.466	.149	-.187	-1.122	.344	1.732	3.000	.051
18	3.798	.781	.445	2.670	6.468	4.392	19.290	5.052
19	3.322	.243	-.093	-.558	2.764	.688	.473	.672
20	3.760	.483	.147	.882	4.642	2.566	6.584	2.242
21	3.008	.525	.189	1.134	4.142	2.066	4.268	2.175
22	1.656	.489	.153	.918	2.574	.498	.248	1.259
23	1.338	.200	-.136	-.816	.522	1.554	2.415	.104
SUMS =	46.887	7.721			47.745		64.979	22.763
MEANS=	2.039	.336			2.076			

$$\Sigma x_i y_5 = \Sigma x_i' Y_5 - \frac{(\Sigma x_i')(\Sigma Y_5)}{n} = 6.735$$

$$\text{SLOPE } (\beta) = \frac{\Sigma x_i y_5}{\Sigma x_i^2} = .104$$

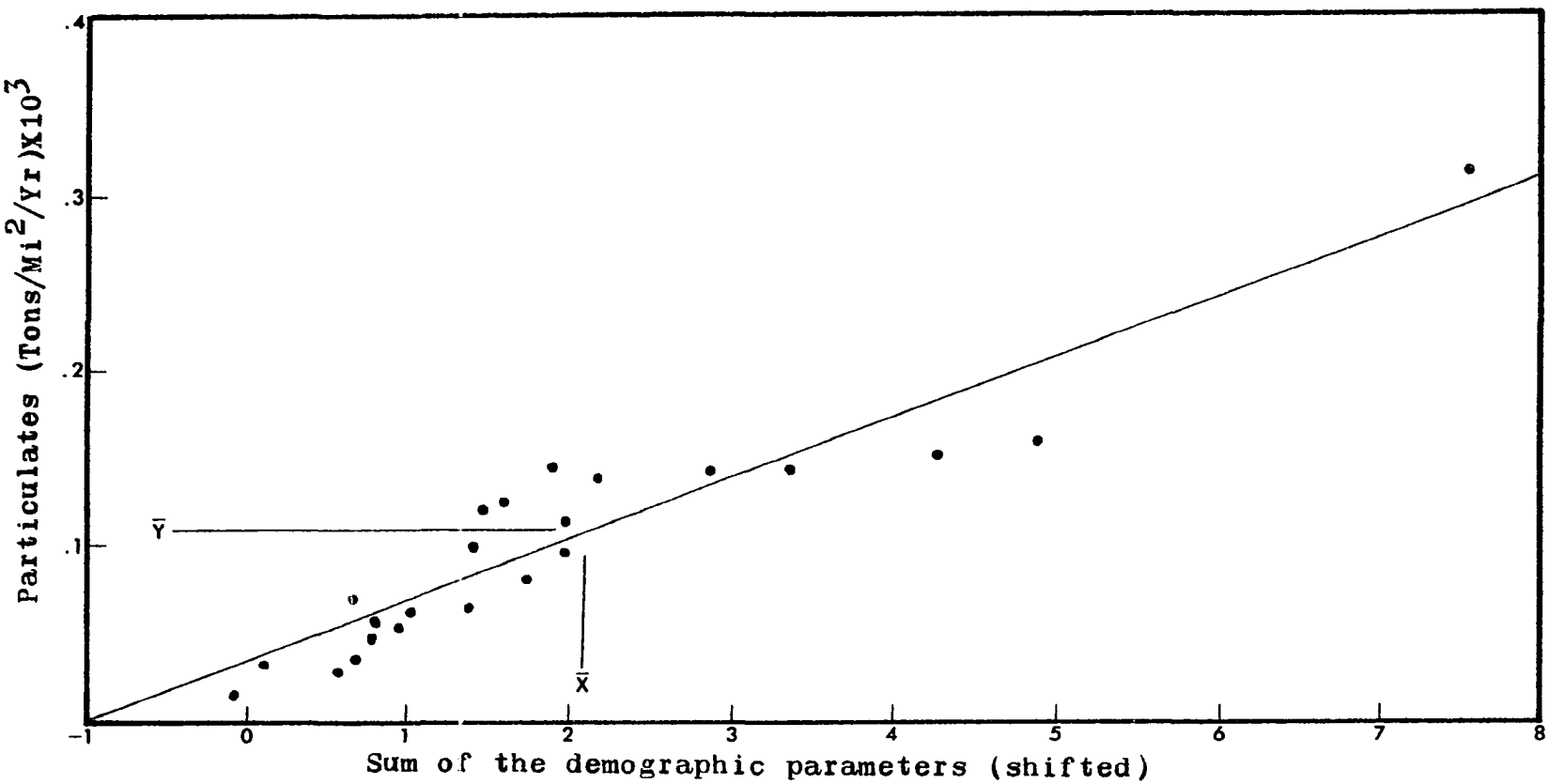

Fig. 10.--Regression of Particulate emissions on the sum of the demographic parameters with Data Shift.

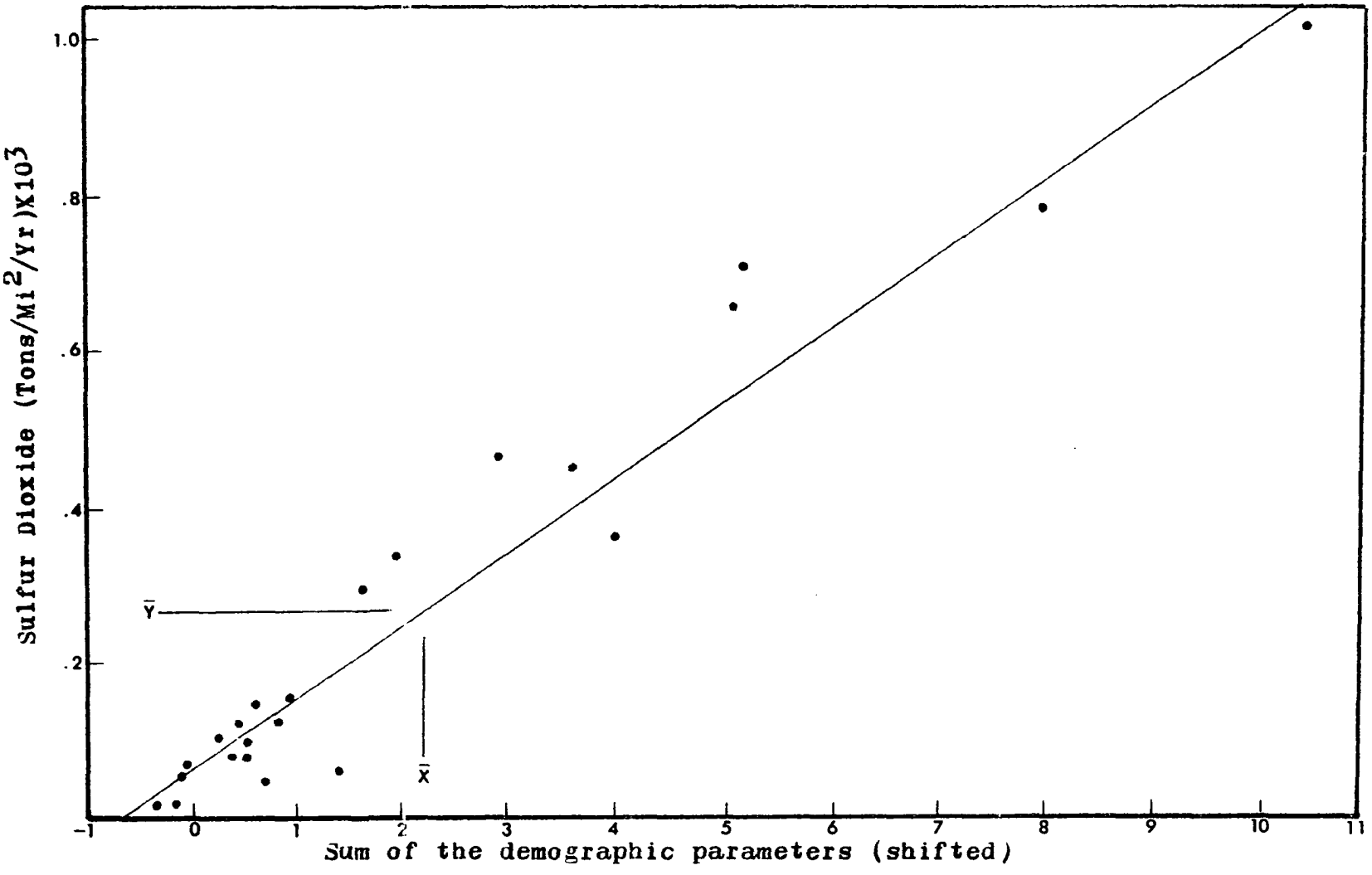

Fig. 11.--Regression of Sulfur Dioxide emissions on the sum of the demographic parameters with Data Shift.

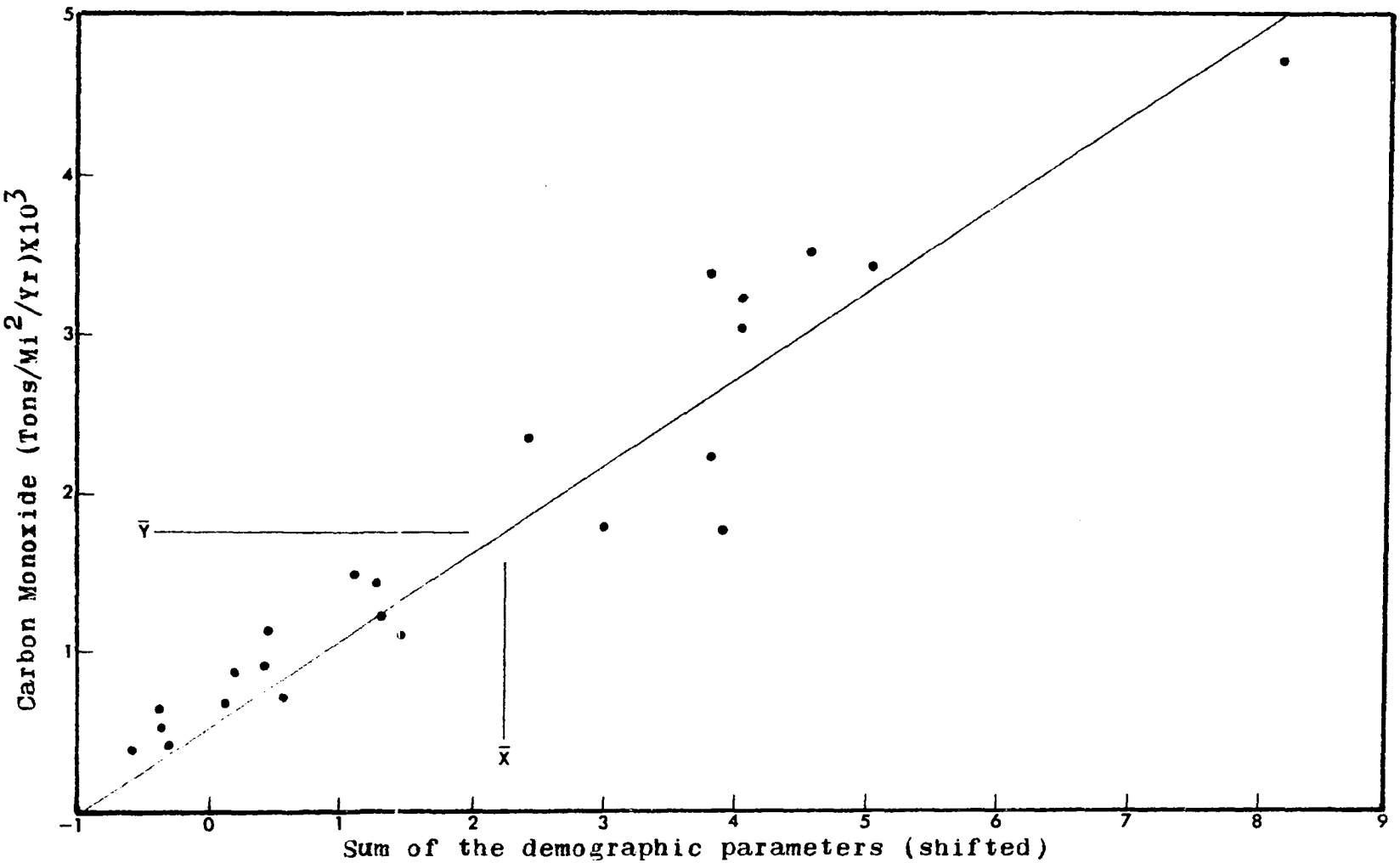

Fig. 12.--Regression of Carbon Monoxide emissions on the sum of the demographic parameters with Data Shift.

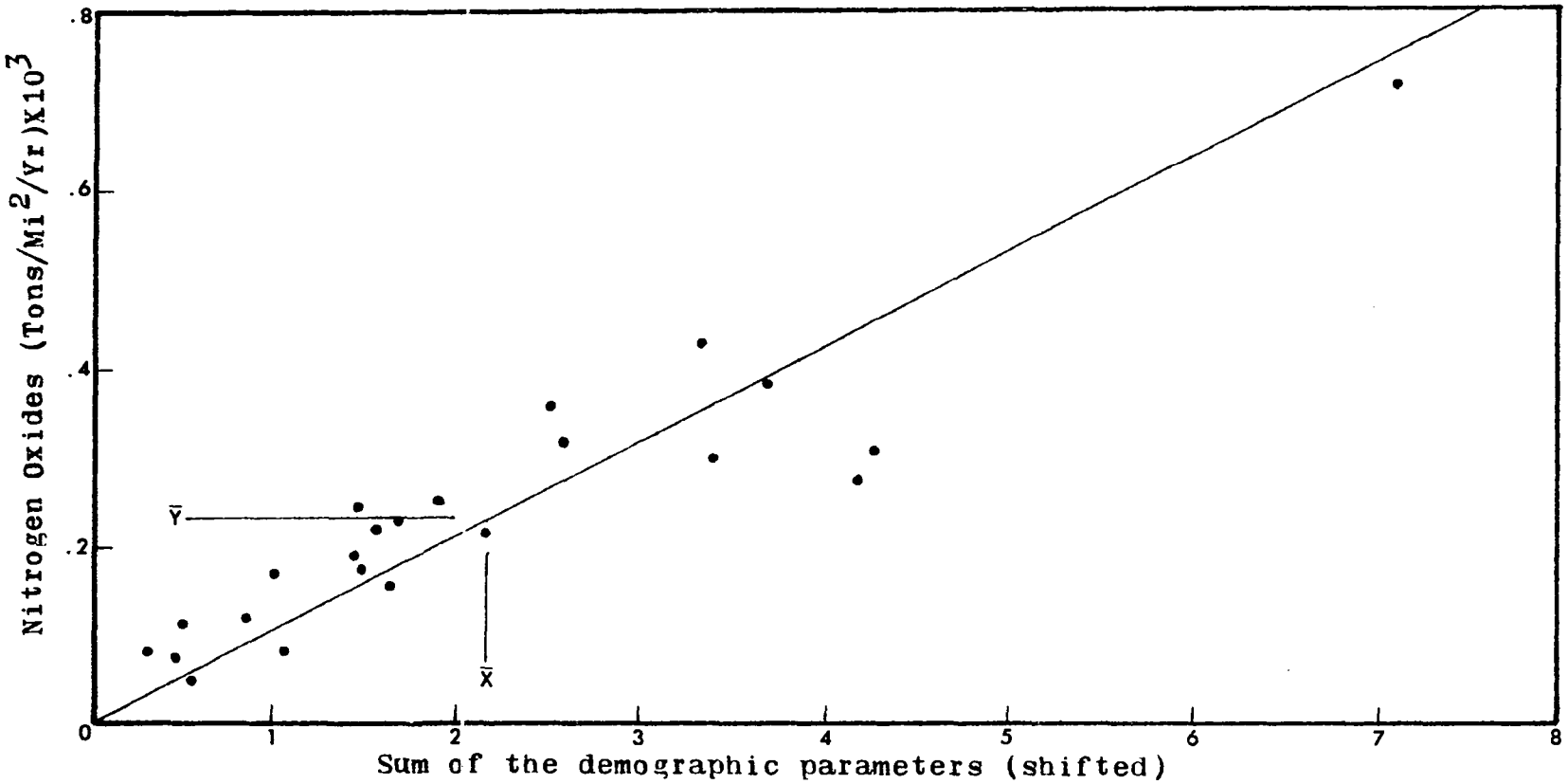

Fig. 13.--Regression of Nitrogen Oxide emissions on the sum of the demographic parameters with Data Shift.

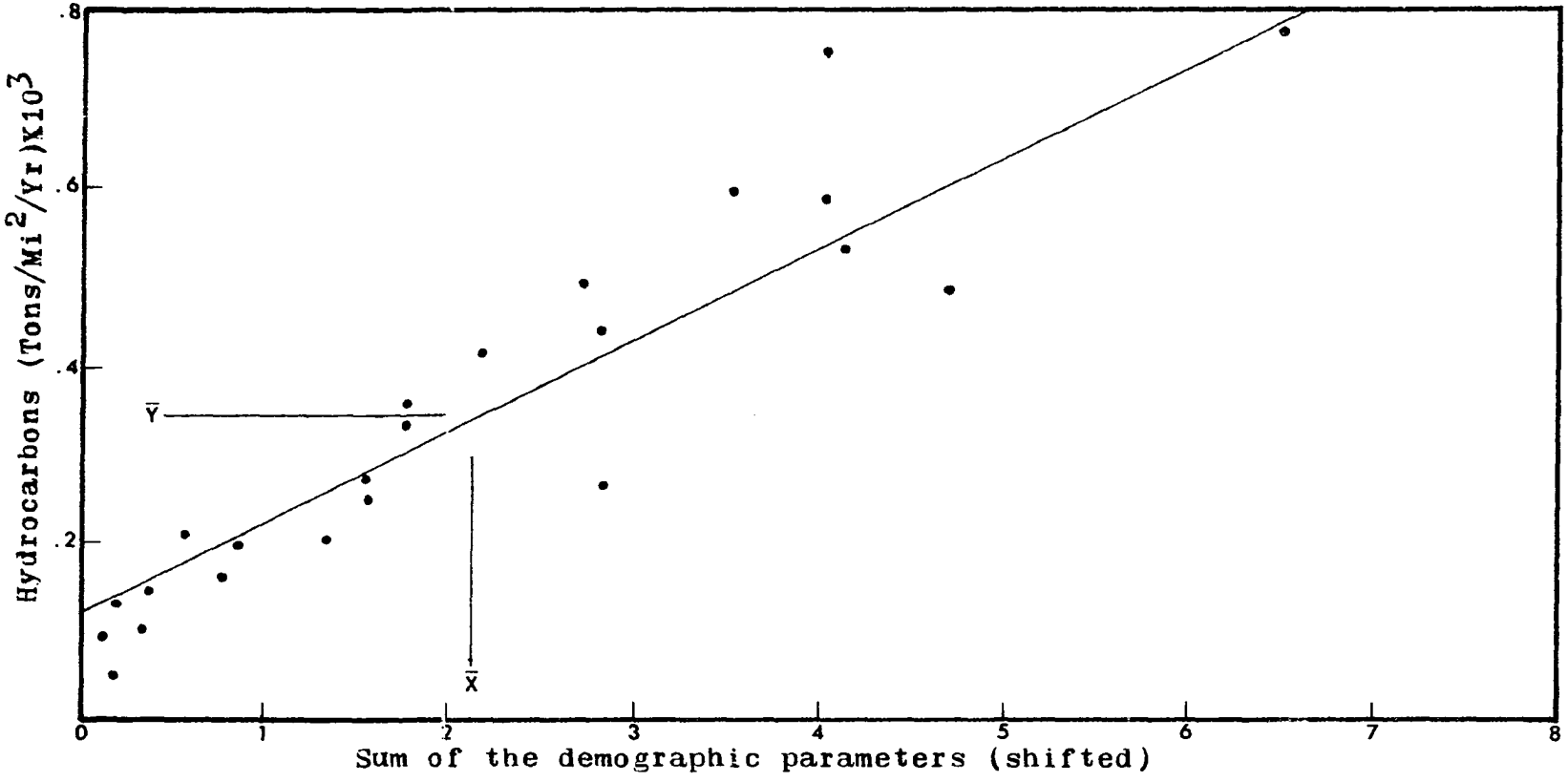

Fig. 14.--Regression of Hydrocarbon emissions on the sum of the demographic parameters with Data Shift.

