The Urban Heat Island, Photochemical Smog, and Chicago: Local Features of the Problem and Solution

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EXECUTIVE SUMMARY

High rates of urbanization have resulted in drastic demographic, economic, land use, and climate changes. The growth and expansion of cities entails the construction of new roads, buildings, and other human made structures to accommodate the growing population, and in turn, the destruction of the natural ground cover and landscape. As a result, urban microclimates, referred to as urban heat islands, with elevated air temperatures of 2-8°F, increased energy demands, and elevated pollution concentrations are created.

It has been proposed that as a result of a decrease in temperature, the modification of an urban surface to include more vegetative cover and lighter, lower albedo surfaces would also reduce ozone exceedances, energy consumption, and detrimental environmental and human health effects associated with high levels of ozone. Chicago is among the cities classified as a severe ozone nonattainment area, and is the focus of this study. The purpose of this investigation is to characterize the ozone and temperature relationship in the Chicago area, review strategies that diminish ambient urban temperatures, with particular attention to comparing the total costs associated with asphalt and concrete pavement design, and present the results of an urban fabric analysis for Chicago that reveals areas and land uses where cooling strategies may have the greatest impact.

The Chicago area ozone and temperature relationship was found to have a rather weak correlation, which suggests that there are other factors present that dictate the quality of Chicago's air. In fact, our analysis, in conjunction with studies conducted by the Ozone Transport Assessment Group (OTAG), established that Chicago's ozone problem is strongly correlated with local and regional wind patterns and atmospheric transport. There is, however, a clear temperature threshold. Over a five year period for 13 monitoring stations, ninety percent of the ozone exceedances in the metropolitan area occurred at temperatures above 80°F and the likelihood of smog events increases at extreme temperatures over 95°F.

The temperature profile of Chicago showed that the actual heat island in the Chicago area consistently appears in the western suburbs (specifically over Lisle), not in the Downtown area. An examination of the ozone data for the Chicago area, specifically Cook County, revealed that the majority of the noncompliance days are not located in Downtown Chicago. Instead, they appear to center around the northern suburbs.

When the heat island and ozone levels in various locations of Chicago are compared, it is observed that the areas having a greater frequency of ozone noncompliance do not correspond to the heat island and these areas are located in a region with few known emissions sources. The result of this comparison supports the hypothesis that atmospheric and surface transport mechanisms greatly influence the ozone distribution in the Chicago area. In addition, this observation indicates that the occurrence of elevated ozone concentrations is a regional issue, although it can be assumed that that a portion of the ozone originates from within the domain as a result of the reactions of O_3 precursors.

Urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. While many of the factors that influence the formation of urban heat islands, including climate, topography, and weather patterns, cannot be changed or altered, there are efficient and cost-effective ways of mitigating heat islands exist. Two heat island factors attributable to human activities can be readily controlled: the amount of vegetation and the color of surfaces.(3) Increasing vegetative cover through strategic landscaping around buildings and throughout cities

can absorb solar radiation, provide shade, and control wind flow benefits. Changing dark colored surfaces to light colored ones would more effectively reflect, rather than absorb, solar energy and emit stored heat energy at a higher rate, thus reducing the cooling energy loads and ground level air temperatures influenced by these surfaces.

While little resistance is typically encountered in devising programs to increase tree plantings and vegetative cover, greater obstacles are met with efforts to change construction and paving practices. This report has focused on evaluating the impacts and costs associated with asphalt verses concrete pavement.

Traditionally in life cycle cost analysis, an emphasis has been placed on the respective costs of different pavement alternative throughout their lifetimes. As a result, when concrete and asphalt systems are compared, the asphalt pavement alternative is usually selected because a concrete system is more expensive to construct and maintain.(35) Life cycle assessment, using environmental value engineering, employs a systems approach methodology to more accurately compare the input requirements and related environmental impacts of pavement alternatives.(42) As a result, when concrete and asphalt highway pavement systems are compared using this revised life cycle analysis approach, concrete proves to be superior. In fact, it has been shown that based on a normalized unit of comparison, overall concrete is approximately 47.6% more efficient than asphalt.

Land use and surface cover are elements of the urban fabric that are commonly altered during the development of metropolitan areas. Because these elements, which include vegetation, building roofs, and pavements, act as the active thermal interfaces between the atmosphere and land surfaces, their composition and structure within the urban canopy layer largely determines the thermal behavior of different areas within a city. Thus, the alteration of these surfaces results in the creation of numerous urban microclimates; the combined result of which is referred to as the heat island effect.(52)

In order to accurately analyze the effect of surface cover modifications, attain pertinent results, and eventually simulate realistic estimates of temperature and ozone reductions resulting from these modifications, the current urban fabric of the Chicago must be quantified as it relates to land use.

Based on our urban fabric analysis it was found that the residential vegetative cover is relatively high, above 45%, over all the different density areas within the city of Chicago. Thus, it is also concluded that Chicago is already doing a relatively good job in the residential areas with respect to maintaining a high vegetative cover to paved surface ratio, of approximately 2.2-4.2. In contrast, the commercial and industrial areas in the Chicago area have the least proportion of vegetative cover, about 10-16%.

The analysis of roofed surface cover revealed that this proportion is dependent upon the building density within a particular land use category. Thus, it was observed that recreational and far suburban residential areas contain the least portion of roofed surfaces, less than 13%, for they have the lowest building density associated with them. In addition, when light/white roofs were separated out, it was revealed that lighter roofing materials are already in wide use in Chicago with the greatest percentage of light/white roofs was found in commercial areas, 66-90%. This point illustrates the feasibility of employing light roofing materials, in the construction and resurfacing of building roofs, as a heat island mitigation strategy in the Chicago area. Specifically, an emphasis should be placed on the suburbs where a high degree of development is occurring.

The paved surface cover was found to be the greatest in the transportation, commercial, and industrial areas, where its proportion is above 50%. In addition, the vegetative cover to paved surface ratio in these three areas is small, about 0.2-0.5. As a result, an emphasis should be placed upon developing and implementing mitigation strategies within the transportation, commercial, and industrial areas of Chicago. These mitigation strategies should include a focus on greater use of concrete over asphalt, and in general, should encourage the use of higher albedo paving materials the suburban areas that almost exclusively use asphalt for pavement. However, a change to the utilization of concrete over asphalt will require urban and suburban planners to compare costs over longer design lives and consider all the environmental costs associated with a material's use, neither of which is currently done. The life cycle analysis reviewed herein presents one methodology for making such a comparison.

The use of cooling strategies, such as increased vegetation and use of high albedo surfaces, if applied to the metropolitan Chicago area may be expected to produce a decrease in temperature, similar to that predicted for the LA Basin. However, most ozone noncompliance days are not solely the result of temperature effects and the majority occurs at temperatures above 85°F. Therefore, a 4°F decrease in temperature, as observed for surface modification simulations within the LA Basin (3,4), would probably have a similar, small effect by promoting a 10-12% reduction in the overall number of ozone noncompliance days in the Chicago area. Based upon observed data, a 10-12% reduction in the total number of ozone noncompliance days would translate into only approximately 0.6 days per year. Therefore, it is important to consider and examine more fully the other benefits, in addition to lower ozone levels, that are promoted by cooling strategies. These additional benefits include reduced energy demands, increased health protection, and increased comfort.

1. INTRODUCTION

1.1 PROBLEM STATEMENT

The purpose of this project is to identify the effect that surface modifications have on the urban heat island phenomenon and related ozone problem in the metropolitan area of Chicago, IL. The basic hypothesis is that urban, summertime temperatures can be significantly lowered by increasing the vegetative landscape cover and enhancing the solar reflectivity of paved and roofed surfaces within an urban area. It is proposed that in addition to a decrease in temperature, the modification of an urban surface to include more vegetative cover and lighter, lower albedo surfaces will also reduce energy consumption, ozone exceedances, and detrimental environmental and human health effects associated with high levels of ozone.

The analysis is divided into three main parts. The first section of this report introduces the causes of ground level ozone and its effects in urban areas. It explains both the chemistry and transport associated with ozone exceedances. The second section is a compilation of the most viable mitigation strategies of urban heat islands: increasing vegetative cover and increasing proportions of light to dark surfaces. The effects, implementation strategies, and specific strengths and weaknesses associated with each approach are described, including a comparison of asphalt and concrete pavements systems using a life cycle analysis approach. The final section provides a case study of the Chicago area. This study entailed an examination of the land use, development of an urban fabric analysis in which total vegetative, paved, and roofed surfaces are investigated and quantified, and discussion on the effectiveness of possible mitigation strategies in the Chicago area. In general, the associated findings of my research are located within this final section.

1.2 OBJECTIVES

The overall goal of this project is to investigate the relationship between the urban heat island phenomenon, the ozone problem, and the effect of urban surface cover and color modifications in the metropolitan area of Chicago, IL.

The specific objectives of this work are to:

- Review the detrimental effects of the urban heat island phenomenon, particularly as a causative factor in promoting exceedances of air quality ozone standards, and identify mitigation alternatives that may reduce the effects of the urban heat island.
- Illustrate the differences in temperature between the urbanized center of Chicago and the surrounding areas in order to identify the heat island in the Chicago region.
- Examine the spatial distribution of ozone levels in the Chicago area and consider probable sources.
- Evaluate of the relationship between temperature and ozone.
- Develop a method to analyze the urban fabric of the Chicago area from aerial photographs, thus allowing the determination of the proportion of vegetative, roofed, and paved surfaces as a function of land use.
- Evaluate of the effectiveness of possible mitigation strategies as applied to the Chicago area, with special focus on vegetation and paving materials.

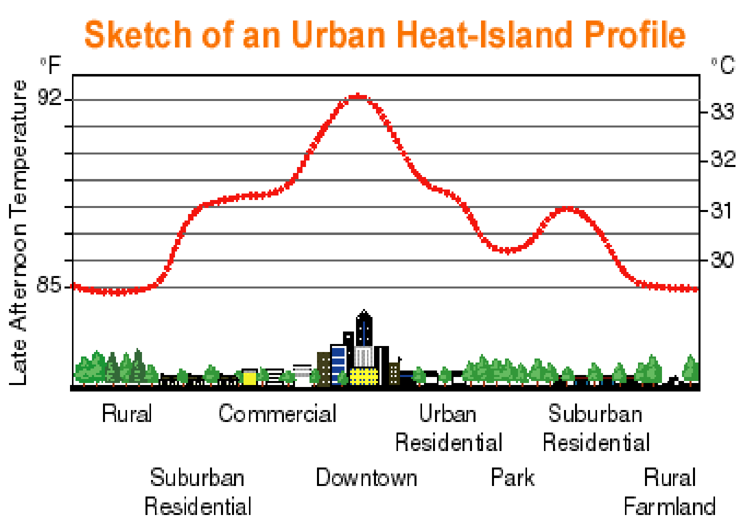
2. BACKGROUND

2.1 THE URBAN HEAT ISLAND

Over the past century, there has been an increasing trend towards urbanization. In 1900, approximately 150 million people lived in urban areas with populations of 20,000 or more. This was less than 10% of the world's population. Today this population has grown to approximately 2.2 billion, which constitutes close to 50% of the world's population.(1) In the United States today, roughly 80% of the people reside in metropolitan areas.(2)

High rates of urbanization have resulted in drastic demographic, economic, land use, and climate changes. The growth and expansion of our urban centers entail the construction of new roads, buildings, and other various human made structures to accommodate the growing population, and in turn, the destruction of the natural ground cover and landscape. This urbanization of the natural landscape can have profound meteorological impacts causing urban microclimates, referred to as **urban heat islands**, with elevated air temperatures of 2-8°F, increased energy demands, and elevated pollution concentrations compared to rural surrounding areas.(3) *Figure 1* provides an illustration of a typical heat island profile for a metropolitan area.

Figure 1



Source: Cooling Our Communities, USEPA (3)

While, most cities today exhibit heat island effects relative to predevelopment conditions, their individual intensities depend on a number of factors: geography, topography, land use, population density, and physical layout.

Urban heat islands are exacerbated by the loss of vegetation combined with the large quantities of low albedo surfaces, such as dark paving and roofing materials in urban areas. Vegetative cover, which includes trees, shrubs, and other plants, not only provides shade for buildings by intercepting solar radiation, but can cool the air by the evapotranspiration of absorbed ground water through its leaves. When this vegetative cover is destroyed, it is usually replaced by either pavement or buildings, which results in not only the loss of beneficial cooling mechanisms but the addition of detrimental heating effects. These detrimental heating effects are related to the albedo and emissivity of the paving and roofing materials utilized in the construction.

Most of materials used in construction produce low albedo and low emissive surfaces. Low albedo surfaces have low reflectivity, and consequently absorb solar radiation, instead of reflecting it back into space. Low emissive surfaces release this trapped heat energy slowly, thus causing the cooling process to progress at a slow rate also. These combined properties may result in an increase in the temperature of the surfaces, as much as 85°F above the ambient air temperature (4), which can sustain high temperatures into the night. For example, on a 90°F day, a dark asphalt parking lot surface can heat up to a temperature of 175°F. When the sun sets, the pavement surface will slowly begin to release the stored heat energy it accumulated throughout the day. However, as the pavement starts to cool off, the air around the surface begins to heat up, consequently maintaining elevated temperatures into the night. Thus, the thermal processes active in a heat island begin with the sunrise in the early morning, continue throughout the day, and often persist into the night.

The heating of urban areas has serious consequences that can effect both human health and the environment. Elevated temperatures can result in the degradation of urban air quality due to an increase in the rate of the formation of ground level ozone, which is the principal component of photochemical smog and the primary component of concern related to the heat island effect. The higher temperatures also create increased energy use, which is primarily due to a greater demand for air conditioning, for prolonged periods of time. It is estimated that for U.S. cities with populations larger than 100,000 people, peak utility loads will increase 1.5 to 2% for every 1°F increase in temperature.(3) Thus, as power plants burn more fossil fuels to meet the increase in energy demand, they also drive up both energy costs and pollution levels which may eventually lead to increased ozone production. In fact, one sixth of the electricity currently consumed in the United States goes to cool buildings, at an annual power cost of $40 billion.(4)

There are various ways of combating the urban heat island effect. One strategy is to increase the vegetative cover in urban areas so as to reestablish the beneficial cooling effects associated with it. Another strategy is to implement the use of lighter, high albedo materials for pavement and roofs. More reflective, cooler pavements have benefits in addition to reduced energy and photochemical smog. The use of cooler pavements can lead to longer pavement lifetimes, for high albedo pavement is less likely to be softened and damaged at high temperatures. In addition, at night, lighter pavements will reflect more light onto pedestrians and signs, helping to avoid accidents.

2.2. AIR QUALITY IN URBAN AREAS – GROUND LEVEL OZONE

Ozone (O_3) is a reactive oxidant gas produced naturally in trace amounts in the earth's atmosphere, and, depending upon its location in the atmosphere, ozone can be good or bad. The majority of the earth's atmospheric ozone, approximately 90%, is found in the stratosphere, where it acts as a protective layer absorbing harmful ultraviolet radiation emitted by the sun and preventing it from reaching the earth's surface. The remaining 10% of the earth's ozone is located in the troposphere and is often referred to as ground level ozone. Here ozone exists as the primary ingredient in photochemical smog and has detrimental effects on human health and the environment.

Smog, traditionally defined as the combination of smoke and fog, is produced when both primary and secondary gaseous, aerosol, and particulate pollutants get trapped in the air. Primary air pollutants, such as carbon monoxide (CO), carbon dioxide (CO_2), sulfuric dioxide (SO_2), nitrous oxide (NO), suspended particulate matter, and hydrocarbons (volatile organic compounds), are substances released directly into the atmosphere. Secondary air pollutants, such as nitrogen dioxide (NO_2) and ozone (O_3), are formed as a result of reactions between primary pollutants and other naturally occurring constituents present in air.

The primary active pollutants in the creation of photochemical smog are nitrogen oxides (NO_x) and volatile organic compounds (VOCs). In the presence of sunlight, these reactants are rapidly converted to secondary pollutants, most of which is ozone, but organic nitrates, oxidized hydrocarbons, and photochemical aerosols are also part of the mix. Understanding the atmospheric chemistry and meteorological parameters and processes responsible for the formation of an occurrence of elevated concentrations of ozone in the ambient air is basic to the formation of strategies and techniques for its abatement. Such an understanding is required for representing those parameters and processes adequately in predictive models used to determine the emission reductions needed for complying with the National Ambient Air Quality Standards (NAAQS). In addition, the identification and quantification of ozone precursors in the ambient air are essential, along with emission inventories or emission models, for the development, verification, and refinement of photochemical air quality mechanisms and models, quantifying emission rates, and adequately characterizing exposure-response factors for both biological and non-biological receptors.(5)

2.2.1. Effects

Over the last several decades, as a result of expanding population and industrial growth, air pollution, specifically ozone, has had increasing serious and wide spread impacts on the natural environment and human society. Ozone is the prime ingredient of photochemical smog in our cities and other areas of the country. Though it occurs naturally in the stratosphere to provide a protective layer high above the earth, at ground level, high concentrations of ozone can be harmful to people, animals, crops, and other materials.

Human Health Effects

Scientists have been studying the effects of ozone on human health for many years and have found that about one out of every three people in the United States is at a higher risk of experiencing ozone related health effects.(6) So far, several types of ozone related short-term health effects have been detected, but the specific mechanism associated with these effects are not known. When inhaled, even at very low levels, ozone can:(6,7,8)

- irritate the respiratory system and cause acute respiratory problems;
- reduce lung function and temporarily decreasing lung capacity approximately 15 to 20 percent in healthy adults;
- aggravate asthma increasing the seriousness and frequency of attacks that require medical attention or the use of additional asthma medication;
- inflame and temporarily damage lung tissue;

- may aggravate chronic lung diseases, such as emphysema, bronchitis, and pneumonia;
- impair the body's immune system defenses, making people more susceptible to respiratory illnesses, including emphysema, bronchitis, and pneumonia; and
- lead to increase hospital admissions and emergency room visits for 10 to 20 percent of all summertime respiratory-related hospital visits in the northeastern U.S. are associated with ozone pollution.

All these effects are considered to be short-term effects because they disappear once exposure has ended. Scientists, however, are concerned that long-term, or repeated short-term, exposures to ozone may irreversible changes in lung. For example, there is concern that repeated ozone impacts on the developing lungs of children may lead to reduced lung function as adults. Also, there is concern that ozone exposure may worsen the decline in lung function that occurs as a natural result of the aging process. Research is ongoing to help better understand the possible long-term effects of ozone exposure.(6)

Children are most at risk from exposure to ozone because they are outside playing and exercising in backyards, playgrounds, neighborhood parks, and summer camps during the summer months when ozone levels are at their peak. In addition, children breathe more air per pound of body weight than adults, and because their respiratory systems are still developing, they are more susceptible than adults to ozone related threats. For example, summer camp studies in the eastern U.S. and southeastern Canada have reported significant reductions in lung function in children active outdoors.(7)

Asthmatics are also at high risk for ozone related problems, and fourteen Americans die every day from asthma, a rate three times greater than just 20 years ago.(7) Although there is no evidence that ozone causes asthma or other chronic respiratory disease, individuals with these conditions will generally experience the effects of ozone earlier and at lower levels than less sensitive individuals. In the United States, asthma is a growing threat to both children and adults. Children, in particular, make up 25 percent of the population and comprise 40 percent of the asthma cases.(7)

Healthy adults who are outdoors and moderately active during the summer months, such as construction workers, landscapers, and joggers, are also among those most at risk because they are exposed to a higher level of ozone than people who are less active outdoors. These individuals are susceptible because during activity, ozone penetrates deeper into the parts of the lungs that are more vulnerable to injury.

Scientists have studied other groups to find out whether they are at increased risk from ozone. So far there is no evidence to suggest that either the elderly or people with heart disease have heightened sensitivity to ozone. However, like other adults, elderly people will be at higher risk from ozone exposure if they suffer from respiratory disease, are active outdoors, or are unusually susceptible to ozone as described above.(6)

Environmental Effects

Review of the scientific literature also highlights a wide range of biological, physical, and chemical factors associated with ozone's effects in the environment. The effects of ozone on terrestrial ecosystems begin with the responses of individual biotic organisms, which vary among species and depend upon pollutant concentration, exposure period, development stage, nutrition, climate, insects, and disease. The effects are initiated by reactions between ozone and the cellular constituents that influence biochemical and physiological plant processes.(9)

Most plants require a balance of resources to maintain optimal growth, and when injured or stressed, plants compensate by allocating their available resources to the point of detriment to minimize stress effects. Exposure of vegetation to tropospheric ground level ozone causes an alteration in the allocation of resources, which can affect all aspects of plant growth. In particular, it has been found that ozone can: (7,9)

- cause injury and premature mortality of plant tissues after entering the plant;
- interfere with the ability of plants to produce and store food, so that growth, reproduction and overall plant health are compromised;
- reduce growth and decrease survivability of plant and tree seedlings;
- increase susceptibility to disease, insects, and environmental stresses;
- kill or damage leaves so that they become spotted or brown or fall off the plants too soon which significantly decrease the natural beauty of an area, such as in national parks and recreation areas; and
- reduce the yield of economically important agricultural crops, such as soybeans, kidney beans, cotton, and wheat, and commercial forests.

The effects of ground-level ozone on long-lived species such as trees are believed to add up over many years so that whole forests or ecosystems can be affected. For example, ozone can adversely impact ecological functions such as water movement, mineral and nutrient cycling, energy flow, and habitat conditions for various animal and plant species. However, a significant level of uncertainty encompasses the effects of O_3 at the population and community levels within an ecosystem. This is because very few studies have been conducted on multi-species systems, for the majority of the documented studies report the response of organisms, not ecosystems, to ozone. Thus, further research is necessary to fill in the knowledge gap.(9)

2.2.2. Regulations and Standards

The predominant part of the United States' population is located in its rapidly expanding metropolitan and other urban areas, which generally cross the boundary lines of local jurisdictions and often extend into two or more States. The growth in the amount and complexity of air pollution associated with urbanization, industrial development, and the increasing use of motor vehicles, has resulted in mounting dangers to the public and environmental health and welfare.(10)

Air pollution comes from many different sources and is a result of a wide variety of pollutants. There are six major pollutants, including ozone, are found all over the United States. These pollutants, known as criteria air pollutants, can injure health, harm the environment and cause property damage.

The Clean Air Act (CAA), established in 1970, was established for multiple purposes. First, it served as a principal technical and financial framework for national, state, and local efforts to protect air quality, develop air pollution prevention, and implement control programs. Second, it worked to protect and enhance the quality of the Nation's air resources as to promote the public health, welfare and the productive capacity of its population. Third, it initiated and accelerates a national research and development program to achieve the prevention and control of air pollution.(10,11)

In 1971, under Clean Air Act, the United States Environmental Protection Agency (USEPA) established the National Ambient Air Quality Standards (NAAQS) for the six criteria pollutants in an attempt to protect public health, the environment, and the quality of life from the adverse effects of air pollution. *Table 1* summarizes the current National Ambient Air Quality Standards.(12)

Table 1: National Ambient Air Quality Standards

POLLUTANT	STANDARD VALUE †		STANDARD TYPE
Carbon Monoxide (CO)			
8-hour Average	9,000 ppb	(10 mg/m^3)**	Primary
1-hour Average	35,000 ppb	(40 mg/m^3)**	Primary
Nitrogen Dioxide (NO_2)			
Annual Arithmetic Mean	53 ppb	(100 $\mu g/m^3$)**	Primary & Secondary
Ozone (O_3)			
1-hour Average*	120 ppb	(235 $\mu g/m^3$)**	Primary & Secondary
8-hour Average	80 ppb	(157 $\mu g/m^3$)**	Primary & Secondary
Lead (Pb)			
Quarterly Average		1.5 $\mu g/m^3$	Primary & Secondary
Particulate < 10 micrometers (PM-10)			
Annual Arithmetic Mean		50 $\mu g/m^3$	Primary & Secondary
24-hour Average		150 $\mu g/m^3$	Primary & Secondary
Particulate < 2.5 micrometers (PM-2.5)			
Annual Arithmetic Mean		15 $\mu g/m^3$	Primary & Secondary
24-hour Average		65 $\mu g/m^3$	Primary & Secondary
Sulfur Dioxide (SO_2)			
Annual Arithmetic Mean	30 ppb	(80 $\mu g/m^3$)**	Primary
24-hour Average	140 ppb	(365 $\mu g/m^3$)**	Primary
3-hour Average	500 ppb	(1300 $\mu g/m^3$)**	Secondary

† Units of measure for the standards are parts per billion (ppb) by volume, milligrams per cubic meter of air (mg/m^3), and micrograms per cubic meter of air at 25 C($\mu g/m^3$)

* The ozone 1-hour standard applies only to areas that were designated nonattainment when the ozone 8-hour standard was adopted in July 1997. An area will attain the standard when the 3-year average of the annual 4th-highest daily maximum 8-hour concentrations is less than or equal to 80 ppb. This provision allows a smooth, legal, and practical transition to the 8-hour standard.

** Parenthetical value is an approximately equivalent concentration.

Source: http://ftp.epa.gov/airs/criteria.html (12)

For each pollutant, two limits were established. The first set of limits, referred to as the primary standard, protects public health and is based entirely on health-related information, without considering the costs of attaining the standard. The second set of limits, or secondary standard, is intended to protect public welfare and prevent environmental and property damage. This includes effects on soils, water, crops, vegetation, buildings, property, animals, wildlife, weather, visibility, transportation, and other economic values, as well as personal comfort and well being.(11,12)

Since the USEPA first established the ozone standards in 1971 it has been known that ozone has clear, documented impacts on human health and environmental ecosystems. In 1993, the USEPA reaffirmed the existing standard based on scientific information obtained from ozone studies published through the late 1980s. Since the early 1970's, however, over 3,000 new studies have been published on the health and ecological effects of ozone, as well as on ozone monitoring and ambient air quality levels.(7,11) Many of these new studies indicate that the health effects associated with ozone occur at exposure levels below the current primary standard. In addition, they showed that exposure times longer than one hour may increase human health risks.(7)

In the mid-1990's, another lengthy scientific review process, which included an extensive external scientific review, was initiated. As a result, the USEPA determined that changes in the regulations were necessary to protect public health and the environment. Thus, the Clean Air Act was amended in 1997 to provide a higher level of protection than the current standard. This was accomplished by lowering and changing the form of the standard from an expected exceedance form to a concentration-based form so that it more directly relates to ozone concentrations associated with health effects. This new form also avoids exceedances, regardless of size, from being counted equally in the attainment tests.(7)

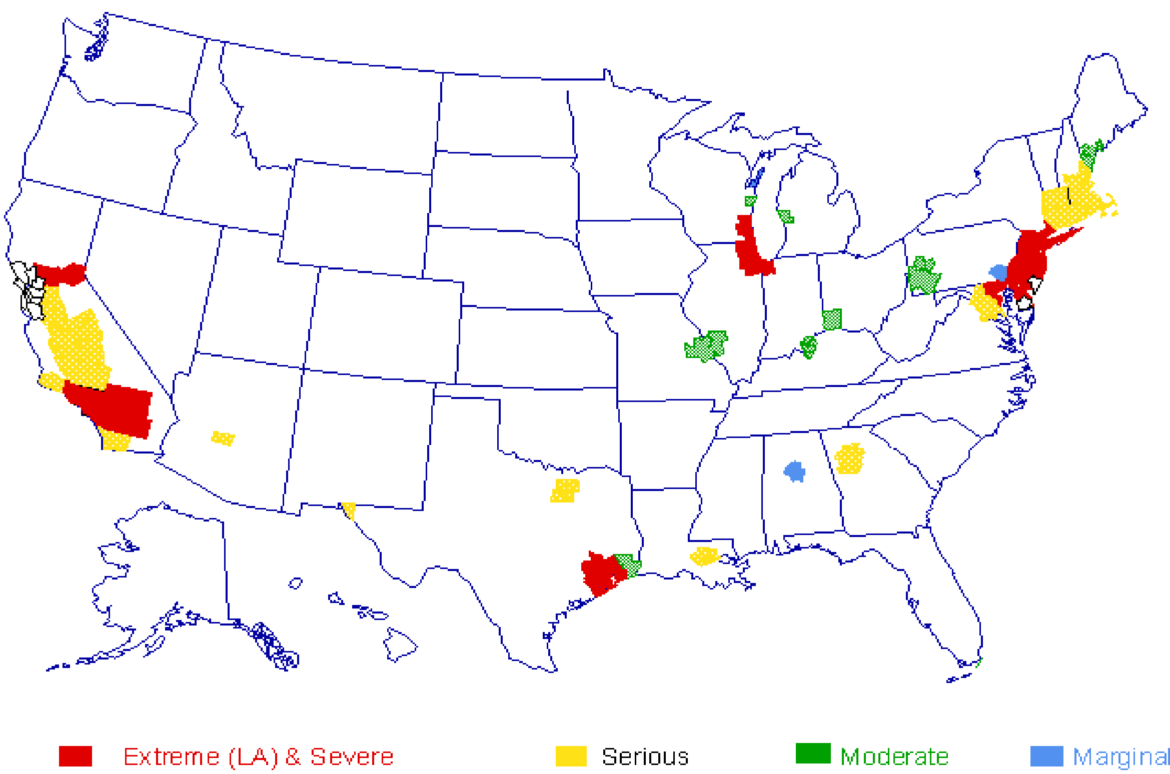
The USEPA sets air quality standards that, above all, protect the public health. The revised standards will provide additional protection to nearly 125 million Americans, including 35 million children by reducing the risk associated with ozone exposure and thus diminishing its damaging effects and prevent approximately 15,000 premature deaths, 350,000 cases of aggravated asthma, and 1 million cases of significantly decreased lung function in children each year.(7,11) However, along with standards for ozone, USEPA will issue an implementation package designed to give states, local governments and business the flexibility they will need to meet protective public health standards in a reasonable, cost-effective way, thus providing for both cleaner air and the nation's continued economic progress.(7)

It is interesting to note that on May 14, 1999, the U.S. Court of Appeals ruled this new standard unconstitutional.(13) Although the USEPA has the authority under the Clean Air Act Amendments of 1990, to set a standard for ozone levels, it does not have the authority to make a stricter standard without conclusive scientific evidence the new standard will improve health. As a result, because ozone does not have a known threshold exposure level, it is difficult to show definitively that a stricter standard of 80 ppb provides better health protection.

A geographic area that meets or surpasses the primary standard is called an attainment area; areas that don't meet the primary standard are called nonattainment areas. Although USEPA has been regulating criteria air pollutants since the 1970 CAA was passed, many urban areas are classified as nonattainment for at least one criteria air pollutant. It has been estimated that about 90 million Americans live in nonattainment areas.(11) The USEPA works with state governors to identify nonattainment areas for each criteria air pollutant, and then classifies these areas according to how badly they are polluted.

There are currently five classes of nonattainment areas for ozone, based on the severity of the pollution problem. These include: marginal, moderate, serious, severe, and extreme. *Figure 2* and *Table 2* provides a map and list, respectively, of the current ozone nonattainment areas for the 1-hour ozone standard, as of July 1998. The results presented with in this table are based on air quality data from 1995-1997. According to these classifications, Chicago is categorized as a severe zone for ozone pollution.(14)

Figure 2: Map of Ozone Nonattainment Areas by Classification



Source: http://www.epa.gov/airprogm/oar/oaqps/ (14)

Table 2: Ozone Nonattainment Areas by Classification

Extreme: 280 ppb and above
• Los Angeles South Coast Air Basin, CA
Severe: 180 up to 280 ppb
• Baltimore, MD • Chicago-Gary-Lake County, IL-IN • Houston-Galveston-Brazoria, TX • Milwaukee-Racine, WI • New York-N. New Jersey-Long Island, NY-NJ-CT • Southeast Desert Modified AQMA, CA • Philadelphia-Wilmington-Trenton, PA-NJ-DE-MD • Sacramento Metro, CA • Ventura Co, CA
Serious: 160 up to 180 ppb
• Atlanta, GA • Baton Rouge, LA • Boston-Lawrence-Worcester (E. MA), MA-NH • Dallas-Fort Worth, TX • El Paso, TX • Greater Connecticut • Phoenix, AZ (Serious as of 12/12/97) • Portsmouth-Dover-Rochester, NH • Providence (All RI), RI • San Diego, CA • San Joaquin Valley, CA • Santa Barbara-Santa Maria-Lompoc, CA (Serious as of 1/9/98) • Springfield (Western MA), MA • Washington, DC-MD-VA
Moderate: 138 up to 160 ppb
• Beaumont-Port Arthur, TX • Cincinnati-Hamilton, OH-KY • Louisville, KY-IN • Manitowoc Co, WI • Muskegon, MI • Pittsburgh-Beaver Valley, PA • Portland, ME • St Louis, MO-IL
Marginal: 121 up to 138 ppb
• Birmingham, AL • Door Co, WI • Kent & Queen Anne's Cos, MD (clean 94-96) • Lancaster, PA (clean 94-96) • Sunland Park, NM (New Area 1995)

Source: http://www.epa.gov/airprogm/oar/oaqps/ (14)

2.3 THE OZONE PROBLEM

2.3.1 Chemistry

The gas phase chemistry of the troposphere involves the oxidation of organic molecules in the presence of nitrogen oxides via free radical chain reactions. Because atmospheric oxidation incorporates very low concentrations of reactants, an external source of energy, in the form of solar radiation, is required to drive the reactions.