TABLE 17

VARIANCE DETERMINATION OF DATA-SHIFTED PARTICULATE EMISSIONS

CITY Nr.	X'	.0342(X')	Y'	Y	Y'-Y	$(Y'-Y)^2$
1	3.312	.1132	.1512	.150	.0012	.0000014
2	2.050	.0701	.1081	.115	.0069	.0000476
3	.577	.0197	.0577	.035	.0227	.0005152
4	1.358	.0464	.0844	.065	.0194	.0003763
5	1.650	.0564	.0944	.085	.0094	.0000883
6	.997	.0340	.0720	.070	.0020	.0000040
7	.782	.0267	.0647	.055	.0097	.0000940
8	.949	.0324	.0704	.060	.0104	.0001081
9	.528	.0180	.0560	.040	.0160	.0002560
10	2.095	.0716	.1096	.130	.0204	.0004161
11	1.383	.0472	.0852	.090	.0048	.0000230
12	1.999	.0683	.1063	.100	.0063	.0000396
13	.251	.0085	.0465	.040	.0065	.0000422
14	1.562	.0534	.0914	.115	.0864	.0074649
15	.666	.0227	.0607	.065	.0043	.0000184
16	2.818	.0963	.1343	.140	.0057	.0000324
17	-.046	-.0015	.0365	.020	.0165	.0002722
18	7.506	.2567	.2947	.310	.0153	.0002340
19	4.240	.1450	.1830	.155	.0280	.0007840
20	4.948	.1692	.2072	.170	.0372	.0013838
21	.882	.0301	.0681	.055	.0131	.0001716
22	1.944	.0664	.1044	.120	.0156	.0002433
23	1.446	.0494	.0380	.110	.0720	.0051840

$\alpha = .038$

$\beta = .0342$

$\Sigma(Y'-Y)^2 = .0178004$

$\sigma^2 = \frac{\Sigma(Y'-Y)^2}{n-1} = .000809$

$Y' = \alpha + \beta(X')$

$\sigma = .0284$

TABLE 18

VARIANCE DETERMINATION OF DATA-SHIFTED SULFUR DIOXIDE EMISSIONS

CITY Nr.	X'	.1025(X')	Y'	Y	Y'-Y	$(Y'-Y)^2$
1	.772	.07912	.137	.050	.087	.00757
2	-.140	-.01435	.044	.015	.029	.00084
3	.707	.07246	.130	.125	.015	.00023
4	.508	.05206	.110	.070	.040	.00160
5	.440	.04509	.103	.070	.033	.00109
6	-.023	-.00236	.056	.080	.024	.00058
7	-.008	-.00082	.057	.055	.018	.00032
8	.909	.09316	.151	.160	.029	.00084
9	-.312	-.03198	.026	.015	.011	.00012
10	.395	.04048	.098	.110	.032	.00102
11	.243	.02491	.083	.090	.027	.00073
12	5.119	.52465	.583	.645	.082	.00672
13	1.611	.16511	.223	.290	.087	.00757
14	1.932	.19801	.256	.335	.099	.00980
15	2.936	.30091	.358	.460	.122	.01489
16	3.618	.37081	.428	.445	.037	.00137
17	-.606	-.06211	.024	.005	.019	.00036
18	10.446	1.07061	1.129	1.095	.034	.00116
19	4.010	.41098	.468	.350	.118	.01392
20	7.888	.80844	.866	.780	.086	.00740
21	1.376	.14103	.199	.060	.139	.01932
22	5.184	.53131	.589	.705	.136	.01850
23	.626	.06416	.122	.075	.047	.00221

α = .058

β = .1025

$\Sigma(Y'-Y)^2$ = .118160

$$\sigma^2 = \frac{\Sigma(Y'-Y)^2}{n-1} = .005370$$

$Y' = \alpha + \beta(X')$

σ = .0733

TABLE 19

VARIANCE DETERMINATION OF DATA-SHIFTED CARBON MONOXIDE EMISSIONS

CITY Nr.	X'	.554(X')	Y'	Y	Y'-Y	$(Y'-Y)^2$
1	4.986	2.7622	3.2552	3.416	.161	.02592
2	3.927	2.1755	2.6685	3.131	.462	.21344
3	-.322	-.1783	.3147	.321	.006	.00003
4	.576	.3191	.8121	.759	.053	.00280
5	4.602	2.5495	3.0425	3.488	.445	.19802
6	-.389	-.2155	.2775	.416	.138	.01904
7	3.902	2.1617	2.6547	3.240	.585	.34222
8	.130	.0720	.5650	.674	.109	.01188
9	.471	.2609	.7539	.942	.188	.03534
10	1.075	.5955	1.0885	1.380	.291	.08468
11	2.381	1.3190	1.8120	2.245	.433	.18748
12	1.196	.6625	1.1555	1.165	.009	.00008
13	-.760	-.4210	.0720	.306	.234	.05461
14	3.689	2.0437	2.5367	3.298	.761	.57912
15	-.441	-.2443	.2487	.542	.294	.08643
16	1.318	.7301	1.2231	1.180	.043	.00184
17	.138	.0764	.5694	.863	.294	.08643
18	8.208	4.5472	5.0402	4.688	.352	.12390
19	3.708	2.0542	2.5472	2.005	.542	.29376
20	3.769	2.0880	2.5810	1.754	.827	.68392
21	3.307	1.6824	2.1754	1.767	.408	.16646
22	1.203	.6664	1.1594	1.446	.287	.08236
23	.468	.2592	.7522	1.168	.416	.17305

$\alpha =$ .493

$\beta =$ .554

$\Sigma(Y'-Y)^2 = 3.45001$

$$\sigma^2 = \frac{\Sigma(Y'-Y)^2}{n-1} = .157$$

$Y' = \alpha+\beta(X')$

$\sigma =$ .396

TABLE 20

VARIANCE DETERMINATION OF DATA-SHIFTED NITROGEN OXIDE EMISSIONS

CITY Nr.	X'	.1101(X')	Y'	Y	Y'-Y	$(Y'-Y)^2$
1	4.283	.4715	.4715	.284	.188	.03534
2	2.629	.2894	.2894	.338	.049	.00240
3	.545	.0600	.0600	.045	.015	.00022
4	1.031	.1135	.1135	.080	.033	.00108
5	3.294	.3626	.3626	.413	.050	.00250
6	.433	.0476	.0476	.059	.011	.00012
7	1.286	.1415	.1415	.173	.031	.00096
8	1.300	.1431	.1431	.164	.021	.00044
9	.812	.0894	.0894	.103	.014	.00019
10	1.578	.1737	.1737	.220	.046	.00211
11	1.761	.1938	.1938	.245	.051	.00260
12	1.567	.1725	.1725	.155	.018	.00032
13	.437	.0481	.0481	.089	.041	.00168
14	2.533	.2788	.2788	.394	.115	.01322
15	.948	.1043	.1043	.167	.063	.00396
16	2.093	.2304	.2304	.216	.014	.00019
17	.395	.0434	.0434	.074	.031	.00096
18	7.130	.7850	.7850	.703	.082	.00672
19	3.728	.4104	.4104	.385	.025	.00062
20	4.334	.4771	.4771	.309	.168	.02822
21	3.372	.3712	.3712	.279	.092	.00846
22	1.516	.1669	.1669	.207	.040	.00160
23	1.331	.1465	.1465	.226	.079	.00624

$\alpha = 0.000$

$\beta = .1101$

$\Sigma(Y'-Y)^2 = .12015$

$$\sigma^2 = \frac{\Sigma(Y'-Y)^2}{n-1} = .00547$$

$$Y' = \alpha+\beta(X')$$

$\sigma = .074$

TABLE 21

VARIANCE DETERMINATION OF DATA-SHIFTED HYDROCARBONS EMISSIONS

CITY Nr.	X'	.104(X')	Y'	Y	Y'-Y	$(Y'-Y)^2$
1	3.984	.414	.531	.586	.055	.00302
2	3.442	.358	.475	.601	.126	.01587
3	.223	.023	.140	.070	.070	.00490
4	1.250	.130	.247	.201	.046	.00211
5	1.500	.156	.273	.254	.019	.00036
6	.253	.026	.143	.110	.033	.00108
7	2.126	.221	.338	.413	.075	.00562
8	.727	.076	.193	.167	.026	.00067
9	.762	.079	.196	.183	.013	.00016
10	1.681	.175	.292	.345	.053	.00280
11	1.677	.174	.291	.343	.052	.00270
12	1.621	.169	.286	.261	.025	.00063
13	.197	.020	.137	.135	.002	.00000
14	4.010	.417	.534	.777	.243	.05904
15	-.150	-.016	.101	.083	.018	.00032
16	2.686	.279	.396	.422	.026	.00067
17	.344	.036	.153	.149	.004	.00001
18	6.468	.673	.790	.781	.009	.00008
19	2.764	.287	.404	.243	.161	.02592
20	4.642	.483	.600	.483	.117	.01368
21	4.142	.431	.548	.525	.023	.00052
22	2.574	.268	.385	.489	.104	.01081
23	.522	.054	.171	.200	.029	.00084
α = .117						
β = .104					$\Sigma(Y'-Y)^2$	.15181

$$\sigma^2 = \frac{\Sigma(Y'-Y)^2}{n-1} = .0069$$

$$Y' = \alpha+\beta(X')$$

$$\sigma = .083$$

Emissions Prediction

Emissions are predicted in tons/Mi^2/yr by comparing the sum of the demographic parameters of the subject city with the emissions from a city of like characteristics in the statistical data base. However, the data base has been subjected to a data-shift which requires that the subject city parameters must also be subjected to this same data-shift.

The technique for locating a point on a linear regression line (Y') is to add to the value of the origin of the line (α) the product of the slope of the line (β) and the number of units to the right of the origin on the X axis that the point is located. This formula is

$$Y' = \alpha + \beta(X) \qquad 1$$

Since X in this particular case is actually the sum of three normalized parameters, ΣX_i is substituted for X in formula 1 resulting in

$$Y' = \alpha + \beta(\Sigma X_i) \qquad 2$$

and, since the base data has been subjected to a data-shift, formula 2 becomes

$$Y' = \alpha + \beta(\Sigma X_i') \qquad 3$$

however, the data-shifted sum of the parameters ($\Sigma X_i'$) is equal to the sum of the original sum of the parameters (ΣX_i) and the product of a constant (K) and the difference between Y and the mean of Y ($\bar{Y}$) as

$$\Sigma X_i' = \Sigma X_i + K\,(Y - \bar{Y}) \qquad 4$$

When this data-shifting equality is substituted for $\Sigma X_i'$ in formula 3, it becomes

$$Y' = \alpha + \beta[\Sigma X_i + K(Y - \bar{Y})] \qquad 5$$

The Y in the above formula is not a constant value, but is a variable that changes with each point on the regression line so that it becomes

$$Y = \alpha + \beta(\Sigma X_i) \qquad 6$$

When this equality is substituted for the Y value in formula 5, it becomes

$$Y' = \alpha + \beta[\Sigma X_i + K(\alpha + \beta\Sigma X_i - \bar{Y})] \qquad 7$$

The mean of the sum of the emissions values ($\bar{Y}$) were calculated statistically for each of the 5 types of pollutants. These calculations are presented in Table 10 and were found to be

$\bar{Y}$ = .104 for particulates

$\bar{Y}$ = .264 for sulfur dioxide

$\bar{Y}$ = 1.748 for carbon monoxide

$\bar{Y}$ = .227 for nitrogen oxides

$\bar{Y}$ = .336 for hydrocarbons

The slope of the regression lines (β) for each of the 5 types of pollutants was calculated by the formula

$$\beta = \frac{\Sigma xy}{\Sigma x^2}$$

Where: $x = X - \bar{X}$

$y = Y - \bar{Y}$

The calculations for the β values are presented in Tables 12, 13, 14, 15, and 16 and were found to be

$\beta =$ .0342 for particulates

$\beta =$ .1025 for sulfur dioxide

$\beta =$ .5540 for carbon monoxide

$\beta =$ .1101 for nitrogen oxides

$\beta =$ .1040 for hydrocarbons

The constants (K) for each of the 5 types of pollutants are

K = 18 for particulates

K = 8 for sulfur dioxide

K = 1.5 for carbon monoxide

K = 7 for nitrogen oxides

K = 6 for hydrocarbons

The value of the origin of the regression line at the point where the $\Sigma X_i'$ is equal to zero is designated as a. The values for a for each of the 5 types of pollutants were calculated by the formula

$$a = \bar{Y} - \beta(\overline{\Sigma X_i'})$$

Where: a = Y value at $\Sigma X_{i0}'$

$\bar{Y}$ = mean of the Y values

$\overline{\Sigma X_i'}$ = mean of the sum of the X values

The a values were found to be

$a =$ .038 for particulates

$a =$ .058 for sulfur dioxide

$a =$ .493 for carbon monoxide

$a =$ .000 for nitrogen oxides

$a =$ .117 for hydrocarbons

When the empirically derived values for α, β, $\bar{Y}$, and K are substituted in formula 7, the emissions prediction formulae become

$$Y'_{PA} = \left| .038 + .0342\left[\Sigma X_i + 18(.038 + .0342\,\Sigma X_i - .104)\right] \right| x10^3$$

$$Y'_{SO} = \left| .058 + .1025\left[\Sigma X_i + 8(.058 + .1025\,\Sigma X_i - .264)\right] \right| x10^3$$

$$Y'_{CO} = \left| .493 + .5540\left[\Sigma X_i + 1.5(.493 + .5540\,\Sigma X_i - 1.748)\right] \right| x10^3$$

$$Y'_{NO} = \left| .000 + .1101\left[\Sigma X_i + 7(.000 + .1101\,\Sigma X_i - .227)\right] \right| x10^3$$

$$Y'_{HC} = \left| .117 + .1040\left[\Sigma X_i + 6(.117 + .1040\,\Sigma X_i - .336)\right] \right| x10^3$$

The accuracy of the prediction formulas can be increased if the results of a current emissions inventory (Y_M) are substituted for the Y factor equalities in formula 6. In effect, this substitution establishes a regression line parallel to the base-data regression but typical of the growth of the subject city. When this Measured Emissions Regression Correction is substituted in the emission prediction formulas they become

$$Y'_{PA} = \left| .038 + .0342\left[\Sigma X_i + 18(Y_{MPA} - .104)\right] \right| x10^3$$

$$Y'_{SO} = \left| .058 + .1025\left[\Sigma X_i + 8(Y_{MSO} - .264)\right] \right| x10^3$$

$$Y'_{CO} = \left| .493 + .5540\left[\Sigma X_i + 1.5(Y_{MCO} - 1.748)\right] \right| x10^3$$

$$Y'_{NO} = \left| .000 + .1101\left[\Sigma X_i + 7(Y_{MNO} - .227)\right] \right| x10^3$$

$$Y'_{HC} = \left| .117 + .1040\left[\Sigma X_i + 6(Y_{MHC} - .336)\right] \right| x10^3$$

Where:

Y_{MPA} = Measured PARTICULATE EMISSIONS IN TONS/Mi^2/YR $X10^{-3}$

Y_{MSO} = Measured SULFUR DIOXIDE EMISSIONS IN TONS/Mi^2/YR $X10^{-3}$

Y_{MCO} = Measured CARBON DIOXIDE EMISSIONS IN TONS/Mi^2/YR $X10^{-3}$

Y_{MNO} = Measured NITROGEN OXIDE EMISSIONS IN TONS/Mi^2/YR $X10^{-3}$

Y_{MHC} = Measured HYDROCARBON EMISSIONS IN TONS/Mi^2/YR $X10^{-3}$

The Air Quality Act of 1967 (Public Law 90-148) established a requirement for the reduction of smog producing air pollutant emissions from new "light duty vehicles and engines" to become effective during 1975 - 1976. Vehicles manufactured during or after model year 1975 are required to reduce the emissions of carbon monoxide and hydrocarbons by 90 percent of these emissions allowed for light duty vehicles and engines for model year 1970. Vehicles manufactured during or after model year 1976 are required to reduce the emissions of oxides of nitrogen by 90 percent of these emissions actually measured from light duty vehicles of model year 1971.

Under the assumption that the automobile manufacturers will develop an engine that will meet the requirements of the Air Quality Act by 1975 - 1976 and that the sales of new automobiles will remain substantially constant, a step-function has been developed to predict these emissions reductions. A percent per year of reduction of carbon monoxide, hydrocarbons, and nitrogen oxides is calculated and is applied for a total of ten years which is the period

required to replace effectively all of the light duty vehicles in use. This percent per year reduction is calculated by

$$\text{Percent/year Reduction} = P_1 \times P_2 \times P_3 \times P_4$$

Where: P_1 = percent of total light duty vehicles which are new each year

P_2 = percent of vehicles which are light duty

P_3 = percent of total emissions produced by mobile sources

P_4 = percent of emissions reductions required by law

The percent of total emissions produced by mobile sources was calculated from the nationwide emissions for 1968 in millions of tons per year published in the Compilation of Air Pollutant Emission Factors (AP-42, 1972) which are presented in Table 22.

The percent of vehicles which are light duty was calculated from a listing of light duty vehicles and trucks in use by age: 1955 to 1970 (Statistical Abstract, 1971). Table 23 shows that 82% of the total vehicles in use in 1970 were light duty. Table 23 also shows that effectively all of the motor vehicles in the United States in 1970 were 12 years old or younger which would indicate that an average of approximately 10% of the vehicles are new each year.

The Air Quality Act of 1967 requires that light duty vehicle emissions be reduced by 90% which completes the data needed to calculate the vehicle emissions reduction. These data are summarized in Table 24.

TABLE 22.

NATIONWIDE EMISSIONS FOR 1968
(MILLIONS OF TONS PER YEAR)

SOURCE	CO	HYDROCARBONS	NO_x
Stationary Combustion	1.9	0.7	10.0
Solid Waste Disposal	7.8	1.6	0.6
Mobile Combustion	63.8	16.6	8.1
Industrial Process	9.7	4.6	0.2
Miscellaneous	16.9	8.5	1.7
TOTAL	100.1	32.0	20.6
Percentage of Emissions from Mobile Sources	**63.7**	**51.9**	**39.3**

TABLE 23

LIGHT DUTY VEHICLES AND TRUCKS IN USE, BY AGE: 1955 TO 1970

AGE (Light Duty Vehicles)	1955 NUMBER (x1000)	1960 NUMBER (x1000)	1965 NUMBER (x1000)	1969 NUMBER (x1000)	1970 NUMBER (x1000)
Under 3 years	14,448	14,186	21,578	23,449	24,403
3 - 5 years	15,164	18,346	18,013	25,185	24,923
6 - 8 years	10,146	12,380	13,571	16,720	18,441
9 - 11 years	7,365	9,199	9,862	7,365	7,735
12 years and over		2,825	5,911	5,727	4,925
Total Light Duty Vehicles	47,123	56,935	68,935	78,445	80,427
Total, all Vehicles	56,234	67,706	82,041	94,018	98,099

(Statistical Abstract, 1971)

TABLE 24.

PERCENTAGE VALUES USED IN CALCULATING THE PERCENT PER YEAR REDUCTION OF AUTOMOBILE EMISSIONS

POLLUTANT	MOBILE COMBUSTION %	AUTOMOBILES % OF TOTAL	NEW AUTOS EACH YR %	REDUCTION OF EMISSIONS %
Carbon monoxide	63.7	82.0	10.0	90.0
Hydrocarbons	51.7	82.0	10.0	90.0
Nitrogen oxides	39.3	82.0	10.0	90.0

The percent per year reduction of emissions from mobile sources were calculated as follows:

Carbon Monoxide

$$10.0 \times 82.0 \times 63.7 \times 90.0 = 4.7\%$$

Hydrocarbons

$$10.0 \times 82.0 \times 51.9 \times 90.0 = 3.8\%$$

Nitrogen Oxides

$$10.0 \times 82.0 \times 39.3 \times 90.0 = 2.9\%$$

The step-functions for predicting the decrease in mobile source emissions provide for the percentage of reduction per year times the number of years past 1975 - 1976 for which the model is being run. The number of years is only to a maximum of 10 years at which time effectively all light duty vehicles should provide the controls required by law.

The formulas in the model are in the form:

$$Y'_{CO} - 4.7\% \sum_{N=1}^{10} n = \text{decrease in vehicle emissions}$$

Where: $n = i-I$

$I = 1974$

$i = 1975,\ldots,1984$

Concentration Prediction

The concentration of air pollution over a city is dependent upon many factors, only one of which is the amount of pollutants emitted to its atmosphere. Concentra-

tions immediately downwind from major sources of pollution are normally higher than the upwind or far-downwind concentrations. Many dispersion models have been developed which predict this variety of concentrations for a city with specific emission, topographical, and meteorological characterisitcs. These models, however, have their highest degree of accuracy and validity in predicting current or near-future conditions. The model described in this paper is designed to predict air pollution conditions up to thirty years or more in the future. Since the exact location of emission sources this far in the future is unknown, in most instances the model confines itself to predicting average concentrations over a geopolitical region of interest. In order to facilitate the ease of operation of the model, ether assumptions were also made.

Since the time of day when the least amount of atmospheric circulation takes place in most cities is early morning, it was assumed that this is the time when the ambient air quality standards are most likely to be exceeded. So this model predicts those concentrations which should exist during the first few hours after sunrise.

It is also assumed that the worst possible conditions for pollution can exist during any portion of the year, so no seasonal variations are calculated.

The average early morning concentrations of air pollutants are calculated by dispersing the predicted emis-

sions over the city according to a meteorological technique developed by George C. Holzworth (1971). Holzworth calculated the average early morning dispersion characteristics for various areas of the United States and expressed them as retention zones. For each retention zone, retention factors were assigned which describe the amount of time that emitted pollutants can be expected to remain over cities of various diameters. These retention factors are expressed in seconds per meter so that when they are multiplied by the emission in grams per square meter per second the resultant concentration will be in grams per cubic meter which is the standard unit in current use to describe concentrations.