Ozone can be considered as the principal product of tropospheric chemistry. The only ozone forming reaction that occurs in the atmosphere is that between atomic and molecular oxygen. The sunlight that reaches the troposphere exhibits wavelengths exceeding only approximately 290 nm. As a result, the source of the atomic oxygen in the troposphere cannot be O_2, for it only absorbs radiation of shorter wavelengths.(15) Instead, the source of atomic oxygen is the photolysis of nitrogen dioxide (NO_2) in the presence of sunlight at wavelengths < 420nm.(15,16) Thus, tropospheric chemistry can be considered to start as a result of the photolysis of NO_2,

$$NO_2 + h\nu \rightarrow NO + O \qquad \text{(E1)}$$

$$O + O_2 + M \rightarrow O_3 + M \qquad \text{(E2)}$$

where M represents N_2, O_2, or another third molecule that can absorb excess vibrational energy thus stabilizing the O_3 molecule formed. Relatively little ozone is formed as a result of reactions (E1) and (E2) alone since O_3, once formed, reacts rapidly with NO to regenerate NO_2,

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad \text{(E3)}$$

Consider for a moment the dynamics of a system in which only reactions (E1), (E2), and (E3) are taking place, assuming that known initial concentrations of NO and NO_2, $[NO]_0$ and $[NO_2]_0$, in the air are placed and irradiated in a reactor of constant volume at constant temperature. The rate of change for the concentration of NO_2 after the irradiation begins is given by,

$$\frac{d[\mathrm{NO_2}]}{dt} = -k_{(1)}[\mathrm{NO_2}] + k_{(3)}[\mathrm{O_3}][\mathrm{NO}] \qquad \text{(E4)}$$

Treating $[O_2]$ as constant, there are four species in the system: NO_2, NO, O, and O_3. The dynamic equation could also be written for NO, O, and O_3, just as was done for NO_2 in equation (E4). For example, the equation for [O] is given by,

$$\frac{d[\mathrm{O}]}{dt} = k_{(1)}[\mathrm{NO_2}] - k_{(2)}[\mathrm{O}][\mathrm{O_2}][\mathrm{M}] \qquad \text{(E5)}$$

If the right hand side of equation (E5) was evaluated numerically, the result would be very close to zero. Physically, this indicates that the oxygen atom is so reactive that it disappears by reaction (E2) virtually as fast as it is formed by reaction (E1). In dealing with highly reactive species such as the oxygen atom, it is customary to invoke the pseudo-steady-state approximation (PSSA) and thereby assume that the rate of formation is exactly equal to the rate of disappearance, for example,

$$k_{(1)}[\mathrm{NO_2}] = k_{(2)}[\mathrm{O}][\mathrm{O_2}][\mathrm{M}] \qquad \text{(E6)}$$

The steady state oxygen atom concentration in this system is then given by,

$$[\mathrm{O}]_{ss} = \frac{k_{(1)}[\mathrm{NO_2}]}{k_2[\mathrm{O_2}][\mathrm{M}]} \qquad \text{(E7)}$$

Note that $[O]_{ss}$ is not constant; rather it varies with $[NO_2]$ in such a way that at any instant a balance is achieved between its rate of production and loss. This approximation illustrates that the oxygen atom concentration adjusts to changes in the NO_2 at a rate many orders of magnitude faster than the rate at which NO_2 concentration changes. As a result, on the time scale of the

NO_2 dynamics concentration, which is dependent on light intensity, the ozone steady state equation (E7) should always be satisfied.(15)

In reality however, the troposphere is not a steady state reactor. Thus, the rate of ozone formation is not simply proportional to the concentration of NO_2. Instead, the rate of O_3 formation is a non-linear function of many factors including temperature, intensity and spectral distribution of sunlight, tropospheric ratios and concentrations of the hydroxyl radical (HO•), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), and their corresponding chemical compositions.

The hydroxyl radical (HO•), in particular, is key with respect to ozone chemistry. Although it does not react with any of the major constituents of the atmosphere, such as N_2, O_2, CO_2, or H_2O, the OH radical is the most reactive species in the troposphere. This is because it reacts with most trace species in the atmosphere, is present in relatively high concentrations (on the order of 10^6 molecules cm^{-1} during daylight hours (15)), and is regenerated as a result of its atmospheric reactions. The OH radical is generated through the photolysis of ozone via the following atmospheric reaction pathway:

$$O_3 + h\nu \rightarrow O(^1D) + O_2 \qquad \text{(E8)}$$

$$O(^1D) + H_2O \rightarrow 2\ HO\bullet \qquad \text{(E9)}$$

where $O(^1D)$ is the exited singlet oxygen atom .

The reaction of OH with many hydrocarbons (RH) leads to alkyl peroxy radicals, and upsets the steady state equilibrium of ozone with respect to NO_x, (E1) through (E3),

$$RH + HO\bullet \rightarrow R\bullet + H_2O \qquad \text{(E10)}$$

$$R\bullet + O_2 + M \rightarrow RO_2\bullet + M \quad \textit{(fast)} \qquad \text{(E11)}$$

For a generalized example of the VOC reaction cycle, the reaction of HO• with aldehydes (RCHO) will be considered.(15) In reactions similar to those presented in (E10) and (E11), aldehydes react with OH radicals to form the acyl (RCO•) and acyl peroxy ($RC(O)O_2$•) radicals,

$$RCHO + HO\bullet \rightarrow RCO\bullet + H_2O \qquad (E12)$$

$$RCO\bullet + O_2 + M \rightarrow RC(O)O_2\bullet + M \quad \textit{(fast)} \qquad (E13)$$

The peroxy radicals react rapidly with the NO, thus competing with O_3 in reaction (E3), to form NO_2 and other free organic radicals,

$$RO_2\bullet + NO \rightarrow RO\bullet + NO_2 \qquad (E14)$$

$$RO_2\bullet + NO + M \rightarrow RONO_2 + M \qquad (E15)$$

$$RC(O)O_2\bullet + NO \rightarrow RC(O)O\bullet + NO_2 \qquad (E16)$$

The most common fate for the smaller alkoxy radicals is reaction with O_2, leading to HO_2 radicals and a carbonyl compound,

$$RO\bullet + O_2 \rightarrow RCHO + HO_2\bullet \qquad (E17)$$

The RC(O)O• radicals are of short lifetime, decomposing to form an alkyl radical (R•) and CO_2, with the subsequent generation of another peroxyalkyl radical,

$$RC(O)O\bullet \rightarrow R\bullet + CO_2 \qquad (E18)$$

$$R\bullet + O_2 \rightarrow RO_2 \qquad (E19)$$

Finally, the hydroperoxyl radicals can react with NO to regenerate OH and complete the cycle,

$$HO_2\bullet + NO \rightarrow NO_2 + HO\bullet \qquad (E20)$$

Atmospheric propagation reactions involve hydrocarbon oxidation steps, illustrated in reactions (E12) to (E19), and NO to NO_2 conversion reactions, such as that found in (E20). The generalized mechanism is a propagation chain in which the hydrocarbon molecule RH is converted into the carbonyl RCHO and two NO to NO_2 conversions occur, with the OH radical recreated at the end of the sequence of reactions. As primary hydrocarbons are oxidized to carbonyls, the carbonyls join the primary hydrocarbons in the suite of compounds that can be attacked by OH. Aldehydes formed as intermediate products can themselves photolyze to create fresh HO_x species; this is actually a branching step since more radicals are produced in the step than consumed. This type of branching is essential to sustain the photochemical cycle.

These propagation reactions affect ozone chemistry in two significant ways. First, NO_2, the major reactant in the formation of ozone (E1) & (E2), is produced as a product of this reaction series. Second, the primary component in the scavenging of ozone (E3), NO, is utilized as a reactant in these reactions. Consequently, as a result of the OH and VOC reactions (E8) through (E20), the overall ozone level may rise, for not only is the production of O_3 increased, but its destruction is decreased.

Key termination reactions in tropospheric chemistry include,

$$HO\bullet + NO_2 + M \rightarrow HNO_3 + M \tag{E21}$$

$$HO_2\bullet + HO_2\bullet \rightarrow H_2O_2 + O_2 \tag{E22}$$

$$RO_2\bullet + HO_2\bullet \leftrightarrow ROOH + O_2 \tag{E23}$$

$$RO_2\bullet + NO + M \rightarrow RONO_2 + M \tag{E24}$$

$$CH_3C(O)OO\bullet + NO_2 + M \leftrightarrow CH_3C(O)O_2NO_2 + M \tag{E25}$$

It should be noted that the nitric acid forming reaction (E21) is the predominant termination step under all but the most pristine (low NO_x) background tropospheric conditions; and, reactions (E23) and (E25) are reversible.

The hydroxyl radical (HO•) is the key reactive species in the chemistry of ozone formation, since reaction with the OH radical determines the atmospheric lifetime of the VOCs that participate in the photochemical production of ozone in the troposphere. The VOC-OH reaction, such as those illustrated in reactions (E10) and (E12), initiates the hydrocarbon oxidation sequence that will eventually accelerate the production of ozone through the generation of NO_2. In addition, the new organic radicals produced may also eventually lead to the additional production of both NO_2 and HO•, as a result of reactions (E17) & (E20). The NO_x-OH reaction (E21) acts as a key termination step that removes OH radicals from the active VOC oxidation cycle, (E12) through (E19), retarding the further production of ozone via this reaction chain. Thus, the rate of ozone production is not simply proportional to the amount of NO_x present.

A competition exists between VOCs and NO_x for the OH radical. At ambient conditions, considering an average urban mix of VOCs, the ratio of the NO_2-OH to VOC-OH rate constants is about 5.5 ($1.7 * 10^{-4}$ ppm^{-1} min^{-1}: $3.1 * 10^{-3}$ $ppmC^{-1}$ min^{-1}). Thus, when the VOC to NO_2 concentration ratio is approximately 5.5:1, the rates of reaction of VOC and NO_2 with OH would be equal. If the VOC to NO_2 ratio is less than 5.5:1, the reaction of OH with NO_2 predominates; whereas, when the ratio exceeds 5.5:1, the OH reacts preferentially with VOCs in a NO_x limited regime. In general, increasing VOC concentrations results in the production of more ozone; while, increasing NO_x concentrations may lead to either more or less ozone depending on the prevailing VOC to NO_x ratio.(15) Therefore, at a given level of VOC, there exists a NO_x concentration at which a minimum amount of ozone is produced. This means that there is an optimum VOC to NO_x ratio.(5,15) Indeed, in most of the troposphere, except in areas of strong NO_x sources, the availability of NO_x governs the rate of ozone production.

2.3.2. Sources

The distribution of ozone in the troposphere is maintained through combined radiative, chemical, and dynamical processes. There are three main sources of ozone in the troposphere: downward transport of stratospheric ozone into the troposphere, surface transport of ozone via meteorological processes, and in situ photochemical production of O_3 from reactions involving ground level emissions of NO_x and VOCs.

Ozone exhibits temporal variability over hourly, diurnal, synoptic (3-5 days), weekly, seasonal, and long-term (5-20 years) time scales. The ozone changes on weekly and long-term scales are caused primarily by anthropogenic emission changes, while changes at the hourly, diurnal, synoptic and seasonal scales are influenced by atmospheric processes and meteorology.(17)

Stratospheric-Tropospheric Transport

The mechanisms by which stratospheric ozone is transported downward and mixed into the troposphere are reasonably well understood. However, there are many different methods utilized to calculate exact concentrations. One approach, based on the 'downward control' principle, uses an average meridional circulation in the stratosphere that is derived from the continuity equation and stratospheric temperature derivations from radiative equilibrium, caused by energy dissipation due to large scale dynamic perturbations (18). Another approach, estimates the stratospheric to tropospheric transfer of ozone using measured distributions of stratospheric constituents, such as N_2O, NO_x, and O_3, along with knowledge of the stratospheric reaction chemistry.(19) In general, the portion of the O_3 near the surface of the earth which can be attributed to stratospheric-tropospheric transport falls in the 5-15 ppb range for a seasonal average (5), and accounts for only approximately 0.1% of all the ozone produced in the stratosphere (16). Thus, it is apparent that the contribution of stratospheric ozone can not alone account for the elevated ground level ozone concentrations.

Surface Transport

Ozone levels result from a complex interaction of atmospheric chemical reactions, atmospheric mixing processes, urban air masses, general meteorology, and distant and local precursor sources. Thus, the identification and understanding of the transport of photochemical O_3 and its precursors by atmospheric and meteorological processes are essential to comprehending photochemical air pollution and the potential extent of its effects.(17)

The concentration of an air pollutant depends significantly on the degree of mixing that occurs between the time a pollutant, or its precursors, is emitted and the time it arrives at the receptor. Surface transport processes, in particular, can not only determine the movement of ozone formation and destruction constituents, but can act on ozone itself determining its distribution throughout much of the atmosphere. Thus, it is essential to examine the atmospheric dynamics of the meteorological factors that are responsible for the transport mechanisms of ozone.

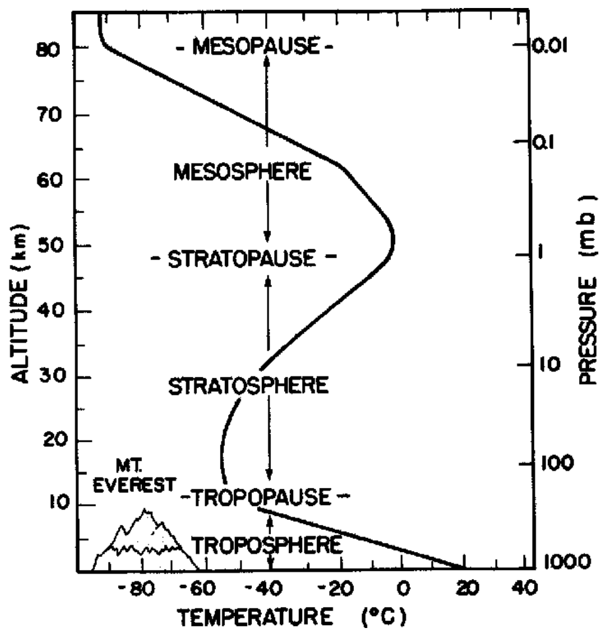
The dominant meteorological factors that influence ground level O_3 concentrations and distributions are atmospheric mixing and temperature. These factors are discussed in the following sections and are examined as they are related to the Chicago region.

Atmospheric Mixing

Atmospheric mixing can exert a powerful influence on the distribution of pollutant concentrations in space and time and can result from thermal turbulence associated with the redistribution of heat energy, or mechanical turbulence, often associated with weather patterns.

The temperature structure of the atmosphere is separated vertically into several layers which is illustrated in *Figure 3*.(16)

Figure 3: The Vertical Structure of the Atmosphere



Source: Singh 1995 (16)

The thermal stability of the atmosphere is a measure of the potential of air to remain vertically static at a constant pressure level and thus, resist overturning. The most stable layers of the atmosphere are those known as inversion layers where temperature increases with height and mixing rates are relatively low. In layers where temperature decreases with height, the static stability varies considerably. This variation occurs mainly in the planetary boundary layer (PBL), defined as the lower layer of the troposphere in contact with the surface of the earth (1-2 km), where the majority of pollutant sources exist.

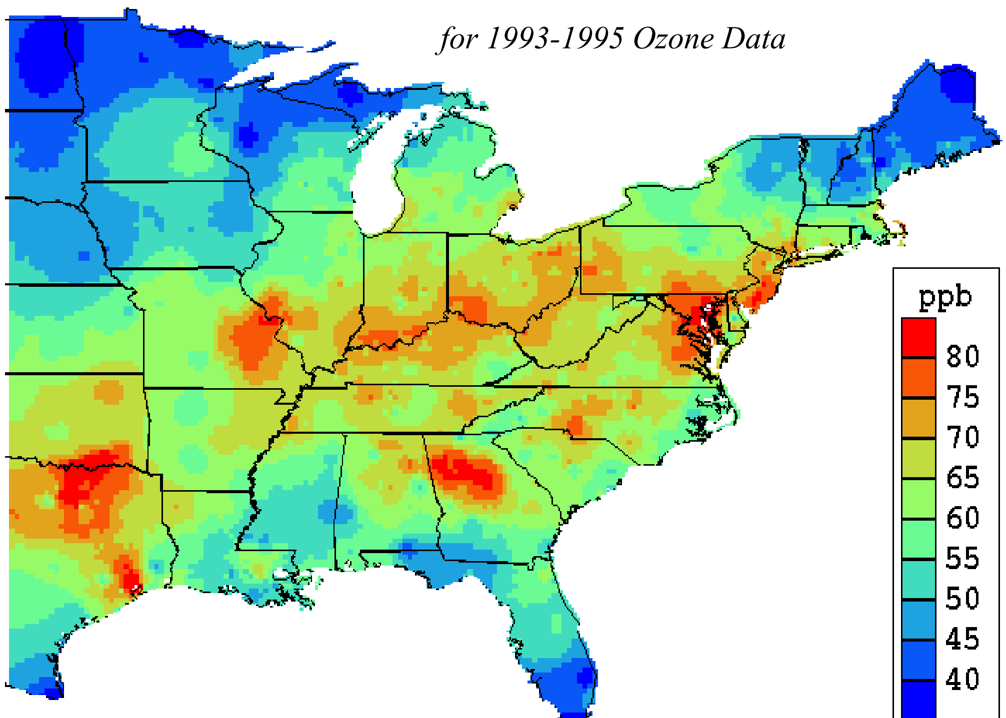
In general, thermal atmospheric mixing through the troposphere is assumed to follow a typical and predictable vertical cycle.(5) The cycle begins with a nocturnal surface inversion that forms when outflow of radiation exceeds the influx radiation. This surface layer inversion persists until surface heating becomes significant, usually 1 to 2 hours after sunrise. In this case, an elevated reservoir of pollutants, initially trapped in the inversion, could be transported vertically downward causing a rapid rise of O_3 concentrations near the ground in the morning hours. After this initial increase, surface concentrations can continue to rise as a result of photochemistry and transport of O_3 rich air to the receptor until the inversion is broken by surface heating. When surface heating decreases in the evening, a surface inversion will again begin to form. The fate of the new elevated inversion is less clear, however, for this layer is exposed to transport processes that can redistribute pollutants throughout the atmosphere.

Similarly, geography can also have a significant impact on the mixing and dispersion of pollutants along a coast or shoreline. For example, Chicago is located on Lake Michigan, where temperature gradients exist between the land and water masses and the air above the land and water masses. In this case, when the water is cooler than the land, the cool air near the water will tend to increase the stability of the boundary layer in the coastal zone, and, as a result, decrease the mixing processes that act on the pollutant emissions. The opposite condition occurs if the water is warmer than the land, which tends to increase pollutant dispersion in such areas.(5)

In the United States and Europe, the most severe regional ozone episodes occur when slow moving, high-pressure weather systems develop during the summer months.(15) These systems are characterized by the widespread sinking of air through most of the troposphere creating a pronounced inversion of the normal temperature profile, where the temperature of the air in the lower troposphere increases with height. This inversion suppresses vertical mixing and acts as a strong lid to contain pollutants in a shallow layer in the troposphere, for cooler air below does not mix with warmer air above.

Major high-pressure systems are also frequently associated with low wind speeds, < 3 m/s, and stagnant circulation during the ozone season. When the slow moving airflow of a high-pressure system surrounds a major metropolitan area, a regional air mass that exhibits the characteristics of that region is created. Thus, if a region is considered an emissions source area, a pollutant air mass will be created in which there exists the potential for the accumulation of O_3 and its precursors near local source areas. This phenomenon is illustrated in *Figure 4*.(17)

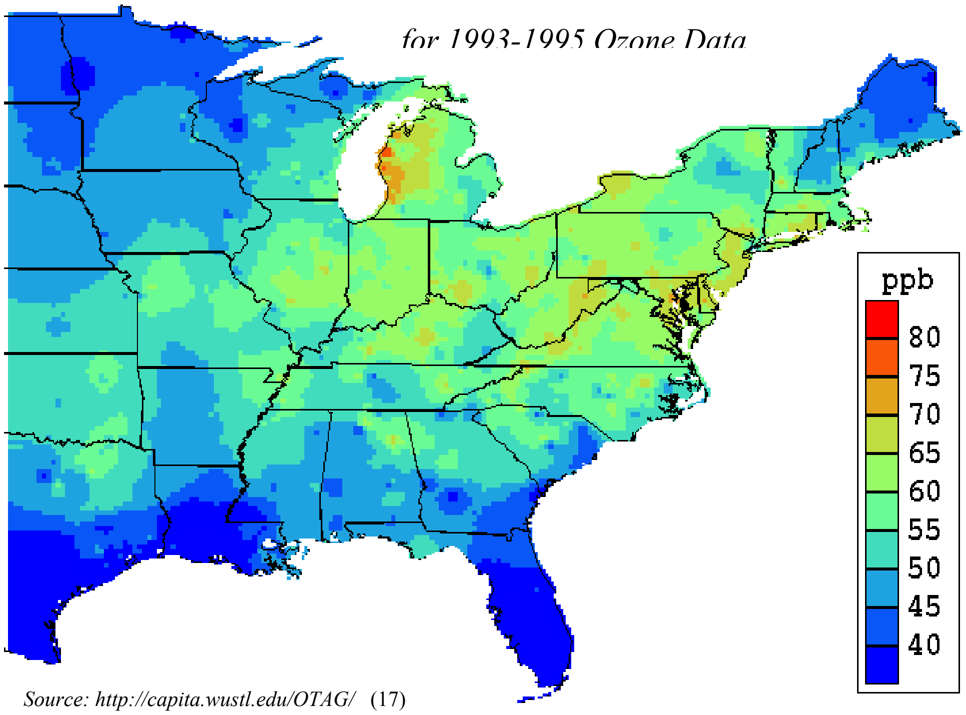
Figure 4: Average Ozone Concentration During Low Wind Speed Conditions (< 3 m/s) for 1993-1995 Ozone Data



Source: http://capita.wustl.edu/OTAG/ (17)

The movement of these air masses facilitates the transfer of O_3 and its precursors beyond the urban scale to neighboring rural and urban areas creating episodes of high O_3 in areas which themselves generate few emissions. Thus, high ozone episodes in an area are often terminated by the passage of a front that brings cooler, cleaner air to a source region moving the polluted air downwind.(15) High wind speeds, > 6 m/s, generate strong ventilation which helps to prevent the local build-up of pollutants near their sources, but contributes to long-range transport and regional ozone episodes. This phenomenon is illustrated in *Figure 5*.

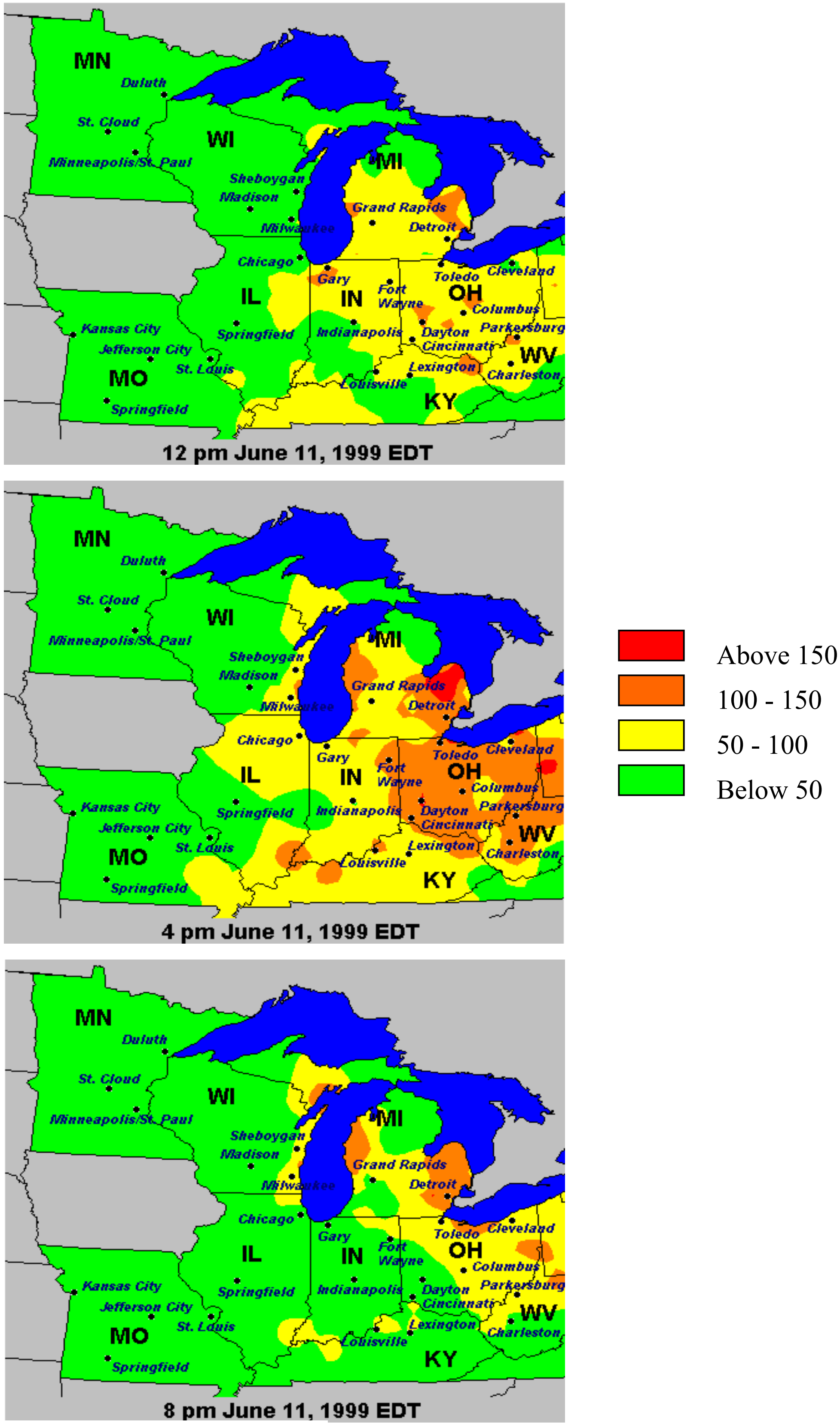
Figure 5: Average Ozone Concentration During High Wind Speed Conditions (> 6 m/s) for 1993-1995 Ozone Data



Source: http://capita.wustl.edu/OTAG/ (17)

The relationship between wind and O_3 varies from one part of the country to another because the transport of ozone manifests itself differently at the local, sub-regional, and regional scales. Through closer inspection of the Lake Michigan region, as illustrated in time series ozone maps in *Figure 6* (20), it can be observed that ozone level distribution varies throughout the day with the greatest degrees of exceedances occur in the late afternoon, in areas other than Chicago. Initially, elevated ozone levels are located primarily over the highly industrial source areas in Indiana and Ohio. However, as the day progresses, the elevated levels appear over western Michigan, the Upper Peninsula of Michigan, and eastern Wisconsin, regions that have relatively few emissions sources. Thus, it is suspected that the observed ozone levels in this region are primarily a result of transport processes.

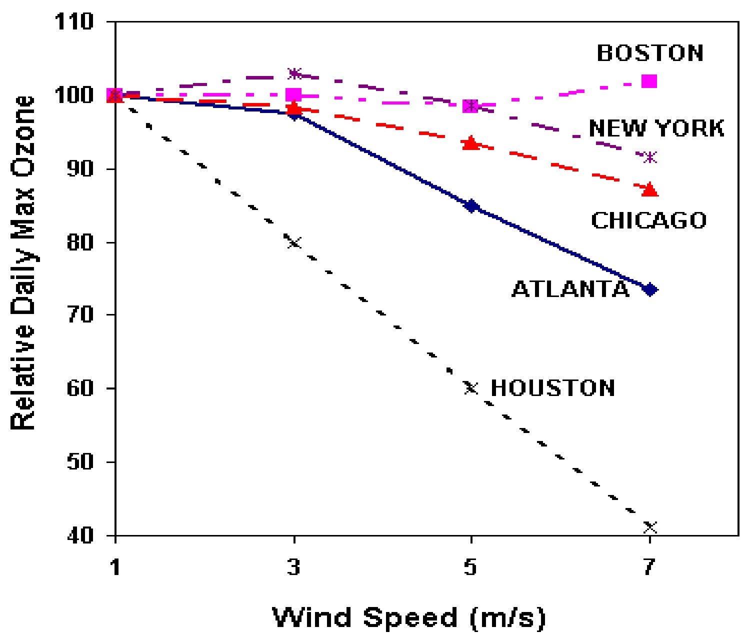
Figure 6: Time Series Ozone Maps



Source: http://www.epa.gov/airnow/ (20)

Most of the ozone 120 ppb nonattainment episodes can be attributed to short range local transport (30-150 miles).(17) Local scale transport conditions can be examined through the breakdown and comparison of ozone and wind correlation for different cities, as depicted in *Figure 7*. In general, for southern urban areas, ozone levels decline rapidly with increasing wind speed. This indicates that ozone episodes are caused primarily by local stagnation conditions. The trends shown in *Figure 7* suggest that in northern cities, however, ozone levels decrease much less rapidly with increasing wind speeds. This indicates that these areas are more heavily influenced by atmospheric transport mechanisms.(17)

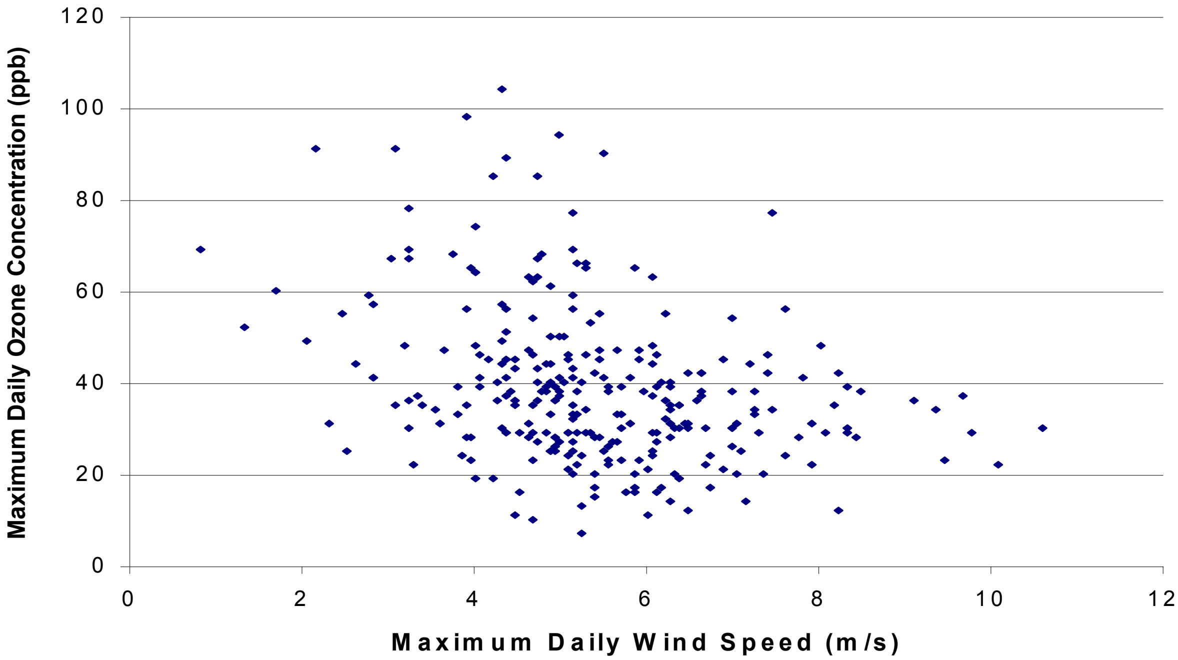
Figure 7: Relative Change of Ozone Concentration with Wind Speed of Different Cities



Source: http://capita.wustl.edu/OTAG/ (17)

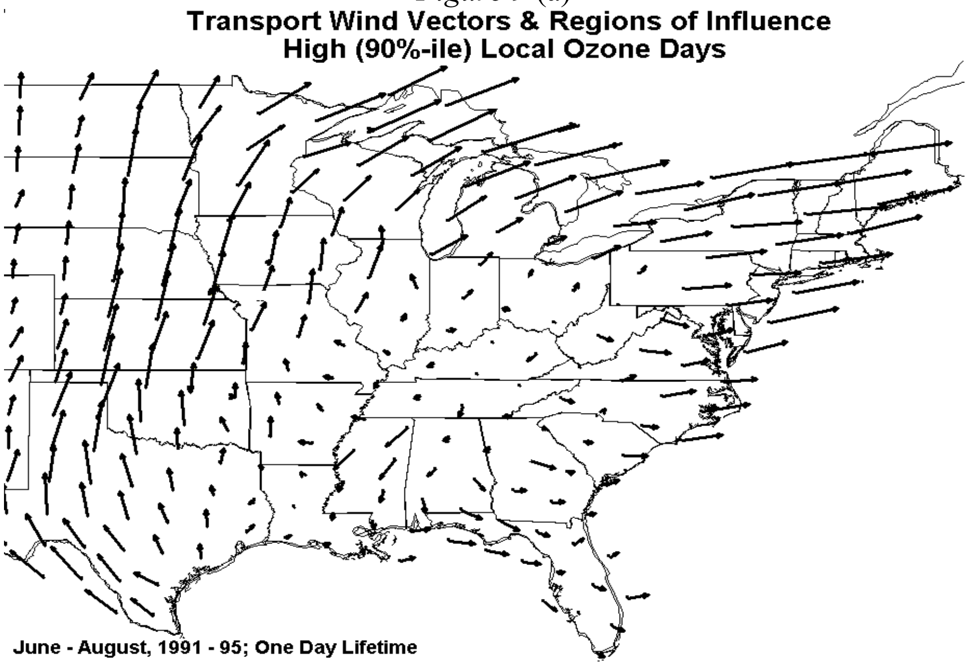
Figure 8, which was generated from data collected during our study, provides a more detailed illustration of this phenomenon for Chicago. It can be observed that when the wind speeds in Chicago are relatively low, less than about 5 m/s, there exists a greater tendency for an ozone episode to occur. Once wind speeds rise above 5 m/s, the number of ozone exceedances begins to drop with increasing speed. This shows that local source emissions are particularly active in the augmentation of ozone noncompliance days during low wind conditions. As wind speeds increase, the emissions that help generate the ozone problem are carried out of the Chicago region, hence lowering the overall incidence of ozone exceedances.

Figure 8: Wind Speed vs. Ozone for Chicago (Jun-Aug,1994-1996)



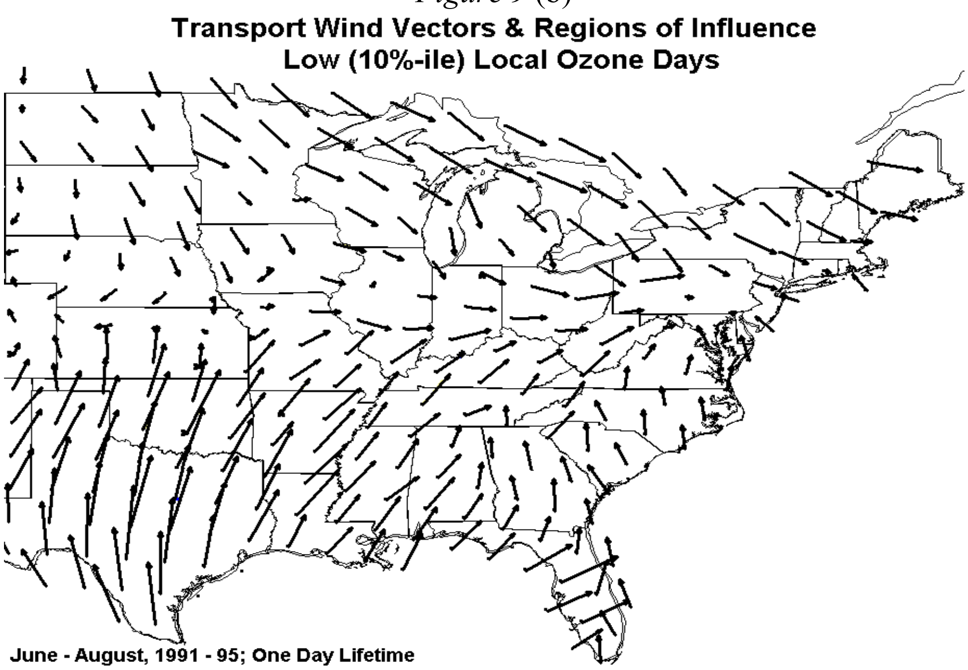
On a regional level, the examination of dispersion conditions can be attained through the analysis of national wind speed and direction trends, which are illustrated in *Figure 9*. During high-ozone days (90th percentile), dispersion in the Southeast is typically poor due to stagnating air masses, shown by the region of small arrows in *Figure 9 (a)*. Whereas, the western and northern sections of the domain experience stronger and more persistent southerly and westerly winds, respectively. This supports the idea that ozone exceedances in the central and southeastern areas are predominantly the result of local emissions, while exceedances in other regions are also influenced by regional transport. In contrast, on low-ozone days (10th percentile), the transport is predominantly from the regions outside the U.S., such as Canada and the Gulf of Mexico. This is illustrated in *Figure 9 (b)*. (17)

Figure 9 (a)



Source: http://capita.wustl.edu/OTAG/ (17)

Figure 9 (b)

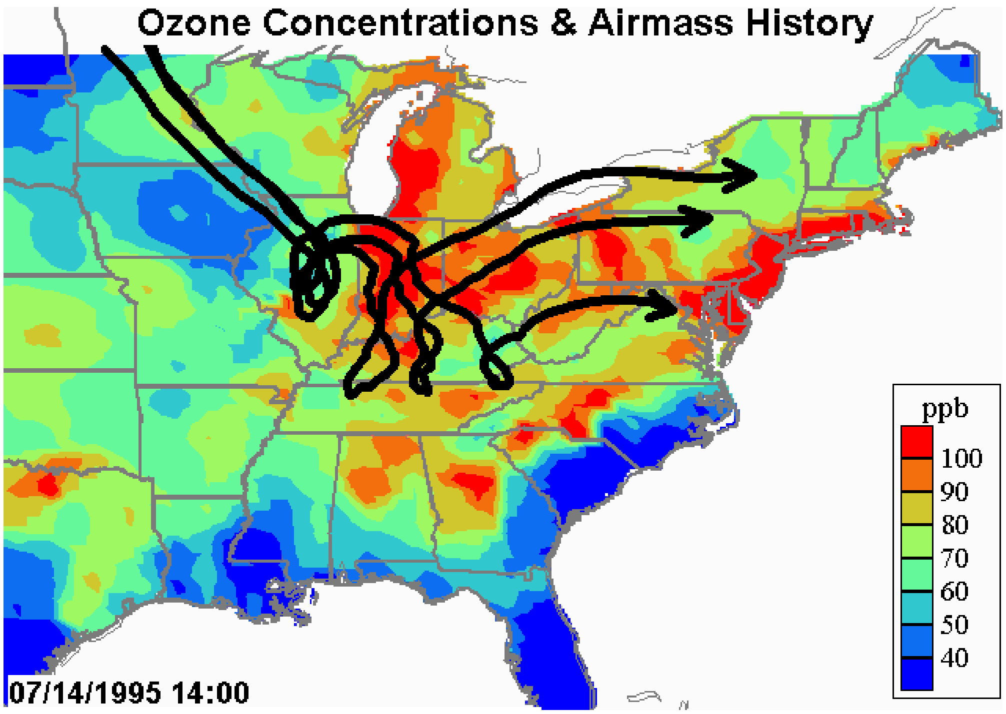


Source: http://capita.wustl.edu/OTAG/ (17)

Regional scale ozone transport episodes often result from several days of air stagnation over multi-state areas and end with the subsequent transport of the elevated O_3 concentrations to downwind states. *Figure 10* illustrates this phenomenon for the Midwestern region of the U.S.

where an atmospheric flow visualization is superimposed on observed ozone concentration patterns. Stagnant atmospheric flow patterns create an air mass that lingers over the Midwest, a high NO_X emission region, causing the accumulation of high ozone concentrations. Near the end of the episode, Midwestern concentrations drop, as the polluted airmass is swiftly transported eastward, carrying high ozone concentrations toward the Northeastern seaboard where regional ozone levels peak a day later.(17)

Figure 10

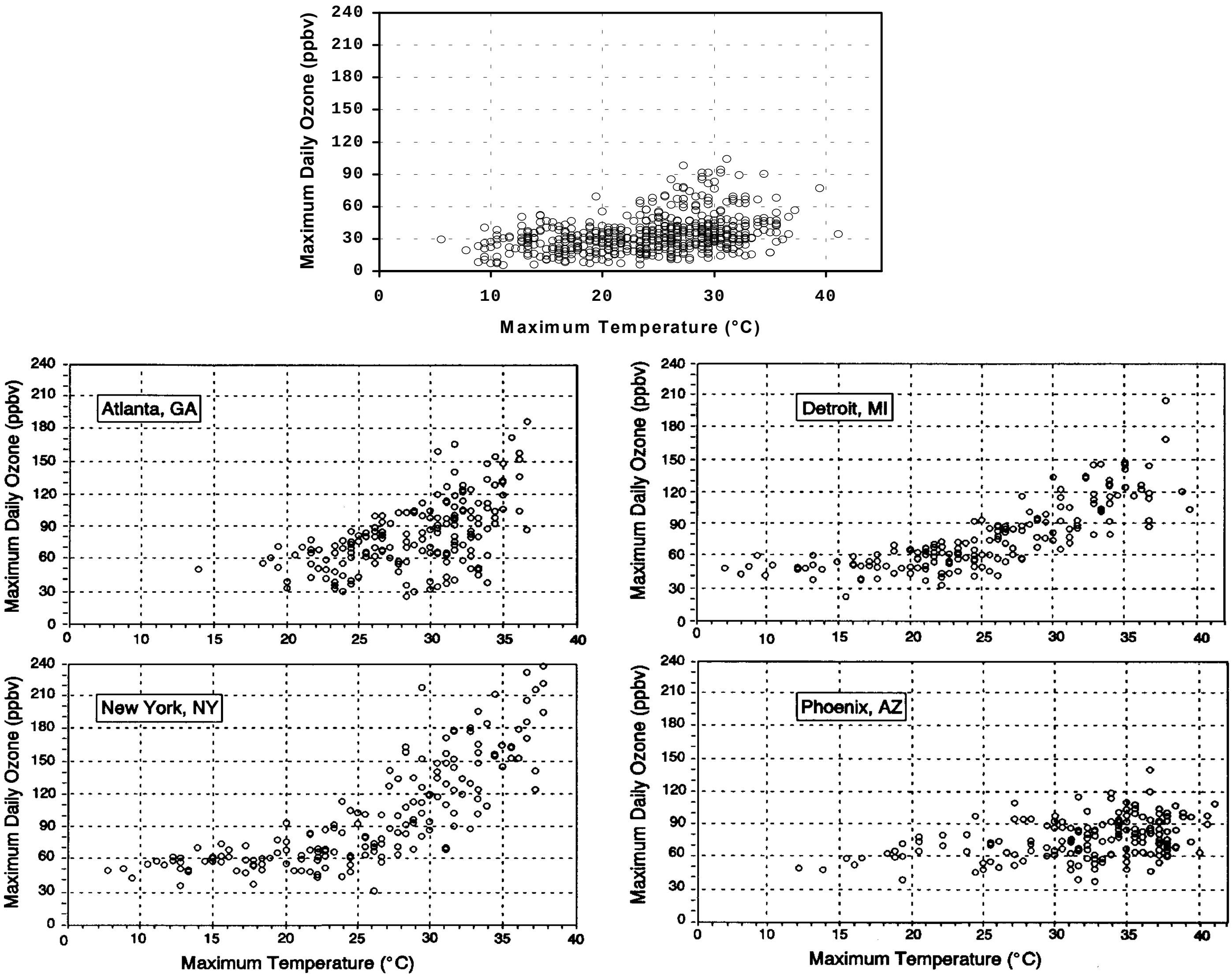


Source: http://capita.wustl.edu/OTAG/ (17)

<u>Temperature</u>

The relationship between tropospheric ozone concentration and temperature has been demonstrated through the examination of the correlation between ambient air ozone concentrations and maximum temperature measurements. A graphical representation of the results from five different cities, including our study of Chicago, is presented in *Figure 11*. This figure shows the maximum daily ozone concentration verses maximum daily temperature for the summer months (May to October) for Chicago, IL, Atlanta, GA, New York, NY, Detroit, MI, and Phoenix, AZ, respectively.

Figure 11: Maximum Daily Ozone Concentration verses Maximum Daily Temperature for Chicago, Atlanta, New York, Detroit, and Phoenix†*



* Scatter plot for a single ozone monitoring station in downtown Chicago, IL for May-October, 1994-1996
† Scatter plot for Atlanta, GA, New York, NY, Detroit, MI, and Phoenix, AZ for May-October, 1988-1990. *Source: Air Quality Criteria for Ozone and Related Photochemical Oxidants, volume I* (5)

In general, two consistent trends are observed: the correlation for temperatures below approximately 20°C is a relatively flat line and the upper bound limit for ozone concentrations tends to increase with temperature. The first observation holds for all the cities, including Chicago. However, above 20°C, a linear increase in maximum daily ozone concentration as a function of increasing temperature is observed in Atlanta, New York, and Detroit. This linear relationship is not seen upon analysis of the data gathered in Chicago or Phoenix

The data in *Figure 11* shows that at any given temperature, an extensive range of ozone concentrations can exist, and this range of ozone levels differs from region to region. For example, at 30°C, the approximate range of possible ozone values in Atlanta is 35–160 ppb; whereas in New York this 30°C range is about 85-220 ppb. In addition, the slope of the ozone verses temperature function also varies. These phenomena are a direct result of the effect of the variation of meteorological factors, other than temperature, and precursor source emissions between different regions of the country. Thus, the upper bound evidently represents the maximum O_3 concentration achieved under the most favorable production conditions within a specific area.(5)

There are numerous reasons hypothesized to explain the positive correlation between ozone and temperature. One of these is the related to the increase in photolysis rates of ozone production with increasing temperature and under meteorological conditions associated with high temperatures. This follows from the fact that an increase in photolysis rates would augment a key source of OH radicals (E8), whose availability plays a key role in the photochemical production of O_3. If the availability of this energy source is enhanced as a result of meteorological conditions associated with high temperatures, more ozone will be produced. Another reason could be attributed to an increase in the production of ozone precursors, such as NO_x and VOC, at high temperatures. This hypothesis arises from the fact that higher temperatures create an increased energy use, mostly due to a greater demand for air conditioning in buildings and automobiles. Thus, as power plants burn more fossil fuels to meet this increase in energy demand, they generate greater a quantity of emissions which increases the levels of ozone precursors present at ground level. In addition, the relationship between high temperatures and stagnant circulation patterns, as discussed previously, can be used to account for the notable trend between ozone and temperature. Unfortunately, an exact mechanistic understanding as to the exact relationships between all these factors causing elevated ozone concentration does not currently exist.

Ground Level Emissions

The photochemical production of the ozone found at the earth's surface is the result of a series of chemical reactions that involve nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The formation of O_3 from its precursors is a complex, non-linear function of many factors: spectral distribution of sunlight, atmospheric mixing, meteorological conditions, temperature, concentrations and reactivity of precursor compounds in ambient air.

Ground-level ozone production and control depends on the emissions of NO_x and VOC from many sources. Until about 150 years ago, the levels of these pollutant precursors were quite low and the sources were mainly natural. As urbanization and industrialization began to grow, the pollution levels in these areas also increased as a result of supplementary man-made sources.(H) Thus, in order to rectify the pollution problem and devise the most appropriate pollution regulations and control strategies, it is important to understand both the sources and source strengths of O_3 precursor species. In the following sections, anthropogenic and biotic NO_x and VOC sources and their relative influence on ambient conditions in the Chicago area will be described.

Nitrogen Oxides (NO_x)

Nitrogen gas (N_2) is an abundant and inert gas, which makes up almost 80 percent of the earth's atmosphere. In this form, it is harmless to humans and essential to plant metabolism, but due to its abundance in the air, it is a frequent reactant in many combustion processes where it combines with oxygen (O_2) to form various oxides of nitrogen (NO_x). Of these, nitric oxide (NO) and nitrogen dioxide (NO_2) are the most important contributors to air pollution and the term NO_x is generally used to represent these two nitrous oxide forms.(21)

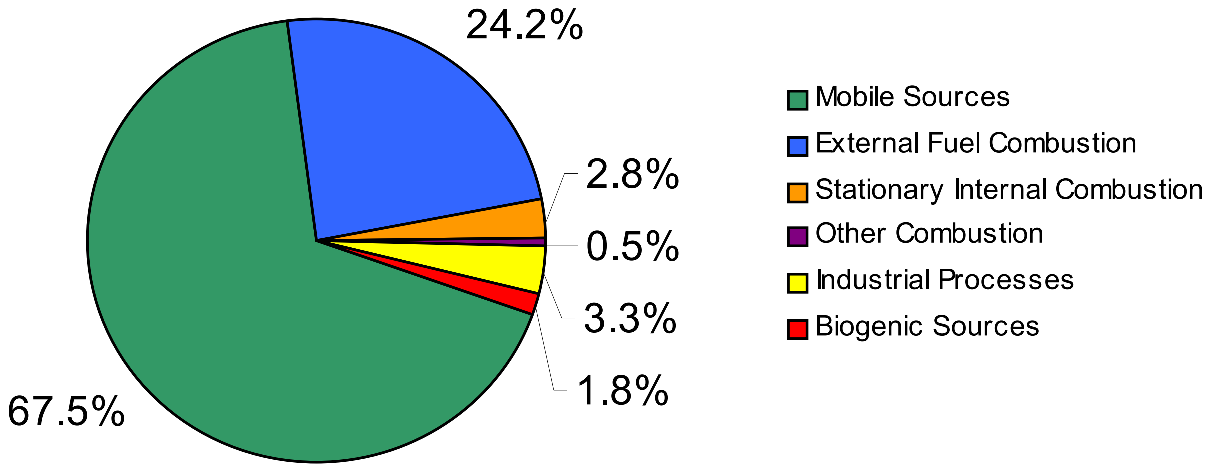
Major NO_x source categories include mobile sources, external fuel combustion, stationary internal combustion, other combustion, industrial processes, and biogenic sources. *Table 3* gives a more detailed summary of what is included within each of these categories, and *Figure 12* provides a pie chart that illustrates the typical summer day contribution of each source category to the total daily NO_x emissions in the Chicago area.(22) Appendix A provides the complete and detailed inventory.

Table 3: Source Categories Used to Inventory Nitrogen Oxide Emissions

Mobile Sources	**External Fuel Combustion**	**Stationary Internal Combustion**	**Other Combustion**	**Industrial Processes**	**Biogenic Sources**
Highway Vehicles: • Gasoline autos and trucks • Diesel autos and trucks • Motorcycles Non-Highway Vehicles • Rail • Aircraft • Vessels • Service, Recreational, Agricultural, Industrial, and Commercial equipment	Utility Boilers Oil Boilers • Industrial • Commercial • Institutional • Residential Gas Boilers • Industrial • Commercial • Institutional • Residential	Reciprocating Engines Gas Turbines	Waste Disposal • Industrial • Governmental • Commercial • Institutional • Residential Open Burning • Structure • Forest • Agricultural • Other	Manufacturing • Chemical • Iron and Steel Coke Ovens Mineral Products Petroleum Refining	Soil • Nitrification • Denitrification

Source: Illinois Statewide Ozone Precursor Emissions Inventory (22)

Figure 12: Typical Summer Day Emissions of NO_x for Chicago the Area (1996)



Source: Illinois Statewide Ozone Precursor Emissions Inventory (22)

Anthropogenic NO_x is primarily associated with combustion processes. The principal pollutant emitted is NO, which is formed at high combustion temperatures from the nitrogen and oxygen in air and from nitrogen in combustion fuel. Anthropogenic emissions of NO_x on a typical summer day in 1996 totaled 1026.58 tons. As shown in *Figure 12*, over 93% of these emissions are from two source categories: mobile sources, at 705.20 tons/day, and external fuel combustion, at 252.84 tons/day.(22)

Natural NO_x sources, which include lighting, soils, wildfires, stratospheric inversion, and oceans, constitute only a small percentage of the total NO_x emissions for the Chicago area and are included within the biogenic slice in *Figure 12*. However, of these natural sources of NO_x, lightning and soils are the only two significant contributors within the United States. Lightning produces high enough temperatures to allow N_2 and O_2 to be converted to NO in the atmosphere, and soils contain both nitrifying and denitrifying organisms, which produce NO_x as a by-product of natural mechanisms.(23) The relative importance of these two pathways varies greatly from organism to organism and is dependent upon soil temperature and fertilization levels.(5)

Volatile Organic Compounds (VOCs)

The term volatile organic compounds (VOCs) is used to denote the entire set of vapor phase atmospheric organics, excluding CO and CO_2. The U.S. National Acid Precipitation Assessment Program (NAPAP) inventory of VOC emissions includes, for example, over 600 different compounds.(15) The major classes of VOCs in the ambient air are alkanes, alkenes, aromatic hydrocarbons, carbonyl compounds, alcohols, and esters.(5) Characterizing VOC emissions ideally requires not just the total VOCs but the individual chemical compounds that constitute the entire mixture since the atmospheric behavior of individual species can vary enormously.

Major VOC source categories include industrial processes, industrial surface coating, non-industrial surface coating, other solvent use, storage and marketing, waste disposal, mobile sources, biogenic sources, and other miscellaneous sources. *Table 4* gives a more detailed summary of each of these categories, and *Figure 13* provides a pie chart that illustrates the typical summer day contribution of each source category to the total daily VOC emissions in the Chicago area.(22) Appendix B provides the complete and detailed inventory.

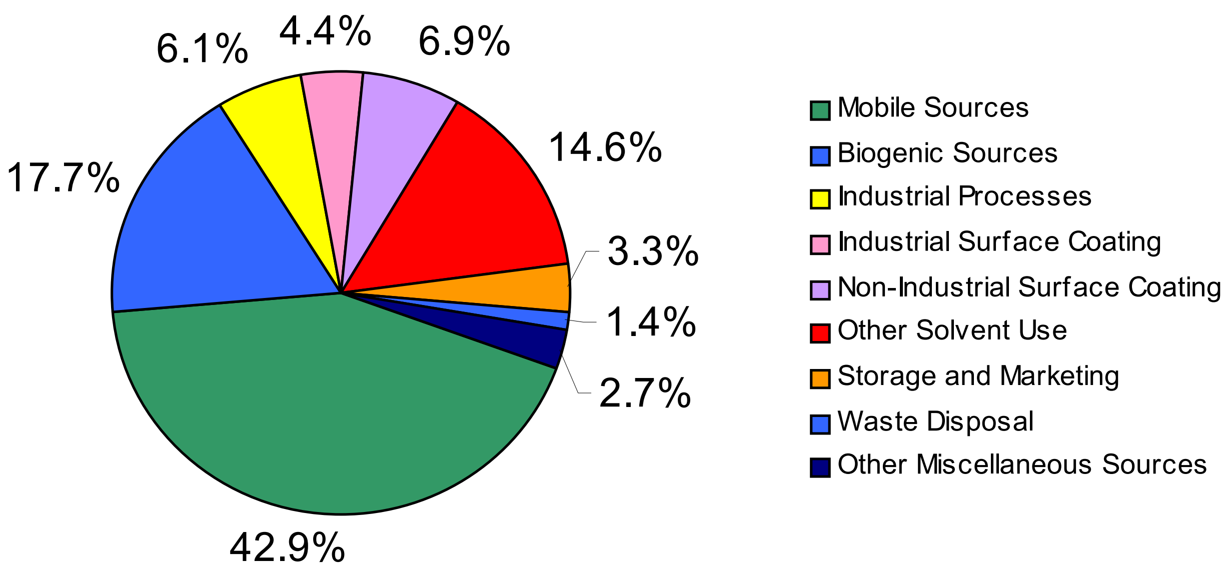
Table 4: Source Categories Used to Inventory Volatile Organic Compound Emissions

Industrial Processes	**Industrial Surface Coating**	**Non-Industrial Surface Coating**	**Other Solvent Use**	**Storage and Marketing of VOC**
Petroleum Refining Manufacturing • Lube Oil • Chemical • Iron and Steel • Pharmaceutical • Plastics • Polymer Coke Ovens	Transportation Vehicles • Autos • Trucks • Ships • Aircraft Furniture Large Appliances Other Products • Metal • Paper • Textile • Wood • Plastic	Architecture Auto Refinishing Traffic/Maintenance Painting	Degreasing Dry Cleaning Graphic Arts Adhesives Emulsified Asphalt Paving Solvents • Commercial • Consumer	Production • Oil and Gas Processing • Oil and Gas Storage • Gasoline • Crude Oil • Volatile Organic Liquid Transfer and Refueling • Gas • Volatile Organic Liquid Leaking and Breathing

Waste Disposal	Mobile Sources	Biogenic Sources	Other Miscellaneous Sources
Municipal Combustion • Residential • Commercial • Institutional • Governmental • Industrial Landfills Hazardous Wastes	Highway Vehicles: • Gasoline autos and trucks • Diesel autos and trucks • Motorcycles Non-Highway Vehicles • Rail • Aircraft • Vessels • Service, Recreational, Agricultural, Industrial, and Commercial equipment	Vegetation	Fuel Combustion • Utilities • Industrial • Commercial • Institutional • Residential Open Burning • Structure • Forest • Agricultural • Other Pesticide Applications Stationary Internal Combustion Engines Bakeries

Source: Illinois Statewide Ozone Precursor Emissions Inventory (22)

Figure 13: Typical Summer Day Emissions of VOC for Chicago the Area (1996)



Source: Illinois Statewide Ozone Precursor Emissions Inventory (22)

VOCs emitted into the atmosphere are primarily the result of evaporative and combustion processes, from a large number of source types. The total Chicago area VOC emissions, for a typical summer day in 1996, amounted to 963.23 tons. As shown in *Figure 13*, the two largest source categories include, once again, mobile sources, at 413.67 tons/day, and, in contrast to the

NO_x emissions, biogenic sources, at 170.71 tons/day. Emissions of VOCs from highway vehicles result from the incomplete combustion of fuel or from its vaporization and account for approximately 65% of the transportation related emissions. In addition, studies have shown that the majority of these VOC emissions originate from only about 20% of the automobiles in service, many of which are poorly maintained older cars.(5) In addition, it is interesting to note that asphalt pavement itself emits 13.41 tons/day, approximately 1.5% of the total daily VOC emissions. Vegetation also emits significant quantities of VOCs into the atmosphere, however, because biogenic emissions are extremely dependent on temperature and the extent of vegetation growth, they vary greatly by season. Coniferous forests are the largest vegetative contributors on a national basis because of their extensive land coverage.(5)

2.3.3 Implications For Chicago

It has been shown that there is a very weak, if any, correlation between ozone levels and temperature in the Chicago area. This suggests that there are other factors present that dictate the level of Chicago's air quality. In fact, our analysis, in conjunction with studies conducted by the Ozone Transport Assessment Group (OTAG), established that Chicago's ozone problem is strongly correlated with wind patterns and atmospheric transport. As a result, the control and reduction of ozone and its precursors requires addressing regional mobile, area, and point sources, and continuing to establish programs and practices that work towards an overall improvement in regional air quality.

3. MITIGATION ALTERNATIVES - COOLING OUR COMMUNITIES

Research on the effects of urban heat islands is progressing at a time of immense public concern about air quality and human health issues. Specifically, the urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. In fact, even within a city, different areas have different temperatures, depending on specific surroundings, type of exposed surface, and ground cover.

It is evident that urban heat islands have major effects on the surface energy balance, heating/cooling costs, and quality of urban life. While many of the factors which influence the formation of urban heat islands, including climate, topography, and weather patterns, can not be changed or altered, it is apparent that efficient and cost-effective ways of mitigating heat islands exist. There are two heat island factors, attributable to human activities, which can be readily controlled: the amount of vegetation and the color of surfaces.(3) Increasing vegetative cover through strategic landscaping around buildings and throughout cities can absorb solar radiation, provide shade, and control wind flow benefits. Changing dark colored surfaces to light colored ones would more effectively reflect, rather than absorb, solar energy and emit stored heat energy at a higher rate, thus reducing the cooling energy loads and ground level air temperatures influenced by these surfaces.

In general, it is observed that parks and areas with significant amounts of vegetation are cooler than neighborhoods full of paved surfaces and buildings. These differences may seem obvious, but they illustrate the fact that the climate in cities is greatly affected by human activities and the creation of the urban landscape.

The synergistic effect of reduced vegetation and significant amounts of dark colored surfaces can cause an increase in the afternoon summer air temperature on a typical city an average about 5°F higher than the surrounding rural area. For example, researchers have found that peak urban utility loads in five U.S. cities, including Los Angeles, CA; Washington, D.C.; Phoenix, AZ; Tucson, AZ; and Colorado Springs, CO increase by 1-2% for each 1°F rise in daily maximum temperature above a threshold of 60- 70°F. Thus, the additional air conditioning use caused by this increase in urban air temperatures is responsible for 5-10% of urban peak electric demand.(3) However, researchers also estimate that if 100 million urban tree spaces in this country were filled (three trees for one-half of the single family homes in this country), and if light colored surfacing programs were implemented, late afternoon air temperatures on a hot summer day could be reduced by 5 to 10° F.(3) Of course, specific results would vary depending upon location, but the combined strategy of increasing vegetative cover and using light color materials could reduce electricity usage by as much as 50 billion kilowatt hours per year (2 percent of annual electricity use in the United States).(3,4)

In addition to reducing temperature and energy demand, increasing vegetative cover and lightening the color of our urban paved and roofed surfaces provide many other physical, functional, and psychological benefits to urban dwellers. For example, they beautify urban areas, mask noise, reduce air pollution, lower smog levels, enhance community relations, and provide valuable habitat for wildlife.(3)

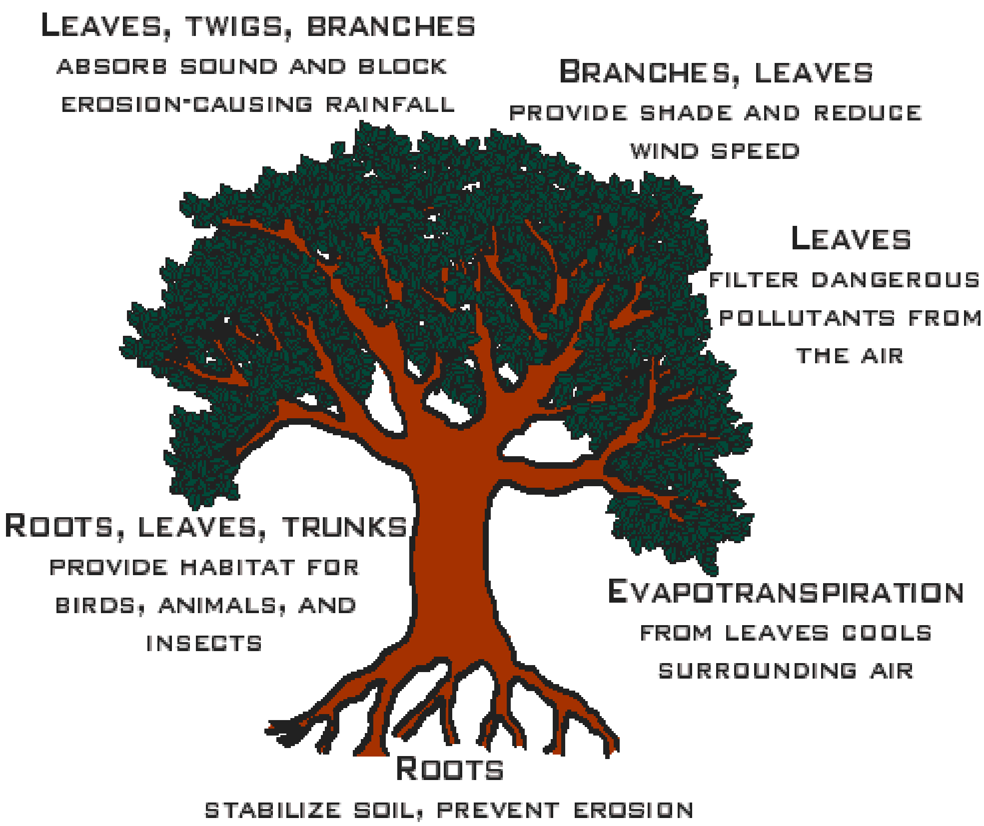
The concepts of strategic landscaping and light colored surfaces are not difficult to understand, but implementation of programs at the community level, or region wide, will require considerable education, public participation, planning, cooperation, policymaking, commitment of resources, and community support. The Cool Communities Program is an action oriented, energy reduction program of American Forests and the Department of Energy (DOE), with cooperative federal support also provided by the U.S. Environmental Protection Agency (USEPA) and the U.S. Department of Agriculture (USDA) Forest Service. This initiative mobilizes government agencies, businesses, and citizens to create positive, measurable change in energy consumption and the urban environment, through use of strategic landscaping and light colored surfacing, and attempts to increase public awareness of these issues.(24)

Unfortunately, wholesale implementation of these strategies is unlikely to occur and once in play, they will show gradual results over time rather than immediate results. A shift from the use of dark color roofing and paving materials to lighter colored alternatives is certain to encounter more resistance. The reasons for this are related to aesthetic sensibilities, preferences based upon habit and experience, availability of alternatives, lack of knowledge about alternatives, perceptions about cost, and uncertainty about true environmental benefits. This chapter provides both an overview of different mitigation strategies and points out some of the existing market barriers to implementation.

3.1 VEGETATION

The replacement of the natural land cover with anthropogenic surfaces alters the thermal, moisture, and visual properties of an urban climate in both direct and indirect ways. Direct benefits, which are generally related to individual buildings, include primarily cover from the solar radiation and protection from the wind; however, trees can also provide filtration of air pollutants, shielding from noise pollution, and stabilization of soil against erosion. Indirectly, vegetation cools buildings by reducing the temperature of the air surrounding them via evapotranspiration, a process by which a plant releases water vapor into the air. The cumulative effect of many trees and plants is the cooling of the air in a large area.(3) Another benefit of trees and vegetation, of particular interest and importance in cities, is their phytoremediation potential with respect to the clean up pollutants in contaminated soil, air and water.(25) In addition, vegetation can greatly increase the aesthetic value of property and ecological quality of an area by providing an important habitat for birds, animals, and insects. The beneficial functions of trees, in particular, are illustrated in *Figure 14*.(4)

Figure 14: Beneficial Functions of Trees



Source: http://eetd.lbl.gov/heatisland/ (4)

Increasing vegetation is fairly simple and relatively inexpensive in the short term, but these are also long term considerations related to the time and money needed for maintenance. Unfortunately, in the last several decades, more and more trees have been removed from urban environments due to construction and development. Today, only one tree is planted in our cities for every four removed.(3) Thus, as vegetation disappears, temperatures began to rise.