Holzworth (1971) expressed these retention factors as:

$$RF = \frac{\bar{X}}{\bar{Q}}$$

Where:

RF = Retention Factor in sec. m^{-1}

$\bar{X}$ = average pollutant concentration over the city in gms/m^3

$\bar{Q}$ = uniform area emission rate in $gms/m^2/sec$

Figure 15 shows Holzworth's isopleths of average normalized concentration, or $\bar{X}/\bar{Q}$, values for city diameters of 10 Km (dashed isopleths) and 100 Km (solid isopleths). Holzworth found that the variation on $\bar{X}/\bar{Q}$ values with city

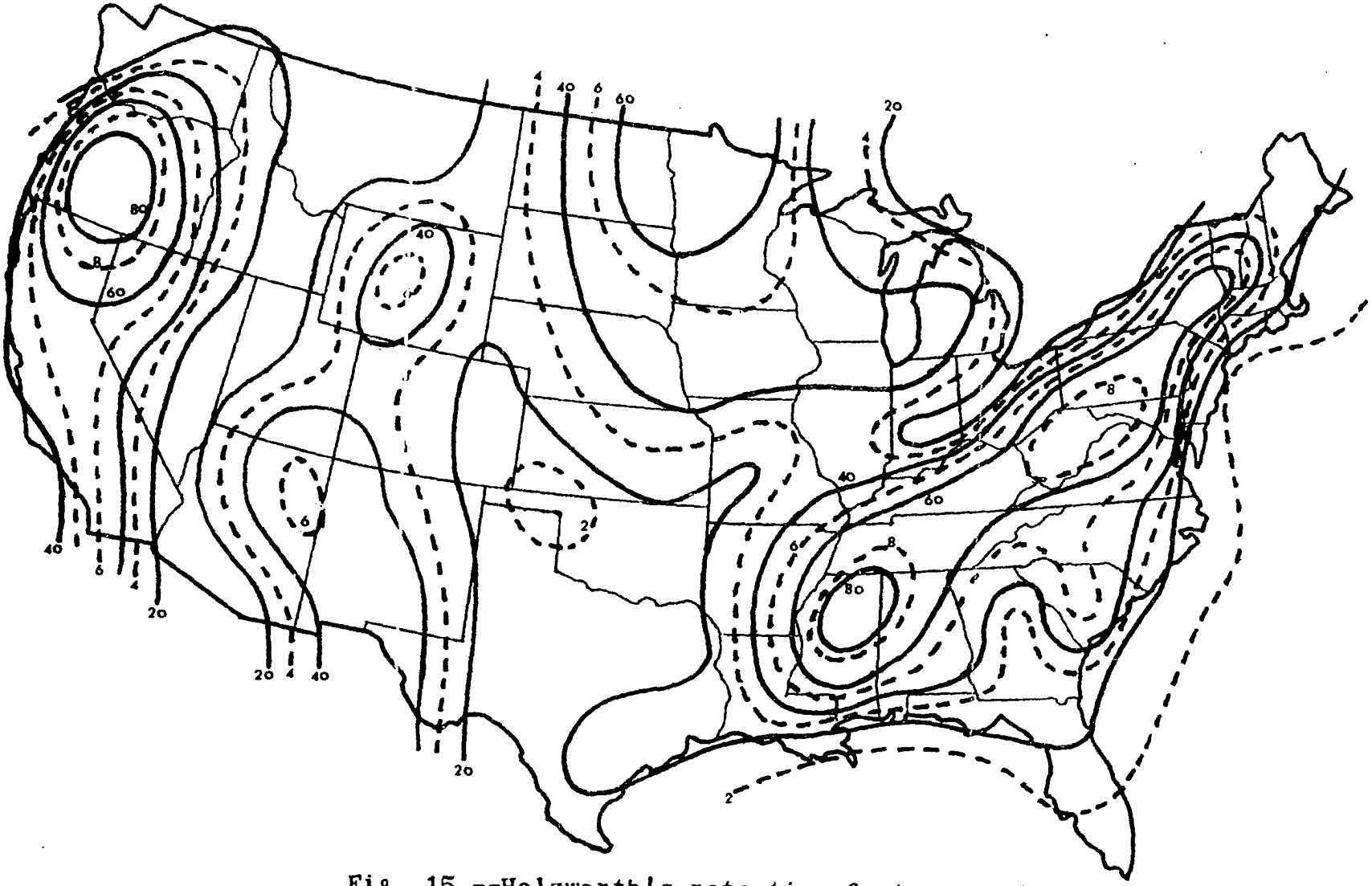

Fig. 15.--Holzworth's retention factors. Solid isopleths for 100 Km cities(sec $M^{-1}X10^{-1}$), dashed isopleths for 10 Km cities(sec $M^{-1}X10^{-1}$).

sizes between 10 and 100 Km is practically linear. Since this linearity exists, it was more expedient in this model to designate retention factor areas for cities of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 Km in diameter. This was accomplished by dividing the area between the 10 Km and the 100 Km isopleths into nine equal area plots and assigning a scaled retention factor to each of these areas.

To use the retention factors, it is necessary that the land area of the city being modeled be converted into a diameter in kilometers according to the following table of equivalents:

Land Area (Mi^2)	Diameter (Km)
0 - 60	10
70 - 184	20
185 - 254	30
255 - 579	40
580 - 859	50
860 - 1199	60
1200 - 1599	70
1600 - 2049	80
2050 - 2559	90
2560 - 3100	100

After the proper city diameter is determined, the geographical location of the city is used to find the

retention factor for that city on the appropriate map shown in Figures 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, and 26.

The predicted average concentrations of the five major pollutants over the subject city are calculated by the following formulas:

$$C_{PA} = Y'_{PA}\ (.0111)RF$$

$$C_{SO} = Y'_{SO}\ (.0111)RF$$

$$C_{CO} = Y'_{CO}\ (.0111)RF$$

$$C_{NO} = Y'_{NO}\ (.0111)RF$$

$$C_{HC} = Y'_{HC}\ (.0111)RF$$

Where: C = concentration in $\mu g/M^3$

Y' = predicted emissions

(.0111) = factor to convert emissions in tons/mi^2/yr into $\mu g/m^2$/sec

RF = Retention Factor

These same average concentrations can also be obtained graphically from figures 27, 28, 29, 30, and 31.

These graphs present the results of the prediction formulas for cities ranging in diameter from 10 Km to 50 Km which should include most United States cities with less than two million population.

Standards Excess

The United States Environmental Protection Agency published the National Primary and Secondary Ambient Air Quality Standards in April, 1971 (Federal Register, April 30, 1971). The primary and secondary standards are defined in