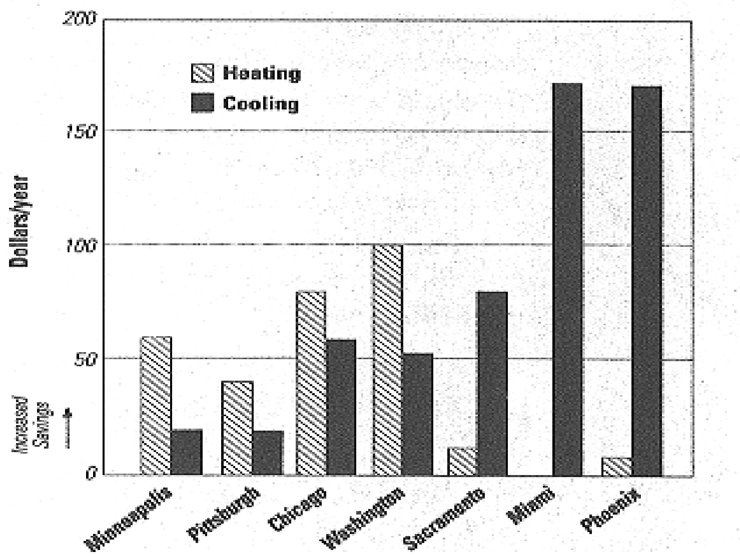
3.3.1 Effects

Direct Effects

Vegetative cover, specifically trees and shrubs, can be directly beneficial to buildings all year round. In the summer months, trees can serve as a barrier against incoming solar radiation, which in turn prevents structures and surfaces from heating up beyond the ambient air temperature. In fact, researchers have found that tree shade does a better job cooling a building and its interior than blinds, plastic coatings, or reflective coatings on glass.(3) Field measurements have shown that through shading, trees and shrubs strategically planted next to buildings can reduce summer air conditioning costs typically by 15 to 35 percent, and by as much as 50 percent or more depending upon specific situations.(3) In addition, simply shading the air conditioner by using shrubs or a vine covered trellis can save up to 10 percent in annual cooling energy costs.(4) In the winter, trees and shrubs can act as a barrier shielding a building from cold winter winds. However, because they also generate shade, trees and shrubs may also be a liability. This is because vegetation can block the warming rays of the sun, particularly those from the south, thus, actually increasing the heating energy consumption in the winter.

When shading and wind shielding effects are considered together, trees are shown to reduce both heating and cooling energy use in warm and temperate climates. These results are illustrated in *Figure15*. This figure shows the results from a computer simulation that looked at the combined shading and wind shielding effects from a 30% increase in tree cover around a typical house built before 1973.(3)

Figure 15: Changes in the Expenditures of Energy – Wind Shielding and Shading Effects



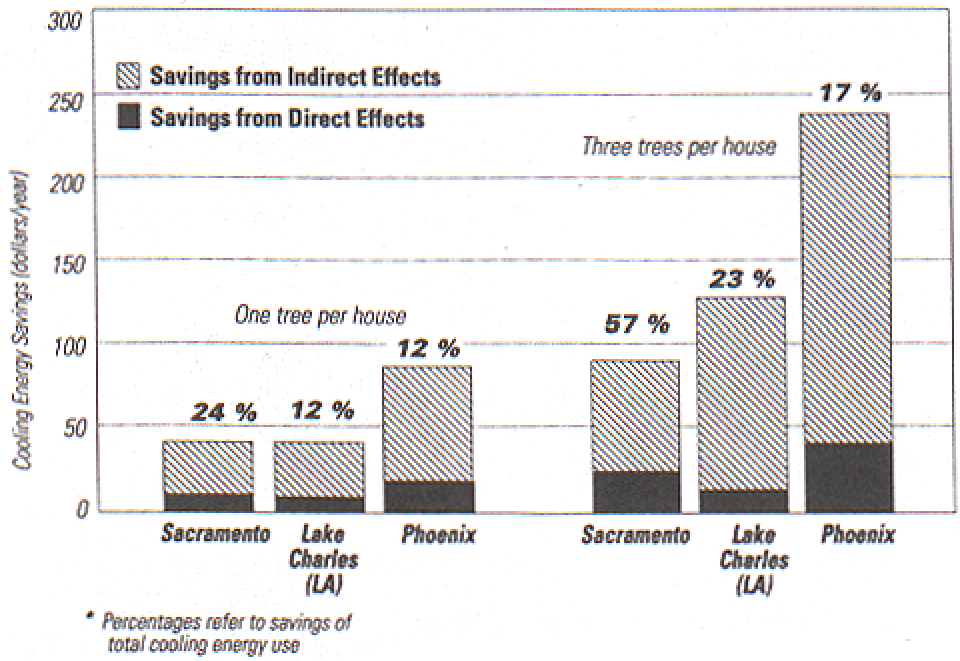
Source: Cooling Our Communities (3)

Indirect Effects

Vegetation has great potential to cool cities through a process known as evapotranspiration.(3,4) Evapotranspiration occurs when plants secrete, or transpire, water through pores in their leaves. The water draws heat as it evaporates, thus cooling the air surrounding the leaves in the process. Trees can transpire up to 100 gallons of water in a day. In a hot dry climate, this cooling effect equals that of five air conditioners running for 20 hours per day.(3) The cumulative effect of many trees and plants grouped together not only creates a pleasant green space within a community, but can act to cool surrounding areas.

The evapotranspirative properties of trees have the potential to produce greater indirect effects on temperature and energy consumption. For example, *Figure 16* shows a comparison of the relative savings attributable to indirect and direct effects of increasing vegetative cover around a typical, well insulated, new house.(3)

Figure 16: Estimated Cooling Energy Savings from Increased Vegetation



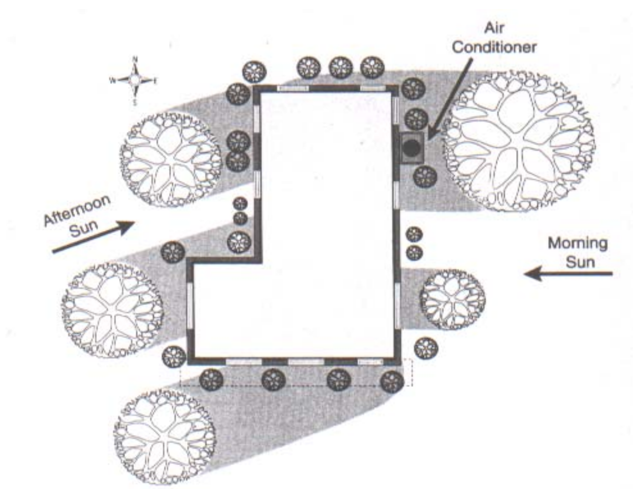
Source: Cooling Our Communities (3)

When the effects of evapotranspiration are combined with the effect of strategically placed shade, temperatures can drop by as much as 9°F in the immediate vicinity of the trees. Increasing vegetative cover by just 10 and 30 percent (about one and three properly placed trees per house, respectively) may reduce cooling energy by as much as 10 to 50 percent, depending on housing stock type, age, construction and other factors. Typically, older and more poorly insulated buildings, and those in hotter, drier regions, will have greater energy savings. As the number of trees increase, the relative contribution of the indirect effect, such as evapotranspiration and aesthetic benefits, grows in comparison to the direct effects, including protection from solar radiation, wind, and noise. However, these numbers generally apply only to trees located in optimal energy conserving locations in order to maximize their shading effects.(3,26)

3.1.2 Implementation Strategies

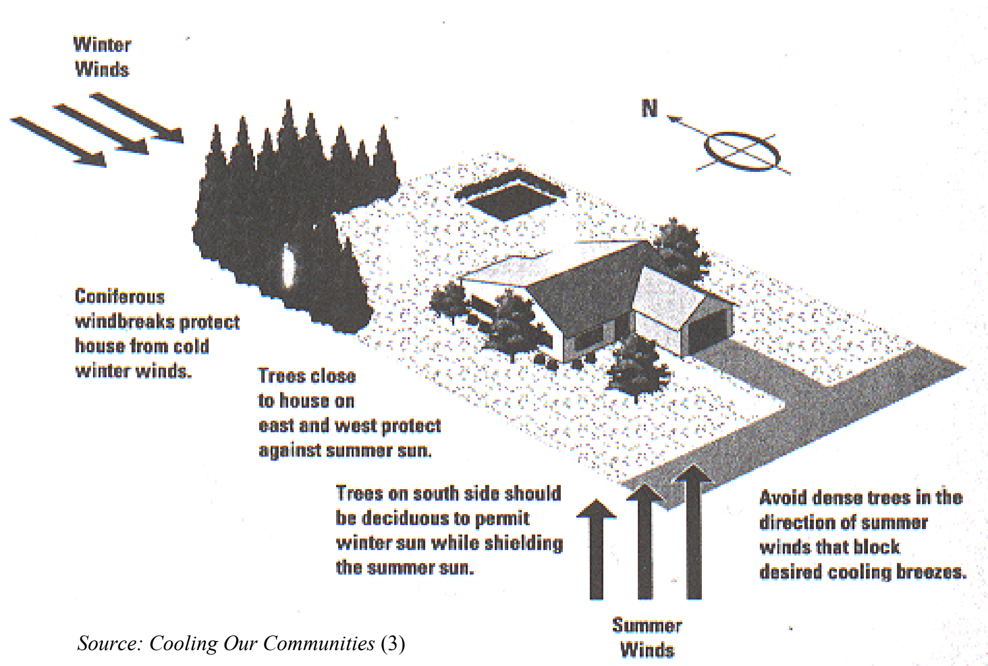
Planting trees and bushes will not only make a city greener, but can help reduce urban temperatures and energy consumption. However, randomly planting trees throughout a city isn't the best way to achieve optimal benefits, for the effectiveness of vegetation depends on its particular type, density, shape, dimensions, and placement. *Figure 17* and *18* illustrate the strategic planting of vegetation around a building.(3)

Figure 17: Sample Residential Landscape



Source: Cooling Our Communities (3)

Figure 18: Strategic Planting Diagram



Source: Cooling Our Communities (3)

In the summer, proper placement can ensure that trees shade the areas most critical in lowering internal temperatures and shade them at the most critical time of the day. For example, trees should be placed to shade the east, west and south sides of a building in order to block late morning, afternoon, and early evening sun. For a home monitored in Sacramento, California, researchers found that this reduced cooling energy use by as much as 30%.(4) Studies in Chicago have shown that shade from a street tree located to the west of a typical brick residence can reduce the annual use of air conditioning energy by 2-7% (138-205 kWh) and peak cooling demand by 2-6% (0.16-0.6 kW).(3) Street trees that shade the east side of buildings can produce similar cooling savings, but have a negligible effect on peak cooling demand and can slightly increase winter heating costs. Shade from street trees to the south, on the other hand, actually increase heating costs more than they decrease cooling costs. (26) As a result, deciduous trees, which drop their foliage in the fall, maximize the beneficial effects of shading because their broad leaves protect a building from detrimental summer radiation, while allowing most of the desirable winter sunlight to shine through the bare limbs. Evergreen or coniferous vegetation can be positioned to reduce the influence of cold winter winds on the heating requirements, as long as these windbreaks do not impede winter sunlight. In South Dakota, for example, houses measured consumed 25 percent less fuel when located on the leeward sides of windbreaks than when exposed. When wind breaks were present on the north, west, and east sides, fuel consumption was reduced by 40 percent.(3)

Increasing the urban canopy of cities is not a faultless measure, for there are many potential problems associated with the addition of vegetative cover. First, increasing the amounts of trees and plants in an area may increase the demand of water needed for irrigation. Fortunately, preliminary analysis suggests that using trees to shade lawns can drastically reduce water needs in a community by saving that which would otherwise go to watering the lawn.(4) In addition, using shrubs or natural groundcover instead of grass or trees may reduce water usage even further.(3)

A second problem is linked to the fact that trees and vegetation emit volatile organic carbons (VOCs) that combine with oxides of nitrogen (NO_x) to form smog. However, different species emit different amounts of VOCs. For example, ash and maple are among the more VOC-free trees, emitting only about 1 VOC unit (defined as one microgram per hour per gram of dry leaf). Eucalyptus trees and weeping willows, on the other hand, are a problem for they emit 32 and 230 VOC units, respectively.(4)

Another problem is associated with the amount of solid waste generated in a community. Specifically, the problem of the disposal of potentially large amounts of leaves, twigs, branches, and other debris from vegetation in landfills. Fortunately, there are many alternative options available for this type of disposal. For example, leaves can be used for compost, whereas branches and trunks can be used for firewood or chipped for mulch. Clearly, any community embarking on a large-scale tree-planting program must also consider the merits of community-wide composting and yard waste recycling programs.(3)

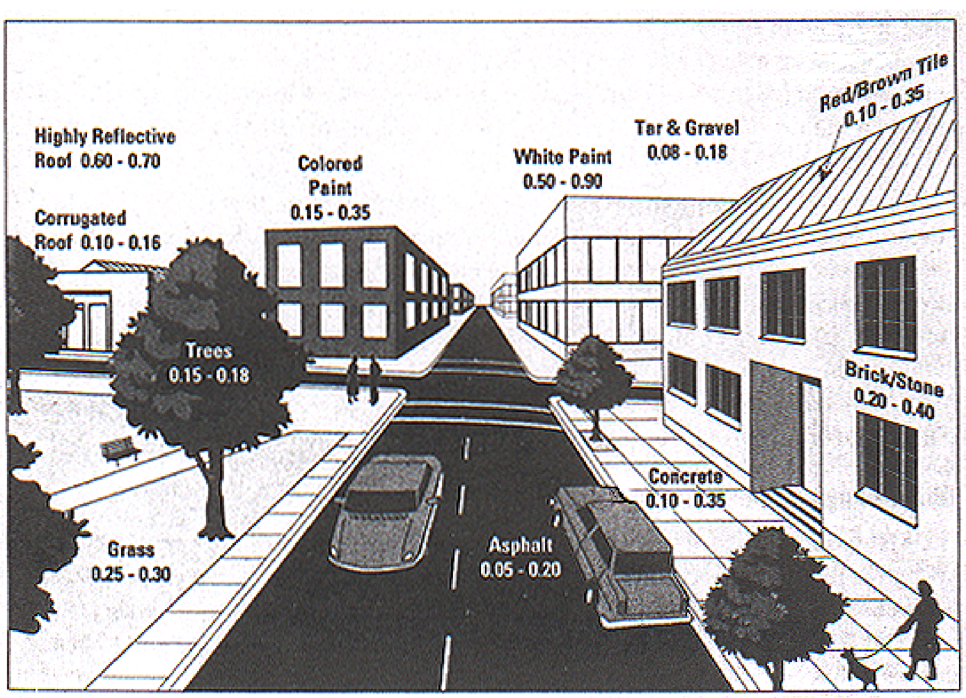
Depending on the region, and including these other factors, the combined benefits of urban tree planting will often be greater than the costs incurred. Unfortunately, achieving this potential is often conditioned upon receiving the necessary local, state, and federal support. Although many communities in this country already have tree-planting programs and ordinances in effect, starting an effective and comprehensive program requires extensive research, material development, technology transfer, education, public participation, implementation guidelines, and community outreach movements.(3)

3.2 LIGHT COLORED SURFACES

Our built urban environments contains innumerable surfaces, including building roofs and walls, streets, freeways, parking lots, driveways, school yards, and playgrounds. Typically, when these surfaces are dark, they absorb the solar energy of the sun and heat up and when they are light, they reflect the sun's rays and stay cooler. Thus, the color of a city's urban surface acutely effects the climate and temperature within that area.

The measure of a surface's reflectivity is called albedo. Albedo is measured on a scale of 0 to 1. A surface with a relatively high albedo, 0.75 or greater, is generally light in color and reflects most of the sun's rays. A surface a low albedo, 0.25 or less, is usually dark in color and will absorb most of the incoming solar energy. *Figure 19* shows the albedos for some common surfaces found in urban areas.

Figure 19: Surface Albedo Values



Source: Cool Communities (3)

3.2.1 Effects

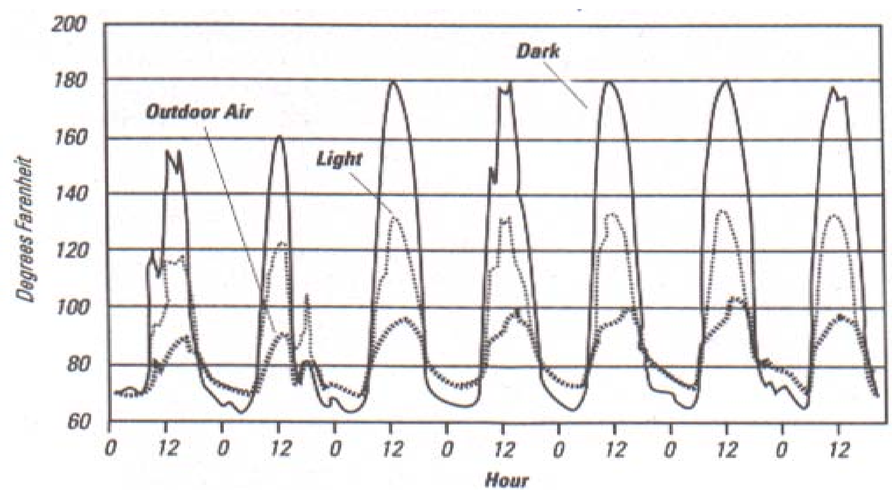
Like vegetation, reductions in temperatures and energy use from albedo modifications accrue to both individual buildings and entire neighborhoods. At the building scale, cool roofs reduce air conditioning loads. For example, numerous experiments on individual buildings in California (4) and Florida (27) show that painting the roof white reduces the air conditioning load between 40 and 70%, depending on the building type, climate zone, thickness of insulation, and angle and orientation of roof. At the community scale, collectively increasing the albedo of urban surfaces can help mitigate the urban heat island effect by lowering area temperatures and reducing total energy use.

Unfortunately, few field measurements exist that document the reductions in temperature or energy use resulting from altering the albedo of surfaces in houses and communities. This is because very few albedo modification programs have been initiated in the U.S. or abroad. However, preliminary analysis and computer simulations of neighborhoods suggest that changing roof, wall, and street colors by increasing surface albedos could significantly reduce air temperatures, decrease cooling energy use, and increase air quality, while keeping cost and potential risks low, for changes can be incorporated into normal maintenance cycles.(3,28,29)

Through these simulations, researchers estimate that albedo changes could reduce a city's air temperature by as much as 4-5°F in hot sunny climates with many dark surfaces.(3,30) This, in turn, could produce total simulated energy savings approaching 50 percent during average periods of cooling demand and 30 percent during peak hours.(3) In addition, simulations of the cooling achieved by increasing the albedo of roads and roofs in the LA Basin, indicated a 4°F cooling by noon resulting in a reduction in population weighted smog exceedances of 10-12%.(30)

Figure 20 illustrates the daily effects of color on surface temperature. For low albedo surfaces, the difference between the surface and ambient air temperature may be as high as 85°F, while for high albedo surfaces, the difference is only about 30-40°F.

Figure 20: Effects of Surface Color on Temperature



Source: *Cooling* ***Our Communities*** (3)

3.2.2 Implementation Strategies

The practice of using light colored surfaces in building is not a new concept. In tropical and sub-tropical regions, such as the Mediterranean and North Africa, for example, surfaces have been white washed for centuries to keep albedos and reflectivity high and temperatures low.(3) Unfortunately, this practice is too commonly overlooked by architects and developers of today with the low cost and widespread use of air conditioning.

Because no urban community in the United States or abroad has yet initiated a formal program of albedo modification, there is little practical experience with respect to successful implementation practices, potential drawbacks, or conflicts with other urban issues. However, one way to begin programs for light-colored surfacing strategies is through public education. Providing information on the albedo of building materials and the related energy savings may help inspire consumers to develop ordinances and implement these measures. Municipalities can pass ordinances that specify the use of light-colored paving materials in road building and renovations or zone for light colored building materials in commercial areas. Likewise, offering financial incentives could motivate architects and developers to design and build light colored, energy efficient buildings and communities.(3)

3.2.3 Roofs

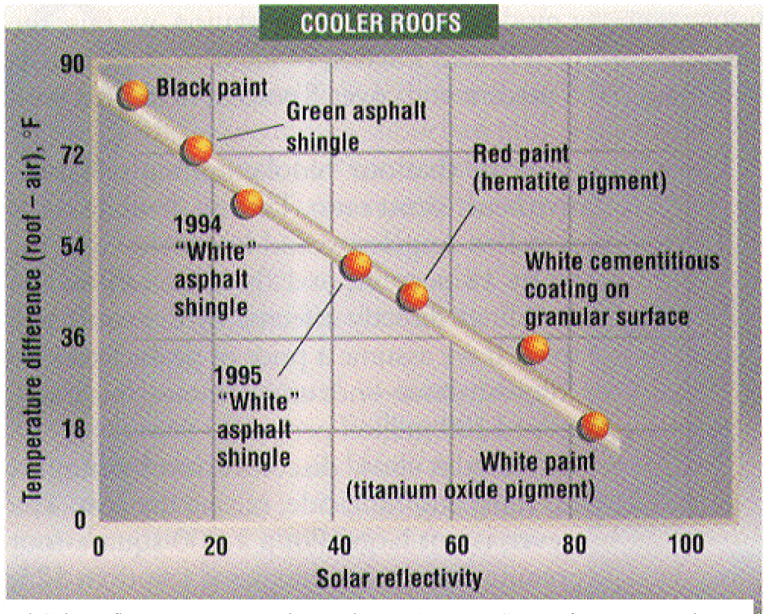
Summer Benefit

Numerous studies have shown that dark materials absorb more heat from the sun. When these dark materials are used on the surfaces of roofs, their temperature increases the heating of the air around them contributing to the heat island effect. In addition, a portion of the radiative heat energy collected by the roof may be transferred to the inside of a building. In the summertime, this unwanted heat energy generates conditions that often lead to more air conditioning and higher utility bills.

There is a sizable body of measured data, primarily collected for the residential sectors of California and Florida, documenting energy-saving effects of light colored roofs.(4,27,31,32, 33,34) This measured data, along with extensive computer simulations, clearly demonstrate that increasing the albedo of roofs can be effective in reducing temperatures and energy use for individual buildings and communities. In addition, studies have suggested that lighter roofs incur no additional cost, other than the incremental cost associated with the high-albedo material, if color changes are incorporated into routine re-roofing and re-surfacing schedules.(31)

Solar reflectivity is used to measure how much radiative heat energy materials collect in the sun. *Figure 21* shows the solar reflectivity of different roofing materials as a function of their individual temperature differences with the surrounding ambient air.(4)

*Figure 21**



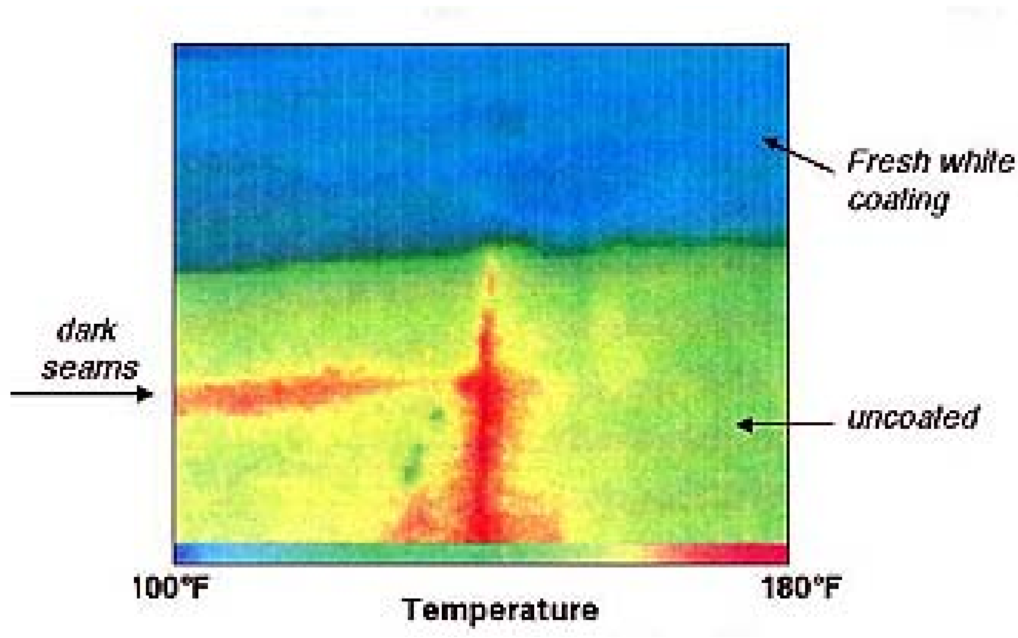
** Solar reflectivity is measured according to American Society for Testing and Materials (ASTM) E903*
Source: http://eetd.lbl.gov/heatisland/ (4)

The extremes of white and black paint define the solar reflectance index (SRI). In general, the temperature difference rises as solar reflectivity decreases. Thus, darker colored shingles significantly raise the roofed surface temperature. Traditional roofing materials have a SRI of between 5% (brown shingles) and 20% (green shingles). Red-painted tiles are cooler than white asphalt because the seemingly darker surface actually reflects infrared better. White shingles with SRI's around 35% were popular in the 1960s, but they lost favor because they became dirty easily and the labor costs of maintaining the high albedo of a roof coating would exceed the cost of conserved energy. Manufacturers have recently developed clean, "self-washing" white shingles with even higher SRIs up to 62%. The current trend is to make roofing materials more reflective so that the sun's radiant energy is reflected back into space instead of absorbed. Roofing with materials whose SRI rating is 50% or higher will keep a buildings and cities cooler and reduce energy bills.(4)

In addition to high solar reflectance, a high infrared emittance and good convective heat transfer is also desirable because roof surface temperature is greatly influenced by the various heat flows at the outside surface. Infrared emittance is a measure of the ability of a surface to emit its energy in the form of heat radiation. Thus, a high infrared emittance would help facilitate the discharge of stored heat energy from the roofing material. Likewise, materials with good convective heat transfer properties would assist in the transfer of heat away from the roof by the surrounding air.(4)

The infrared image of a roof painted with a light reflective coating shows a dramatic reduction in roof temperature between the low and high albedo sections. This phenomenon is depicted in *Figure 22*.

Figure 22: Infrared Roof Image

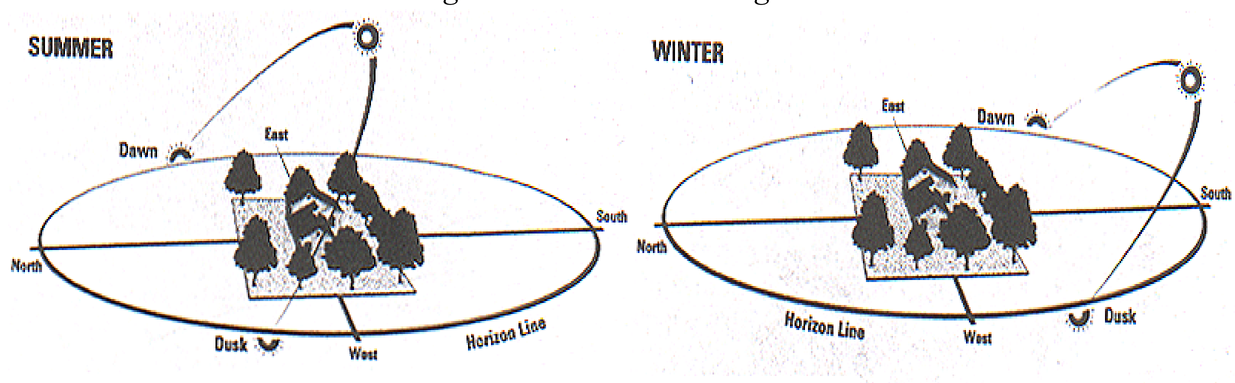


Source: http://eetd.lbl.gov/heatisland/ (4)

Winter Penalty

The same steps that make buildings easier to cool in the summer also can make them more difficult and expensive to heat in winter. However, in hot climates, the summertime benefit greatly outweighs the wintertime penalty. This is because the sun is high overhead in the summer, and shines mainly on the roof of a building. In winter the low sun shines primarily on the building side walls and through the windows. *Figure 23* illustrates the solar path diagram for the summer and winter sun.(3)

Figure 23: Solar Path Diagram



Source: Cooling Our Communities (3)

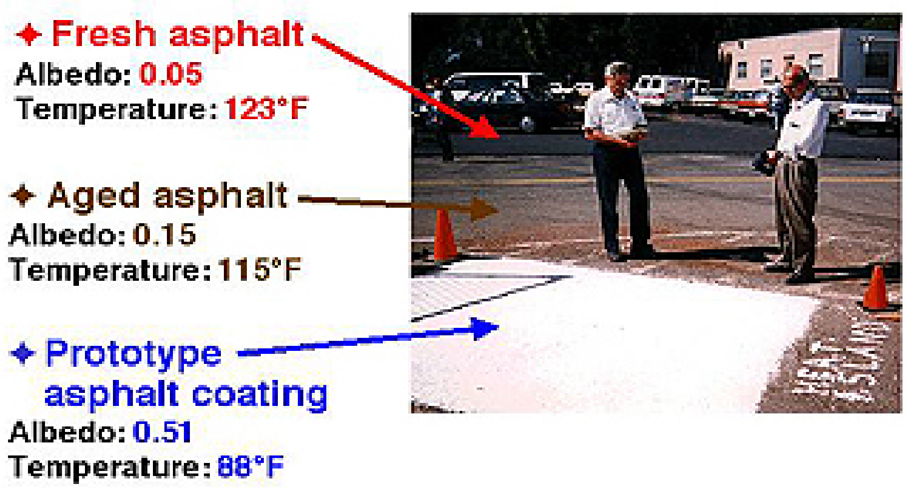
In a climate like that of San Fernando Valley, CA, a homeowner would save about $40 over a season of air conditioning use if the roof were white rather than green. On the other hand, the winter heating bill for the white roofed home would be only $10 more than the green roofed home. This produces a net savings of $30.(4) In the U.S., white roofs also retain their energy advantage surprisingly far north. This is due to the fact that the length of the day is approximately halved in the winter, the sun is relatively low so that it shines on only half the roof area compared to summer, and the skies are about three times cloudier in winter than summer.(4) The combination of these three factors combined illustrate the greatly reduced potential of solar absorption by a roof during the winter. Thus, because so little winter sunlight ever makes it to the roof at all, the color of the roof has an insignificant winter penalty.

3.2.4 Pavement

Another contributor to the heat island effect is pavement. It has been well documented that dark materials absorb more heat from the sun. In fact, dark, low albedo surfaces in the sun can become up to 55°F hotter than corresponding light, high albedo surfaces, as seen previously in *Figure 20* (page 52).(4) Thus, roadways and parking lots paved with dark materials absorb immense amounts of solar energy, heat the air around them, and contribute greatly to the heat island effect.

Today, there are many new paving materials being developed that can reflect more sunlight so that they absorb less solar radiation and stay cooler. *Figure 24* demonstrates how one such prototypical material compared to new and aged asphalt during a study conducted by the Lawrence Berkeley National Laboratory (LBNL) in collaboration with Reed and Graham, Co. of San Jose, California.(4) In general, it was found that for a increase in albedo of 0.1, the pavement temperature decreases by about 8°F.

Figure 24: Comparison of Pavement Albedos and Temperatures



Prior to embarking on a large-scale heat island mitigation program that promotes the use of high albedo pavement materials, it is necessary to rigorously consider all of the costs and benefits of each pavement alternative. Life cycle analysis is a technique utilized for the comparative evaluation of the overall effects of alternative methods.

Life Cycle Analysis

Methodology

A life cycle analysis provides an entire life assessment of a product, process, or activity encompassing: extracting and processing raw materials; manufacturing; transportation; distribution; use; re-use; maintenance; recycling; and final disposal. There are two different methods of life cycle analysis currently being utilized in industry: life cycle cost analysis (LCCA) and life cycle assessment (LCA).

Traditional methods, such as those often used in the analysis of alternative pavement designs (35), employ LCCA as the accepted way of comparing products or services. In this procedure, the comparison of competing products is based solely on total lifetime cost and performance. Increased concern over improving the sustainability of industrial operations has introduced the need to consider resource depletion, human health effects, and environmental impact in product selection, yet this is not routinely done in LCCA. Thus, LCA offers a structured way of introducing these considerations into the decision making processes and examining alternatives, such as selection of a building material or choice of a manufacturing process.(36) Life cycle assessment is a way of compiling and examining the inputs and outputs of the energy, resource, and environmental impacts directly associated with a product or service system through every step of its life. The associated overall impacts can then be determined and weighed in order to identify possible system issues, analyze tradeoffs, assist in more detailed research, and set the stage for improvements.

In general, a life cycle assessment can be utilized internally or externally by an organization in the material selection for infrastructure design. The potential uses of LCA internally include: environmental strategy development; product process design, improvement, and optimization; identification of opportunities for environmental improvement; environmental auditing and waste minimization. Subsequently, the external applications of LCA for an organization encompass: comparison of competing products or services; advocacy of products or services; establishment of government policy; eco-labeling; and public education and communication.(36)

In order for legitimate claims to be made about how one product compares to another, the LCA and subsequent comparison must be based on analyses conducted using a uniform set of rules. A complete life cycle assessment study can be generalized into four phases: project characterization, inventory analysis, impact assessment, and improvement assessment.(36,37)

Phases

At the beginning of a product LCA, the scope and purpose of the current assessment must be specified. This is important because different parties have different underlying values and principles, which will lead to diverse formulations of environmental issues and impact how LCA results are used and interpreted. Thus, as a guide, the use and application of an LCA, in addition to the principles and goals of the study, should be clearly stated in the scope of an LCA study.(37) Furthermore, the LCA process must make provisions for a critical review of the findings. The degree to which a critical review is required, and how it should be done, depends on the purpose of the LCA. For example, if the LCA is to be used for comparative claims that are made public, an in depth review is essential in order to ensure the validity of the scientific and technical methods used, the quality of the data in relation to the goal, the validity of the LCA conclusions relative to the limitations identified in the study, and the transparency and consistency of the study. (36)

The second phase of a LCA begins with the construction of a process flow chart, listing all mechanisms involved in each life cycle phase and specifying system boundaries. The product or service being inventoried is described as a system that performs a defined function. The system is separated from its surrounding environment by a system boundary across which there is an inflow of materials and energy and an outflow of products and emissions. Thus, after the process diagram is complete, all relevant inputs and outputs from a product or service are compiled and quantified for each stage in the life cycle.

The value and credibility of any LCA depends upon the quality of its data that must be maintained throughout a life cycle assessment if the user is to have any confidence in its results. Data quality is defined as the degree of confidence in individual input data, in the data set as a whole, and ultimately in decisions based on the LCA study using such data as input. Unfortunately data quality is influenced by many factors and varies enormously. The major issues of concern include the collection method, data source, representativeness, amount, age, consistency, and reproducibility of the data, level of aggregation, and completeness of coverage.(36,38) Poor quality data limits the external uses of an LCA. For example, it may be impossible to compare two competing products if the data for one of the products is not sufficiently representative or accurate.(36) Specifically, this issue is often associated with the acquisition of emissions and other environmental data, from the individual industries involved in a product's life cycle, for a great deal of this type of information is not a matter of public record and is thus not easily accessible to an outsider.(39)

In the third phase, an evaluation is done on the magnitude and significance of the potential impacts associated with those inputs and outputs. These outcomes, which usually consist of a list of emissions to water, air, solid waste and use of raw materials, are translated into a normalized functional unit used to illustrate their respective contributions to relevant issues of concern. This allows a LCA to focus on relative comparisons of whole systems with respect to resource use, human health effect, and environmental impact in relation to the defined functional unit. As a result, life cycle assessment does not represent measuring or predicting actual impacts, predicting potential impacts (in the sense of possible future impacts), estimating risks, or assessing safety.(37)

Instead, in the final stage, the results are used as indicators that enable a better understanding of the environmental impact of the product during its life cycle, set priorities in the design process, and focus attention on the issues that offer the best opportunity for improvement. Of course, in this interpretation phase, it must be ascertained that, for comparative studies, equivalent assumptions have been made and all uncertainties identified.(37)

In some ideal cases an LCA will show a clear single dominant impact that can be easily addressed; however, impacts are usually spread over the different phases of the life cycle and over different environmental effects. Thus, in order to make explicit comparisons, the true and meaningful differences among the results of the category indicators must be identified. This can be accomplished through the utilization of a number of further analytical techniques. Some specific techniques are gravity analysis, sensitivity analysis, and error or uncertainty analysis. Gravity analysis allows the specification of which processes or life-cycle stages are the major contributors to the LCA results. Sensitivity analysis evaluates the effects that the ranges in data, methodological assumptions, reference values, etc., have on model outcomes. This can help interpret which of these factors may most influence the results. Finally, error or uncertainty analysis evaluates the natural variability of error in the data and methods, and allows one to assess if measured system parameters are significantly different from zero and each another. These techniques and the information they provide may help identify areas for additional analysis and interpretation and explain the significance of the LCA results.(37)

The assessment and comparison of an entire system or a network of industrial operations over a product's life cycle is difficult due to the complexity and disparity of study systems, for example, differences in unit operations among alternative systems. It becomes even more difficult as one then attempts to relate the elaborate systems to a diverse range of even more complex environmental issues. The LCA system wide approach is a necessary contribution to this assessment of an entire system; however, in order to simplify the LCA process, a number of assumptions, value choices, and subjective judgments are required during the analysis. As a result, a certain amount of discontinuity and inconsistency within the LCA inventory data quality, methods, and results are inevitable.(37) This is not to say that life cycle assessment methodology is valueless or lacks credibility. In fact, LCA is a very useful design tool if the methodology and assumptions used in the assessment are clearly stated and caution is exercised in the interpretation of results.

Concrete and Asphalt Pavement

Currently, the primary components in highway design are cost of construction, economy of maintenance, durability, and safety.(40) However, increased concern over improving the overall sustainability of a design has introduced the need to also consider resource depletion potential, human health effects, and environmental impact of a design. Life cycle assessment offers a way of compiling and examining the inputs and outputs of a design through every step of its life

In this section, a comparison of concrete and asphalt pavement will be examined and discussed. The research reported, which is based upon the LCA technique, was conducted by Wilfred H. Roudebush, Ph.D. with the sponsorship of the Portland Cement Association (PCA Project Index No. 94-04) through a subcontract with Construction Technology Laboratories, Inc. The Portland Cement Concrete LCA project followed the guidelines proposed by the Society of Environmental Toxicology and Chemistry (SETAC). These guidelines parallel the draft standards proposed by the International Organization for Standardization (ISO) in the 14040 series, 'Environmental Management - Life Cycle Assessment - Principles and Framework' and other ISO draft documents.

Project Characterization

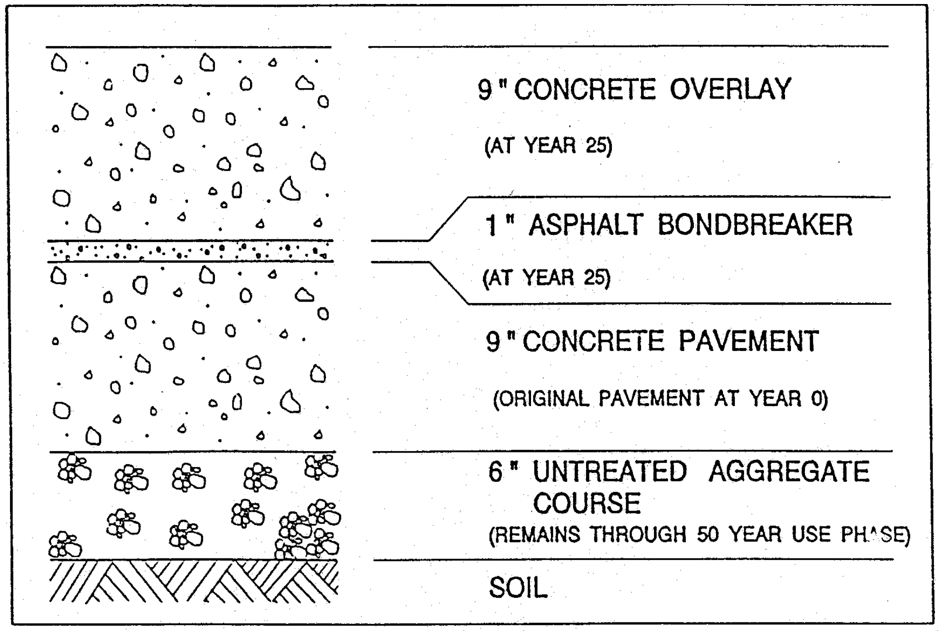
One of the first steps in conducting an LCA is to determine and designate the scope of the project, including the comparable subsystems of the alternatives being considered. These subsystem designations already exist for many alternatives related to highways and can be found in Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-92).(41) The concrete highway system used in this assessment included United States Department of Transportation (USDOT) divisions 301-Untreated Aggregate Courses and 501-Portland Cement Concrete Pavement. The asphalt highway system employed included USDOT divisions 301-Untreated Aggregate Courses and 401-Hot Asphalt Concrete Pavement.(42)

The PCA project compares a kilometer of portland cement concrete and asphalt concrete pavements for a 50 year design life. The pavement dimensions for both highway pavement system alternatives were 24 feet wide and are American Association of State Highway and Transportation Officials (AASHTO) equivalent designs according to the American Concrete Pavement Association.

The concrete highway pavement system consisted of a 9 inch thick portland cement concrete layer on a 6 inch untreated aggregate base course. After 25 years, the pavement system is resurfaced with a 1 inch asphalt concrete bond breaker and a 9 inch portland cement concrete overlay. The components of the concrete highway pavement system are given in *Figure 25*. The original concrete pavement, asphalt bondbreaker, and concrete overlay were demolished and removed at the end of year 50. The untreated aggregate base course remained after demolition of the pavement. Sequencing of subsystem components during the use phase is graphically given in *Figure 26*.

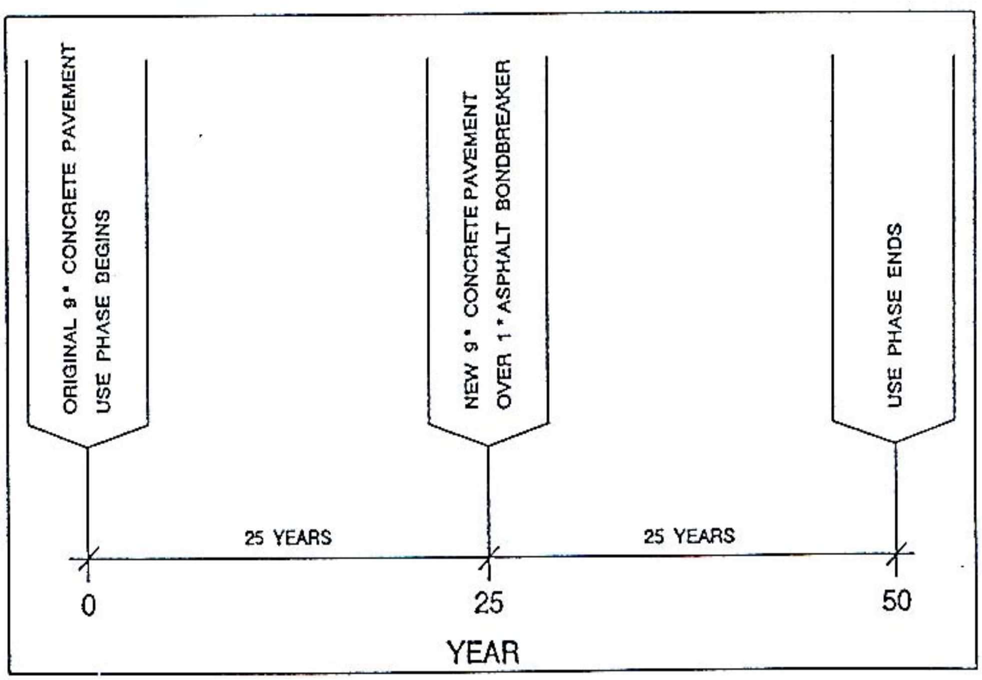
The asphalt highway pavement system consisted of a 5 inch thick asphalt concrete pavement on a 14 inch untreated aggregate base course. At the end of year 14, the pavement is resurfaced with a 5 inch asphalt concrete overlay. Both the original pavement system and the overlay are removed and reconstructed after 25 years. At the end of year 39, the pavement is resurfaced with a 5 inch asphalt concrete overlay. The reconstructed asphalt concrete pavement and overlay are demolished and removed at the end of year 50. The untreated aggregate base course remained after pavement demolition. The components of the asphalt highway pavement system are given in *Figure 27*, and the sequencing of subsystem components during the phase is graphically given in *Figure 28*.

Figure 25: Concrete Highway Pavement System Components



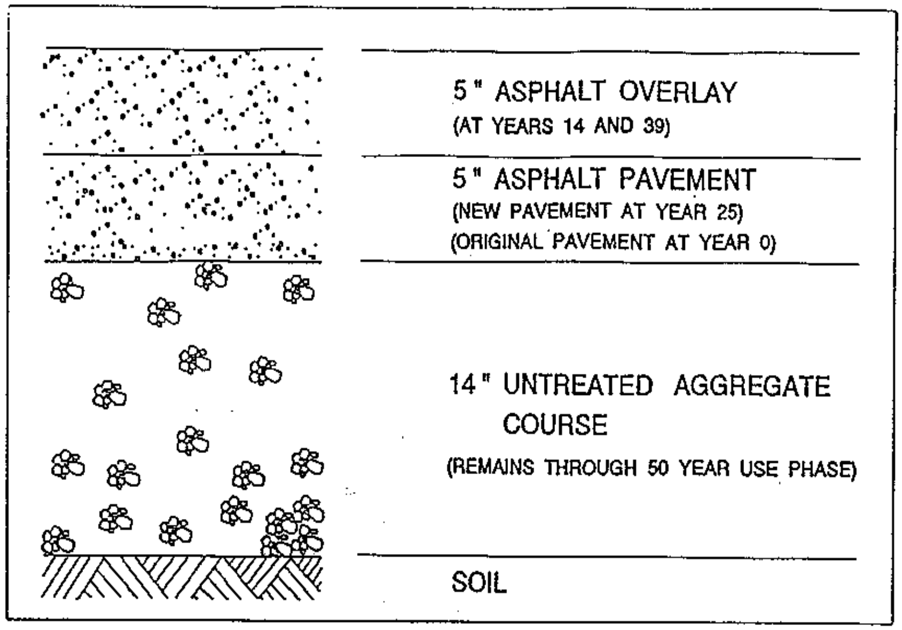
Source: Roudebush, W.H., 1996 (42)

Figure 26: Concrete Highway Pavement Subsystem Component Sequencing



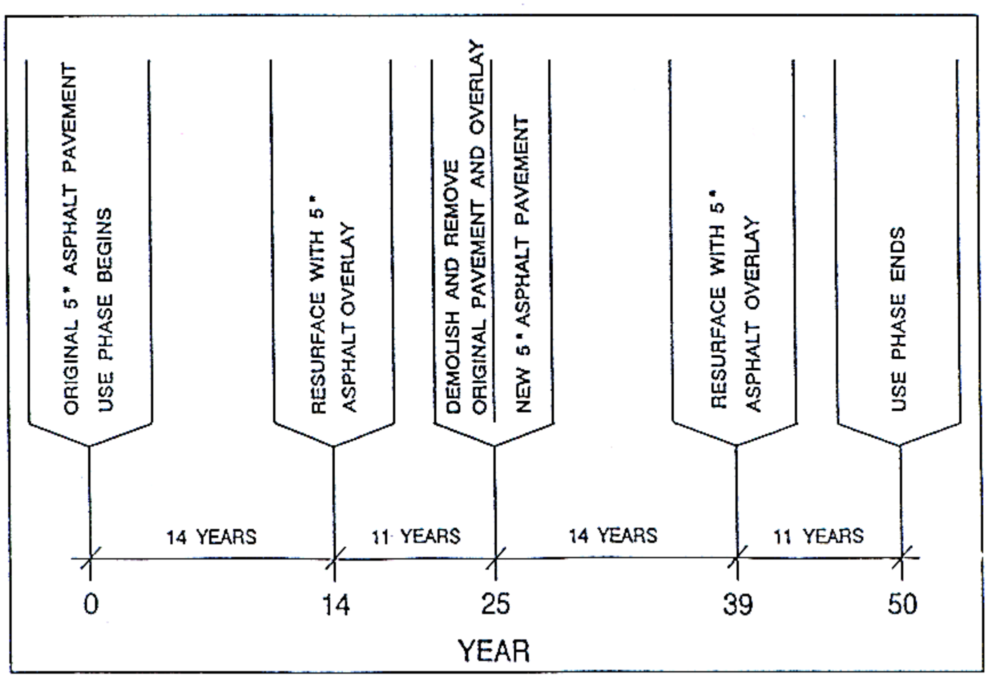
Source: Roudebush, W.H., 1996 (42)

Figure 27: Asphalt Highway Pavement System Components



Source: Roudebush, W.H., 1996 (42)

Figure 28: Asphalt Highway Pavement Subsystem Component Sequencing



Source: Roudebush, W.H., 1996 (42)

The assessment period is subdivided into 10 life cycle phases through which the alternative pavement materials, components, and systems proceed. These phases are described in *Table 5*.(42) It should be noted that life cycle phases A through C are not generally included in LCCA, and thus, at present time do not influence the selection process. These phases comprise the material transformity phase, which incorporate all the factors that go into processing and transforming a raw material into the material utilized in a design.

Table 5: Life Cycle Phases

Phase	Description
(A) Natural Resource Formation	• production and consumption of various environmental system (ecosystems, geology systems, etc.) which include minerals, which are formed by earth processes over millions of years and biomass, resulting from living organism net production occurring over shorter periods of time
(B) Natural Resource Exploration and Extraction	• renewable environmental inputs in the form of land used during extraction and storage of extracted natural resources • reclamation of land, after natural resource extraction • transportation of natural resources for material production
(C) Material Production	• conversion of natural resources into materials used in pavement component production
(D) Design	• inclusion of five sub-phases, according to the American Institute of Architects (1987): 1) schematic design 2) design development 3) construction documents 4) bidding and negotiations 5) construction administration
(E) Component Production	• production, storage, as needed before use, and transportation of components to the site for construction • conducted by manufacturing facilities specializing in various alternative components
(F) Construction	• construction of initial concrete and asphalt pavements • work done during the guarantee and warranty periods of the construction contract • dependent upon such factors as type of construction, techniques of construction, time of construction, quality of materials, components and subsystems, and workmanship
(G) Use	• operation, maintenance, alteration, repair, replacement, financing, tax elements, insurance, and any other activities related to the pavement system from substantial completion of construction to the time of demolition, including periods of nonuse or abandonment • affected by quality of materials, decisions on utilization of recycled materials, components, subsystems, and phase duration.
(H) Demolition	• demolition and removal the materials, components, and subsystems of a pavement system • sensitive to decisions on reuse and recycling of materials, components, and systems during this phase
(I) Natural Resource Recycling	• reduces the demand for raw materials that are made by the environment during natural resource formation (Phase A), natural resource exploration and extraction (Phase B), material production (Phase C), and component production (Phase E) requirements of future systems • reduces the need for disposal and landfill land use

(J) Disposal	• evaluation of demolition debris placement, compaction, and landfill containment • estimate of landfill closure and landfill postclosure which include groundwater monitoring, final cover, contour grading, surface water diversion, gas mitigation control, re-vegetation, and security/monitoring systems.

Source: Roudebush, W.H., 1996. (42)

Inventory Analysis

The methodology utilized in this life cycle assessment comparison of cement and asphalt pavement is referred to as environmental value engineering (EVE). Using this methodology, which is based on a system developed by Dr. Howard E. Odum, University of Florida, Gainesville, environmental impacts of different system alternatives can be compared using one system of normalized units denoted as *emergy*.

Emergy is defined as all the available energy that was used directly and indirectly in the making of a product, including the environmental impacts related to inputs of environment, fuel energy, goods, and services. However, energy of one kind is not equivalent to energy of another kind and accumulates from one phase to the next. Thus, in order to sum up all the available energies used, they must expressed in terms of one common quantity, *emergy*. This resultant *emergy* has units of solar emjoules (sej), which are related to the amount of solar energy required to generate the inputs.(43)

The inputs of environment, fuel energy, goods, and services that occurred for each of the various subsystem components during each life cycle phase of the pavement alternatives, were first accounted for in raw data units (i.e.: grams, joules, dollars). This input information was obtained from companies, individuals, and documents related to specific life cycle phases.(42) In general, the input information collected consisted of primary data, from operating companies. If primary data were not available, secondary data were used.

This would include information from equipment vendors, public sources and commercial databases, and estimates from similar operations.(36)

From this energy information, an *emergy* input table was constructed for each pavement alternative system and each life cycle phase using the appropriate emergy conversions. These conversion factors were obtained from research data of the *emergy* analysis and are based on the scientific methods of Dr. Howard T. Odum and his associates at the University of Florida, Gainesville, FL, and Dr. Wilfred H. Rotidebush at Bowling Green State University, Bowling Green, OH.(42) (See Appendix C)

The individual subsystem *emergy* input data were then complied for every source within each life cycle stage and aggregated into an overall *emergy* input data table for each pavement alternative. The tables of aggregated *emergy* input source data for the highway pavement systems, concrete (Alternative A) and asphalt (Alternative B), are given in *Table 6* and *Table 7*, respectively. Referring to these tables, the *emergy* input sources of environment, fuel energy, goods, and services are given in the *emergy* input source data columns, and life cycle phases are represented in the rows along the left side of the table. Phase *emergy* totals and the individual input *emergy* source proportions of the total phase *emergies*, supplied in the right column, are given below each input source at applicable life cycle phases. Total *emergy* for the highway pavement system alternative is given in the lower right hand corner of each aggregated *emergy* input source data table.(42) It should be noted that subsystems and life cycle phases had identical *emergy* inputs for both alternates and thus, were excluded from the assessment.

Table 6: Aggregated Emergy Input Source Data for Concrete Highway Pavement System (Alternative A)

Life Cycle Phase	*Emergy* Input Source Data (sej) (fraction of the total)				Total Phase *Emergy* (sej)
	Environment	Fuel Energy	Goods	Services	
A-C: Transformity	5.33e18 (0.8883)	3.15e17 (0.0525)	1.13e17 (0.0188)	2.45e17 (0.0408)	6.00e18 (0.5505)
D: Design	0	0	0	0	0
E: Component Production	0	0	0	0	0
F: Construction	2.63e13 (0.0004)	1.59e16 (0.2646)	2.60e15 (0.0433)	4.16e16 (0.6922)	6.01e16 (0.0055)
G: Use	3.99e18 (0.8400)	3.42e17 (0.0720)	1.22e17 (0.0257)	2.93e17 (0.0617)	4.75e18 (0.04358)
H: Demolition	2.62e13 (0.0003)	2.98e16 (0.3539)	1.04e16 (0.1235)	4.40e16 (0.5226)	8.42e16 (0.0077)
I: Recycling	0	0	0	0	0
J: Disposal	0	0	0	0	0
INPUT SUMS	**9.32e18**	**7.03e17**	**2.48e18**	**6.24e17**	
TOTAL CONCRETE PAVEMENT SYSTEM *EMERGY*					**1.09e19**

Source: Roudebush. W.H.. 1996 (42)

Table 7: Aggregated Emergy Input Source Data for Asphalt Highway Pavement System (Alternative B)

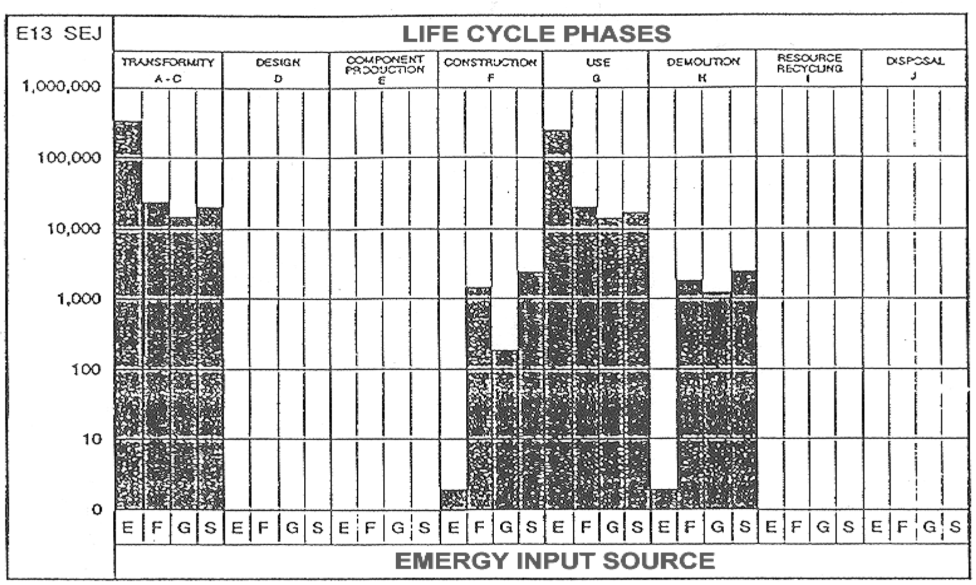
Life Cycle Phase	*Emergy* Input Source Data (sej) (fraction of the total)				Total Phase *Emergy* (sej)
	Environment	Fuel Energy	Goods	Services	
A-C: Transformity	6.40e18 (0.7232)	8.49e17 (0.0959)	8.01e17 (0.0905)	8.01e17 (0.0905)	8.85e18 (0.4255)
D: Design	0	0	0	0	0
E: Component Production	0	0	0	0	0
F: Construction	8.67e13 (0.0019)	2.34e16 (0.5189)	3.39e15 (0.0752)	1.82e16 (0.4036)	4.51e16 (0.0022)
G: Use	6.69e18 (0.5622)	1.84e18 (0.1546)	1.68e18 (0.1412)	1.69e18 (0.1420)	1.19e19 (0.5721)
H: Demolition	3.34e13 (0.0019)	9.57e15 (0.5500)	1.25e15 (0.0718)	6.54e15 (0.3759)	1.74e16 (0.0008)
I: Recycling	0	0	0	0	0
J: Disposal	0	0	0	0	0
INPUT SUMS	**1.31e19**	**2.72e18**	**2.49e18**	**2.52e18**	
TOTAL ASPHALT PAVEMENT SYSTEM *EMERGY*					**2.08e19**

Source: Roudebush. W.H.. 1996 (42)

From these aggregated data in *Tables 6 & 7*, the total *emergy* input ranking for each pavement alternative can be ascertained. For the concrete pavement system, the ranking from greatest to least is material transformity phases A-C, use phase G, demolition phase H, and construction phase F. For the asphalt pavement system, the ranking from greatest to least is use phase G, material transformity phase A-C, construction phase F, and demolition phase H.

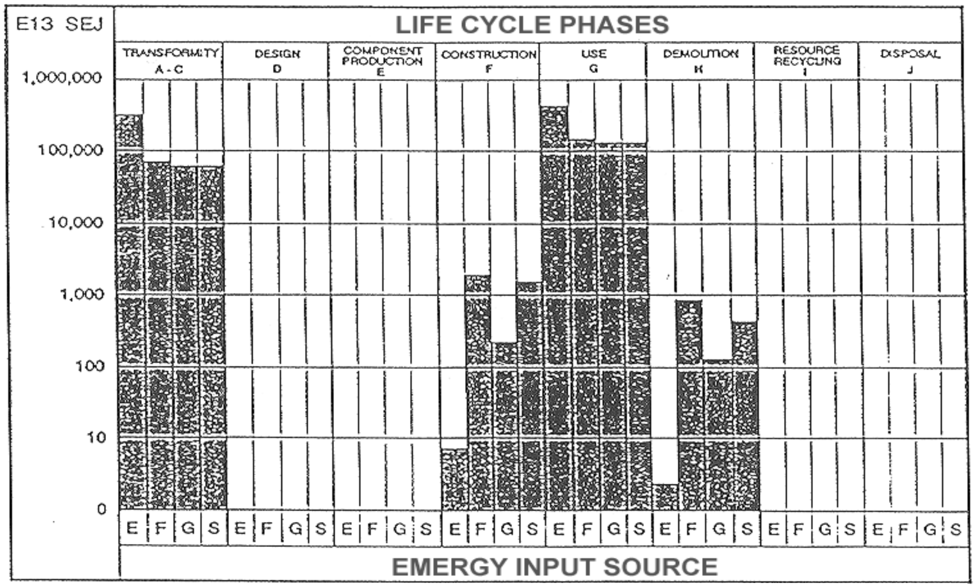
These data tables were then used to construct aggregated *emergy* input signatures that illustrate the total *emergies* from the input sources of the different pavement alternatives during each phase of the assessment life cycle. The aggregated phase *emergy* input signatures for the highway pavement systems, Alternative A and B, are given in *Figure 29* and *Figure 30*, respectively. Referring to these figures, the *emergy* input sources of environment (E), fuel energy (F), goods (G), and services (S) are given under each life cycle phase in columns and labeled along the bottom of the signature. The input source *emergy* values are represented along the left side of the figure with each horizontal quantity line representing an order of magnitude change. It should be noted again that subsystems and life cycle phases that had identical *emergy* inputs for both alternates were excluded from the assessment. (42)

Figure 29: Concrete Highway Pavement System Aggregated Emergy Input Signature



Source: Roudebush, W.H., 1996 (42)

Figure 30: Asphalt Highway Pavement System Aggregated Emergy Input Signature



Source: Roudebush, W.H., 1996 (42)

From the aggregated emergy input diagrams, portrayed in Figures 29 & 30, the ranking for the emergy inputs, across all of the phases, could be ascertained for each pavement alternative. For the concrete pavement system, the ranking from greatest to least is:

1. environment for phases A-C
2. environment for phase G
3. fuel energy for phase G
4. fuel energy for phases A-C
5. services for phase G
6. services for phases A-C
7. goods for phase G
8. goods for phases A-C
9. services for phase H
10. services for phase F
11. fuel energy phase H
12. fuel energy phase F
13. goods phase H
14. goods phase F
15. environment phase F
16. environment phase H

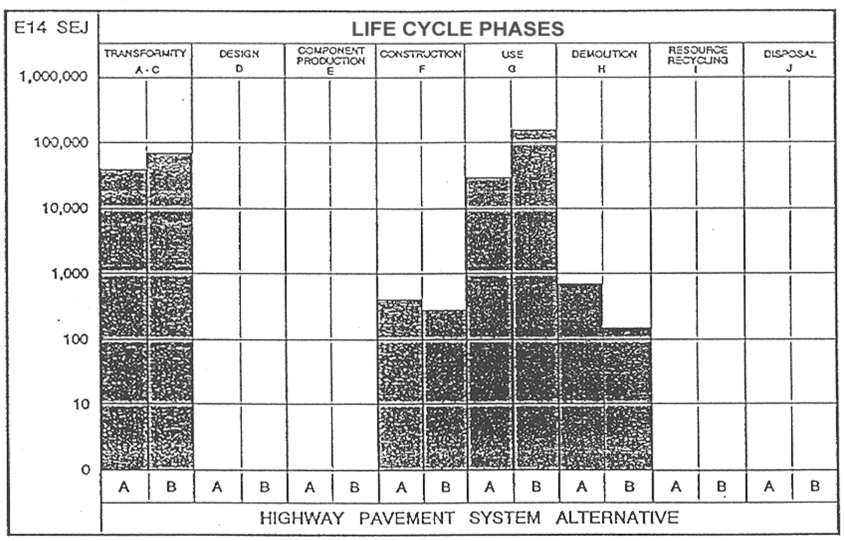
For the asphalt pavement system, the ranking from greatest to least is:

1. environment for phase G
2. environment for phases A-C
3. fuel energy for phase G
4. services for phases G
5. goods for phase G
6. fuel energy for phases A-C
7. goods for phase A-C
8. services for phases A-C
9. fuel energy for phase F
10. services for phase F
11. fuel energy phase H
12. services phase H
13. goods phase F
14. goods phase H
15. environment phase F
16. environment phase H

Impact Assessment

The primary purpose of the aggregated *emergy* input data tables and signatures is to compare the inputs of the different pavement alternatives and locate *emergy* concentrations within each assessment life cycle that should be a focus for potential reductions. Thus, a total *emergy* input signature, given in *Figure 31*, was constructed to provide a graphical representation of the *emergy* concentrations, presented in *Tables 6 & 7*, that occurred for all the systems of each pavement alternative, (A) concrete and (B) asphalt, during the life cycle phases. Referring to this figure, the values for the total input source *emergy* are specified for both alternatives within each life cycle phase and are represented along the left side of the figure with each horizontal quantity line representing an order of magnitude change. Once again subsystems and life cycle phases having identical *emergy* inputs for both alternates were excluded from the assessment.(42)

Figure 31: Total Phase Emergy Input Signature

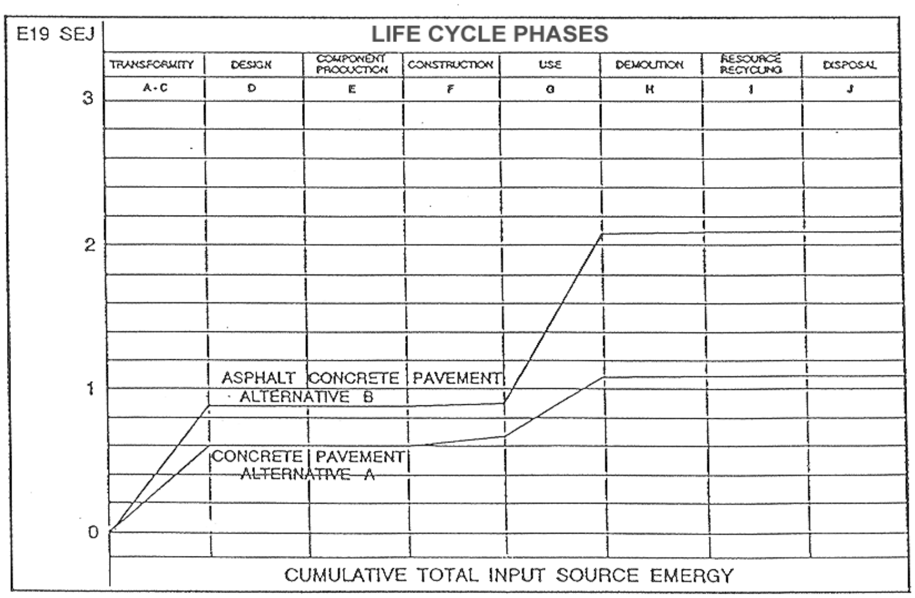


Source: Roudebush, W.H., 1996 (42)

A few comparative observations can be made based on data contained in *Tables 6 & 7* and illustrated in *Figure 31*. First, for the material transformity phases (A-C) and the use phase (G), alternative A required 32.2% and 60.1% **less** *emergy*, respectively, than alternative B. This is primarily due to the fact that the asphalt system uses a greater volume of material during construction, reconstruction, and resurfacing. Second, during the construction phase (F) and demolition phase (H), alternative A required 33.3% and 383.9% **more** *emergy*, respectively, than alternative B. However, the construction phase (F) and demolition phase (H) only account for approximately 1% of the total pavement system *emergy* of both pavement alternatives. Moreover, the environment *emergy* inputs of phases F and H specifically account for less than one percent of total inputs during these phases. As a result, in order to reduce total *emergy*, the inputs of fuel energy and services should be the focus. Finally, because the transformity phases (A-C) and the use phase (H) account for about 99% of the total system *emergy* in both alternatives, a reduction in any of the inputs would result in a reduction of the overall pavement system *emergy*.