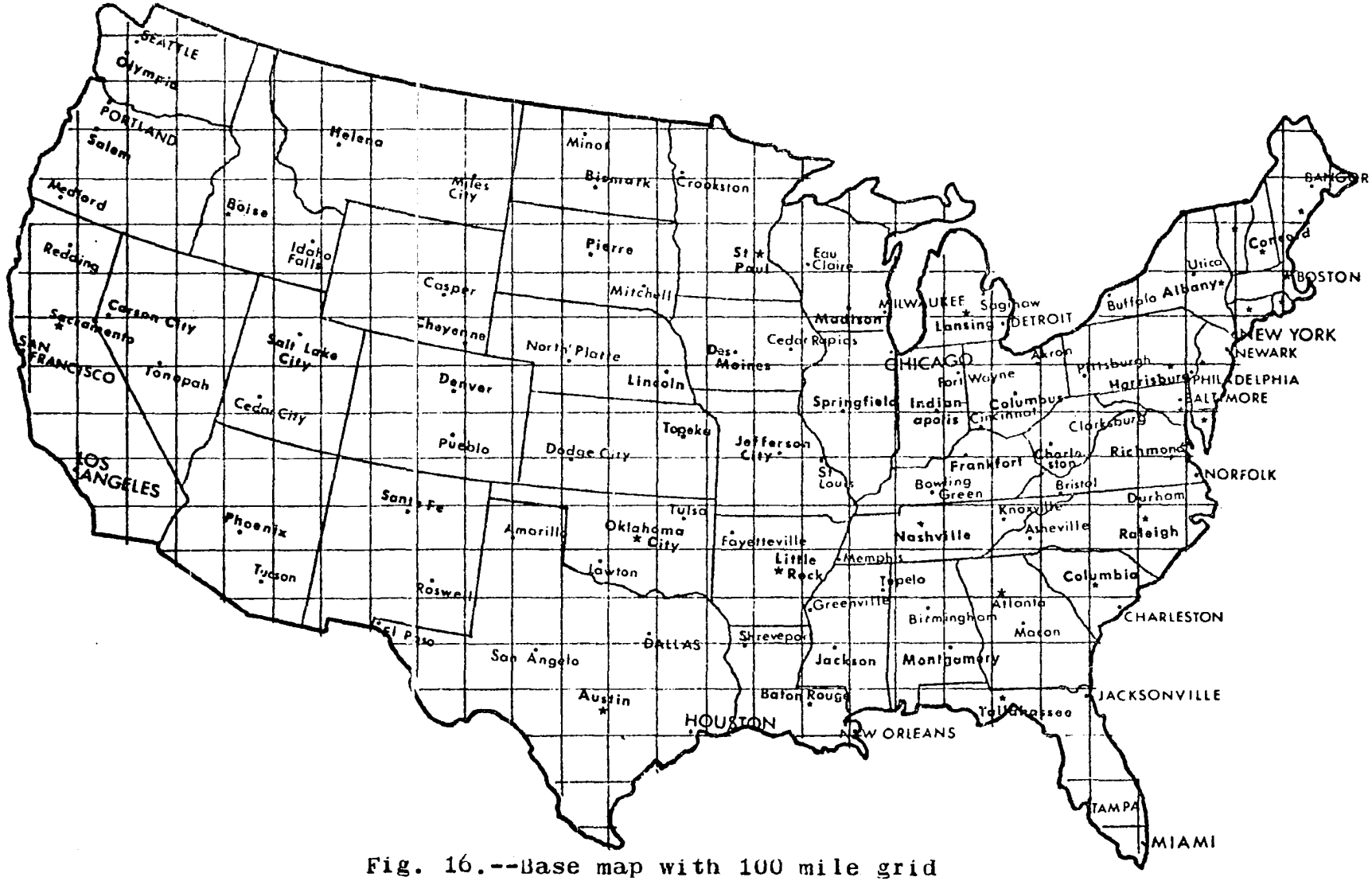

Fig. 16.--Base map with 100 mile grid

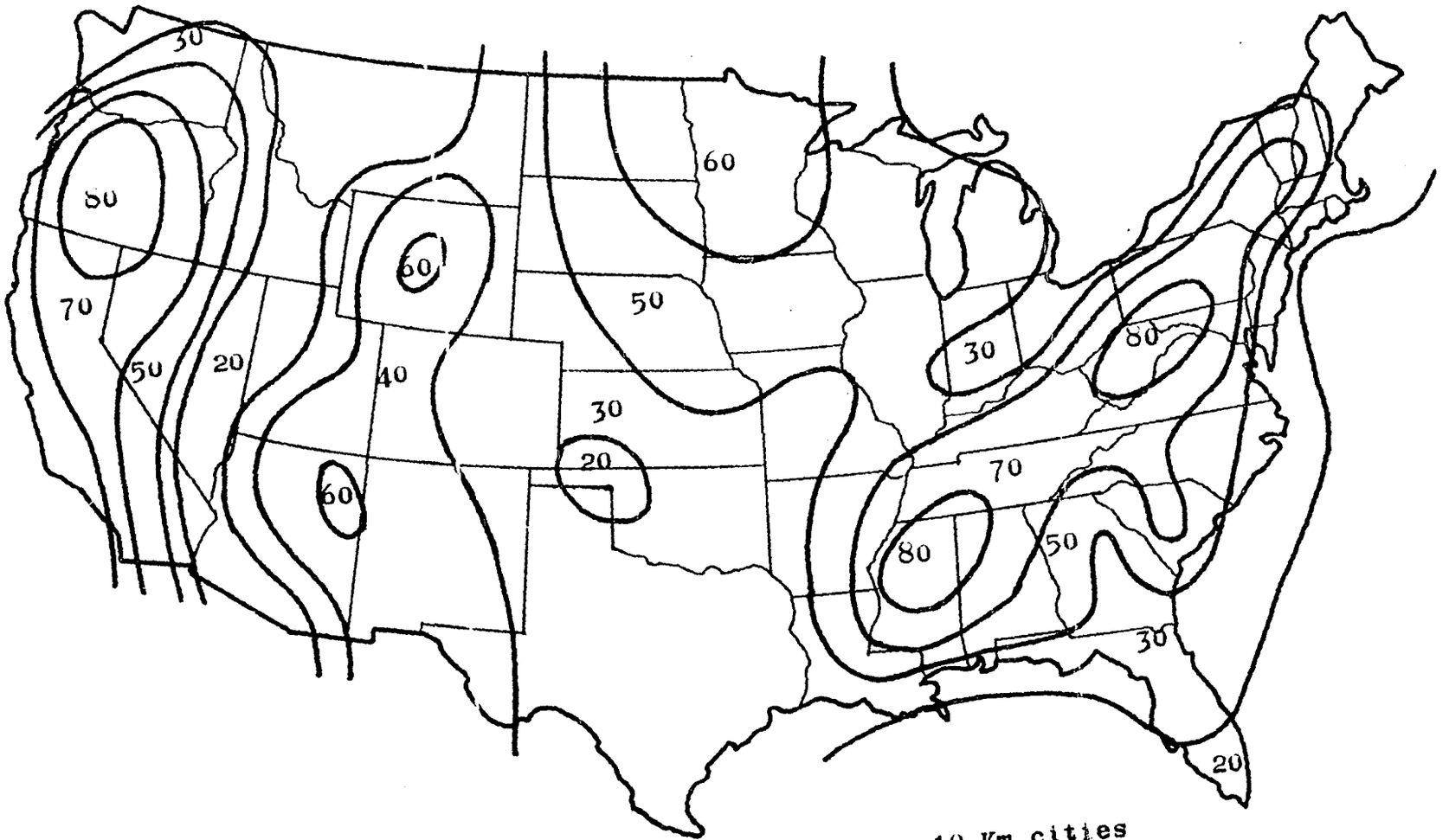

Fig. 17.--Retention factors for 10 Km cities

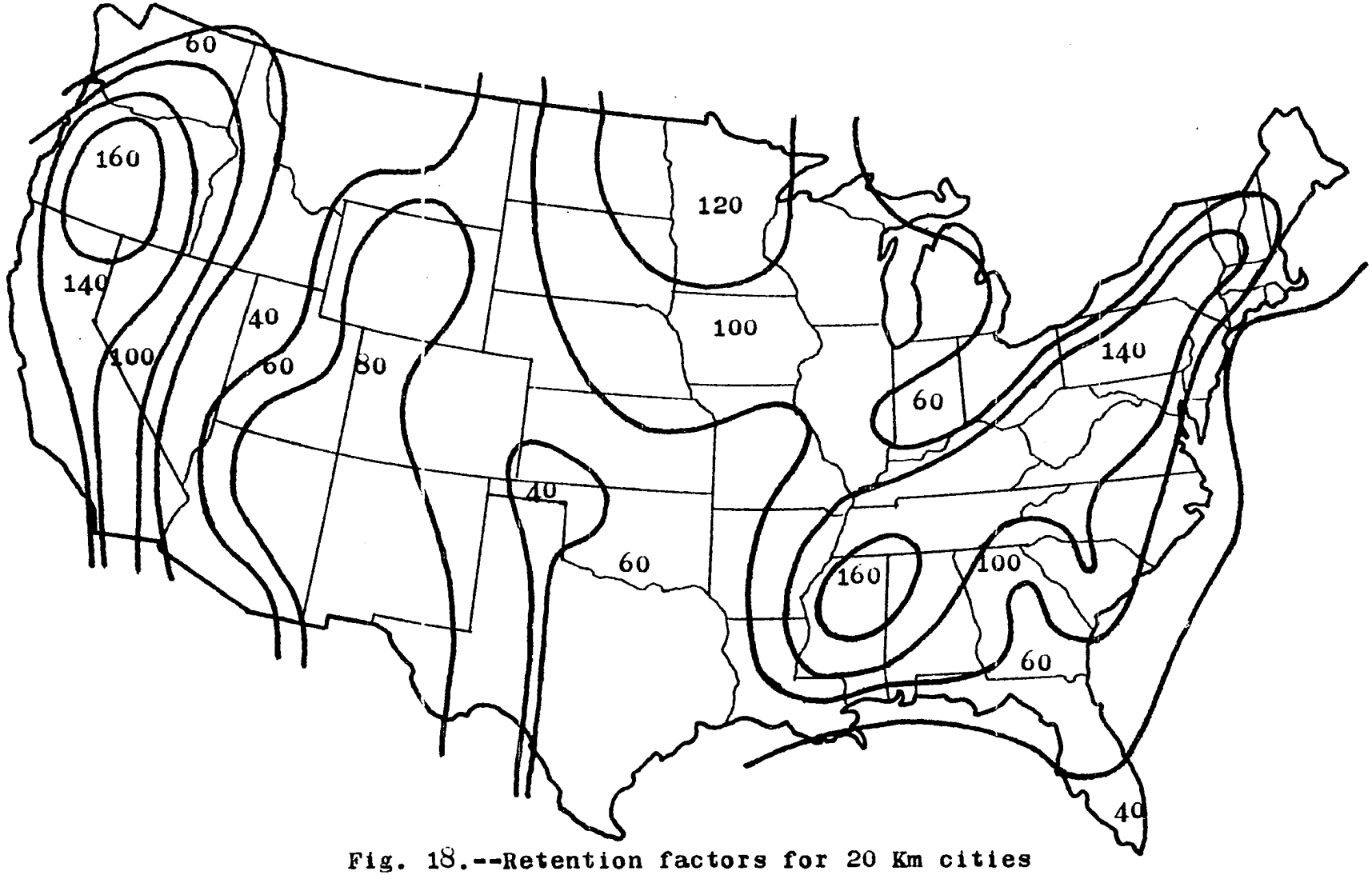

Fig. 18.--Retention factors for 20 Km cities

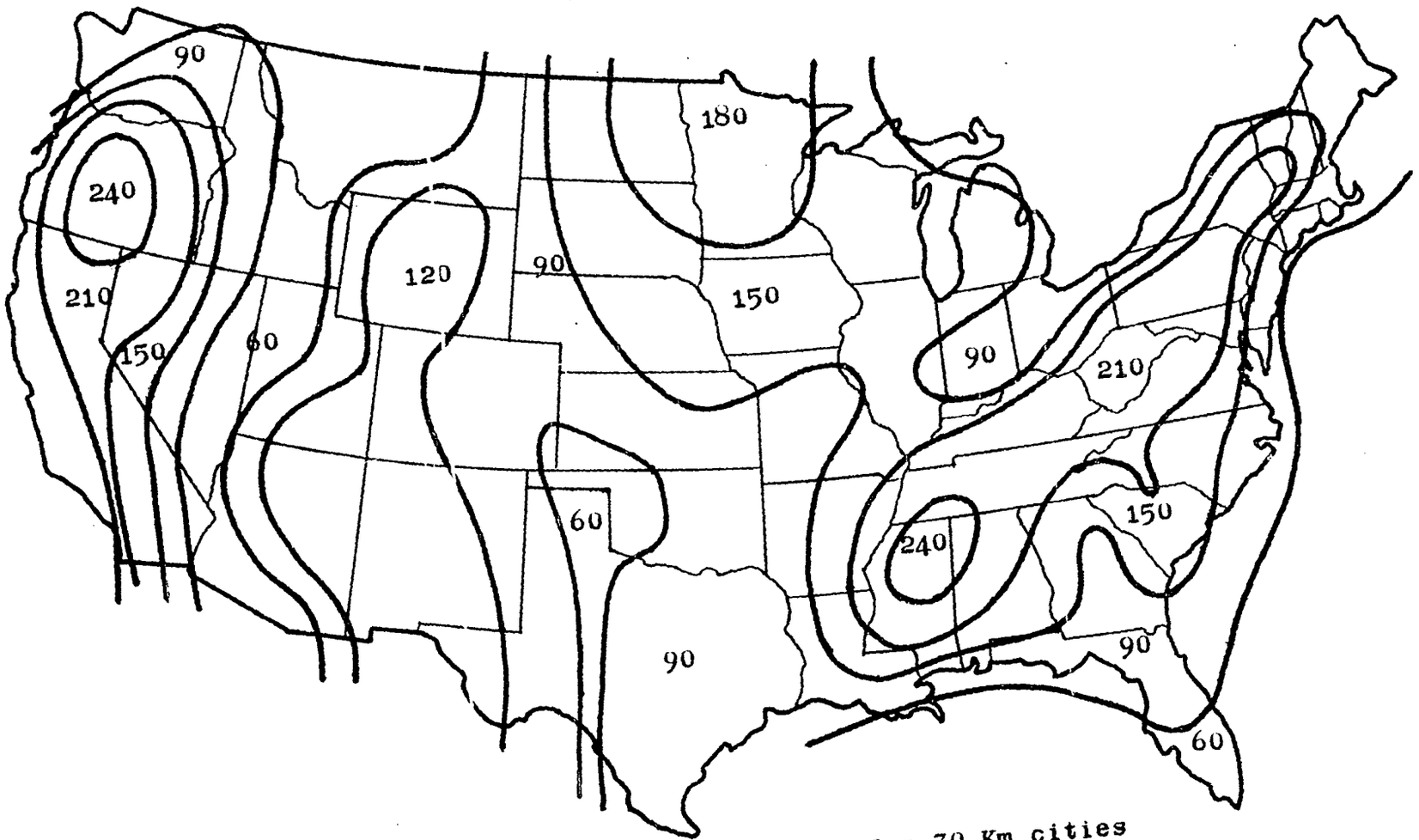

Fig. 19.--Retention factors for 30 Km cities

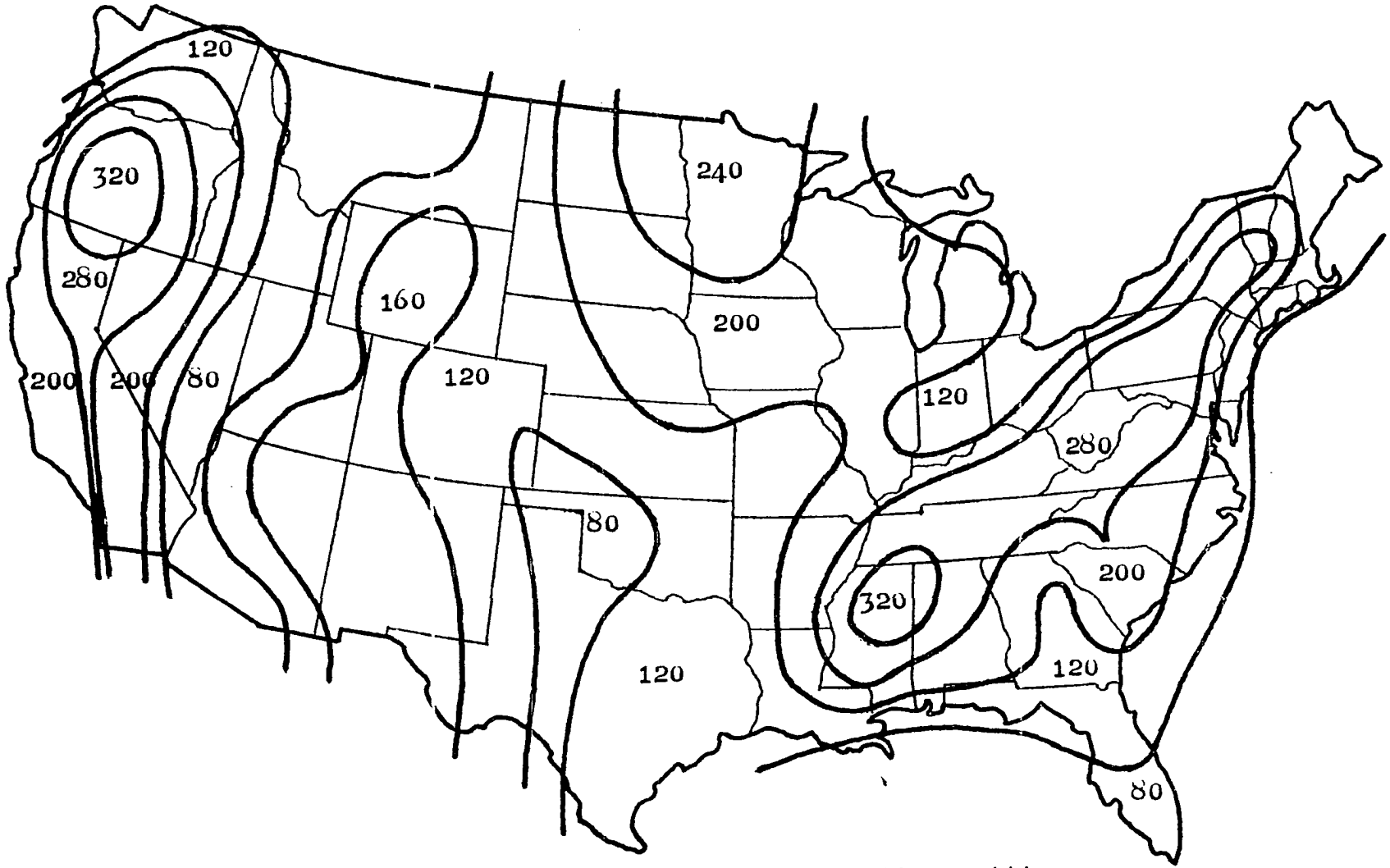

Fig. 20.--Retention factors for 40 Km cities

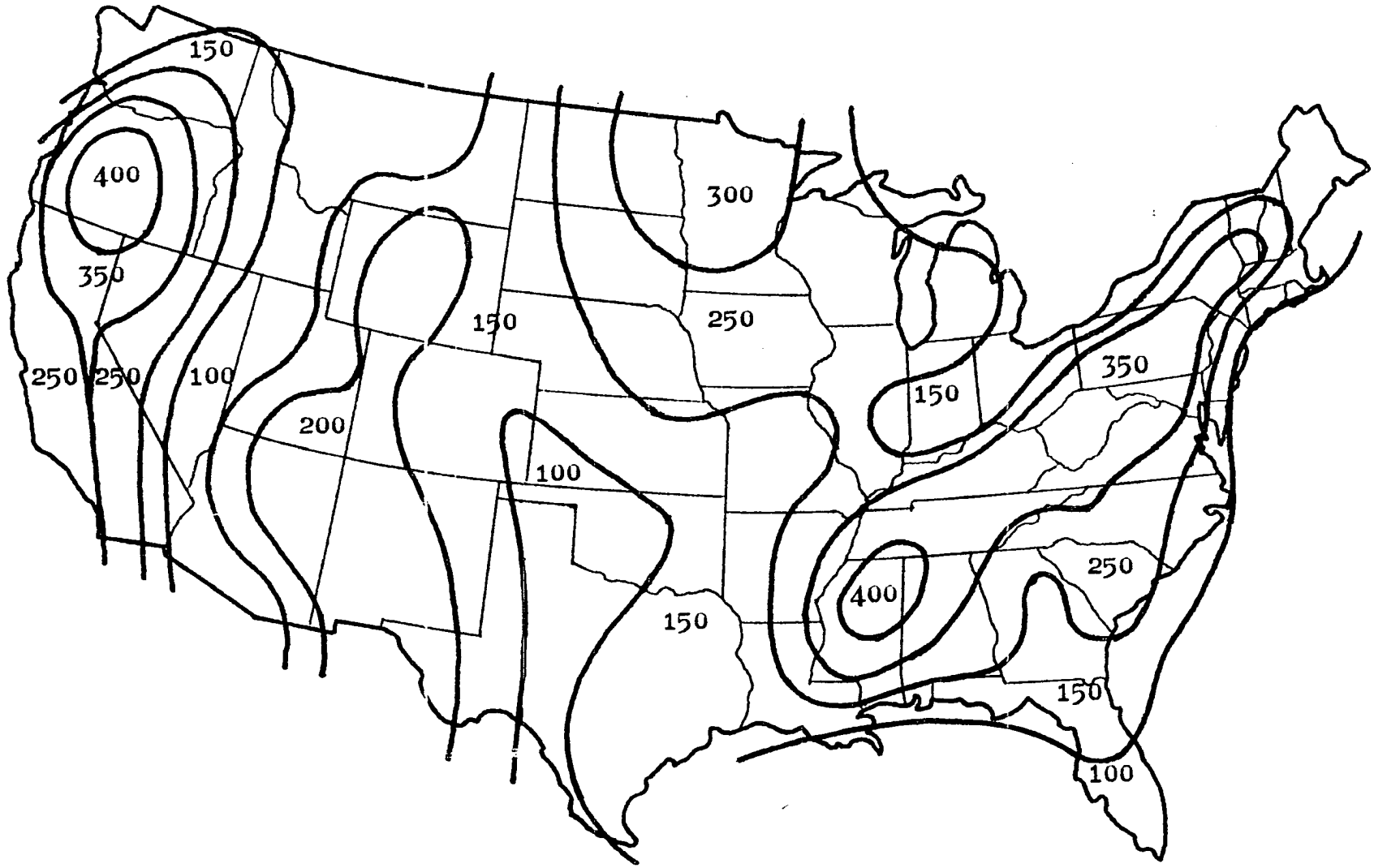

Fig. 21.--Retention factors for 50 Km cities

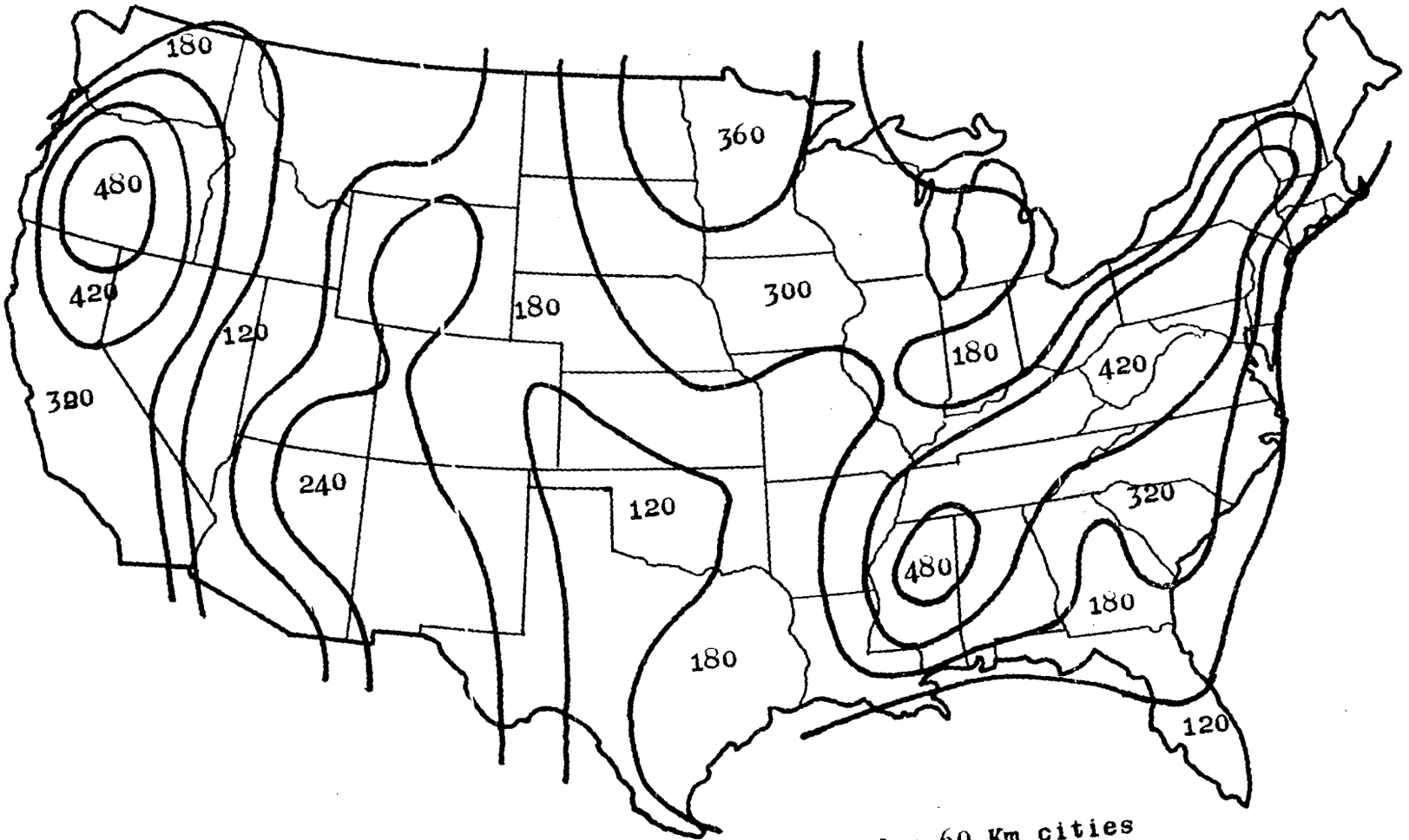

Fig. 22.--Retention factors for 60 Km cities

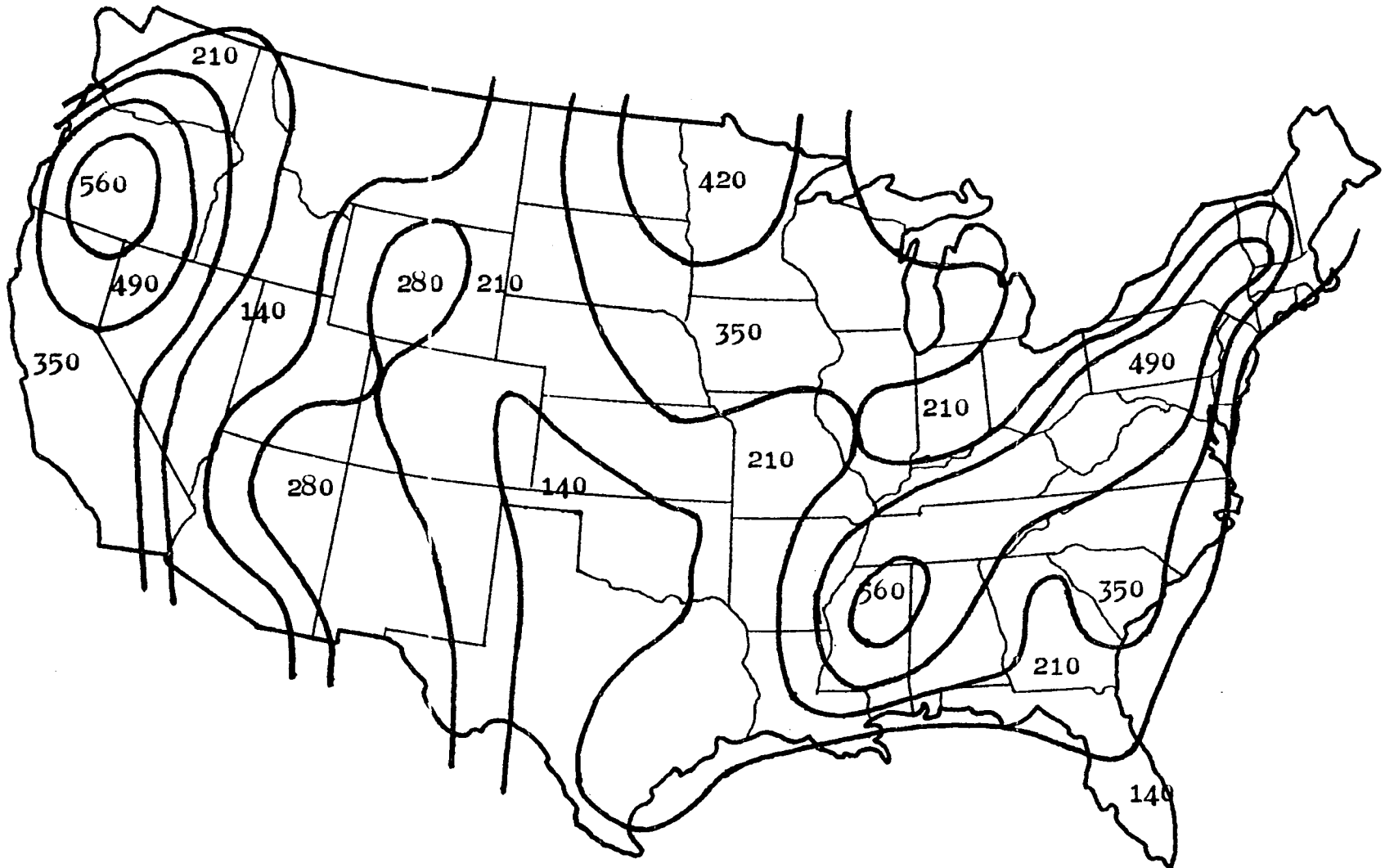

Fig. 23.--Retention factors for 70 Km cities

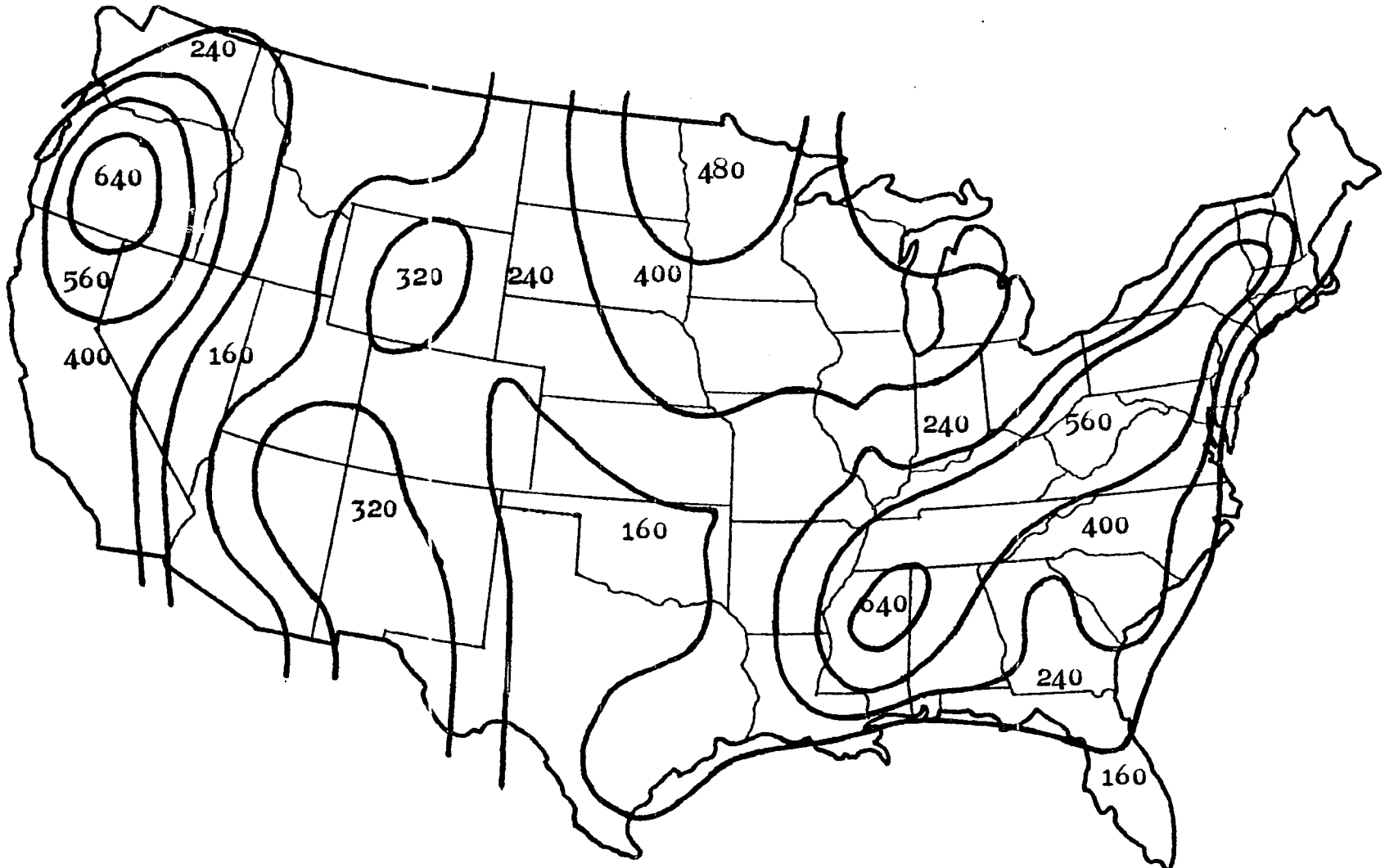

Fig. 24.--Retention factors for 80 Km cities

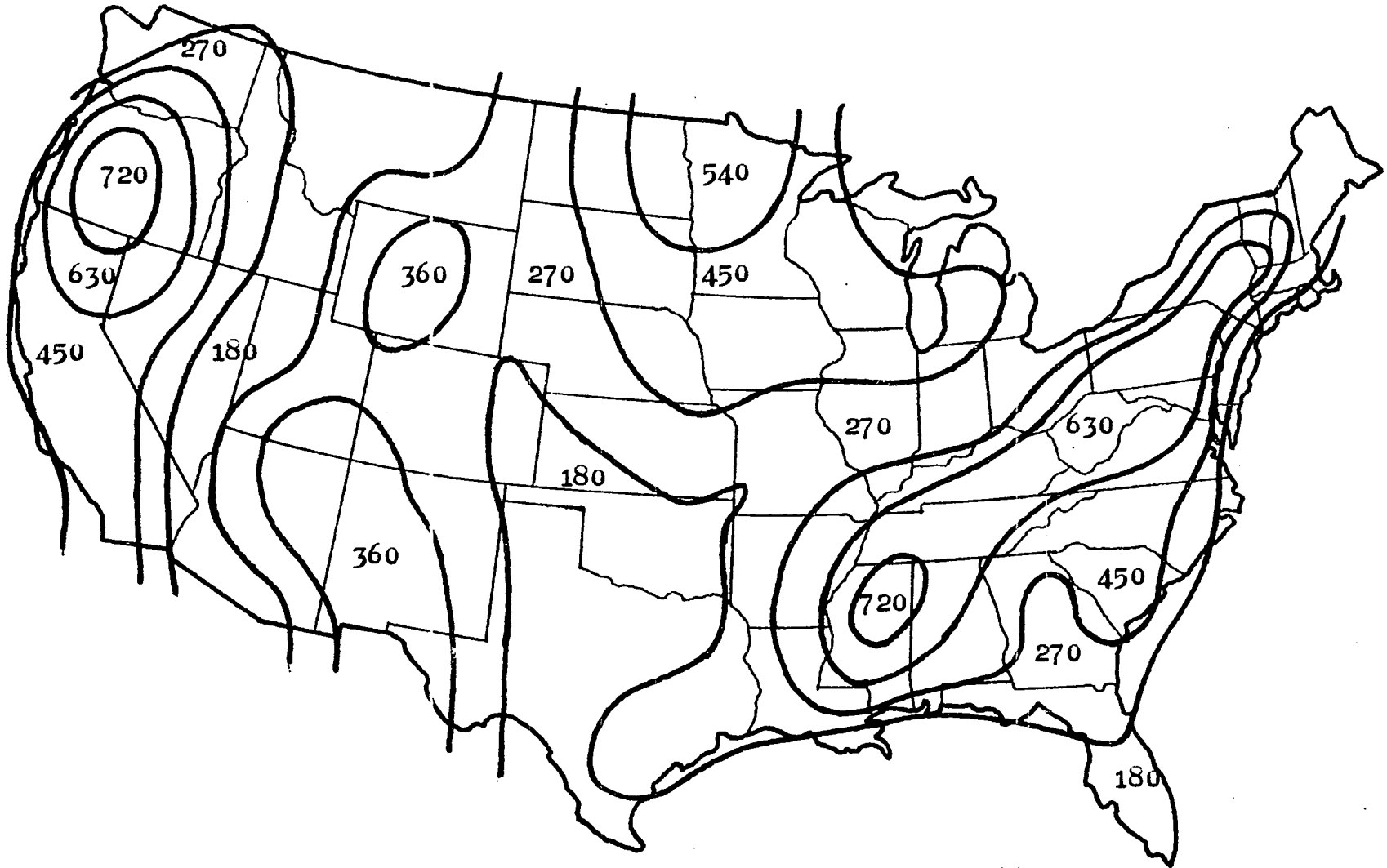

Fig. 25.--Retention factors for 90 Km cities

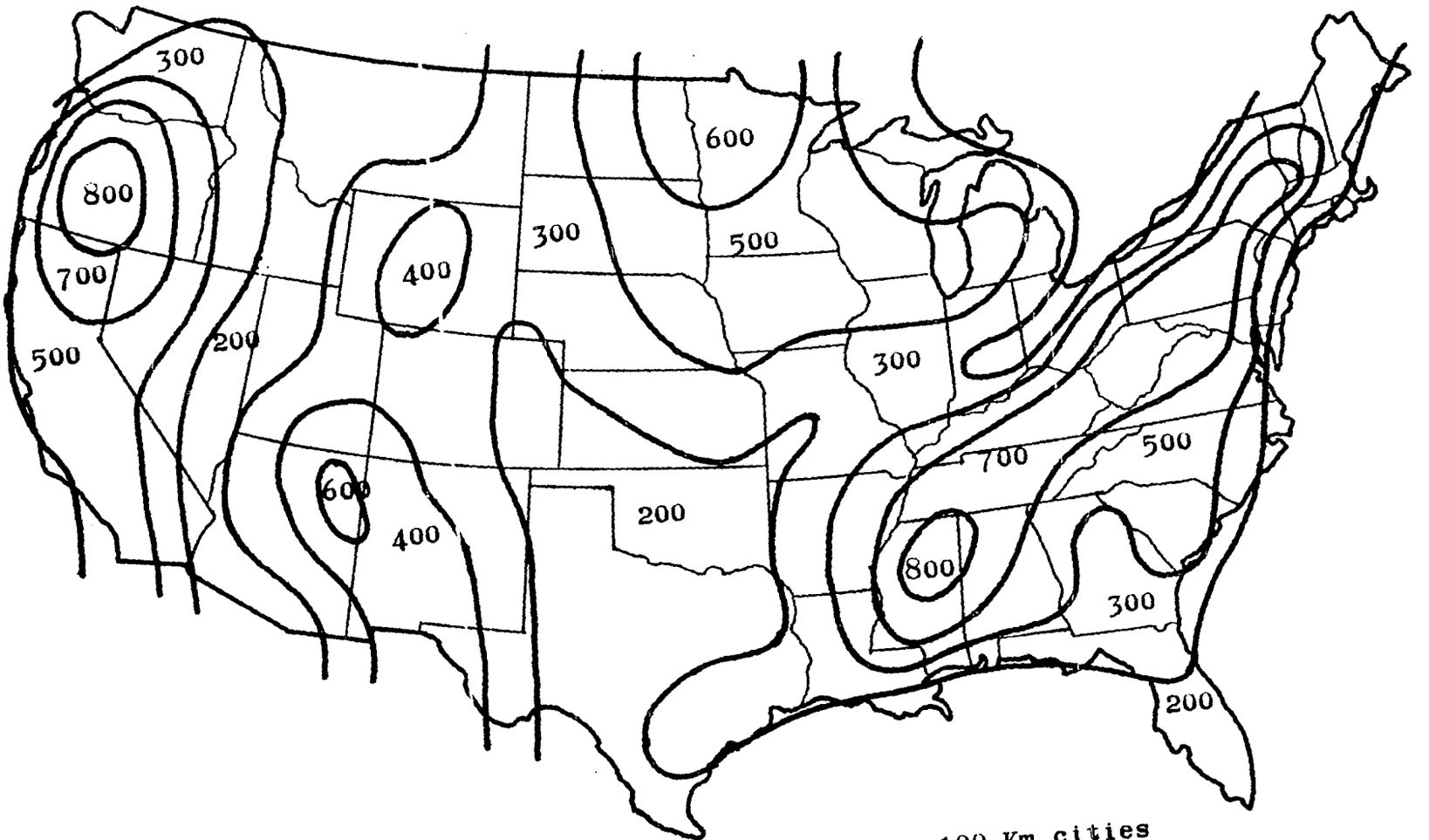

Fig. 26.--Retention factors for 100 Km cities

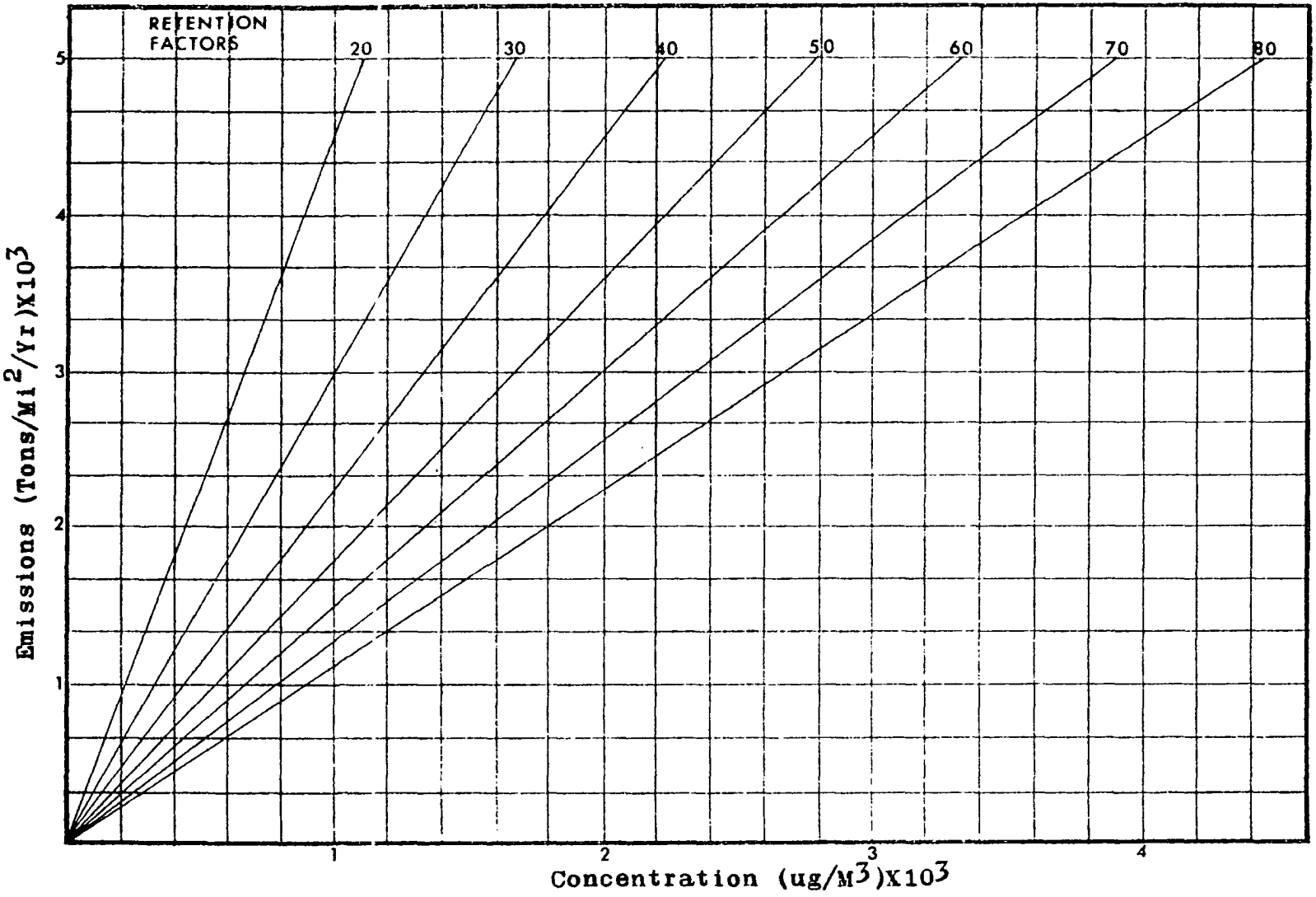