Overall, alternative A used approximately 47.6% less system *emergy* overall, thus revealing concrete as the better alternative from this environmental LCA point of view. This is graphically presented in *Figure 32* using the total cumulative impact *emergy* of input sources for both pavement system alternatives.

Figure 32: Cumulative Total Input Source Emergy



Source: Roudebush, W.H., 1996 (42)

It should be note that the slopes of the cumulative *emergy* do not reflect true *emergy* intensity because the life cycle phases are not represented by actual periods of length.(42)

Improvement Assessment

Traditionally in life cycle analysis, an emphasis has been placed on the respective costs of different pavement alternative throughout their lifetimes. As a result, when concrete and asphalt systems are compared, the asphalt pavement alternative was usually selected because a concrete system is more expensive to construct and maintain.(35) However, increased concern over improving the sustainability of industrial operations has promoted the need to look at the fuller perspective. Thus, a new life cycle assessment strategy must be developed that accounts for items such as resource depletion, human health effects, and environmental impact in product selection.

Life cycle assessment, using environmental value engineering, employs a systems approach methodology to more accurately compare the input requirements and related environmental impacts of pavement alternatives.(42) As a result, when concrete and asphalt highway pavement systems are compared using this revised life cycle analysis approach, concrete proves to be superior. Unfortunately, the current market and technology barriers to shifting from the use of asphalt as a repair and resurfacing material to concrete or another alternative material are substantial in many areas for reasons often associated with material handling, ease of construction, and amortized cost. Moreover, it should be noted that these results only represent one particular approach. Thus, in order for a clearer overall perspective to be attained, additional life cycle assessment techniques must be established and refined.

In addition, other variable inputs related to the use of concrete and asphalt highway pavement system alternatives, such as pavement lighting and vehicle fuel consumption, should also be considered and included in future assessment for a more accurate comparison.(42) For example, preliminary studies have shown that lighting requirements for concrete pavement are approximately 30% less than for asphalt pavement (44), and trucks consume approximately 20% less fuel on concrete pavements than on asphalt concrete pavements (45).

4. <u>CHICAGO AREA CASE STUDY</u>

Through the manipulation of the ratios between the percentage of vegetative cover and high and low albedo surfaces, it may be possible to substantially reduce urban heat island effects. For example, research at the Lawrence Berkeley National Laboratory (LBNL) has examined these effects in simulations of the cooling achieved by increasing the albedo of roofs and roadways in the LA Basin. Researchers showed that a 4°F cooling was obtained by noon, which in turn resulted in a 10-12% population based reduction in smog exceedances.(46)

As shown previously in *Table 2* (page 16), Los Angeles is the only area in the extreme classification for ozone nonattainment. Chicago is among the cities classified as severe ozone nonattainment areas, which serves as the impetus for this study evaluating the estimated effects of cooling strategies to abate the urban heat island effect and ozone problem in Chicago.

In this chapter, the heat island and ozone exceedance distribution of the immediate Chicago area are located geographically. The relationship between temperature and ozone is examined in order to obtain an understanding of the regional features associated with the observed ozone exceedance distribution. Finally, an urban fabric analysis is conducted for the city of Chicago as an initial step in the investigation of how increased vegetative cover and the use of cooler roof and pavement materials may help decrease the effects of the urban heat island

4.1. TRENDS IN METROPOLITAN CHICAGO

4.1.1. Monitoring Stations

Ozone is generally monitored only between the months of April and October, the so-called ozone season. Several Chicago monitoring stations may collect data over a longer period of the year, but since ozone levels are much lower during the winter months, this project utilizes only the summer ozone data (April – October).

Ozone concentration data for the Chicago area were obtained from the Aerometric Information Retrieval System (AIRS). This system is a database of air quality monitoring site data from local, regional, and national monitoring stations throughout the United States. Unfortunately, the AIRS database has two major shortcomings. First, complete station data records are not always available. For example, although the AIRS database contained pollutant data for 23 stations in the Chicago area, only 17 stations collected ozone data. Second, different monitoring locations have varying collection periods. As a result, hourly ozone concentrations were collected from only 13, of the total 17, different monitoring stations throughout the Chicago region for the longest, most current and complete time frame available, 1992-1996. From these data, the daily maximum concentrations were extracted and analyzed. *Figure 33* shows the coordinates and locations of these sites that monitored ozone.

Figure 33: Ozone Monitoring Stations in the Chicago Region

Station Location	ID	Latitude (N)	Longitude (W)
Alsip	A	41°40′	87°43.5′
Chicago (Lakefront)	B	41°45′	87°32.5′
Stony Island	C	41°42′	87°34′
Lincolnwood	D	41°59′	87°47′
Lemont	E	41°40′	87°59′
Cicero	F	41°51′	87°45′
Evanston	G	41°63.5′	87°40′
Wrigleyville	H	41°58.5′	87°40′
Chicago (Downtown)	I	41°52.5′	87°38′
University of Chicago	J	41°47′	87°36′
Lisle	K	41°49′	88°04′
Deerfield	L	42°10.5′	87°50′
Elgin	M	42°03′	88°16′

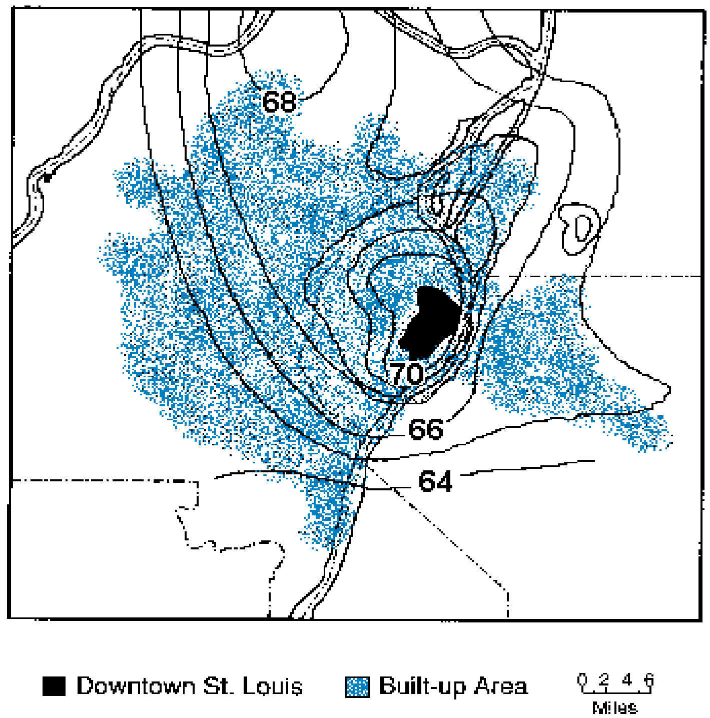
Figure 33 (continued)

Source: Microsoft Expedia Streets98

4.1.2 Temperature and Ozone Trends

The definition of "heat island" is an area with heightened air temperatures of 2-8°F, increased energy demands, and elevated pollution concentrations as compared to the surrounding areas. This phenomenon is illustrated for St. Louis in *Figure 34.*

Figure 34: Heat Island Profile for St. Louis, Missouri

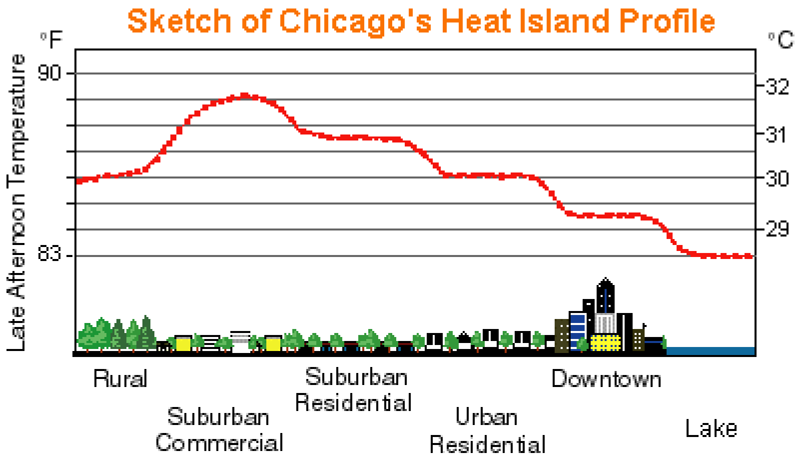


Source: Cool Communities (3)

The temperature profile of a heat island can vary significantly throughout an area. In order to identify the location of the Chicago heat island, data for the daily maximum temperature were obtained from the National Climate Data Center (NCDC). These data were collected for locations in the Chicago area that corresponded to the ozone monitoring stations (*Figure 33*) so that the relationship between ozone and temperature could be evaluated.

In contrast to St. Louis, when the average temperature distribution in the summer months (June-August) for the 1992-1996 time frame, is analyzed for the Chicago Area, the actual Chicago Heat Island consistently appears in the western suburbs, not in the Downtown area. In this case, the climate of Downtown Chicago is influenced to a great extent by Lake Michigan, which results in a suburban heat island centered on an area of rapid suburban development. This is illustrated in *Figure 35*. More specifically, as shown in *Figure 36*, there is on average about a 3-5°F temperature gradient between Lisle and Downtown Chicago.

Figure 35



An examination of the ozone data for the Chicago Area, specifically Cook County, revealed that the majority of the ozone noncompliance days do not occur in Downtown Chicago. Instead, they appear to center around the northern suburbs, specifically Evanston. *Figure 37* shows a surface plot of the total number of days where ozone levels exceeded 120 ppb as a function of their geographical location around Chicago.

In order to verify that the location of the Chicago heat island did not coincide with the local region of greatest ozone noncompliance, *Figure 38* was generated. This figure shows a histogram of the daily temperature difference found at the center of the heat island (Lisle) and in the area of greatest ozone noncompliance (Evanston). From examination of these data, it is observed that the temperature in Lisle is almost always higher. The few days where the temperature in Evanston was found to be higher occurred mostly on days in the early spring (April/May) or early fall (September/October). Furthermore, if one examines this temperature difference on each of the six days of ozone noncompliance in Evanston, it is also found that the temperature was almost always greater in Lisle. The one exception occurred on a day in mid July of 1995 when the temperature in Lisle was 99°F and the temperature in Evanston was 102°F.

Figure 36: Summer Heat Island Profile for the Chicago Area

Maximum daily temperatures averaged over the ozone season

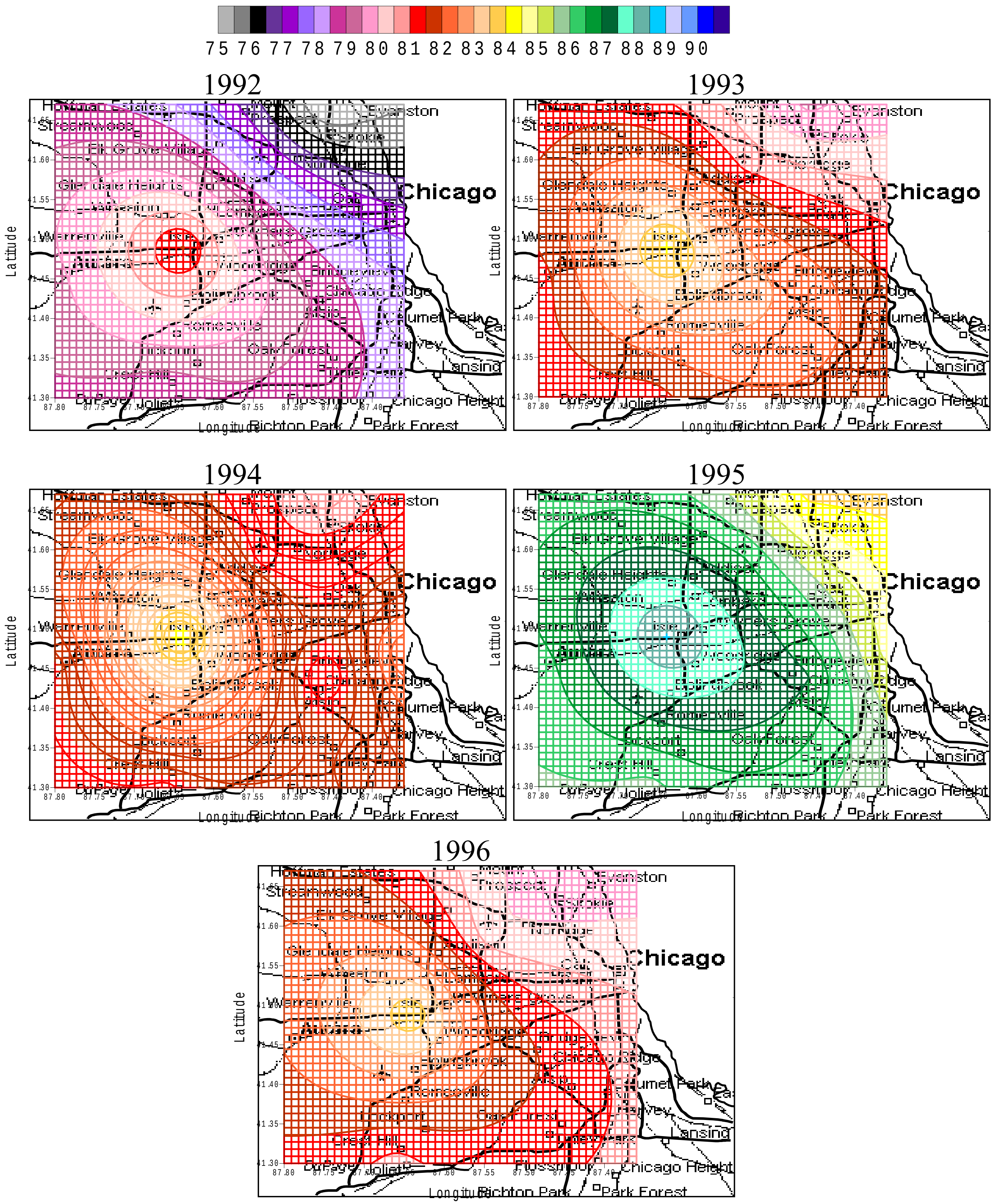


Figure 37: Ozone Noncompliance Distribution for the Chicago Region for April – October 1992 to 1996

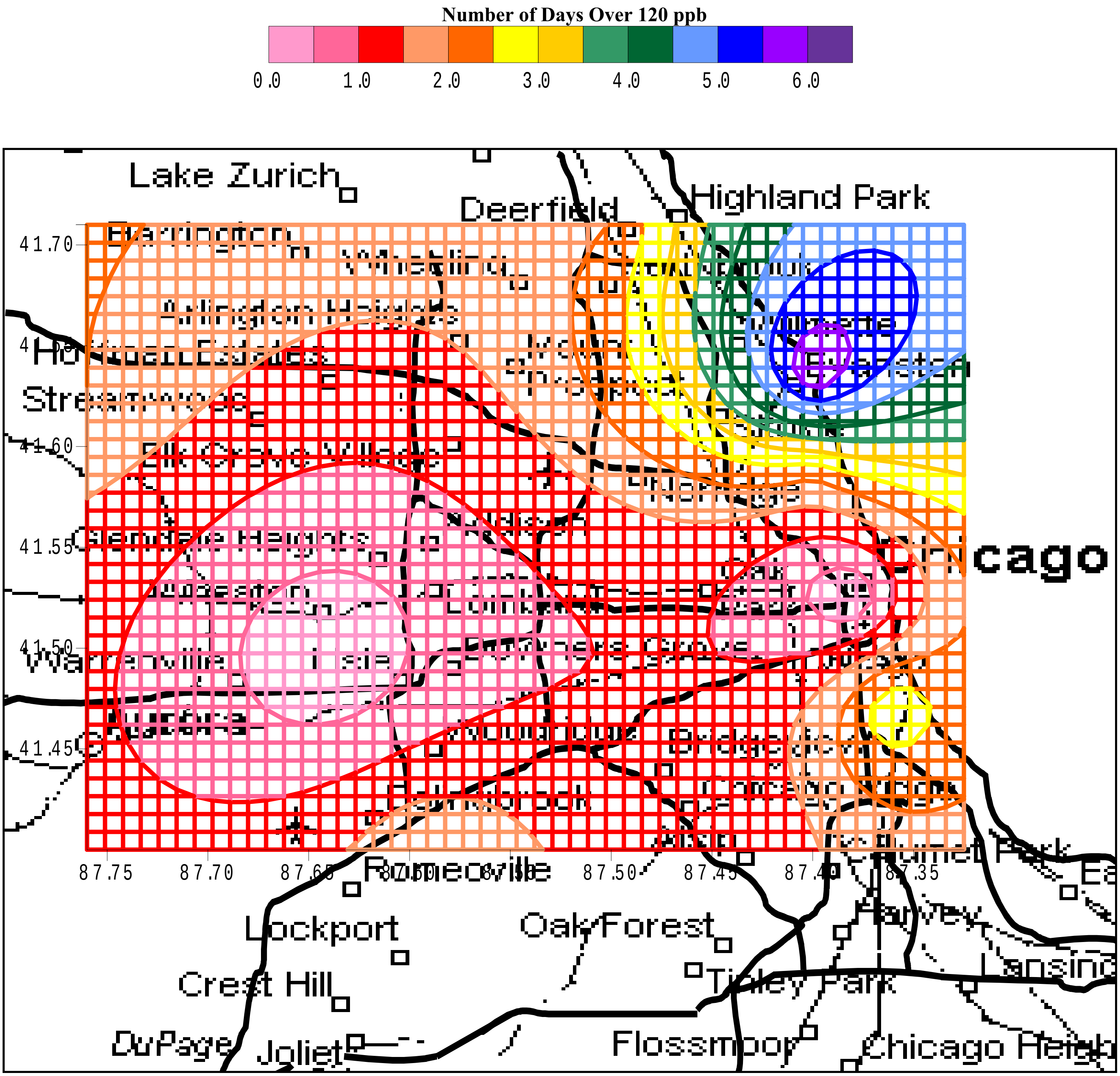
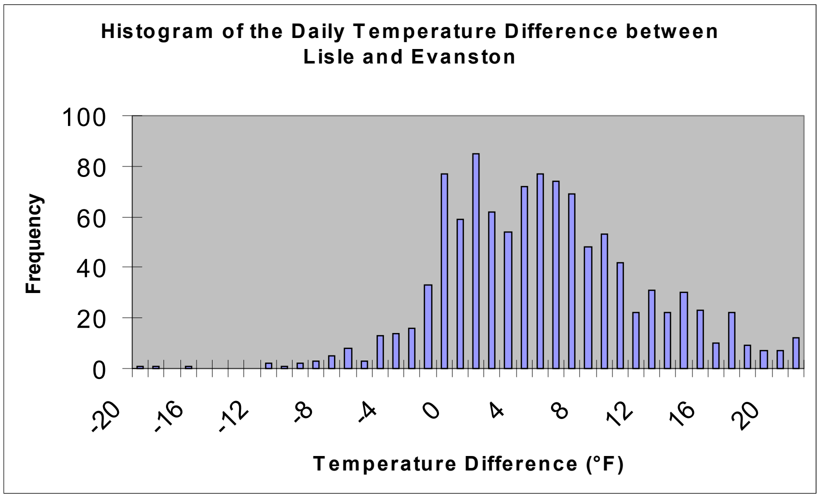


Figure 38



In summary, it is observed that the ozone noncompliance distribution does not coincide with the heat island and is over an area with few known emissions sources. The result of this comparison supports the hypothesis that atmospheric and surface transport mechanisms greatly influence the ozone distribution in the Chicago area, as discussed in section 2.3.2 (page 23). This conclusion is reinforced by the fact that, during the summer ozone season, the Chicago Area is frequently ventilated by prevailing northeasterly transport winds, illustrated previously in Figure 9, which assist in the redistribution of high ozone concentrations to areas with little to no emissions sources. This phenomenon, in association with other research conducted within this area (15,17,28), supports the idea that ozone exceedance is a regional issue. The movement of air masses facilitates the transfer of O_3 and its precursors beyond their originating sources to adjacent areas creating episodes of high O_3 in locations that have few emissions. As shown in Figure 6, while Chicago may serve as an emissions source, the actual ozone exceedances often occur in western Michigan and eastern Wisconsin.

In general, all the noncompliance days in the Chicago Region occur in the deep summer months (June-August) and at relatively high temperatures. It was observed that during this five year time interval (1992-1996), approximately 70% of the ozone exceedances occurred on days having temperatures above 85°F, approximately 90% of the exceedances were observed at temperatures above 80°F, and there were no exceedances observed below 77°F. A summary of the Chicago area noncompliance data is located in *Table 8*, which shows the location of each monitoring station, the date of ozone exceedance, the maximum daily temperature corresponding to the location and date of each exceedance, and the recorded ozone concentration level corresponding to every episode.

Table 8: Ozone Noncompliance Summary for the Chicago Area

Data Station Location	Date	**Maximum Temperature (°F)**	**Maximum Ozone Concentration (ppb)**
Suburb - North (Deerfield)	07/01/92	78	127
	06/16/94	98	126
Suburb - North (Evanston)	6/13/92	83	121.3
	7/1/92	78	129.3
	8/9/92	84	135.3
	7/15/95	102	149.3
	8/12/95	93	140.3
	6/27/96	81	122.3
City - North (Wrigleyville)	7/15/95	103	121.3
	6/28/96	94	125.3
Suburb - Northwest (Elgin)	06/13/92	86	128
	06/18/94	96	127
City - Northwest (Lincolnwood)	7/1/92	91	121.3
	6/24/95	94	124.3
Suburb - West (Lisle)	N/A	N/A	N/A
City - West (Cicero)	7/1/92	88	121.3
City – Downtown	N/A	N/A	N/A
City - Southwest (Alsip)	7/13/95	106	129.3
City - South (U of C)	7/1/92	82	133.3
	6/24/95	88	134.3
	7/13/95	96	130.3
City - South (Lakefront)	6/27/95	79	127.3
	6/27/96	82	127.3
City - South (Stony Island)	6/24/95	88	166.3
	7/13/95	96	126.3
Suburb - Southwest (Lemont)	6/13/92	91	131.3
	6/18/94	95	169.3

The relationship between ozone and temperature levels for the ozone noncompliance days in Chicago is further illustrated in *Figures 39* and *40*. *Figure 38* is a graphical representation of the maximum ozone concentration and temperature data presented in *Table 8*, and illustrates once again, the absence of a positive linear relationship between temperature and ozone. The frequency of ozone episodes occurring in a particular temperature range relative to the total number of days observed in that temperature range is shown in *Figure 40*. The data in this chart represent values collected throughout the Chicago area during the 1992-1996 ozone seasons. The numbers above each bar depicts the total number of days that fell in that temperature range.

Figure 39: Ozone Noncompliance Distribution for the Chicago Area

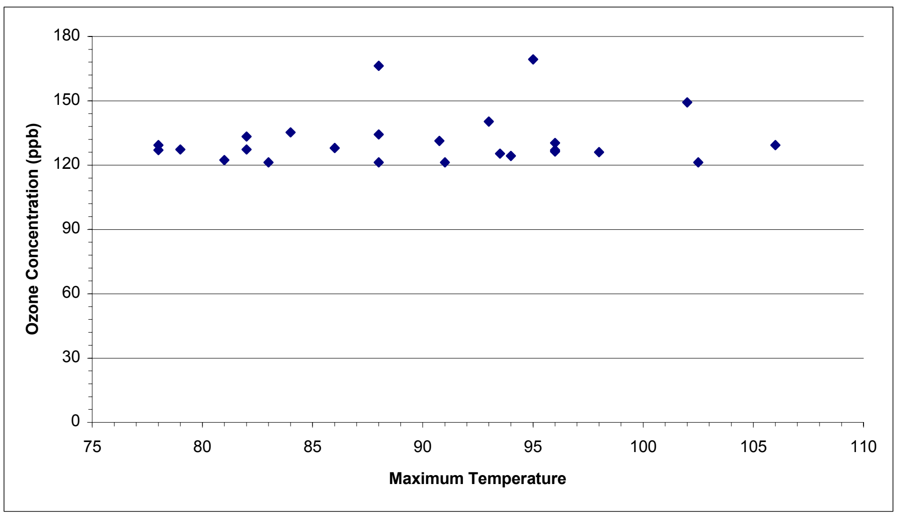
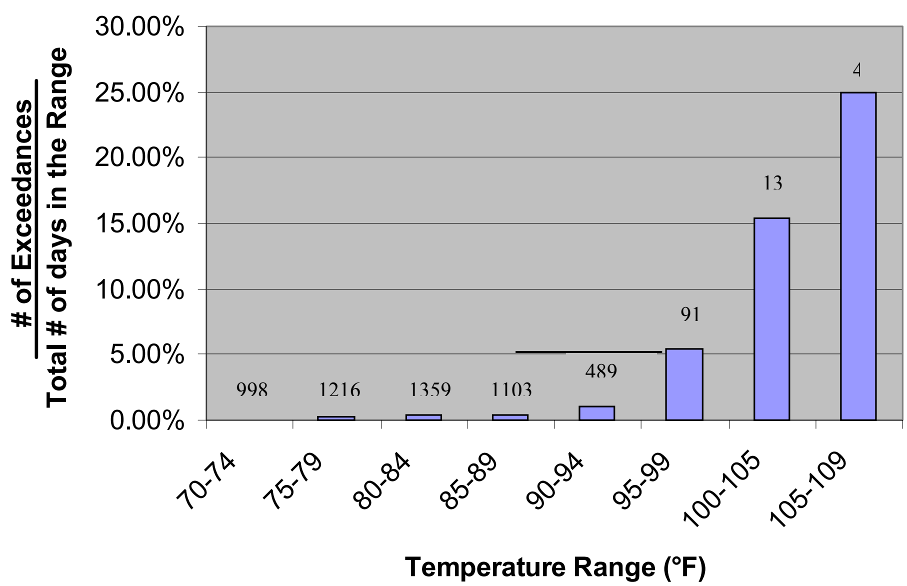


Figure 40: Frequency of Ozone Episodes in a Specific Temperature Range Relative to the Total Number of Days in that Range



These data illustrate that despite the very weak direct relationship found between temperature and ozone concentration in Chicago (*Figures 11* and *39*), there is a temperature threshold below which ozone exceedances are less likely to occur. Over the time interval of these monitoring data, no ozone exceedances were observed at temperatures below 77°F and the majority of the ozone exceedances occurred at temperatures above 80°F. Yet, for all the monitoring stations studied in the Chicago area, relatively few days in the temperature range of 80-95°F, range relative to the total number of days registering that temperature, experience smog events, typically 1% or less.

The trend shown in *Figure 40* illustrates that at extreme temperatures, above 95°F, the likelihood of ozone exceedances increases with temperature. The data reveal that the number of ozone exceedances relative to the total number of days in the 95-99°F temperature range jumps to 5% and then continues to increase as temperature increases. *Figure 40* also shows that, although a very high frequency of occurrence (25%) was observed in the 105-109°F temperature range, the total number of temperature observations was very low. Finally, these data suggest that there is a temperature threshold of 95°F to more frequent occurrence of ozone exceedances. Thus, in Chicago, while higher temperatures do not promote higher ozone concentrations, very high temperatures (95°F and above) do show a greater proportion of smog events relative to the total number of days in the same high range.

4.1.3 Implications for Chicago

There are various ways of combating the urban heat island. If properly applied, these strategies, discussed in detail in the next section, can help reduce the temperature, energy demand, and pollutant level within a city. For example, simulations of the cooling achieved through the replacement of dark roofs and roadways with alternate “cooler” materials were done for the Los Angeles Basin. The results showed a 4°F cooling by noon and a 10-12% reduction of smog exceedance.(47)

The use of cooling strategies if applied to the metropolitan Chicago area may produce a decrease in temperature, similar to that predicted for the LA Basin. However, ozone noncompliance days are not solely the result of temperature effects, particularly those that occurred in the city of Chicago. Instead, the Chicago area is greatly affected by a combination of various meteorological processes that together are responsible for transporting polluted air into (and out of) the region. These phenomena have been documented by the Ozone Transport Assessment Group (OTAG) (17) and Lake Michigan Ozone Study (LMOS) (28).

Of the eight noncompliance days from 1992-1996 that occurred at temperatures below 85°F, only three exceedance measurements were made in the city limits of Chicago (at two sites - the University of Chicago and Southern Lakefront). The other five ozone exceedances occurring at temperatures below 85°F were measured in the Northern Suburbs of Chicago (Evanston and Deerfield). At all of the aforementioned locations, it is likely that factors other than temperature are at play, although it can be assumed that that a portion of the ozone originates from within the domain as a result of the reactions of O_3 precursors.

Based on the simulations for the LA Basin, a 4°F decrease in temperature may also produce a 10-12% reduction of the smog events in the Chicago area, eliminating the ozone episodes that occurred at temperatures below 80°F. For the Chicago area, this translates to eliminating approximately 3 exceedance episodes over a five year period.

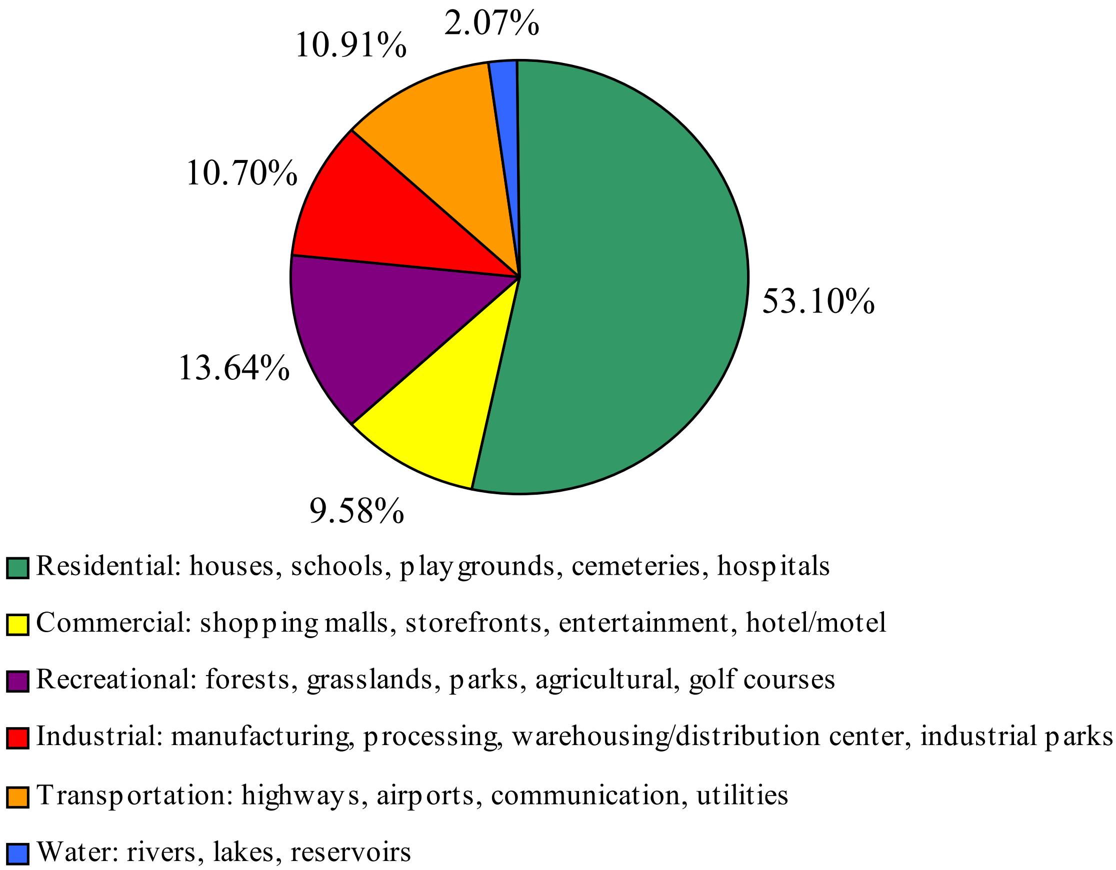
Since the reduction in the absolute number of ozone exceedances is small, it is important to stress the many other benefits cooling strategies promote. In addition to eliminating smog events, cooling strategies and decreased summer temperatures result in diminished energy use, fewer deleterious health effects, and an enhanced comfort level. These factors are likely to produce additional cascading benefits. Thus, simulations of cooling benefits should include these other outcomes, in addition to reductions in ozone exceedances.

4.2. URBAN FABRIC ANALYSIS

4.2.1. Land Use

An urban fabric analysis determines the proportions of vegetative, roofed, and paved surface cover relative to the total urban surface in the city. In order to accurately analyze the effect of surface cover modifications, attain pertinent results, and eventually simulate realistic estimates of temperature and ozone reductions resulting from these modifications in Chicago, the current urban fabric of the Chicago must be quantified as it relates to different land use. As a result, each land use category specified was analyzed according to the relative percentages of vegetative, roofed, and paved surfaces. *Figure 41* shows the classification and relative proportions of land use in the city of Chicago for 1990.(48) From this figure, it is observed that the largest section of land use is residential, at 53%; unfortunately, there were not sufficient data available to specifically distinguish between high, medium, and low density residential areas. The remaining sections, which include transportation, industrial, recreational, and commercial, are relatively equivalent and have an average cover of approximately 11.5%.

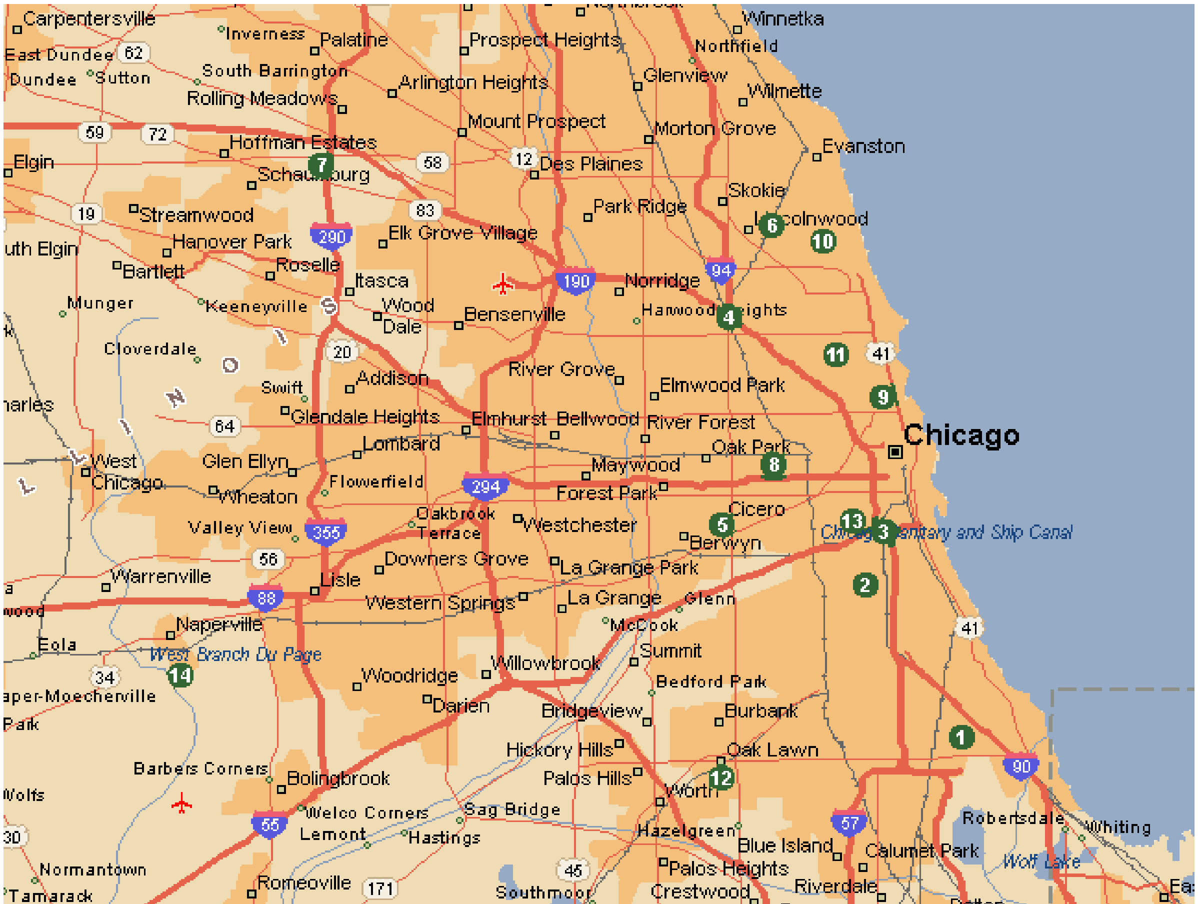
Figure 41: Land Use in the City of Chicago, 1990



4.2.2 Methodology

The urban fabric analysis of Chicago was completed through the examination of color digital aerial photographs (1 ft by 1 ft resolution) obtained from Image Scans Inc., Wheat Ridge, CO, during an October 1998 fly over. Because the city of Chicago covers over 225 one square miles, budget and time constraints made it impossible to analyze the entire Chicago area. Therefore, in order to obtain an accurate estimate of Chicago's urban fabric, fourteen distinct square mile sectors were selected to serve as a representative basis for the overall land use in the Chicago area. The locations of these areas are shown in *Figure 42* and given in Appendix D.

Figure 42: Urban Fabric Analysis Sector Locations



Sector #	Location Description	Land Use Categories
1	Stony Island - Burnside	residential, commercial
2	Stockyards – International Amphitheater	industrial
3	Interchange 55/90/94	transportation
4	Kennedy Interchange 90/94	residential, transportation, commercial
5	Cicero	residential, industrial
6	Lincolnwood	residential, commercial
7	Schaumburg – Woodfield Mall	commercial
8	Garfield Park	residential, recreational
9	Lincoln Park	residential, recreational
10	Rogers Park	residential, recreational
11	Wrigleyville	residential, commercial
12	Oak Lawn	residential
13	Blue Island – Pilsen	residential, industrial
14	Naperville	residential

In addition to representing the five basic land use categories, residential, commercial, recreational, industrial, and transportation, the 14 sample areas were selected to permit an assessment of variation based on location and density. As shown in *Figure 42*, the areas sampled included high, medium, and low density residential, urban and suburban commercial, and southern and western industrial. Furthermore, many of the 14 square mile sectors displayed mixed land uses, for example, residential neighborhoods surrounding recreational areas or industrial areas. Thus, the fourteen sections also included multiple samples for each land use category.

The fourteen sectors were chosen based upon our knowledge of Chicago and information from Northeastern Illinois Planning Commission (NIPC) land use maps. It was relatively simple to identify all of the land use categories, except for industrial, using a map of the Chicago area and our knowledge of its current urban layout. The NIPC information was used primarily to confirm our assumptions. The industrial areas within Chicago were located based on information and maps provided by the Chicago Department of Planning and Development (DPD).(47)

Analyzing the aerial photographs was an extremely complicated and time consuming process. It was initially intended that the entire analysis be performed using image analysis software developed by the Scion Corporation, Frederick, MD. This program allows objects to be segmented on the basis of color. However, due to the complex nature of the ground cover coloring, no consistent pattern between the various surfaces could be detected directly from the digital photographs. Thus, before applying the analysis software, it was necessary to visually and manually classify the distinctions between the land cover categories, vegetative, roofed and paved surfaces, for each land use category within every sector. This was accomplished using

Adobe Photoshop 4.0 to manually alter the digital photographs. First, two to four subsections were chosen for analysis within each land use category for each square mile area. Then each surface cover type was differentiated from the others using a single color, which was used as the basis for a density slice analysis of the total area. The results of these analyses were then utilized to calculate the overall percentages of vegetative, roofed and paved surfaces for each land use category in each sector.

4.3. RESULTS AND EVALUATION

The results of the urban fabric analysis are summarized in *Table 9* (a detailed synopsis is provided in Appendix E). In general, the percentages are reasonably consistent within the different areas of the city for same type of land use category, although in a few cases a relatively wide range was measured. The variations that arise are dependent upon the surface type being examined and the specific area of the city analyzed, for different areas are naturally diverse with respect to specific land cover. These variations are further explained in the 'Comments' column of *Table 9* and summarized in *Table 10*. For example, the paved surface range for the urban commercial areas varied about 30% from highest to lowest depending upon which area was specifically analyzed. In general, this percentage is dependent on the amount of area devoted to parking lots and decreases as one moves from southern to northern sections of the city. Unfortunately, it is extremely difficult to incorporate all these variations. As a result, an average value that can be applied to the city as a whole is utilized in this research for comparison and analysis purposes.

The residential category included the greatest number of samples, 12, and represented three different density regions within Chicago. The specific areas represented within the urban,

Table 9: Urban Fabric Analysis for the Chicago Area

CATEGORY	***VEGETATIVE AVERAGE***	***VEGETATIVE RANGE***	***ROOFED AVERAGE***	***ROOFED RANGE***	***PAVED AVERAGE***	***PAVED RANGE***	***# OF SAMPLES***	***COMMENTS***
Residential – Urban (Medium/High Density)	45.12 %	33.36 % - 55.00 %	34.42 %	26.05 % - 51.07 %	20.47 %	14.60 % - 28.02 %	12	These values vary depending upon which area of the city was analyzed. They include areas north, west, and south of the city.
Residential - Near Suburban (Medium/Low Density)	49.67 %	42.27 % - 57.80 %	27.17 %	21.36 % - 35.64 %	23.16 %	20.84 % - 25.32 %	4	These values vary depending upon which suburb was analyzed. They are representative of three near suburbs: Lincolnwood, Oak Lawn, & Cicero.
Residential – Far Suburban (Low Density)	70.51 %	64.86 % - 76.15 %	12.70 %	11.99 % - 13.42 %	16.79 %	11.86 % - 21.72 %	2	These values are representative of only one far suburb: Naperville.
Recreational	67.19 %	56.49 % - 79.82 %	6.66 %	2.82 % - 9.62 %	21.61 %	17.36 % - 26.70 %	4	The variation occurs because this category includes analysis of large parks, small parks, and schools with athletic fields.
Transportation	31.74 %	23.55 % - 40.77 %	0.00 %	0.00 %	68.26 %	59.23 % - 76.45 %	3	These values are based major highways running through downtown Chicago (i.e. 55, 90, & 94). This category does not include any developed areas surrounding the highways.
Commercial – Urban	16.10 %	11.79 % - 20.99 %	33.14 %	22.32 % - 46.95 %	50.77 %	32.07 % - 62.17	3	These values vary depending upon which area of the city was analyzed. They include areas north, west, and south of the city.
Commercial - Suburban	12.15 %	9.55 % - 17.33 %	26.24 %	17.88 % - 35.44 %	61.61 %	52.44 % - 72.58 %	4	These values vary depending upon which suburb was analyzed. They are representative of both a near and far suburb: Lincolnwood & Schaumburg.
Industrial	10.32%	1.71 % - 20.98 %	42.05 %	35.22 % - 50.20 %	47.63 %	43.80 % - 51.01 %	3	These values vary depending upon type of industrial category was present in the particular area analyzed. The variation occurs because this category includes the analysis of warehouses, stockyards, and industrial office complexes.

Table 10: Geographical Variations of the Urban Fabric within each Land Use Category

Category	***Location***	***Areas***	***Vegetative Surface***	***Total Roofed Surface***	***White/Light Roofed (% of total roof)***	***Total Paved Surface***	***Water***
Residential – Urban/Near Suburban (Low/Medium Density)	North	Rogers Park, Lincolnwood	44.06%	30.31%	40.35%	25.62%	x
	Central	90/94, Wrigleyville, Garfield Park, Lincoln Park, Cicero,	44.78%	36.90%	39.26%	18.32%	x
	South	Blue Island/Pilsen, Stony Island, Oaklawn	46.41%	29.80%	29.37%	23.78%	x
Recreational	North	Rogers Park	65.71%	9.62%	29.06%	24.67%	x
	Central	Garfield Park, Lincoln Park	67.68%	5.68%	33.47%	20.59%	9.08%
	South	x	x	x	x	x	x
Transportation – Highway Exchange (w/o surrounding area)	North	90/94	30.89%	0.00%	0.00%	69.11%	x
	Central	55/90/94	32.16%	0.00%	0.00%	67.84%	x
	South	x	x	x	x	x	x
Transportation - Highway Exchange (with surrounding area)	North	90/94	33.05%	9.52%	25.19%	57.44%	x
	Central	55/90/94	22.71%	15.85%	11.98%	61.44%	x
	South	x	x	x	x	x	x
Commercial – Urban	North	x	x	x	x	x	x
	Central	90/94, Wrigleyville	16.39%	38.54%	72.20%	45.07%	x
	South	Stony Island	15.51%	22.32%	53.75%	62.17%	x
Commercial – Suburban	North	Lincolnwood	11.59%	35.44%	59.00%	52.97%	x
	Central	Schaumburg	12.33%	23.18%	100.00%	64.49%	x
	South	x	x	x	x	x	x
Industrial	North	x	x	x	x	x	x
	Central	x	x	x	x	x	x
	South	Stockyards/International Amphitheater, Blue Island/Pilsen, Cicero	10.32%	42.05%	14.39%	47.63%	x

or high/medium density, category were: Rogers Park, 90/94 Interchange, Wrigleyville, Garfield Park, Lincoln Park, Blue Island/Pilsen, and Stony Island. The areas represented within the near suburban, or medium/low density, category were: Lincolnwood, Oak Lawn, and Cicero. Finally, only one area was represented within the far suburban, or low density, category: Naperville.

The variation within the recreational category was not primarily due to location; instead, it occurred because this category included analysis of large parks, small parks, and schools with athletic fields.

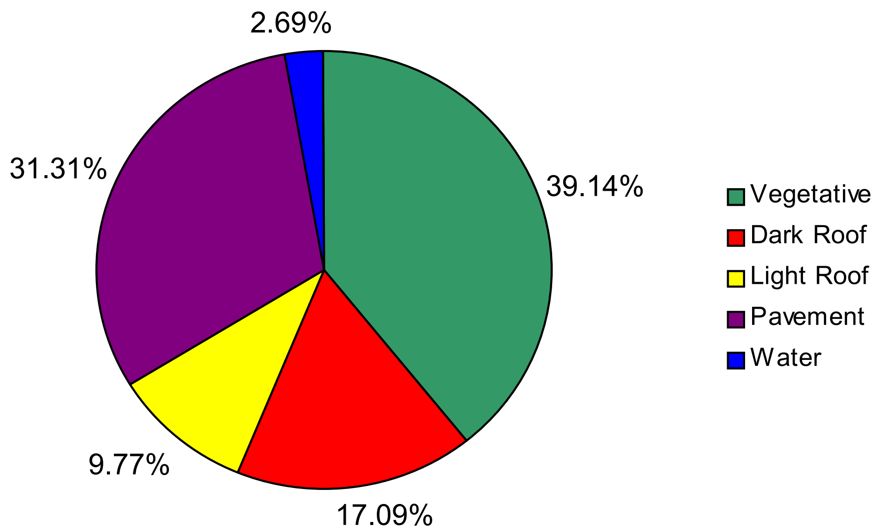
The transportation category included values based on major highways running through the downtown section of Chicago (i.e. 55, 90, & 94). This category only takes into account the highway system, median area, and shoulder region; it does not include any developed areas surrounding the highways.

The commercial category had the second greatest number of samples, 7, and represented both urban and suburban regions of Chicago. There again is variation within this category depending upon which areas were analyzed. The specific areas represented within the urban commercial category were: 90/94 Interchange, Wrigleyville, and Stony Island. The areas represented within the suburban commercial category included one near and far area: Lincolnwood and Naperville.

Finally, the variation within the industrial category occurred because this category includes the analysis of warehouses, stockyards, and industrial office complexes. Thus, the values within the industrial category varied depending upon what type of specific structures or buildings were present in the particular area analyzed.

Based on the average values for the each type of surface displayed in *Tables 9* and *10* and the overall land use breakdown given in *Figure 41*, the overall average urban fabric for all of the land use categories in Chicago was estimated and is summarized in *Figure 43*. This pie chart illustrates that the largest portion of Chicago's urban fabric is vegetative land cover at almost 40%, followed by paved at about 31%, and total roofed at approximately 27%. The following sections discuss with greater detail what was specifically observed within each of these land cover categories

Figure 43: Chicago's Urban Fabric



4.3.1. Chicago's Vegetative Cover

For vegetative surfaces, including both the ground and canopy cover, *Table 11* lists the order, from greatest to least, of each category and its corresponding percentage of the total urban fabric surface area.

Table 11: Vegetative Surface Cover for Chicago

CATEGORY	***PERCENTAGE VEGETATIVE***
Residential – Far Suburban (Low Density)	70.51 %
Recreational	67.19 %
Residential – Near Suburban (Medium/Low Density)	49.67 %
Residential – Urban (Medium/High Density)	45.12 %
Transportation	30.89 %
Commercial – Urban	16.10 %
Commercial – Suburban	12.15 %
Industrial	10.32 %

For more than 160 years, Urbs in Horto, "City in a Garden", has been Chicago's motto. There are currently 4.1 million trees in the City of Chicago (26), and a minimum of 5,000 new trees is planted each year by Chicago's Bureau of Forestry (49). The majority of Chicago's vegetative cover is located in residential and recreational areas. Street trees in particular are a significant part of this landscape, accounting for 10% of the city's trees and 24% of the total leaf surface area, which provides building and pavement shade and allows for the atmospheric exchange of gases.(26)

It is observed that for vegetative ground and canopy cover, there is a considerable percentage difference between the highest and lowest values. Specifically, the four highest percentages are at least 1.5 to 7 times greater than the five lowest ones. This indicates that vegetative planting strategies should be focused on the transportation, commercial, and industrial categories. Within these top four values it is also interesting to note that the urban and near suburban values are very similar to each other, which suggests that the densities of these areas are relatively equal.

In addition, the categories that have the highest percent of vegetative cover, residential and recreational, have the lowest percentage of paved surfaces, as seen in *Table 13*. This phenomenon is likely facilitated by not only greater amounts of vegetative ground cover, but by an increased contribution from the canopy cover of trees, that shade paved surfaces from solar radiation.

4.3.2 Chicago's Roofed Surface

For roofed surfaces, *Table 12* lists the order, from greatest to least, of each category and its corresponding percentage of the total urban fabric surface area.

Table 12: Roofed Surface Cover for Chicago

CATEGORY	***PERCENTAGE ROOFED***	***PERCENTAGE LIGHT/WHITE***
Industrial	42.05 %	14.39 %
Residential – Urban (Medium/High Density)	34.42 %	36.84 %
Commercial – Urban	33.14 %	66.05 %
Residential – Near Suburban (Medium/Low Density)	27.17 %	35.30 %
Commercial – Suburban	26.24 %	89.75 %
Residential – Far Suburban (Low Density)	12.70 %	27.45 %
Recreational	6.66 %	32.37 %
Transportation	0.00 %	0.00 %

The percentage of roofed surfaces indicates the quantity of buildings located within a particular land use category. It can be observed that the roofed surfaces in Chicago's far suburban residential and recreational areas are at least 2 to 7 times less than the other categories, which suggests that the building density in these areas is also lower.

For this fabric element, the percentage of the total roofed surface that is light/white in color could be extracted. This reveals that lighter roofing materials are already in frequent use in Chicago for all of the building categories analyzed. It is observed that by far the largest fraction of light roofs is related to the commercial category, at 66 - 90%; whereas the smallest fraction of light roofs is associated with the industrial category, at 14%. The residential and recreational categories, which constitute the lowest overall roofed surface percentages, fall between these other two land use types and show a relatively uniform light roofed coverage of approximately 30-35%. These results suggest that industrial and residential areas would receive the greatest benefit from an increased use of light colored roofed surfaces.

4.3.3 Chicago's Paved Surface

For paved surfaces, *Table 13* lists the order, from greatest to least, of each category and its corresponding percentage of the total urban fabric surface area.

Table 13: Paved Surface Cover for Chicago

CATEGORY	***PERCENTAGE PAVED***
Transportation	69.11 %
Commercial – Suburban	61.61 %
Commercial – Urban	50.77 %
Industrial	47.63 %
Residential – Near Suburban (Medium/Low Density)	23.16 %
Recreational	21.61 %
Residential – Urban (Medium/High Density)	20.47 %
Residential – Far Suburban (Low Density)	16.79 %

Currently, the primary components considered in the pavement selection of highway design are cost of construction, economy of maintenance, durability, and safety.(40) In general, asphalt roads are less expensive to build and maintain than concrete roads when costs are compared over short time intervals (less than 20 years) and do not incorporate environmental impacts. However, concrete pavement becomes more cost effective (using conventional cost comparison techniques) when the roadway can be built in long sections, such as that produced using the slip form pavement technique.(50) Unfortunately, city roadways have many obstacles, associated with utility placement and accessibility, which requires the road to be built in a series of relatively short individual sections. Therefore, the construction and repair costs analogous with concrete city roadway are higher relative to asphalt city roads.(51)

Within the city of Chicago, roads are constructed using a nine inch concrete based with a three inch asphalt overlay.(51) This technique, however, does not apply to all of the roadways in Chicago. This is due to the presence of state and county roads, which are built to different specifications.

It should also be noted that for paved surface cover there is a considerable percentage difference between the highest and lowest values; specifically, the four highest percentages are at least 2 to 3 times greater than the four lowest ones. This suggests that cool pavement strategies should be focused on the transportation, commercial, and industrial categories. Specifically, a focus should be placed upon the western suburban commercial areas, which maintain the highest percent paved surface cover, have the largest amount of new development, and which are located in and around the core of the Chicago heat island.

In addition, in relation to alleys, it was observed that they are significantly present only within the urban and near suburban areas of the residential category. They comprise approximately 15% of the total paved surface, which are in turn approximately 3.5% of the total overall urban fabric surface area. Thus, it may not be very practical to focus a substantial amount of money and attention to the repavement of the city’s alleys.

5. CONCLUSIONS

5.1 URBAN HEAT ISLAND AND OZONE

High rates of urbanization have resulted in drastic demographic, economic, land use, and climate changes in urban areas. These changes in turn have created urban microclimates, referred to as urban heat islands, which exhibit elevated air temperatures of 2-8°F, increased energy demands, elevated pollution concentrations, and increased human health and environmental risk compared to surrounding areas. Most cities today exhibit heat island effects relative to predevelopment conditions; however, their individual intensities depend on a number of factors: geography, topography, land use, population density, and physical layout.

Urban areas are not only centers of heat, but also of air pollution in the form of photochemical smog. The primary active pollutants in the creation of photochemical smog are nitrogen oxides (NO_x) and volatile organic compounds (VOCs). In the presence of sunlight, these reactants are rapidly converted to secondary pollutants, most of which is ozone. Thus, ozone exists in the troposphere as the primary ingredient in photochemical smog and has detrimental effects on human health and the environment.

The elevated temperatures of cities accelerate the photochemical formation of ozone and are considered a primary causative factor in smog episodes. There are numerous reasons hypothesized to explain the positive correlation observed between ozone and temperature. The first of these is related to the increase in photolysis rates of ozone production with increasing temperature and under meteorological conditions associated with high temperatures. A second reason is attributed to an increase in the production of ozone precursors, such as NO_x and VOC, at high temperatures. This hypothesis arises from the fact that higher temperatures create increased energy use, mostly due to a greater demand for air conditioning in buildings and automobiles. Thus, as power plants burn more fossil fuels to meet this increase in energy demand, they generate a greater quantity of emissions, which increases the levels of ozone precursors present at ground level. Finally, the relationship between high temperatures and stagnant circulation patterns, as discussed previously, can be used to account for the notable trend between ozone and temperature. Unfortunately, an exact mechanistic understanding of the relationships between all these factors thought to contribute to elevated ozone concentration does not currently exist. Thus, each city tends to exhibit a unique relationship between temperature and maximum ozone concentration.

In general, the modification of an urban surface to include more vegetative cover and lighter, lower albedo surfaces is believed to decrease temperatures, energy consumption, ozone exceedances, and detrimental environmental and human health effects associated with high levels of ozone. This thesis evaluates the accuracy of this premise for the metropolitan Chicago area.

5.2 THE CHICAGO REGION

Chicago is among the cities classified as severe ozone nonattainment areas, making it a likely candidate for a case study evaluating the estimated effects of cooling strategies to abate the urban heat island effect and ozone problem in Chicago. The purpose of this project was to identify the relationship between temperature and ozone in the Chicago region, locate the heat island in Chicago, and describe the regional features associated with ozone exceedances. In addition, an urban fabric analysis of Chicago was conducted as the first step towards investigating the effect that surface modifications have on the urban heat island phenomenon and related ozone problem in the metropolitan area of Chicago, IL. Finally, to aid in the analysis of surface modifications, a full life cycle analysis, including environmental costs and factors, of concrete verses asphalt pavement was reviewed.

5.2.1 Temperature and Ozone Relationship in Chicago

The Chicago area ozone and temperature relationship was found to be complicated and in contrast to data from other northern cities, upon analysis of the ozone verses temperature data for Chicago, a rather weak correlation is observed. There is, however, a temperature threshold of approximately 80°F below which very few ozone exceedances are observed. Furthermore, for all the monitoring stations studied, the number of ozone exceedances at a particular temperature above 80°F relative to the total number of days registering that temperature is typically 1% or less, except at the extreme temperatures above 95°F.

This phenomenon suggests that there are other factors present that dictate the quality of Chicago’s air. In fact, our analysis, in conjunction with studies conducted by the Ozone Transport Assessment Group (OTAG), established that Chicago’s ozone problem is strongly correlated with wind patterns and atmospheric transport. It is also likely that Chicago’s emissions act as precursors for the formation of ozone over Lake Michigan, western Michigan, and eastern Wisconsin. As a result, the control and reduction of ozone and its precursors require addressing regional mobile, point, and area sources.

Although elevated summertime temperatures do not appear to be a direct causative factor in ozone exceedances in the metropolitan Chicago area, there may be an indirect relationship between high temperatures, increased energy demand, and ozone. The high cooling demand may contribute to greater emissions of ozone precursors due to elevated energy use. Thus, a more compelling reason to lower summertime temperatures in Chicago may be related to diminished energy use, decreased fossil fuel consumption, and reduced emissions.

5.2.2 Chicago's Urban Heat Island and Ozone Distribution

The temperature profile of a heat island can vary significantly throughout an area. Thus, in order to assess the location of the Chicago heat island, the temperature distribution, for the summer months (June-August) for the 1992-1996 time frame, was analyzed. Results show that the actual heat island in the Chicago area consistently appears in the western suburbs (specifically over Lisle), not in the Downtown area. An examination of the ozone data for the Chicago Area, specifically Cook County, revealed that the majority of the noncompliance days are also not in Downtown Chicago. Instead, they appear centered around the northern suburbs.

When the heat island and ozone distribution in Chicago are compared, it is observed that the ozone noncompliance distribution does not correspond with the heat island and the maximum is over an area with few known emissions sources. These results are consistent with the finding that maximum ozone levels are not positively correlated with temperature and support the hypothesis that atmospheric and surface transport mechanisms greatly influence the ozone distribution in the Chicago area. This conclusion, in association with other research conducted within this area (28,17), furthers the hypothesis that ozone is a regional issue and during the summer ozone season, prevailing southeasterly transport wind vectors frequently ventilates the Chicago Area. These winds assist in the redistribution of high precursor and ozone concentrations beyond their originating sources to adjacent areas with little to no emissions sources.

In general, all the noncompliance days in the Chicago Region occur in the deep summer months (June-August) and at relatively high temperatures, almost 70% above 85°F. Of the eight noncompliance days from 1992-1996 that occurred at a temperature below 85°F, only three exceedance measurements were made in the city limits of Chicago. The other five ozone exceedances occurring at temperatures below 85°F were measured in the Northern Suburbs of Chicago. At all of the aforementioned locations, it is likely that factors other than temperature are at play, although it can be assumed that a portion of the ozone originates from within the domain as a result of the reactions of O_3 precursors.

5.2.3 Cooling Chicago

Urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. While many of the factors that influence the formation of urban heat islands, including climate, topography, and weather patterns, can not be changed or altered, efficient and cost-effective ways of mitigating heat islands do exist. Two heat island factors attributable to human activities can be readily controlled: the amount of vegetation and the color of surfaces.(3) Increasing vegetative cover through strategic landscaping around buildings and throughout cities can absorb solar radiation, provide shade, and control wind flow benefits. Changing dark colored surfaces to light colored ones would more effectively reflect, rather than absorb, solar energy and emit stored heat energy at a higher rate, thus reducing the cooling energy loads and ground level air temperatures influenced by these surfaces.

The use of cooling strategies if applied to the metropolitan Chicago area can be expected to produce a proportional decrease in temperature. However, since few ozone noncompliance days are solely the result of temperature effects and the majority occur at temperatures above 85°F, a four degree decrease in temperature, as found in simulations of surface modification within the LA Basin (3,4), would probably have a minor effect on the overall number of ozone noncompliance days in the Chicago area. Assuming simulations in Chicago produce results similar to the LA Basin and based upon observed data, a 10-12% reduction in the total number of ozone noncompliance days would translate into only approximately 0.6 days per year. Therefore, it is important to consider and examine more fully the other benefits, in addition to lower ozone levels, that are promoted via cooling strategies. These additional benefits include reduced energy demands, enhanced human health and ecological protection, and increased comfort.

While little resistance is encountered in devising programs to increase tree plantings and vegetative cover, greater obstacles are met with efforts to change construction and paving practices. This report has focused on evaluating the impacts and costs associated with asphalt verses concrete pavement.

Traditionally in life cycle cost analysis, an emphasis has been placed on the respective costs of different pavement alternatives throughout their design lifetimes. As a result, when concrete and asphalt systems are compared, the asphalt pavement alternative was usually selected because a concrete system is more expensive to construct and maintain.(35) However, increased concern over improving the sustainability of engineered operations has promoted the need to look at the fuller perspective. Thus, new life cycle assessment strategies are being developed that account for factors such as resource depletion, human health effects, and environmental impact in product selection.

Life cycle assessment, using environmental value engineering, employs a systems approach methodology to more accurately compare the input requirements and related environmental impacts of pavement alternatives.(42) As a result, when concrete and asphalt highway pavement systems are compared using this revised life cycle analysis approach, concrete proves to be superior. In fact, it was shown in the example presented in section 3.2.4. that based on a normalized unit of comparison, concrete is approximately 47.6% more efficient overall than asphalt.

Unfortunately, the current market and technology barriers to shifting from the use of asphalt as a repair and resurfacing material to concrete or another alternative material are substantial in many areas for reasons often associated with experience, material handling, ease of construction, and amortized cost over short time intervals. Moreover, it should be noted that these results only represent one particular approach. Thus, in order to develop a more compelling and convincing perspective, additional life cycle assessment techniques must be considered.

5.2.4 Chicago's Urban Fabric

Land use and surface cover are elements of the urban fabric that are commonly altered during the development of metropolitan areas. Because these elements, which include vegetation, building roofs, and pavements, act as the active thermal interfaces between the atmosphere and land surfaces, their composition and structure within the urban canopy layer largely determine the thermal behavior of different areas within a city. Thus, the alteration of these surfaces results in the creation of numerous urban microclimates, the combined result of which is referred to as the heat island effect.(52)

In order to accurately analyze the effect of surface cover modifications, attain pertinent results, and eventually simulate realistic estimates of temperature and ozone reductions resulting from these modifications, the current urban fabric of the Chicago area was evaluated as it relates to land use. This analysis was accomplished using color aerial photographs to determine the proportions of vegetative, roofed, and paved surface cover within each of the five land use categories: residential, recreational, commercial, industrial, and transportation.

From this urban fabric analysis it was found that the residential vegetative cover was relatively high, above 45%, over all the different density areas within the city of Chicago. Thus, it was also concluded that Chicago is already doing a relatively good job in the residential areas with respect to maintaining a high vegetative cover to paved surface ratio, of approximately 2.2-4.2. In contrast, the commercial and industrial areas in the Chicago area had the lowest proportion of vegetative cover, about 10-16%. As a result, programs that promote tree planting and increased vegetative cover should be concentrated primarily on the commercial and industrial areas in the Chicago region.

The analysis of roofed surface cover revealed that this percentage is dependent upon the building density within a particular land use category. Thus, it was observed that recreational and far suburban residential areas contained the least relative amount of roofed surfaces, less than 13%, for they have the lowest building density associated with them. In addition, when light/white roofs were separated out, it was revealed that lighter roofing materials are already in wide use in Chicago with the greatest percentage of light/white roofs was found in commercial areas, 66-90%. This point illustrates the ease of employing light roofing materials, in the construction and resurfacing of building roofs, as a feasible heat island mitigation strategy in the

Chicago area. Specifically, an emphasis should be placed on the suburbs where a high degree of development is occurring.