Fig. 27.--Concentration plots for 10 kilometer cities

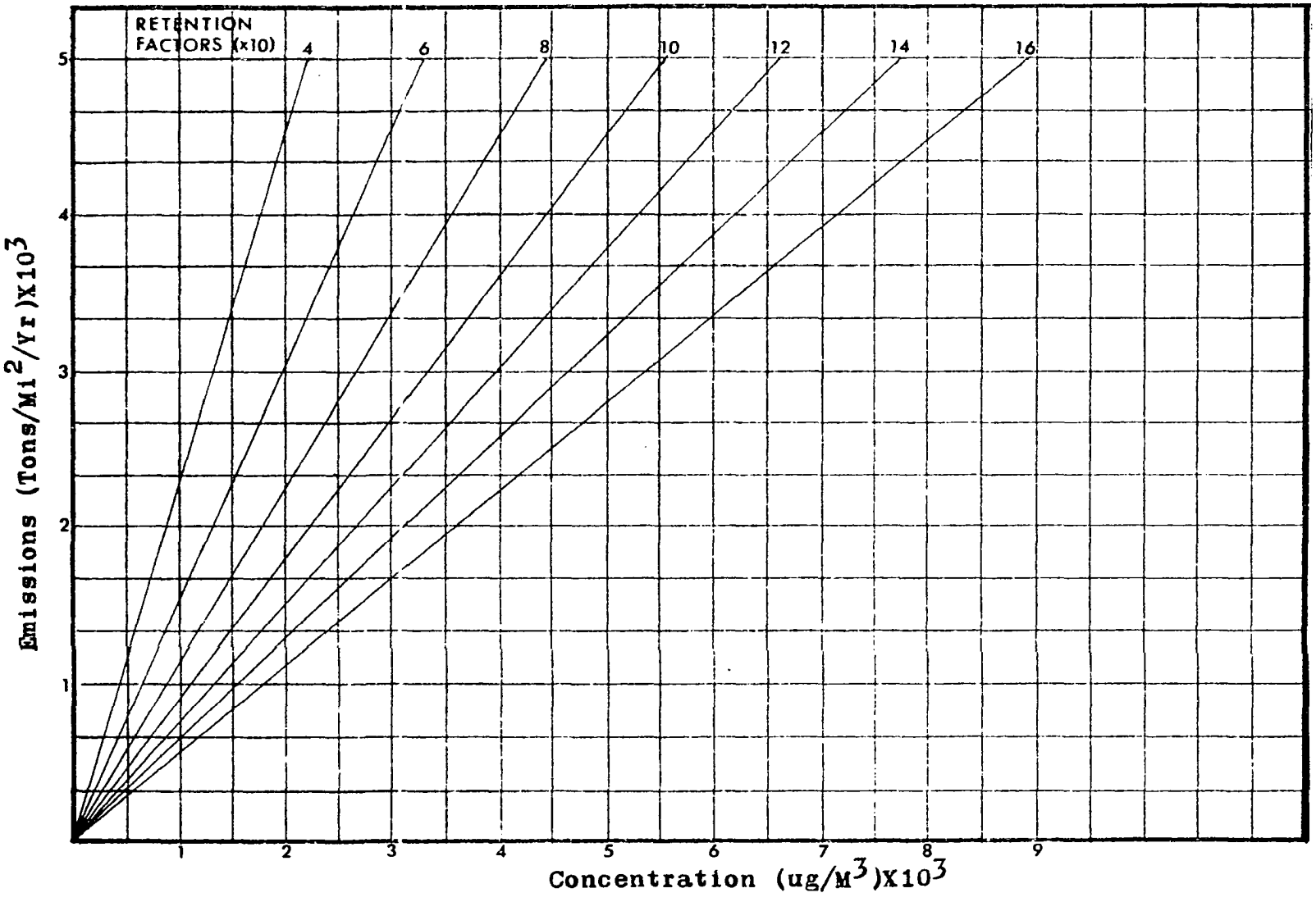

Fig. 28.--Concentration Plots for 20 Kilometer Cities

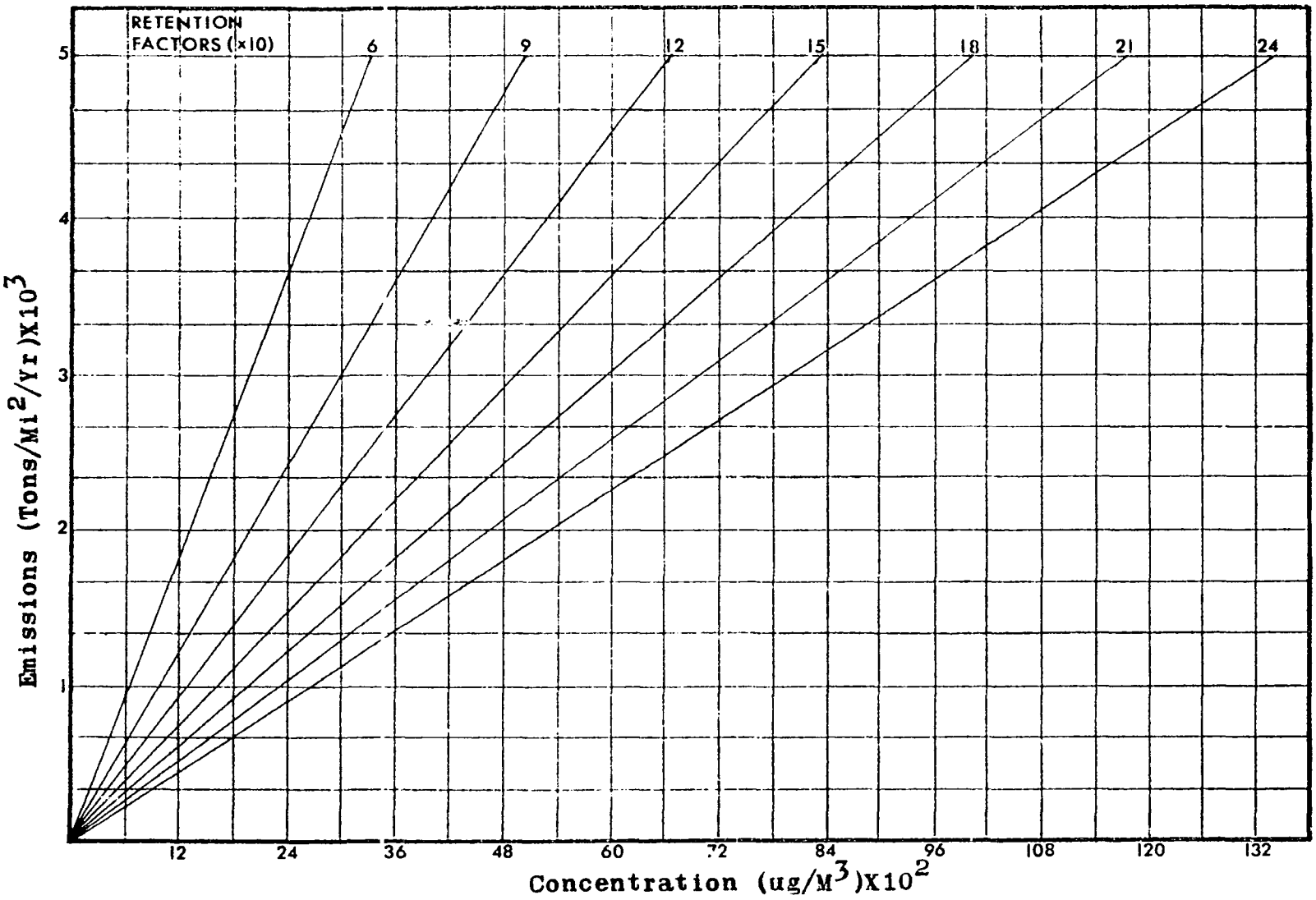

Fig. 29.--Concentration plots for 30 kilometer cities

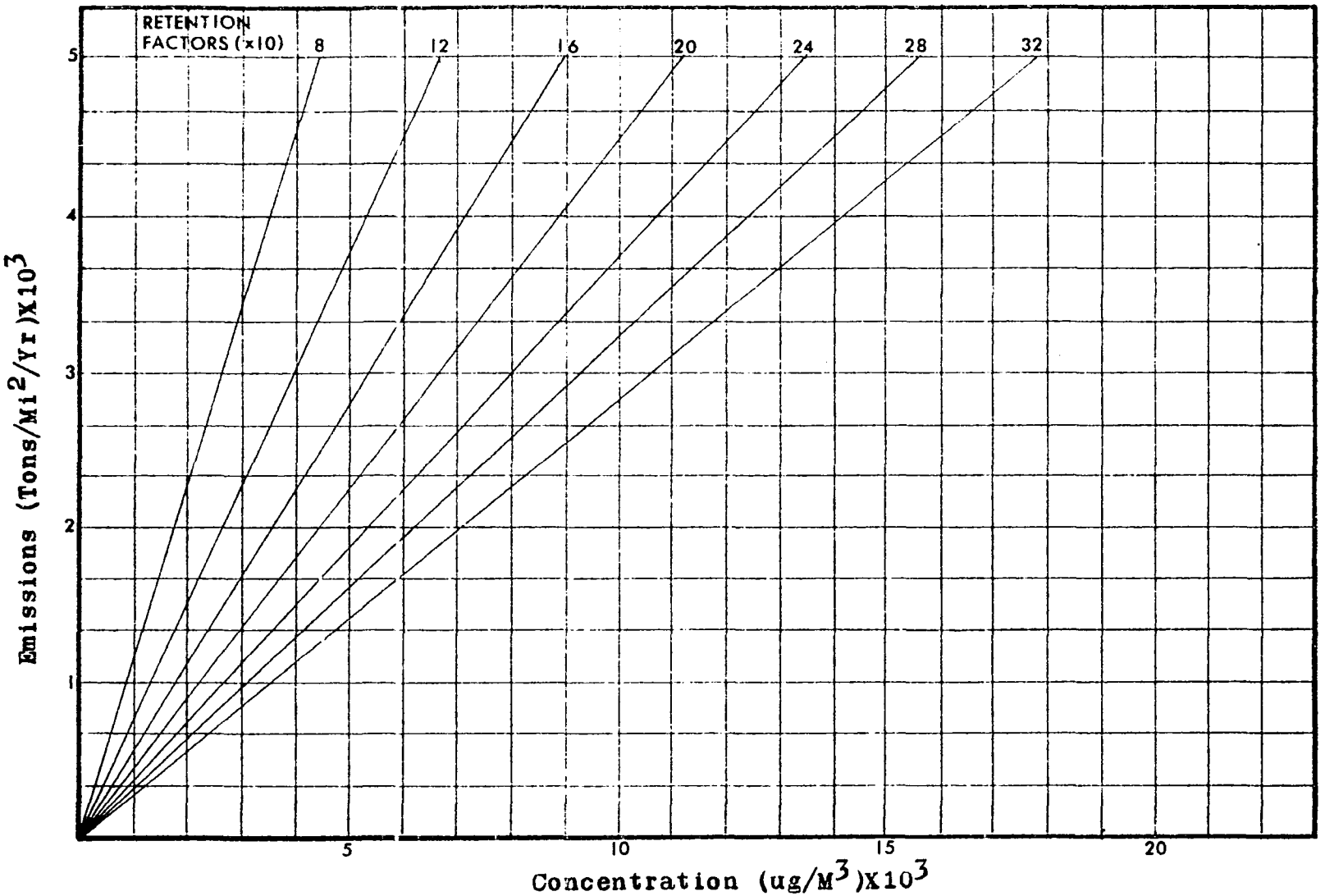

Fig. 30.--Concentration plots for 40 kilometer cities

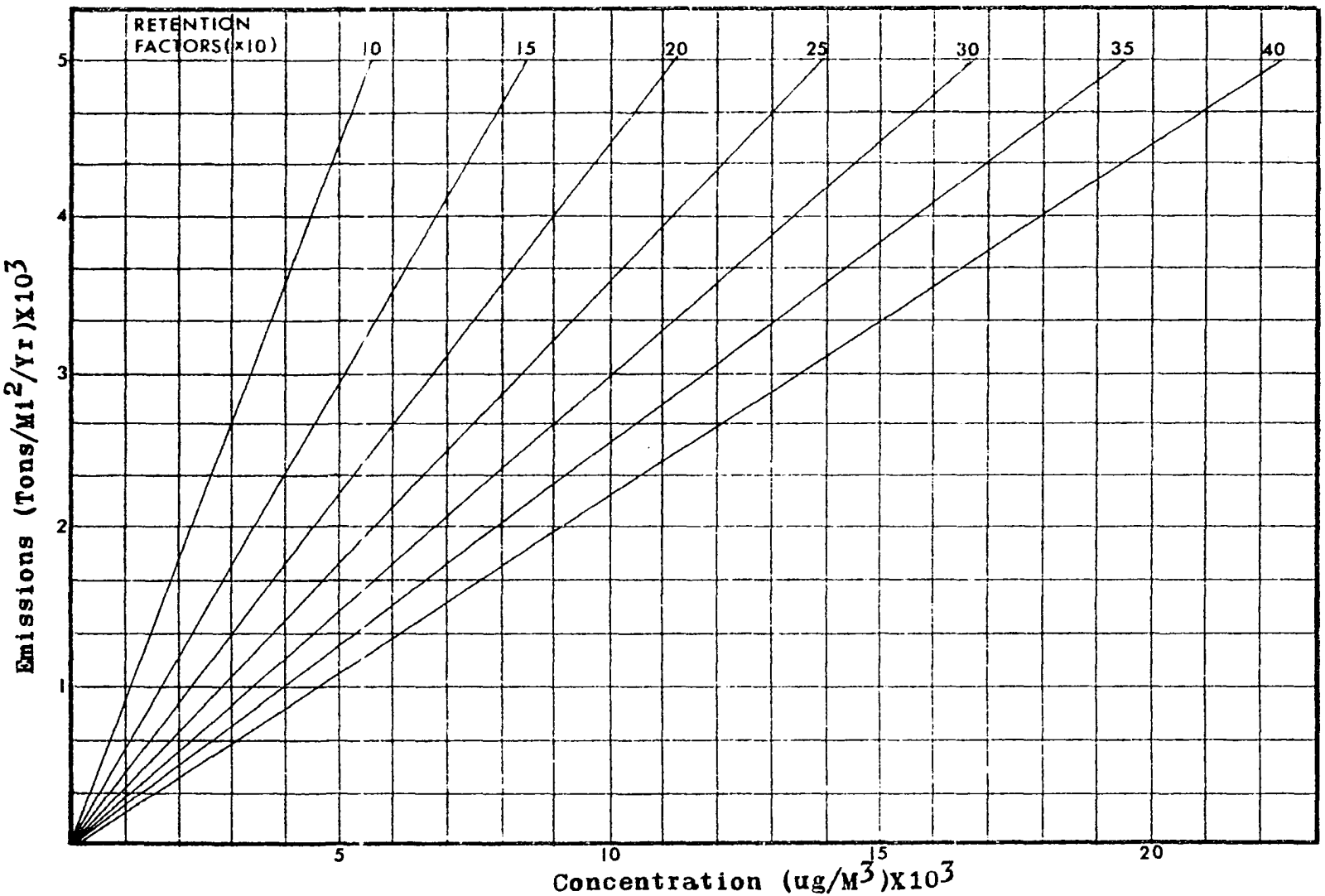

Fig. 31.--Concentration plots for 50 kilometer cities

that document as:

> National primary ambient air quality standards are those which, in the judgement of the Administration, based on the air quality criteria and allowing an adequate margin of safety, are requisite to protect the public health.
>
> National secondary ambient air quality standards are those which, in the judgement of the Administration, based on the air quality criteria, are requisite to protect the public welfare from any known or anticipated adverse effects associated with the presence of air pollutants in the ambient air.

Although these minimum standards are established for the entire nation, it is recognized that conditions exist in certain geographical areas where even more stringent standards might be needed and that the actual maintenance of these standards would be the responsibility of the individual states. So the ruling provided that:

> Nine months after the date of publication of this notice, the States are required to submit to the Administrator, in accordance with Section 110 of the Act (Air Quality Act of 1967), implementation plans for the attainment and maintenance of the national primary and secondary standards specified in this part.

This model allows the use of either the national or the individual state air quality standards in the determination of the amount of emissions in a city in excess of those standards. The procedure used to determine these standards excess (E) is to subtract the amount of the standard (STD) from the predicted emissions (Y'). But since the standard is expressed as $\mu g/M^3$ and the predicted emissions are expressed as $tons/mi^2/yr$ it is necessary to

change the units of the standard into the equivilant tons/mi^2/yr of emissions that they represent for that city. This is accomplished by dividing the standard by the Retention factor for that city and then dividing this dividend by .0111 thusly:

$$E = Y' - \frac{STD}{0.0111\ RF}$$

Where: E = Standards excess

Y' = Predicted emissions in tons/mi^3/yr

STD = Air Quality Standard in $\mu g/m^3$

RF = Retention Factor

.0111 = Factor to convert from $\mu g/m^2$/sec into tons/mi^2/yr

When E has a positive value the concentrations are in excess of the standards. When E has a negative value the concentrations are below the standards.

The formulas for computing the standards excess for the five major pollutants are:

$E_{PA} = Y'_{PA} - STD_{PA}/RF/.0111$

$E_{SO} = Y'_{SO} - STD_{SO}/RF/.0111$

$E_{CO} = Y'_{CO} - STD_{CO}/RF/.0111$

$E_{NO} = Y'_{NO} - STD_{NO}/RF/.0111$

$E_{HC} = Y'_{HC} - STD_{HC}/RF/.0111$

Abatement Costs

It was assumed that only the air pollution emissions that create concentrations in excess of the ambient air

quality standards must, by law, be abated. It was further assumed that if these standards can be maintained in the future, considering the rapid world population and industrial growth, this will not only be a reasonable but a magnificent accomplishment.

The standards excess section of the model described in the previous section provides a prediction of the amount of emissions in tons/mi^2/yr that may be expected in future years. In order to predict the total cost-to-abate in dollars, it is only necessary to determine the average cost-to-abate one ton of air pollution emissions. D. A. LeSourd, et. al. (1970) calculated the total expenditures that will be required to abate air pollution emissions sufficient to comply with the Air Quality Act of 1967 (as amended) by fiscal year 1976. This was accomplished by predicting the amount of pollutants that might be expected in 1976 without controls and the amounts that might be expected with controls.

In Table 4 of Chapter II a summary of LeSourd's calculations for solid Waste Disposal and Stationary Fuel Combustion is presented. Table 5 of Chapter II presented this same information for Industrial Process Sources. A summary of LeSourd's estimates of potential and reduced emission levels and associated costs for all stationary sources are presented in Table 25.

TABLE 25

STATIONARY SOURCES - ESTIMATES OF POTENTIAL AND REDUCED EMISSION LEVELS AND ASSOCIATED COSTS

Source	Year	QUANTITY OF EMISSIONS (Thousands of Tons Per Year) Part	SO_x	CO	HC	CONTROL COSTS (Dollars X 10^6) Initial	Annual
Solid Waste Disposal	FY76 W/O	1,500		5,450	2,020		
	FY76 W	185		414	293	201	113
Stationary Fuel Combustion	FY76 W/O	3,867	14,447				
	FY76 W	930	4,697			2,432	1,006
Industrial Processes	FY76 W/O	6,053	6,229	10,040	1,736		
	FY76 W	453	1,720	539	849	3,877	1,095
Total	FY76 W/O	11,420	20,676	15,490	3,756		
	FY76 W	1,568	6,417	953	1,142	6,510	2,214

W/O - Without implementation of the Clean Air Act.
W - With implementation of the Clean Air Act.

An average cost-per-ton to abate any of the air pollutants was calculated by dividing the total cost to abate all pollutants by the total number of tons that should be abated in fiscal year 1976. LeSourd expressed the control costs as an initial investment cost and an annual maintenance cost. Since the total tons abated represent only one year, it was necessary to prorate the initial cost over a period of 15 years according to a standard presented in AP-51 (1969). This investment cost of $6,510,000,000 prorated over a fifteen year period becomes a cost of $43,400,000 per year. The annual maintenance cost is $2,214,000,000 which when added to the annualized initial cost equals $2,257,400,000. This is the total cost to abate an expected 41,346,000 tons of air pollution emissions in year 1976 as:

$$\frac{\dfrac{\text{Initial cost} + \text{Annual cost}}{15}}{\text{Tons abated}} = \text{Cost/ton to abate}$$

This cost-to-abate of $54.59 per ton is multiplied by the number of tons/mi^2/yr that must be abated to maintain the standards. This formula becomes:

$$A = E_i\ (\$54.59)$$

Where: A = Cost/mi^2/yr to abate

E_i = Sum of the excess emissions to be abated in tons/mi^2/yr

$\$54.59$ = Average cost/ton to abate

It will be noted that no mobile sources are included in the above calculations and predictions. It is assumed that the provisions of the Air Quality Act of 1967 as pertains to emissions controls of vehicular pollutants will be complied with and that this will bring mobile source contributions to the pollution load within the standards. This reduction is predicted by the step-function described in the Emissions Prediction section of this chapter.

Figure 32 presents the complete mathematical model used to predict early morning conditions. The inputs (X_i) of percent of work force employed in manufacturing, number of automobiles registered in the county, and population are normalized to a mean of .680 and then summed (ΣX_i). Using this ΣX_i, emissions (Y') are predicted through the use of a formula based on the derived values for α, β, K, and $\bar{Y}$. The predicted emission values are multiplied by 10^3 to correct for a previous reduction by 10^{-3} to facilitate the mathematical calculations. A step-function predicts the reduction in vehicle emissions as a result of the Air Quality Act of 1967 requirement for cleaner engines by 1975 - 1976. Concentrations are predicted by converting emissions into concentrations through the use of a meteorological retention factor. The amount of emissions in excess of the air quality standards are calculated by subtracting the amount of the emissions predicted from the amount of the emissions represented by the standards. Abatement costs are

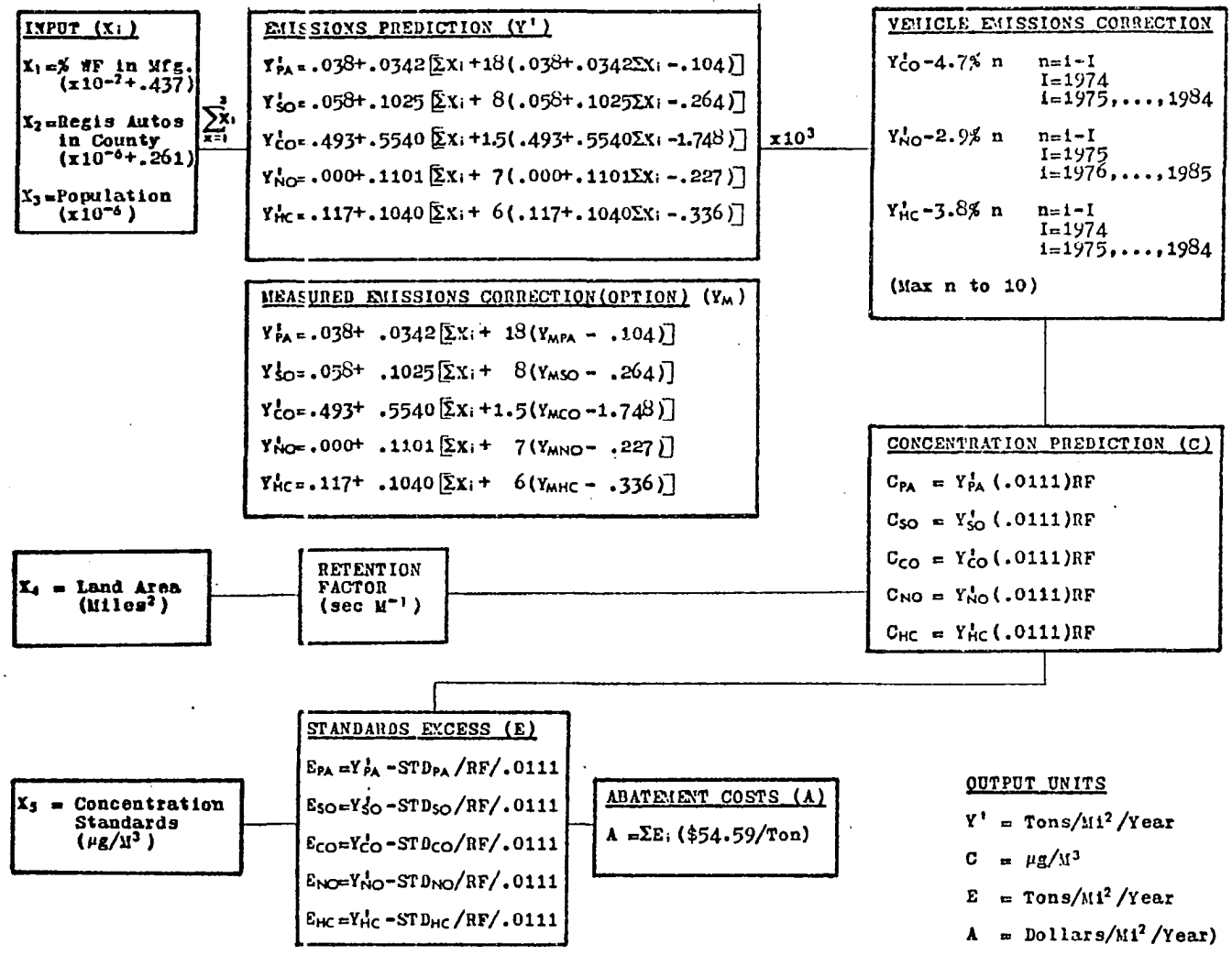

Fig. 32.--Mathematical Model

calculated by multiplying the total tons of pollutants to be abated by a per ton cost to abate.

CHAPTER IV

VALIDATION

Methods

One who attempts to validate a model that predicts future conditions must assume a wait-and-see attitude before removing the tongue from the cheek. Although we can't, with great precision, know what the future will bring, we can, however, accurately describe the present. Since the present is yesterday's future we can tentatively judge a prediction model by how well it predicts the present. This present conditions prediction was used to validate the model described in this paper.

The first step in validation was the procurement of accurate data which describes the present in the same categories and with the same units that the model expresses as output. In the second step the model was operated to predict these same data. The third step was to determine the prediction accuracy of the model by comparing the measured present conditions data with the predicted conditions data. These comparisons were expressed as a percent of prediction accuracy.

The gathering of base data for this model has been the most difficult and time-consuming task that was required. The selection of cities to be used in the validation proved to be no less a task. Many cities have developed emissions inventories which provide accurate emissions data, especially emissions of particulates, sulfur oxides, and carbon monoxide. Some of these same cities do not report the measurement of nitrogen oxide and hydrocarbon emissions. Likewise, only a few cities have established a comprehensive air sampling system which provides accurate measurements of all five of the major pollutants. The most commonly sampled pollutants were particulates and sulfur oxides. Nine cities provided concentration measurements of particulates and sulfur oxides. Of these 9 cities 3 provided measurements of carbon monoxide, 2 provided measurements of nitrogen oxides, and only 1 provided measurements of hydrocarbons. Three of these cities were not used in developing the base data for the model; these were Tulsa, Oklahoma; Indianopolis, Indiana; and Milwaukee, Wisconsin. The remaining 6 cities used to validate the model were the previously used cities of Denver, Colorado; Chattanooga, Tennessee; Atlanta, Georgia; St. Louis, Missouri; Memphis, Tennessee; and Detroit, Michigan. Although these cities were chosen solely because they were the only ones providing measured concentrations data, fortunately they represent a large portion of the contiguous United States.

Emissions Validation

The average emissions prediction accuracy of the model is 63.93%, ranging from a minimum of 45.59% average accuracy for sulfur oxides to 97.08% average accuracy for hydrocarbons. Table 26 presents the predicted and measured data for the validation cities and provides a breakdown of the average emissions prediction accuracy for each of the 5 major pollutants.

The results suggest that the prediction accuracy of sulfur oxide and carbon monoxide emissions is relatively low for cities that have undergone rapid industrial growth during the past two decades such as Atlanta, Georgia; Tulsa, Oklahoma; and Denver, Colorado. This prediction accuracy is also low for cities that have recently undergone an extensive program of emissions control. Chattanooga, Tennessee has adopted rather rigid controls of excess industrial pollution during the past decade, and St. Louis, Missouri only recently converted its electric power production to natural gas and low sulfur coal. When the emissions of the original 23 cities were plotted against the demographic parameters in Chapter III, a high variance around the regression line resulted (see Figures 6 and 7). This high variance for individual cities causes an extremely wide margin of error when predicting the emissions for those cities. Since only one example for hydrocarbons and only two examples for nitrogen oxides were

TABLE 26

PREDICTED AND MEASURED EMISSIONS
FOR VALIDATION CITIES

CITY	EMISSIONS (TONS/Mi^2/YR)									
	PART		SO_2		CO		NO_x		HC	
	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS
DENVER	89	57	199	57	1138	173				
TULSA	78	110	162	66			110	110		
CHATTANOOGA	71	110	139	77			86	226	206	200
ATLANTA	90	38	202	17						
INDIANAPOLIS	102	139	241	280	1364	1641				
ST. LOUIS	111	64	273	72	1540	759				
MEMPHIS	98	35	228	123						
MILWAUKEE	120	311	304	865						
DETROIT	205	168	591	780						
AVERAGE PREDICTION ACCURACY %	58.77		45.59		49.19		69.02		97.08	

AVERAGE EMISSIONS PREDICTION ACCURACY FOR ALL POLLUTANTS = 63.93%

obtainable, the average prediction accuracy for these emissions is probably lower than this validation indicates.

Concentration Validation

Predicted concentrations were run by the model and compared with the measured concentrations for the 9 cities. This comparison is presented in Table 29 of the Appendix which shows that the early morning retention factors predicted 72% too high for particulates, an approximate factor of 2, and an average of 180% too high for gases, an approximate factor of 3. When the average predicted concentrations for 8 hours or longer are desired it then becomes necessary to divide the retention factor by 2 for particulates and by 3 for gases.

The concentration prediction accuracy of the model has been appreciably increased over its emissions prediction accuracy. This was accomplished by the use of the emperically derived divisors for the retention factors in each pollutant concentration prediction formula. The Holzworth retention factors are based upon the worst possible conditions existing during the first few hours after sunrise. When predicting average concentrations during the entire 24 hour day, it was found that particulates required a divisor of 2; sulfur oxides, carbon monoxide, and nitrogen oxides a divisor of 3; and, since the National Primary and Secondary Standards for hydrocarbons is for the first 3 hours after sunrise, no divisor is required. Particulates

require a divisor of only 2 as compared to the divisor of 3 for gases due to the settleable fraction of particulates which does not remain in the atmosphere for sufficient time to be included in a suspended particulate sample. Those settleable particulates, however, are included in the emissions inventories of the cities.

The average concentrations prediction accuracy of the model is 83.59%, ranging from a minimum of 79.20% average accuracy for hydrocarbons to 87.77% average accuracy for carbon monoxide. Table 27 presents the predicted and measured data for the validation cities and provides a breakdown of the average concentration prediction accuracy for each of the 5 major pollutants. The predicted and measured data is also graphically presented in Figures 33, 34, 35, and 36.