The paved surface cover was found to be the greatest in the transportation, commercial, and industrial areas, where its proportion is above 50%. In addition, the vegetative cover to paved surface ratio in these three areas is small, about 0.2-0.5. Thus, a concentration should be placed upon developing and implementing mitigation strategies within the transportation, commercial, and industrial areas of Chicago. These mitigation strategies should include a focus on greater use of concrete over asphalt, and in general, an emphasis should be placed on the use of higher albedo paving materials in the suburban areas that almost exclusively use asphalt for pavement. However, a change to the utilization of concrete over asphalt will require urban and suburban planners to compare costs over longer design lives and consider all the environmental costs associated with a material's use, neither of which is currently done. The life cycle analysis reviewed herein presents one methodology for making such a comparison.

APPENDIXES

A. Illinois Statewide Ozone Precursor Emissions Inventory – 1996 Typical Summer Day Emissions of Oxides of Nitrogen (NO_x) Chicago Nonattainment Area

B. Illinois Statewide Ozone Precursor Emissions Inventory – 1996 Typical Summer Day Emissions of Volatile Organic Materials (VOC) Chicago Nonattainment Area

C. Transformities/Emergy Conversions

D. Urban Fabric Analysis Sector Locations

E. Urban Fabric Analysis Results

APPENDIX A

ILLINOIS STATEWIDE OZONE PRECUSOR EMISSIONS INVENTORY
1996 TYPICAL SUMMER DAY EMISSIONS OF OXIDES OF NITROGEN (NOx)
CHICAGO NONATTAINMENT AREA

* Emissions Stated in Tons Per Day (TPD) *

SOURCE CATEGORIES	itegory NOxde	POINT	AREA	ON-ROAD	OFF-ROAD	TOTAL
EXTERNAL FUEL COMBUSTION:		227.06	25.78	0.00	0.00	252.84
Utility Boilers		118.00	0.00	0.00	0.00	118.00
Industrial Boilers		76.25	0.00	0.00	0.00	76.25
Distillate Oil	##	0.00	5.28	0.00	0.00	5.28
Residual Oil	##	0.00	4.59	0.00	0.00	4.59
Natural Gas	##	0.00	0.04	0.00	0.00	0.04
Subtotal		78.60	9.91	0.00	0.00	88.52
Commercial/Institutional		9.44	0.00	0.00	0.00	9.44
Distillate Oil	##	0.00	1.11	0.00	0.00	1.11
Residual Oil	##	0.00	4.62	0.00	0.00	4.62
Natural Gas	##	0.00	0.93	0.00	0.00	0.93
Subtotal		9.88	6.66	0.00	0.00	16.54
Residential						
Distillate Oil	##	0.00	2.44	0.00	0.00	2.44
Natural Gas	##	0.00	6.78	0.00	0.00	6.78
Subtotal		0.00	9.21	0.00	0.00	9.21
STATIONARY INTERNAL COMBUSTION:		29.63	0.00	0.00	0.00	29.63
Reciprocating Engines		20.71	0.00	0.00	0.00	20.71
Gas Turbines		8.92	0.00	0.00	0.00	8.92
OTHER COMBUSTION:		0.60	4.17	0.00	0.00	4.77
Waste Disposal (incineration):						
Industrial		0.17	0.00	0.00	0.00	0.17
Governmental		0.34	0.00	0.00	0.00	0.34
Commercial/Institutional	##	0.08	2.64	0.00	0.00	2.72
Residential	##	0.00	1.20	0.00	0.00	1.20
Total		0.60	3.84	0.00	0.00	4.44
Open Burning:						
Structural Fires	##	0.00	0.12	0.00	0.00	0.12
Forest/Agricultural	##	0.00	0.02	0.00	0.00	0.02
Other	##	0.00	0.19	0.00	0.00	0.19
Total		0.00	0.33	0.00	0.00	0.33
INDUSTRIAL PROCESSES:		34.14	0.00	0.00	0.00	34.14
Chemical Manufacturing:						
Adipic Acid		0.00	0.00	0.00	0.00	0.00
Nitric Acid		0.00	0.00	0.00	0.00	0.00
Other Acid		0.00	0.00	0.00	0.00	0.00

Other		0.66	0.00	0.00	0.00	0.66
Total		0.66	0.00	0.00	0.00	0.66
Iron and Steel Manufacturing		1.29	0.00	0.00	0.00	1.29
Coke Ovens		4.74	0.00	0.00	0.00	4.74
Fugitive	##	0.27	0.00	0.00	0.00	0.27
Mineral Products:						
Cement		8.22	0.00	0.00	0.00	8.22
Glass		6.32	0.00	0.00	0.00	6.32
Other		8.28	0.00	0.00	0.00	8.28
Total		10.71	0.00	0.00	0.00	10.71
Petroleum Refining		13.95	0.00	0.00	0.00	13.95
Other		2.44	0.00	0.00	0.00	2.44
MOBILE SOURCES:		0.00	0.00	520.00	185.20	705.20
On-highway Vehicles:						
Light-duty Gasoline Autos (LDGV)		0.00	0.00	190.07	0.00	190.07
Light-duty Gasoline Trucks (LDGT1&LDG		0.00	0.00	112.83	0.00	112.83
Heavy-duty Gasoline Trucks (HDGV)		0.00	0.00	17.95	0.00	17.95
Heavy-duty Diesel Trucks (HDDV)		0.00	0.00	201.33	0.00	201.33
Other Highway Vehicles:						
Motorcycles (MC)		0.00	0.00	1.89	0.00	1.89
Diesel Autos (LDDV)		0.00	0.00	2.19	0.00	2.19
Diesel Trucks (LDDT)		0.00	0.00	0.66	0.00	0.66
Sub-total		0.00	0.00	4.74	0.00	4.74
Inspection & Maintenance Credits		0.00	0.00	6.92	0.00	6.92
TCMs Credits		0.00	0.00	0.00	0.00	0.00
Total		0.00	0.00	520.00	0.00	520.00
Non-highway Vehicles:						
Rail	##	0.00	0.00	0.00	23.19	23.19
Aircraft						
Military	##	0.00	0.00	0.00	0.11	0.11
Commercial	##	0.00	0.00	0.00	17.01	17.01
Civil	##	0.00	0.00	0.00	0.18	0.18
Subtotal		0.00	0.00	0.00	17.31	17.31
Airport Service Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.02	0.02
4-Stroke Gasoline	##	0.00	0.00	0.00	0.28	0.28
Diesel	##	0.00	0.00	0.00	14.18	14.18
Subtotal		0.00	0.00	0.00	14.48	14.48
Vessels:						
Commercial Vessels						
Distillate	##	0.00	0.00	0.00	2.22	2.22
Residual	##	0.00	0.00	0.00	0.01	0.01
Subtotal		0.00	0.00	0.00	2.24	2.24
Pleasure Craft						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.21	0.21
4-Stroke Gasoline	##	0.00	0.00	0.00	0.69	0.69
Diesel	##	0.00	0.00	0.00	0.40	0.40
Subtotal		0.00	0.00	0.00	1.30	1.30
Vessels Subtotal		0.00	0.00	0.00	3.54	3.54
Others:						
Recreational Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
4-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
Diesel	##	0.00	0.00	0.00	0.00	0.00
Subtotal		0.00	0.00	0.00	0.00	0.00
Agricultural Equipment						

2-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
4-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
Diesel	##	0.00	0.00	0.00	11.14	11.14
Subtotal		0.00	0.00	0.00	11.14	11.14
Lawn & Garden Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.01	0.01
4-Stroke Gasoline	##	0.00	0.00	0.00	0.63	0.63
Diesel	##	0.00	0.00	0.00	0.50	0.50
Subtotal		0.00	0.00	0.00	1.14	1.14
Industrial Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	5.65	5.65
4-Stroke Gasoline	##	0.00	0.00	0.00	1.91	1.91
Diesel	##	0.00	0.00	0.00	12.18	12.18
Subtotal		0.00	0.00	0.00	19.74	19.74
Light Commercial Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.04	0.04
4-Stroke Gasoline	##	0.00	0.00	0.00	0.32	0.32
Diesel	##	0.00	0.00	0.00	1.72	1.72
Subtotal		0.00	0.00	0.00	2.09	2.09
Logging Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
4-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
Diesel	##	0.00	0.00	0.00	0.00	0.00
Subtotal		0.00	0.00	0.00	0.00	0.00
Construction Equipment						
2-Stroke Gasoline	##	0.00	0.00	0.00	0.00	0.00
4-Stroke Gasoline	##	0.00	0.00	0.00	0.31	0.31
Diesel	##	0.00	0.00	0.00	92.27	92.27
Subtotal		0.00	0.00	0.00	92.57	92.57
Others Subtotal		0.00	0.00	0.00	126.68	126.68
Total Non-Highway		0.00	0.00	0.00	185.20	185.20
Biogenic Sources		0.00	18.68	0.00	0.00	18.68
SUB-TOTALS ANTHROPOGENIC		291.43	29.95	520.00	185.20	1026.58
GRAND TOTALS		291.43	48.63	520.00	185.20	1045.26

APPENDIX B

ILLINOIS STATEWIDE OZONE PRECURSOR EMISSIONS INVENTORY
1996 TYPICAL SUMMER DAY EMISSIONS OF VOLATILE ORGANIC MATERIALS (VOM)
CHICAGO NONATTAINMENT AREA

* Emissions Stated in Tons Per Day (TPD) *

SOURCE CATEGORIES	Cate Code	POINT	AREA	ON-ROAD	OFF-ROAD	TOTAL
STORAGE & MARKETING OF VOC:		16.91	15.12	0.00	0.00	32.03
-						
Oil & Gas Production		0.00	0.00	0.00	0.00	0.00
Natural Gas & Gasoline Processing		0.00	0.00	0.00	0.00	0.00
Other Petroleum Processing		1.24	0.00	0.00	0.00	1.24
Gasoline & Crude Oil Storage:						
Floating Roof Tanks		1.94	0.00	0.00	0.00	1.94
All Other Tanks		2.75	0.00	0.00	0.00	2.75
Total		4.69	0.00	0.00	0.00	4.69
Volatile Organic Liquid Storage		9.76	0.00	0.00	0.00	9.76
VOL Transfer:						
Ship and Barge	#	0.08	0.66	0.00	0.00	0.74
Tanker Ballasting	#	0.00	0.00	0.00	0.00	0.00
Total		0.08	0.66	0.00	0.00	0.74
Barge and Tanker Cleaning	#	0.00	0.30	0.00	0.00	0.30
Bulk Gasoline Terminals		0.90	0.00	0.00	0.00	0.90
Bulk Gasoline Plants		0.25	0.00	0.00	0.00	0.25
Service Station Loading (Stage I)	#	0.00	5.54	0.00	0.00	5.54
Vehicle Refueling (Stage II)	#	0.00	6.75	0.00	0.00	6.75
Gasoline Tank Truck Leaks	#	0.00	1.09	0.00	0.00	1.09
Underground Storage Tank Breathing	#	0.00	0.17	0.00	0.00	0.17
Aircraft Refueling	#	0.00	0.61	0.00	0.00	0.61
INDUSTRIAL PROCESSES:		59.09	0.00	0.00	0.00	59.09
-						
Petroleum Refineries:						
Vacuum Systems		1.75	0.00	0.00	0.00	1.75
Fugitive Leaks	#	1.56	0.00	0.00	0.00	1.56
Wastewater Collection-Process	#	0.27	0.00	0.00	0.00	0.27
Wastewater Collection-Fugitive		0.00	0.00	0.00	0.00	0.00
Total	#	3.58	0.00	0.00	0.00	3.58
Lube Oil Manufacture		0.00	0.00	0.00	0.00	0.00
Organic Chemical Manufacture:		5.60	0.00	0.00	0.00	5.60
SOCMI:						
Polyethylene		0.00	0.00	0.00	0.00	0.00
Polypropylene		0.00	0.00	0.00	0.00	0.00
Polystyrene		0.00	0.00	0.00	0.00	0.00
Fugitive Leaks		0.00	0.00	0.00	0.00	0.00
Air Oxidation		0.34	0.00	0.00	0.00	0.34
Others		1.03	0.00	0.00	0.00	1.03
Total	#	1.37	0.00	0.00	0.00	1.37
Inorganic Chemical Manufacture		1.17	0.00	0.00	0.00	1.17
Fermentation Processes		0.00	0.00	0.00	0.00	0.00
Vegetable Oil Processing		0.04	0.00	0.00	0.00	0.04

Pharmaceutical Manufacture		1.79	0.00	0.00	0.00	1.79
Plastics Products Manufacture		4.10	0.00	0.00	0.00	4.10
Rubber Tire Manufacture		0.01	0.00	0.00	0.00	0.01
SBR Rubber Manufacture		0.23	0.00	0.00	0.00	0.23
Textile, Polymers and Resins Manufacture		0.07	0.00	0.00	0.00	0.07
Synthetic Fiber Manufacture		0.00	0.00	0.00	0.00	0.00
Iron and Steel Manufacture						
Iron and Steel - Process		1.05	0.00	0.00	0.00	1.05
Iron and Steel - Hot/Cold Rolling		0.04	0.00	0.00	0.00	0.04
Coke Ovens - Process		0.29	0.00	0.00	0.00	0.29
Coke Ovens - Fugitive	#	0.01	0.00	0.00	0.00	0.01
Total		1.38	0.00	0.00	0.00	1.38
Other	#	39.73	0.00	0.00	0.00	39.73
INDUSTRIAL SURFACE COATING:		42.25	0.00	0.00	0.00	42.25
Large Appliances		0.01	0.00	0.00	0.00	0.01
Magnet Wire		0.20	0.00	0.00	0.00	0.20
Autos and Light Trucks		2.05	0.00	0.00	0.00	2.05
Cans		1.26	0.00	0.00	0.00	1.26
Metal Coils		1.72	0.00	0.00	0.00	1.72
Paper		10.98	0.00	0.00	0.00	10.98
Fabric		0.00	0.00	0.00	0.00	0.00
Metal and Wood Furniture:						
Metal Furniture		0.66	0.00	0.00	0.00	0.66
Wood Furniture		0.93	0.00	0.00	0.00	0.93
Total		1.59	0.00	0.00	0.00	1.59
Miscellaneous Metal Products		3.81	0.00	0.00	0.00	3.81
Flatwood Products		0.07	0.00	0.00	0.00	0.07
Plastic Products		1.03	0.00	0.00	0.00	1.03
Large Ships		0.00	0.00	0.00	0.00	0.00
Large Aircraft		0.00	0.00	0.00	0.00	0.00
Others		19.55	0.00	0.00	0.00	19.55
NON-INDUSTRIAL SURFACE COATING:		0.00	66.12	0.00	0.00	66.12
Architectural Coatings		0.00	53.44	0.00	0.00	53.44
Auto Refinishing	#	0.00	6.50	0.00	0.00	6.50
Others:	#					
Traffic/Maintenance Painting		0.00	6.18	0.00	0.00	6.18
	#					
OTHER SOLVENT USE:		19.34	121.41	0.00	0.00	140.75
Degreasing:						
Cold Cleaners		0.73	33.35	0.00	0.00	34.08
Vapor/Conveyorized	#	2.76	0.00	0.00	0.00	2.76
Total		3.49	33.35	0.00	0.00	36.85
Dry Cleaning:						
Perchloroethylene		0.00	0.00	0.00	0.00	0.00
Petroleum	#	1.19	0.00	0.00	0.00	1.19
Total	#	1.19	0.00	0.00	0.00	1.19
Graphic Arts		14.02	8.93	0.00	0.00	22.95
Adhesives	#	0.00	0.00	0.00	0.00	0.00
Emulsified Asphalt Paving		0.00	13.41	0.00	0.00	13.41

Consumer & Commercial Solvents	#					
Personal Care Products		0.00	14.60	0.00	0.00	14.60
Household Products	#	0.00	22.95	0.00	0.00	22.95
Auto Aftermarket Products	#	0.00	6.26	0.00	0.00	6.26
Adhesive Products	#	0.00	3.13	0.00	0.00	3.13
Pesticide Products	#	0.00	1.04	0.00	0.00	1.04
Miscellaneous Consumer Products	#	0.00	17.73	0.00	0.00	17.73
Total	#	0.00	65.72	0.00	0.00	65.72
Others	#	0.64	0.00	0.00	0.00	0.64
WASTE DISPOSAL:		10.63	2.99	0.00	0.00	13.62
-						
Municipal Waste:						
Combustion:						
Residential		0.00	0.84	0.00	0.00	0.84
Commercial/Institutional	#	0.00	1.20	0.00	0.00	1.20
Governmental	#	0.00	0.00	0.00	0.00	0.00
Industrial		0.20	0.00	0.00	0.00	0.20
Sub-total		0.20	2.04	0.00	0.00	2.24
Landfills		0.00	0.00	0.00	0.00	0.00
Municipal Waste Total		0.20	2.04	0.00	0.00	2.24
Hazardous Wastes TSDFs:						
Process	#	0.00	0.00	0.00	0.00	0.00
Fugitive		0.03	0.00	0.00	0.00	0.03
Solvent Waste Recovery		0.00	0.00	0.00	0.00	0.00
Sub-Total	#	0.03	0.00	0.00	0.00	0.03
POTWs	#	0.00	0.00	0.00	0.00	0.00
Industrial WWTFs		3.88	0.00	0.00	0.00	3.88
Pretreatment	#	1.59	0.95	0.00	0.00	2.54
Subtotal		5.47	0.95	0.00	0.00	6.42
Industrial Boiler Co-firing		0.00	0.00	0.00	0.00	0.00
Others		4.94	0.00	0.00	0.00	4.94
OTHER MISCELLANEOUS SOURCES:		9.86	186.38	0.00	0.00	196.24
-						
Fuel Combustion (external):						
Utilities		1.26	0.00	0.00	0.00	1.26
Industrial		2.88	0.00	0.00	0.00	2.88
Distillate Oil	#	0.00	0.05	0.00	0.00	0.05
Residual Oil	#	0.00	0.02	0.00	0.00	0.02
Natural Gas	#	0.00	0.00	0.00	0.00	0.00
Subtotal		2.88	0.08	0.00	0.00	2.96
Commercial/Institutional		0.40	0.00	0.00	0.00	0.40
Distillate Oil	#	0.00	0.02	0.00	0.00	0.02
Residual Oil	#	0.00	0.09	0.00	0.00	0.09
Natural Gas	#	0.00	0.22	0.00	0.00	0.22
Subtotal		0.40	0.33	0.00	0.00	0.74
Residential						
Distillate Oil	#	0.00	0.10	0.00	0.00	0.10
Natural Gas	#	0.00	0.36	0.00	0.00	0.36
Subtotal		0.00	0.46	0.00	0.00	0.46
Total		4.54	0.87	0.00	0.00	5.41
Open Burning:						
Structural Fires	#	0.00	1.49	0.00	0.00	1.49
Forest/Agricultural	#	0.00	0.20	0.00	0.00	0.20

Other	#	0.07	0.93	0.00	0.00	0.99
Total		0.07	2.62	0.00	0.00	2.69
Pesticide Applications	#	0.00	12.17	0.00	0.00	12.17
Stationary Internal Combustion Engines:		0.00	0.00	0.00	0.00	0.00
By Utilities		0.74	0.00	0.00	0.00	0.74
By Others		1.68	0.00	0.00	0.00	1.68
Total		2.41	0.00	0.00	0.00	2.41
Bakeries		2.84	0.00	0.00	0.00	2.84
Biogenic Sources		0.00	170.71	0.00	0.00	170.71
MOBILE SOURCES:		0.00	0.00	268.48	145.19	413.67
On-highway Vehicles:						
Light-duty Gasoline Cars (LDGV)		0.00	0.00	156.01	0.00	156.01
Light-duty Gasoline Trucks (LDGT1&2)		0.00	0.00	101.33	0.00	101.33
Heavy-duty Gasoline Trucks (HDGV)		0.00	0.00	10.77	0.00	10.77
Heavy-duty Diesel Trucks (HDDV)		0.00	0.00	15.80	0.00	15.80
Other Highway Vehicles:						
Motorcycles (MC)		0.00	0.00	7.37	0.00	7.37
Light-duty Diesel Cars (LDDV)		0.00	0.00	0.66	0.00	0.66
Light-duty Diesel Trucks (LDDT)		0.00	0.00	0.25	0.00	0.25
Sub-Total		0.00	0.00	8.28	0.00	8.28
Inspection & Maintenance Credits		0.00	0.00	23.72	0.00	23.72
TCMs Credits		0.00	0.00	0.00	0.00	0.00
Total		0.00	0.00	268.48	0.00	268.48
Non-highway Vehicles:						
Rail	#	0.00	0.00	5.77	5.77	11.55
Aircraft						
Military	#	0.00	0.00	0.00	0.63	0.63
Commercial	#	0.00	0.00	0.00	4.94	4.94
Civil	#	0.00	0.00	0.00	0.73	0.73
Subtotal		0.00	0.00	0.00	6.30	6.30
Airport Service Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	0.00	0.00
4-Stroke Gasoline	#	0.00	0.00	0.00	0.74	0.74
Diesel	#	0.00	0.00	0.00	1.64	1.64
Subtotal		0.00	0.00	0.00	2.38	2.38
Vessels:						
Commercial Vessels						
Distillate	#	0.00	0.00	0.00	0.43	0.43
Residual	#	0.00	0.00	0.00	0.00	0.00
Subtotal		0.00	0.00	0.00	0.43	0.43
Pleasure Craft						
2-Stroke Gasoline	#	0.00	0.00	0.00	20.60	20.60
4-Stroke Gasoline	#	0.00	0.00	0.00	4.13	4.13
Diesel	#	0.00	0.00	0.00	0.05	0.05
Subtotal		0.00	0.00	0.00	24.78	24.78
Vessels Subtotal		0.00	0.00	0.00	25.21	25.21
Others:						
Recreational Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	1.94	1.94
4-Stroke Gasoline	#	0.00	0.00	0.00	1.29	1.29
Diesel	#	0.00	0.00	0.00	0.00	0.00
Subtotal		0.00	0.00	0.00	3.23	3.23
Agricultural Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	0.00	0.00

4-Stroke Gasoline	#	0.00	0.00	0.00	0.24	0.24
Diesel	#	0.00	0.00	0.00	2.18	2.18
Subtotal		.0.00	0.00	0.00	2.42	2.42
Lawn & Garden Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	29.61	29.61
4-Stroke Gasoline	#	0.00	0.00	0.00	30.54	30.54
Diesel	#	0.00	0.00	0.00	0.05	0.05
Subtotal		0.00	0.00	0.00	60.21	60.21
Industrial Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	2.69	2.69
4-Stroke Gasoline	#	0.00	0.00	0.00	5.07	5.07
Diesel	#	0.00	0.00	0.00	1.38	1.38
Subtotal		0.00	0.00	0.00	9.14	9.14
Light Commercial Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	5.75	5.75
4-Stroke Gasoline	#	0.00	0.00	0.00	9.78	9.78
Diesel	#	0.00	0.00	0.00	0.24	0.24
Subtotal		0.00	0.00	0.00	15.76	15.76
Logging Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	0.35	0.35
4-Stroke Gasoline	#	0.00	0.00	0.00	0.00	0.00
Diesel	#	0.00	0.00	0.00	0.00	0.00
Subtotal		0.00	0.00	0.00	0.35	0.35
Construction Equipment						
2-Stroke Gasoline	#	0.00	0.00	0.00	1.15	1.15
4-Stroke Gasoline	#	0.00	0.00	0.00	1.76	1.76
Diesel	#	0.00	0.00	0.00	11.50	11.50
Subtotal		0.00	0.00	0.00	14.41	14.41
Others Subtotal		0.00	0.00	0.00	105.53	105.53
Total Non-Highway		0.00	0.00	0.00	145.19	145.19
SUB-TOTALS ANTHROPOGENIC		158.08	221.31	268.48	145.19	793.06
GRAND TOTALS		158.08	392.02	268.48	145.19	963.77

APPENDIX C

Transformities (EMERGY conversions) for energies, resources, and commodities related to the built environment.

MATERIAL	TRANSFORMITIES (Refer to notes 1 and 2 unless noted otherwise)
Aluminum inguts (g)	1.60E10
Asphalt (J)	3.47E5
Asphalt concrete (g)	1.78E9 (Refer to note 3.)
Coal (J)	3.98E4
Concrete (g)	9.99E8 (Refer to note 4.)
Copper (g)	6.80E10
Electricity (J)	1.59E5
Glass (g)	8.40E8
Grain (J)	6.80E4
Iron (g)	1.80E9
Machinery (g)	6.70E9
Natural gas (J)	4.80E4
Nitrogen fertilizer (J)	1.69E6
Oil (J)	5.30E4
Paper (J)	2.15E5
Petroleum product (J)	6.60E4
Plastic (g)	3.80E8
Rubber (g)	4.30E9
Service, labor (US $)	2.00E12 (Refer to note 5.)
Steel (g)	1.80E9
Stone, mined (g)	1.00E9
Stone, natural state (g)	8.50E8
Topsoil (J)	6.30E4
Water, consumer (J)	6.66E5
Water, waste (J)	4.10E4
Wood (J)	3.49E4
Zinc Alloys (g)	6.80E10

Notes:

1. Transformity units are solar emjoules/Joule, solar emjoules/gram or solar emjoules/US $.
2. Source: Dr. Howard T. Odum, Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida.
3. Transformity calculations are given in Appendix G.
4. Transformity calculations are given in Appendix F.
5. Units in 1990 U. S. dollars.

Copied from: Roudebush, W.H.; Environmental Value Engineering (EVE) Environmental Life Cycle Assessment of Concrete and Asphalt Highway Pavement Systems; Portland Cement Association: Skokie, IL, 1996.

APPENDIX D

Sector #	Location	Corners							
		NW		NE		SW		SE	
		Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
1	Stony Island - Burnside Industrial Corridor	41°44.43'	87°35.59'	41°44.43'	87°34.42'	41°43.57'	87°35.59'	41°43.57'	87°34.42'
2	Stockyards - International Amphitheater	41°49.39'	87°39.92'	41°49.39'	87°38.76'	41°48.52'	87°39.92'	41°48.52'	87°38.76'
3	Interchange 55/90/94	41°51.14'	87°38.78'	41°51.14'	87°37.63'	41°50.28'	87°38.78'	41°50.28'	87°37.63'
4	Kennedy Interchange 90/94	41°58.28'	87°45.45'	41°58.28'	87°44.29'	41°57.41'	87°45.45'	41°57.41'	87°44.29'
5	Cicero	41°51.50'	87°45.83'	41°51.50'	87°44.67'	41°50.63'	87°45.83'	41°50.63'	87°44.67'
6	Lincolnwood	42°00.26'	87°43.73'	42°00.26'	87°42.56'	41°59.39'	87°43.73'	41°59.39'	87°42.56'
7	Schaumburg - Woodfield Mall	42°03.17'	87°03.02'	42°03.17'	87°01.85'	42°02.31'	87°03.02'	42°02.31'	87°01.85'
8	Garfield Park	41°53.38'	87°43.23'	41°53.38'	87°42.06'	41°52.52'	87°43.23'	41°52.52'	87°42.06'
9	Lincoln Park	41°55.57'	87°38.95'	41°55.57'	87°37.79'	41°54.70'	87°38.95'	41°54.70'	87°37.79'
10	Rogers Park	42°01.17'	87°41.43'	42°01.17'	87°40.26'	42°00.30'	87°41.43'	42°00.30'	87°40.26'
11	Wrigleyville	41°57.03'	87°40.73'	41°57.03'	87°39.56'	41°56.16'	87°40.73'	41°56.16'	87°39.56'
12	Oak Lawn	41°43.18'	87°45.61'	41°43.18'	87°44.44'	41°42.31'	87°45.61'	41°42.31'	87°44.44'
13	Blue Island - Pilson	41°51.60'	87°41.11'	41°51.60'	87°39.95'	41°50.73'	87°41.11'	41°50.73'	87°39.95'
14	Naperville	41°46.43	88°08.38'	41°46.43	88°07.21	41°45.56'	88°08.38'	41°45.56'	88°07.21

APPENDIX E

Area	*Category*	*Total Roof*	*White/Light Roof (% of total roof)*	*Total Paved*	*Alley (% of paved)*	*Vegetative*	*Water*
Rogers Park	Residential - Low/Med Density	32.57%	44.32%	25.83%	14.78%	41.60%	x
Rogers Park	Residential - Low/Med Density (with school/fields)	30.56%	40.33%	24.39%	13.01%	45.05%	x
Rogers Park	Residential - Low/Med Density	30.95%	40.35%	26.95%	15.95%	42.10%	x
Kennedy - 90/94	Residential	29.46%	43.64%	15.54%	22.23%	55.00%	x
Garfield Park	Residential - Med Density	26.05%	13.10%	22.77%	10.41%	51.19%	x
Wrigleyville	Residential - Med Density	35.44%	55.09%	15.80%	23.45%	48.76%	x
Wrigleyville	Residential - Low/Med Density	38.89%	49.04%	14.60%	16.53%	46.51%	x
Wrigleyville	Residential - Med Density	51.07%	31.94%	15.57%	19.44%	33.36%	x
Lincoln Park	Residential - Med Density	34.78%	59.59%	16.37%	23.51%	48.85%	x
Blue Island - Pilsen	Residential	38.19%	19.73%	28.02%	8.96%	33.79%	x
Stony Island	Residential - Low/Med Density	31.52%	23.53%	22.76%	20.33%	45.72%	x
Stony Island	Residential - Low/Med Density	33.55%	21.45%	16.99%	27.70%	49.46%	x
		34.42%	36.84%	20.47%	18.02%	45.12%	x
Lincolnwood	Residential - Low Density	27.17%	36.39%	25.32%	10.24%	47.50%	x
Cicero	Residential - ???	35.64%	19.48%	22.08%	18.46%	42.27%	x
Oak Lawn	Residential - ???	24.51%	38.92%	24.40%	6.35%	51.09%	x
Oak Lawn	Residential - ???	21.36%	46.41%	20.84%	x	57.80%	x
		27.17%	35.30%	23.16%	11.69%	49.67%	x

Area	Category	Total Roof	White/Light Roof (% of total roof)	Total Paved	Alley (% of paved)	Vegetative	Water
Naperville	Residential - Low Density (Suburban)	11.99%	41.73%	11.86%	x	76.15%	x
Naperville	Residential - Low Density (Suburban)	13.42%	13.17%	21.72%	x	64.86%	x
		12.70%	27.45%	16.79%	x	70.51%	x
Rogers Park	Recreational - school/ fields	9.62%	29.06%	24.67%	x	65.71%	x
Garfield Park	Recreational - Garfield Park	2.82%	27.17%	17.36%	x	79.82%	x
Lincoln Park	Recreational - North Lincoln Park (with zoo)	7.84%	32.10%	26.70%	x	56.49%	8.97%
Lincoln Park	Recreational - South Lincoln Park (w/o zoo)	6.36%	41.14%	17.70%	x	66.75%	9.18%
		6.66%	32.37%	21.61%	x	67.19%	9.08%
Kennedy - 90/94	Transportation - Highway Exchange (w/o surrounding area)	0.00%	0.00%	69.11%	x	30.89%	x
Downtown - 55/90/94	Transportation - Highway Exchange (w/o surrounding area)	0.00%	0.00%	76.45%	x	23.55%	x
Downtown - 55/90/94	Transportation - Highway Exchange (w/o surrounding area)	0.00%	0.00%	59.23%	x	40.77%	x
		0.00%	0.00%	68.26%	x	31.74%	x
Kennedy - 90/94	Transportation - Highway Exchange (with surrounding area)	9.52%	25.19%	57.44%	x	33.05%	x
Downtown - 55/90/94	Transportation - Highway Exchange (with surrounding area)	16.59%	13.27%	67.12%	x	16.29%	x
Downtown - 55/90/94	Transportation - Highway Exchange (with surrounding area)	15.12%	10.70%	55.75%	x	29.13%	x
		13.74%	16.39%	60.10%	x	26.16%	x

Area	Category	Total Roof	White/Light Roof (% of total roof)	Total Paved	Alley (% of paved)	Vegetative	Water
Kennedy - 90/94	Urban Commercial	46.95%	44.39%	32.07%	2.61%	20.99%	x
Wrigleyville	Urban Commercial	30.14%	100.00%	58.07%	4.90%	11.79%	x
Stony Island	Urban Commercial	22.32%	53.75%	62.17%	8.26%	15.51%	x
		33.14%	66.05%	50.77%	x	16.10%	x
Schaumburg - Woodfield Mall	Commercial - North Woodfield Mall (suburban)	17.88%	100.00%	72.58%	x	9.55%	x
Schaumburg - Woodfield Mall	Commercial - South Woodfield Mall (suburban)	21.43%	100.00%	68.45%	x	10.12%	x
Schaumburg - Woodfield Mall	Commercial - Other (suburban)	30.22%	100.00%	52.44%	x	17.33%	x
Lincolnwood	Commercial (suburban)	35.44%	59.00%	52.97%	x	11.59%	x
		26.24%	89.75%	61.61%	x	12.15%	x
Cicero	Industrial	40.73%	33.18%	51.01%	x	8.25%	x
Stockyards - International Amphitheater	Industrial	35.22%	0.00%	43.80%	x	20.98%	x
Blue Island - Pilsen	Industrial - Corridor	50.20%	10.00%	48.09%	x	1.71%	x
		42.05%	14.39%	47.63%	x	10.32%	x

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