TABLE 27

PREDICTED AND MEASURED CONCENTRATIONS
FOR VALIDATION CITIES

CITY	CONCENTRATION ($\mu g/M^3$)									
	PART		SO_2		CO		NO_x		HC	
	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS
DETROIT	171	140	328	300						
MEMPHIS	82	90	127	130						
DENVER	30	40	44	60	253	320				
CHATTANOOGA	55	72	72	52			45	58	320	404
ST. LOUIS	74	95	121	130	683	650				
ATLANTA	60	70	90	100						
INDIANAPOLIS	68	80	107	130	606	540				
MILWAUKEE	100	117	169	156						
TULSA	39	53	54	78			37	40		
AVERAGE PREDICTION ACCURACY %	81.33		84.62		87.77		85.04		79.20	

AVERAGE CONCENTRATION PREDICTION ACCURACY FOR ALL POLLUTANTS = 83.59%

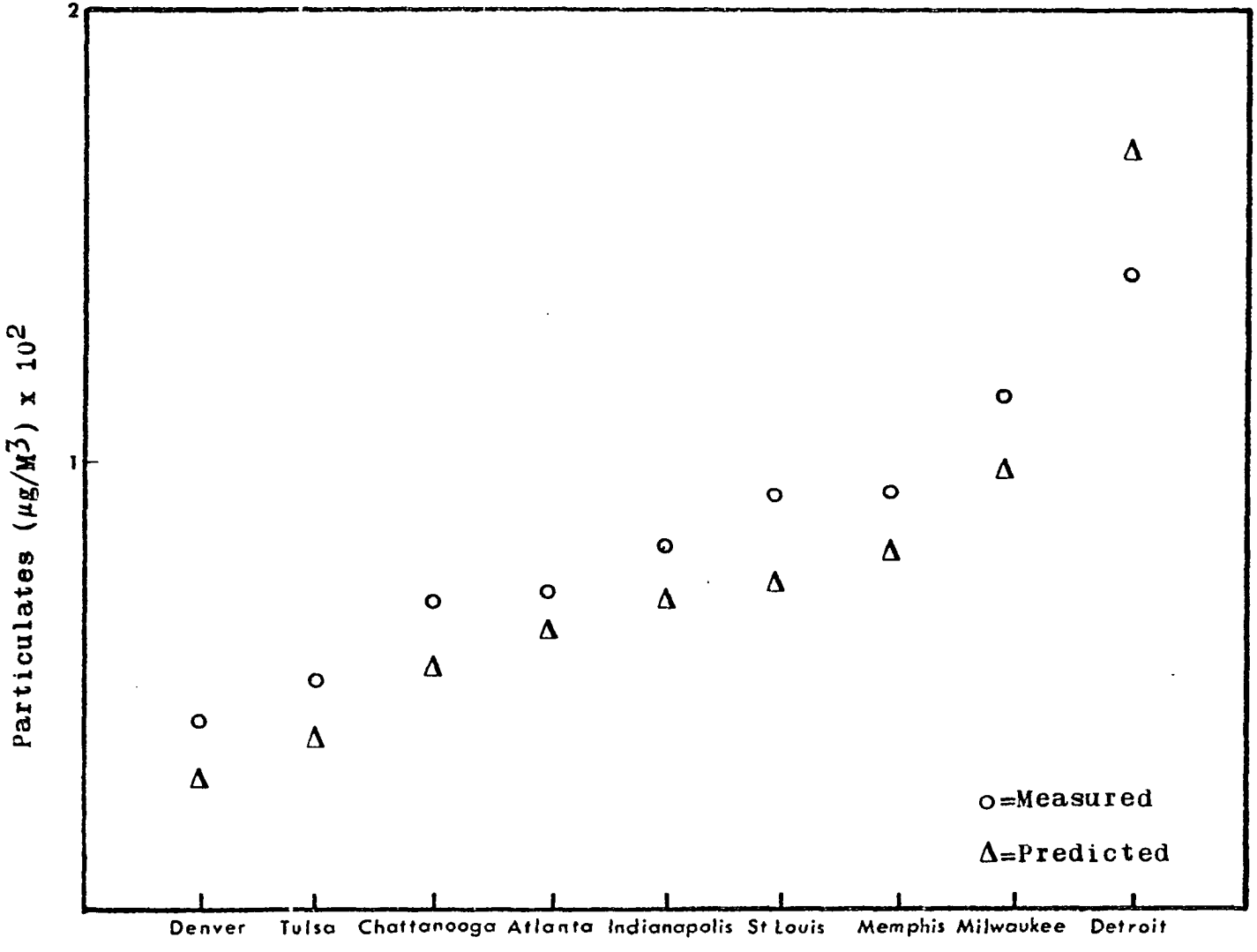

Fig. 33.--Predicted vs measured Concentrations of Particulates

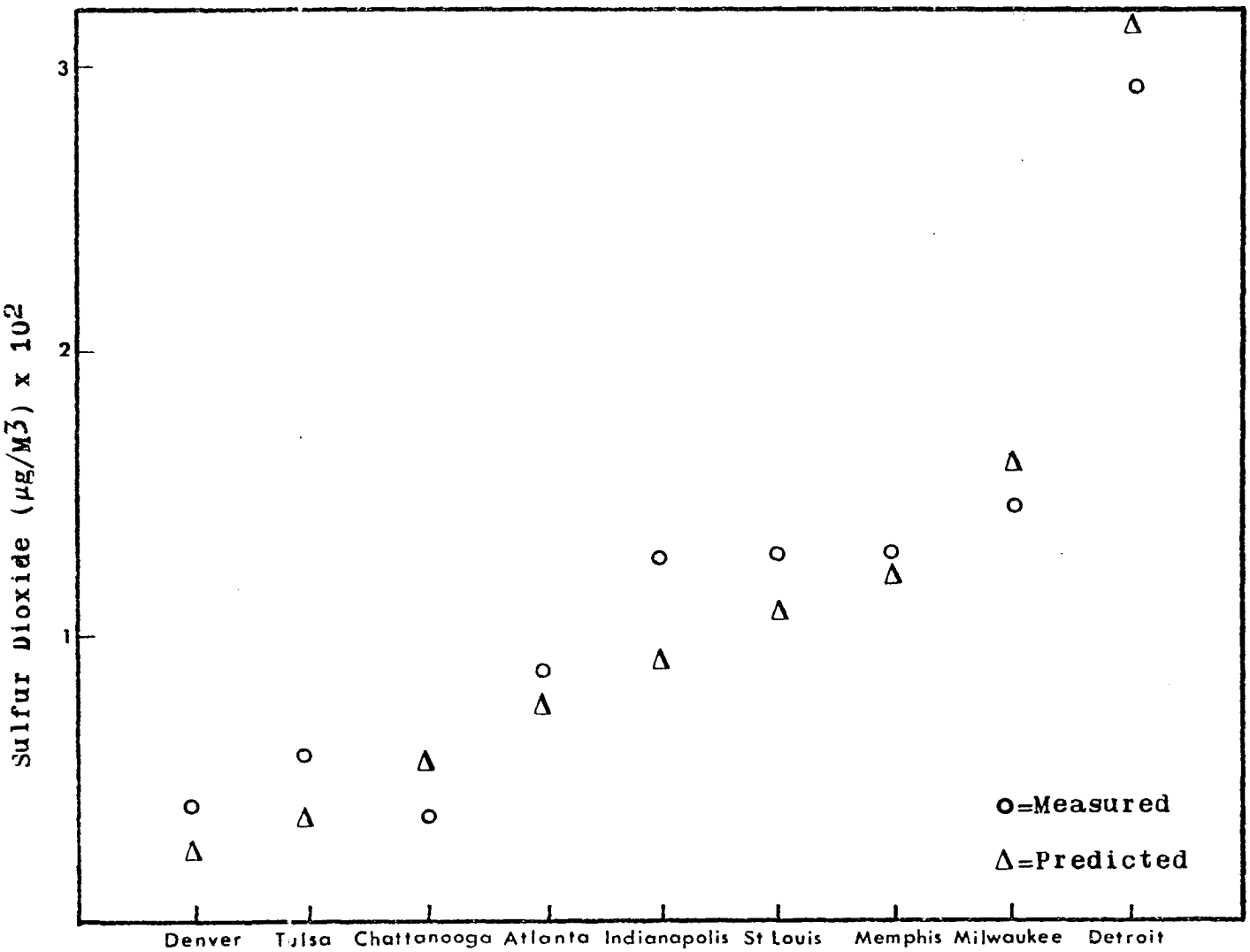

Fig. 34.--Predicted vs measured concentrations of Sulfur Dioxide

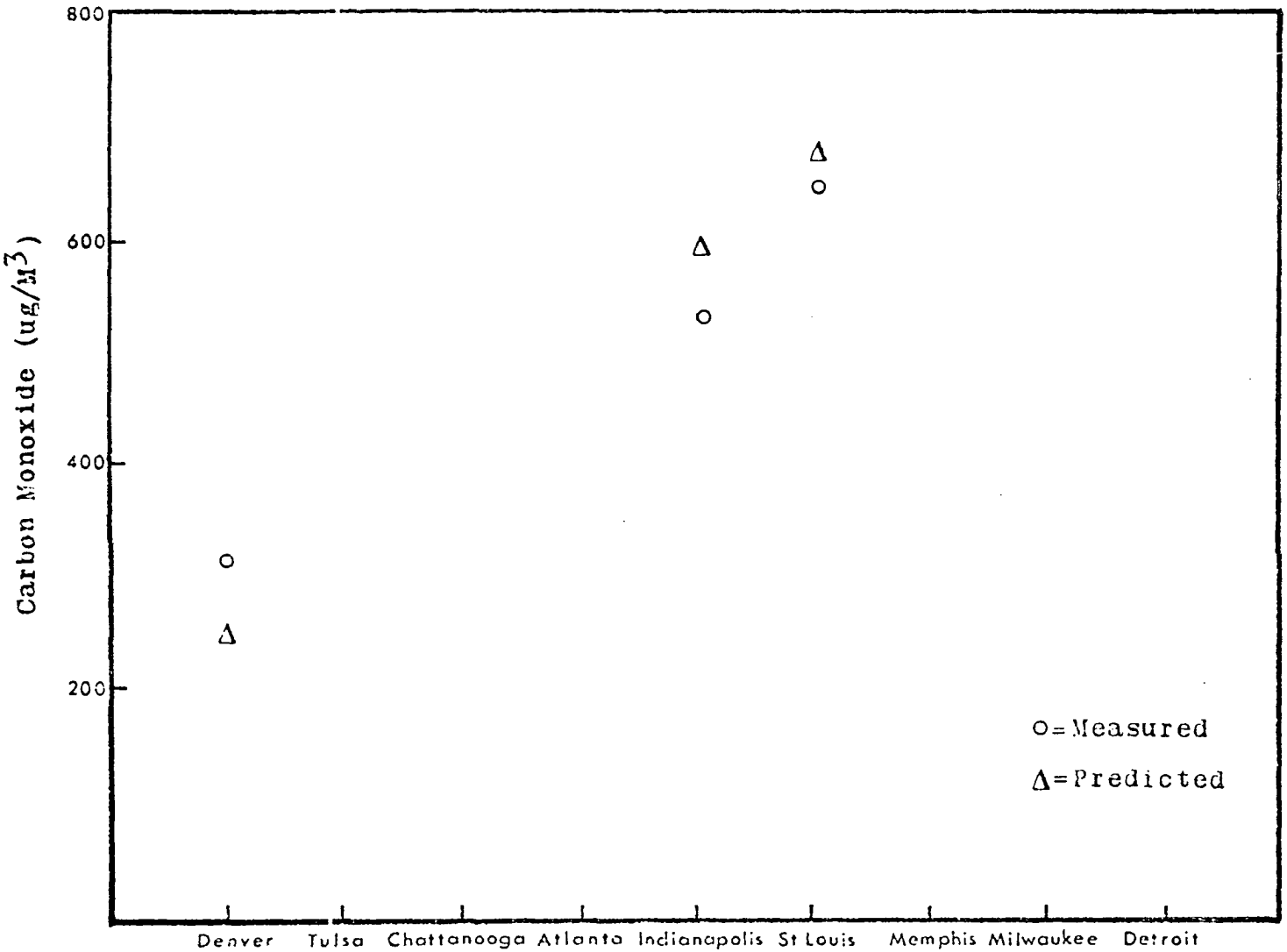

Fig. 35.--Predicted vs measured concentrations of Carbon Monoxide

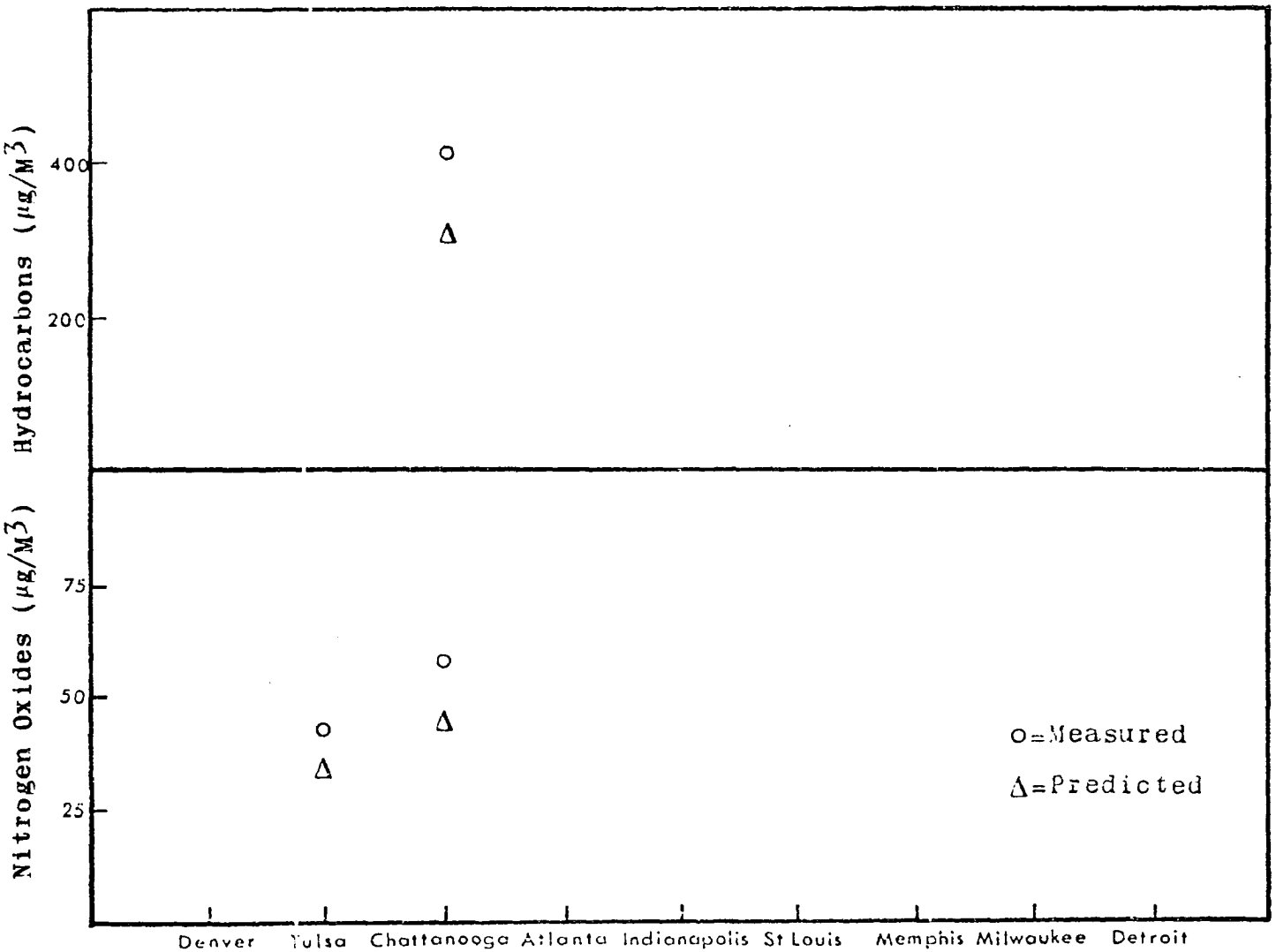

Fig. 36.--Predicted vs measured concentrations of Nitrogen Oxides and Hydrocarbons

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this model is to function along with other models to predict the future conditions in a developing city. It is important that urban planners, both civil and political, be able to visualize the eventual growth of their city, the problems that will most probably occur, and the cost to eliminate these problems. As concerns air pollution, this model develops from the predicted growth of cities, ranging in size from 40,000 to 2 million population, a projection of the expected emissions, concentrations, and costs-to-abate of air pollutants. It can be used to determine the approximate time in the future that a specific city might exceed the air quality standards.

This research used the correlations between the progression of demographic data and emissions data to construct a model that will predict the air pollution concentrations and costs-to-control based upon demographic data inputs alone from a population model. Correlations were run for twenty-three cities ranging in size from 40,000 to 2,000,000

population. These correlations are between total pollutant emissions and demographic factors such as population, number of passenger vehicles registered in the county, and the percent of the work force employed in manufacturing. Land area is used to unitize the emissions on a ton per square mile per year basis. Using these correlations to describe cities of increasing size and age, a linear modeling technique is used to describe the future air pollution emissions in a growing city either on a geographical growth pattern or a population-industrial growth pattern.

The model also provides that the measured emission values for a city may be substituted in the predicted emissions formulae to establish a more representative regression for that city.

Reductions in air pollution emissions from mobile sources as a result of the Air Quality Act's requirements for the manufacture of reduced-pollution engines by 1975 - 1976 are predicted by a step-function. It is estimated that a ten year period will be required for the eventual replacement of high pollution-potential engines.

Future concentrations of air pollution in a growing city are predicted through the use of meteorological retention factors developed by George C. Holzworth. The Holzworth retention factors, presented as isopleth values, are integrated into zones with average retention factor values. This averaging is considered to be valid since

Holzworth found that the progression of the values between isopleths was practically linear.

In order to determine if the predicted air pollution concentrations will be within the limits of the existing legal standards the difference between the predicted concentration and the standards are calculated. If the concentrations exceed the standards, the amount of the excess is considered to be the amount that must be abated in the future.

The total costs-to-abate are predicted by multiplying an average cost-per-ton to abate, (developed by LeSourd, et. al.), by the number of tons in excess of the standards.

The three parameters of population, percent of work force employed in manufacturing, and the number of passenger vehicles registered in the county were added together after their means had been normalized to 0.680 which was the mean of the population. This was accomplished by adding .437 to each value of percent of work force employed in manufacturing, and adding .261 to each value of the passenger vehicles registered in the county.

Statistical sample regressions were calculated and, although definite linear progression trends were indicated, the data was so widely scattered around the regression line that any prediction made from the data would have such a large margin of error as to render it highly inaccurate. In order to make the data display more linear and, therefore, more predictive of city growth it was determined that a data-

shift technique might be employed.

A function was developed so that a different numerical constant for each of the five types of pollutants would move the data points horizontally to near the regression line. Emissions are predicted in tons/Mi^2/yr by comparing the sum of the demographic parameters of the subject city with the emissions from a city of like characteristics in the statistical data base. However, the data base has been subjected to a data-shift which requires that the subject city parameters must also be subjected to this same data-shift.

The accuracy of the prediction formulas can be increased if the results of a current emissions inventory (Y_M) are substituted for the Y factor equalities. In effect, this substitution establishes a regression line parallel to the base-data regression but typical of the growth of the subject city.

Under the assumption that the automobile manufacturers will develop an engine that will meet the requirements of the Air Quality Act by 1975-1976 and that the sales of new automobiles will remain substantially constant, a step-function was developed to predict these emissions reductions. A percent per year of reduction of carbon monoxide, hydrocarbons, and nitrogen oxides is calculated and is applied for a total of ten years which is the period required to replace effectively all of the light duty vehicles in use.

The average early morning concentrations of air pollutants are calculated by dispersing the predicted emissions

over the city according to a meteorological technique developed by George C. Holzworth.

The model provides for the use of either the national or the individual state air quality standards to be used in the determination of the amount of emissions in excess of those standards.

Holzworth (1966) found that source strengths derived for the afternoon, when the maximum polluting activities tend to occur, had a tendency to cause his model to over-calculate early morning concentrations. Holzworth (1971) also found that the $\bar{X}/\bar{Q}$ values, or retention factors, are generally much less for afternoon than for early morning mixing height and wind speed values. Most ambient air concentration standards describe the average concentrations over an 8 hour period or longer, therefore, it was necessary to determine how much the Holzworth retention factors must be reduced to make the model predict average, rather than early morning concentrations.

The necessary amount of reduction became known when the predicted concentrations for 9 cities were compared with the measured concentrations of those cities (Table 29 of the Appendix). The model predicted particulate concentrations too high by an approximate factor of 2 and predicted gaseous concentrations too high by an approximate factor of 3. When the retention factors are divided by 2, for particulates, and by 3, for gases, the model predicts

concentrations somewhat lower than the measured concentrations but with an approximate 84% accuracy. This tendency to predict low can be accounted for by the inclusion of background pollutants and windborne pollution from other cities in the measured concentrations of the 9 cities used in the validation.

The emissions prediction accuracy of the model is only 64%, however, when the high variance of the distribution of the original data around the regression lines, as shown in Figures 5, 6, 7, 8, and 9, is taken into consideration a 64% prediction accuracy becomes a reasonable achievement.

No information concerning the amounts that individual cities exceeded the standards was available although several cities reported that the concentrations of certain pollutants were above the standards. The excess emissions predicted by the model were calculated and are presented in Table 28 along with the predicted costs-to-abate for these cities. It was found that 7 of the 9 cities were exceeding the standards in their concentrations of sulfur oxides, 3 of 9 cities were exceeding the standards in particulate concentrations, and one city had excess concentrations of hydrocarbons.

The total costs-to-abate are calculated for the excess emissions that are predicted and are intended to be more comparative than suggestive. As an example: The model

TABLE 28

EXCESS EMISSIONS AND COST-TO-ABATE
FOR VALIDATION CITIES

	EXCESS EMISSIONS (TONS/Mi^2/YR)					COST-TO-ABATE (DOLLARS/Mi^2/YR)				
	PA	SO_2	CO	NO_x	HC	PA	SO_2	CO	NO_x	HC
DENVER			-	-				-	-	
TULSA										
CHATTANOOGA					103.1					5628.23
ATLANTA		21.8					1190.06			
INDIANAPOLIS		60.8	-	-			3319.07	-	-	
ST. LOUIS		92.8					5065.95			
MEMPHIS	7.9	83.9				431.26	4580.10			
MILWAUKEE	29.9	159.8				1632.24	8723.48			
DETROIT	114.9	445.8	-	-		6272.39	24336.22	-	-	

U.S. PRIMARY STANDARDS	COST-TO-ABATE/TON
PA = 75 $\mu g/M^3$	$54.59
SO_2 = 80 $\mu g/M^3$	
CO = 10 mg/M^3	
NO_x = 100 $\mu g/M^3$	
HC = 160 $\mu g/M^3$	

indicates that Memphis, Tennessee must spend $431.26 per square mile to reduce its particulate concentrations to a level commensurate with the standards, where Detroit, Michigan would be required to spend $6,272.39 per square mile to comply with these same standards.

Conclusions

This model will provide urban planners with a method for predicting future air pollution problems. Since it provides the capability of predicting the approximate time in the future when a city might be expected to exceed the Air Quality Standards, it allows planners to calculate projected monetary requirements sufficiently in advance to more easily facilitate budgeting. This advance warning of potential air pollution problems will also aid planners in determining the best location and magnetude of industrial development projects. Decisions concerning the location and type of electric power production will be made more accurate by this model, as will the proper location of maximum utilization transportation facilities. In short, the future development and utilization of all forms of air pollution emitters may become more predictable and more controlable as a result of this model.

The model will provide predictions of future air pollution emissions for cities ranging in size from 40,000 to 2,000,000 population with a 63.93% prediction accuracy. It will provide predictions of future air pollution concentrations with an 83.59% accuracy. Future costs-to-abate can be projected and it can identify the type of pollution that will most probably need to be abated. However, as with every other type of model there are limitations that must be realized in its application.

Since this model uses as input the population, percent of work force employed in manufacturing, and the number of registered vehicles in the county that are predicted by population forecast models, the predictions made by this model can not be more accurate than the accuracy of the population forecast models.

Further, this is a probability model, therefore it does not take into consideration the possible world which can be one of large disaster or unforeseen prosperity. It is based upon present-day technological knowledges and techniques and does not provide for scientific progress nor gross sociological changes.

All costs are based upon the expected costs of 1976 and no provision is made for either future inflation or depression of the economy.

Attempts to extrapolate the model for cities below 40,000 or above 2 million population may greatly decrease the prediction accuracy.

The model may not predict accurately for cities with relatively little manufacturing and with either nuclear or natural gas power production.

It does not predict the concentration's of vehicle emissions gases accurately for resort areas where the majority of the motor vehicle travel is by vehicles registered outside the county.

Future updating of the model, using the current emissions data from 100 or more cities, will probably increase the prediction accuracy by several percentage points. It is feasible that with sufficient reference data the model can be driven by the projected increases of population and land area only with at least as great a prediction accuracy as it now possesses. These improvements may be recognized only after additional data is generated.

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APPENDIX

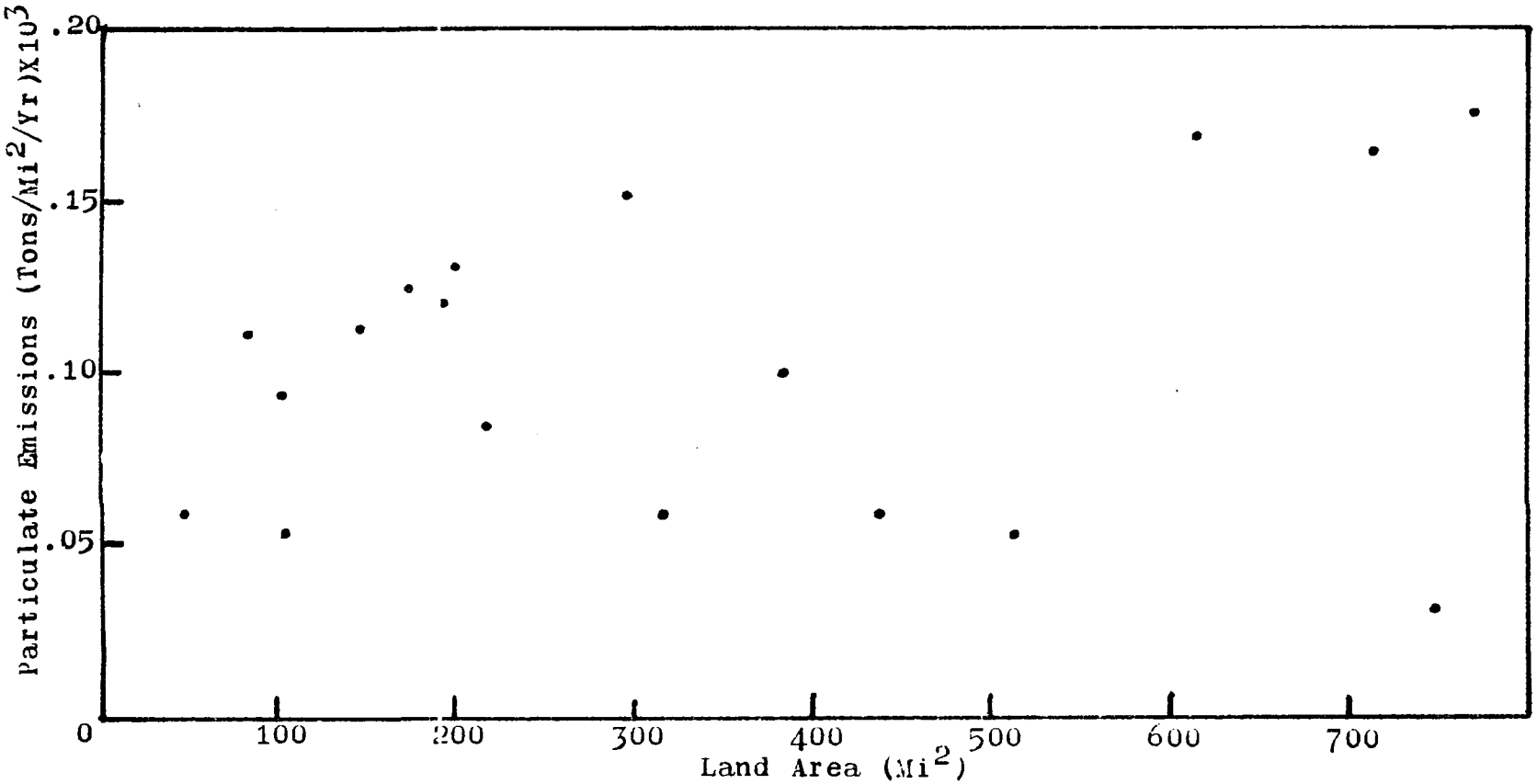

Fig. 37.--Particulate emissions as a function of Land Area

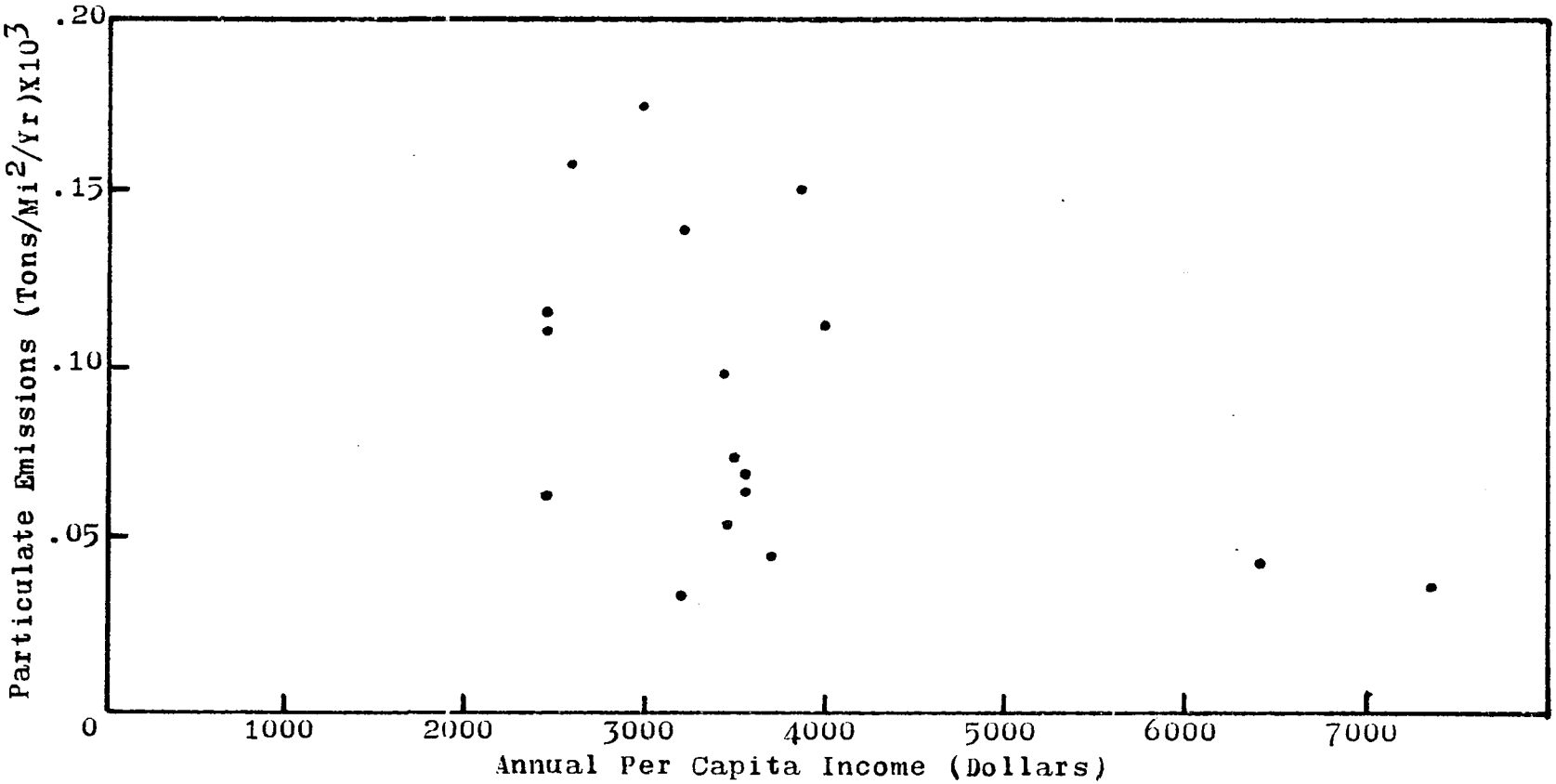

Fig. 38.--Particulate emissions as a function of Annual Per Capita Income

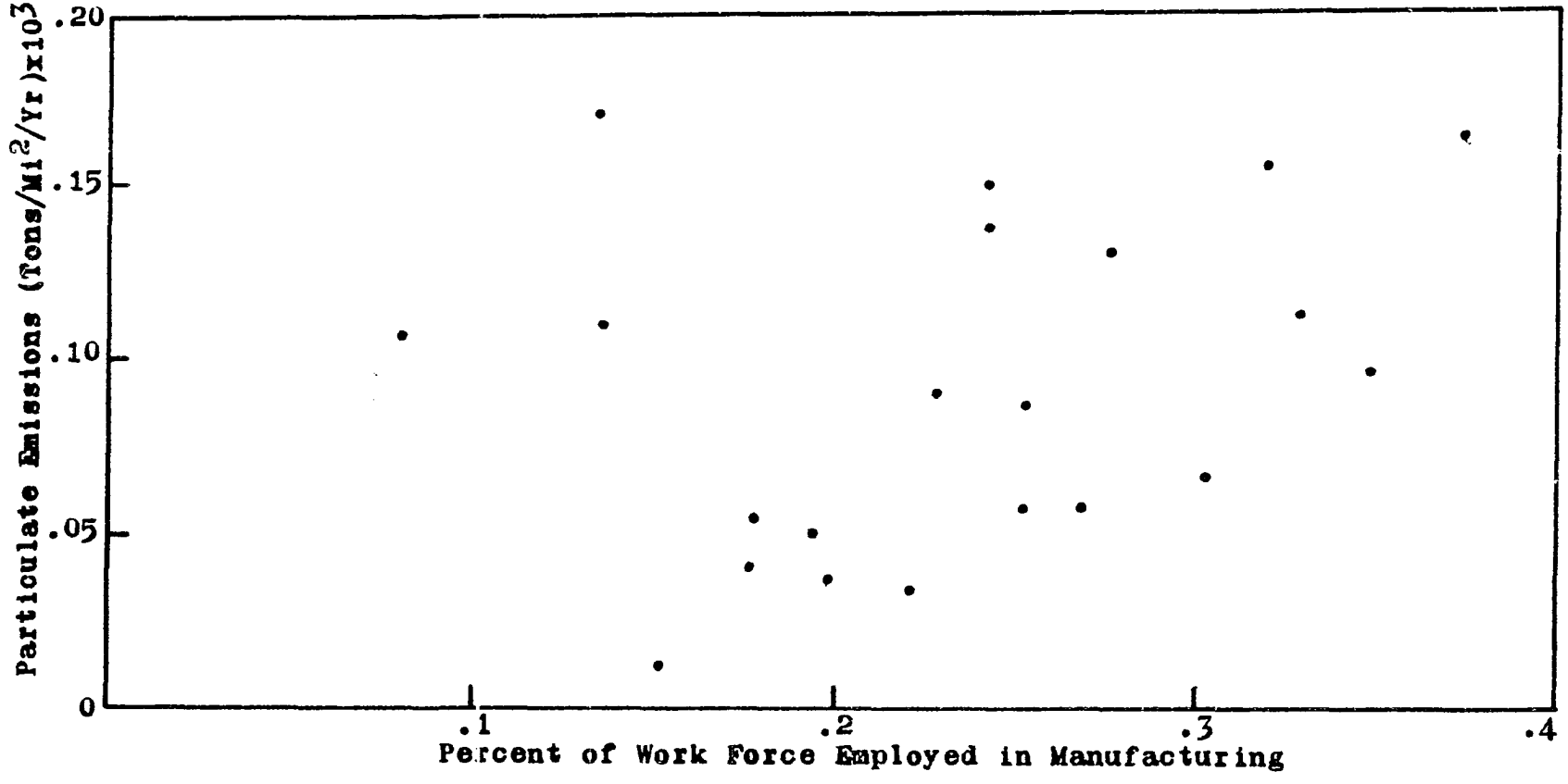

Fig. 39.--Particulate emissions as a function of percent of work force employed in manufacturing

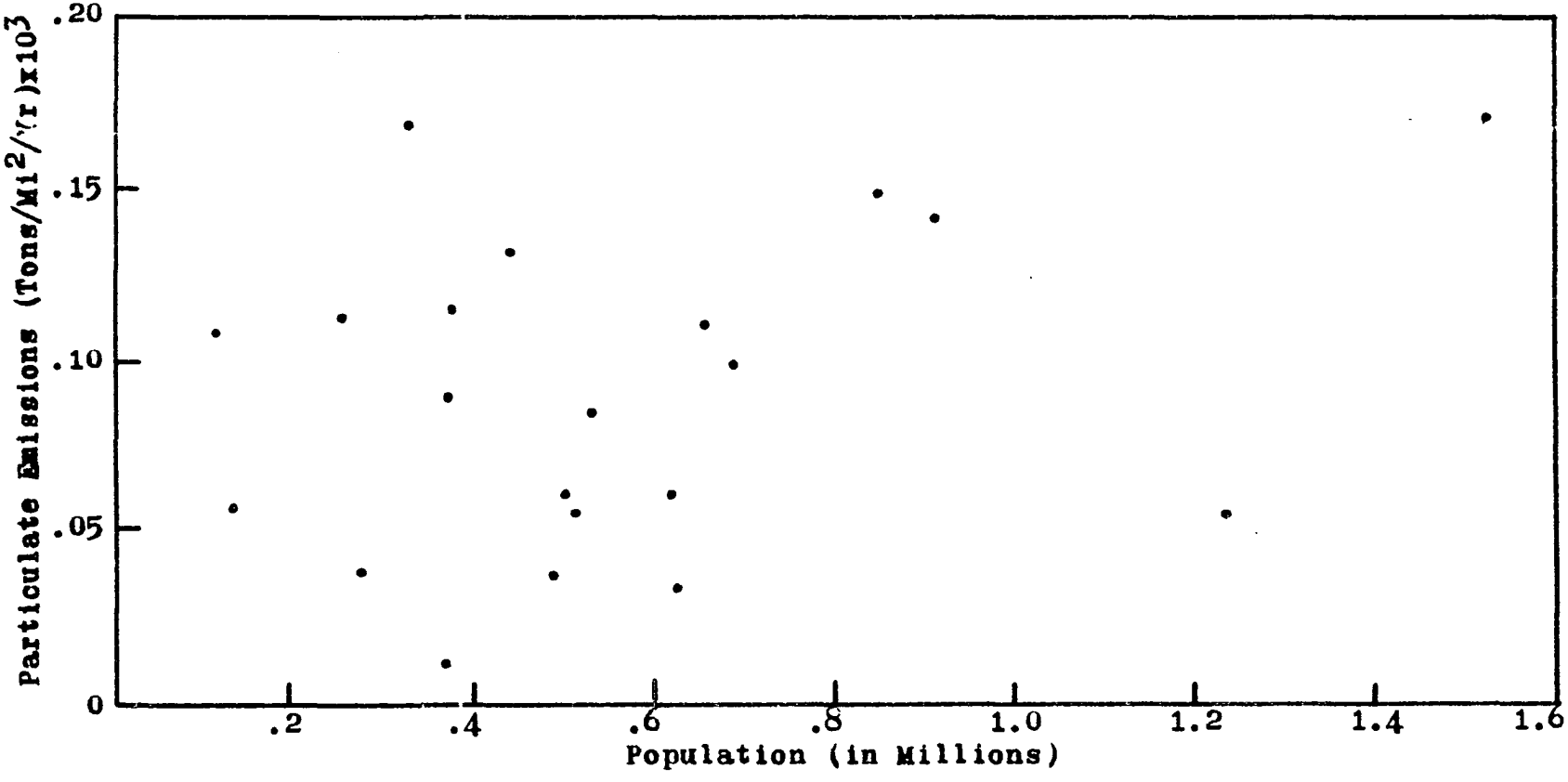

Fig. 40.--Particulate emissions as a function of population

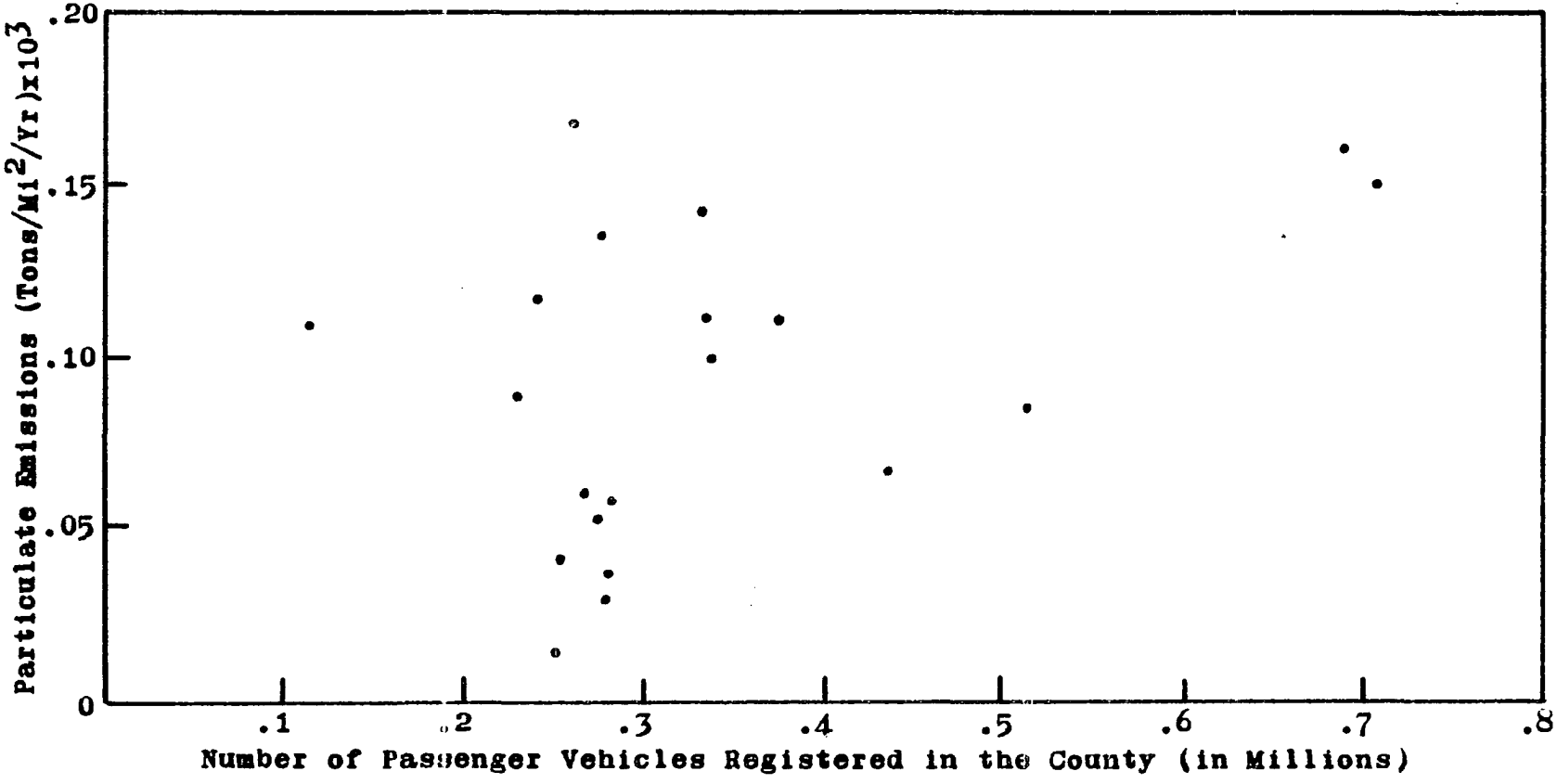

Fig. 41.--Particulate emissions as a function of the number of passenger vehicles registered in the county

TABLE 29

ERROR OF CONCENTRATIONS PREDICTED BY THE HOLZWORTH RETENTION FACTORS

City	CONCENTRATION ($\mu g/M^3$)											
	PART			SO_2			CO			NO_X		
	Pred	Meas	% Error	Pred	Meas	% Error	Pred	Meas	% Error	Pred	Meas	% Error
Detroit	342	140	144	984	300	228						
Memphis	164	90	82	381	130	193						
Denver	60	40	50	132	60	120	759	320	137			
Chattanooga	110	72	53	216	52	315				135	58	133
St. Louis	148	95	56	363	130	179	2049	650	215			
Atlanta	120	70	71	270	100	170						
Indianapolis	136	80	70	321	130	147	1818	540	237			
Milwaukee	200	117	71	507	156	225						
Tulsa	78	53	47	162	78	108				111	40	178
Average Percent of Error			+72			+187			+196			+156
Average Error for All Gases												+150