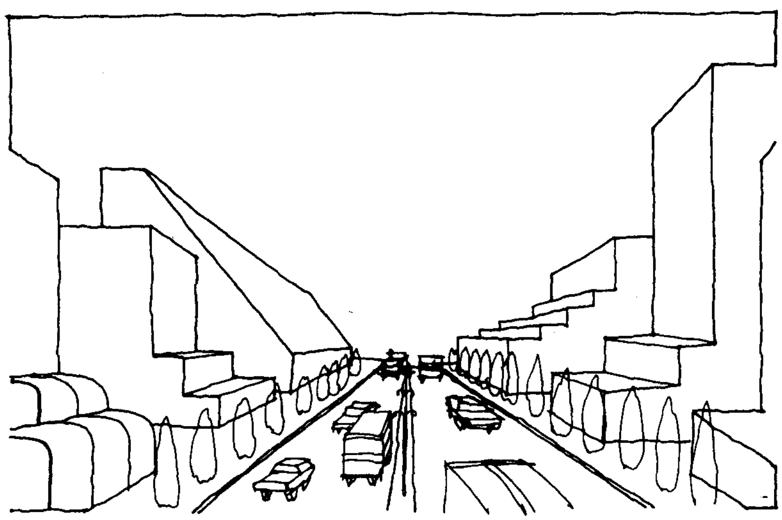
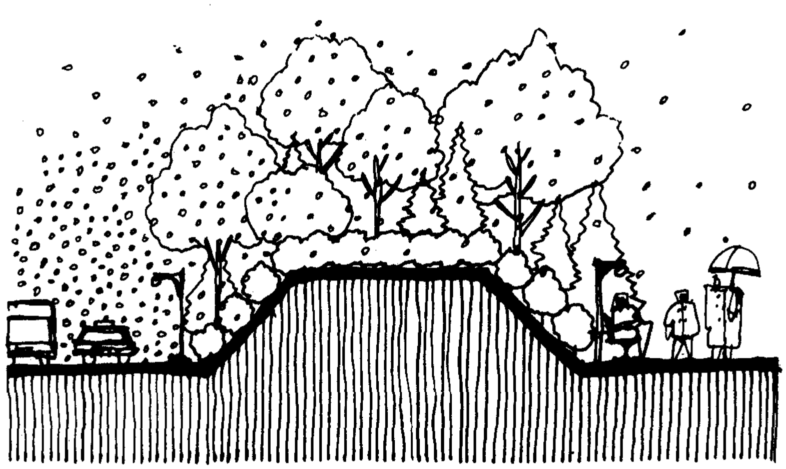
AIR QUALITY AT STREET-LEVEL: STRATEGIES FOR URBAN DESIGN





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William George Batchelor was co-author with Anne Whiston Spirn of a preliminary report entitled "Street-Level Air Pollution and Urban Form: A Review of Recent Literature" (June 1985) that was prepared for the Boston Redevelopment Authority as part of a separate contract. Much of the text of this earlier report has been incorporated into Chapters II and III of this document. Mr. Batchelor also worked on preliminary conceptual work for Chapter IV and on early versions of many diagrams for the present study. Raveevarn Choksombatchai worked with the principal investigator to develop the diagrams and was responsible for the execution of all final drawings. Kate McCollum coordinated production of the manuscript. John Spengler reviewed the manuscript and provided valuable information.

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I. INTRODUCTION

This is a study about air pollution at street-level, and how urban design can help to reduce both the concentration of those pollutants and human exposure to them. This subject is important for several reasons. Much of the city's air pollution is emitted along the street,[1] and, in certain locales, concentration of air pollutants may exceed the standard for one-hour exposure, the length of a normal lunch break. The street is also a place where people who live and work in the city spend much of their time; some people like policemen, street vendors, and taxi drivers may even spend their entire workday on the street.[2] Street-level air pollution can also contribute to poor air quality in building interiors; for example, when entrances to buildings or intake vents for ventilation systems are located in such a way that they suck in air pollutants generated along the street.

Urban air quality has attracted much study in the past two decades, but attention has been focused largely upon ambient air quality. Air pollution varies considerably from spot to spot within the city, however, and studies of ambient air quality fail to give an accurate picture of the considerable variation along the street.

Air Quality Management: The Potential Contribution of Urban Design

There are a number of approaches one might take to protect city residents from the potential ill effects of transportation-related air pollution.[3] Some of these approaches are of concern mainly to air quality managers and transportation engineers, while others fall within the domain of public health officials or urban designers. An air quality specialist, for example, might be concerned with strategies that involve detection of high pollution episodes and a program of temporary measures to be implemented during such air quality alerts. A transportation engineer, on the other hand, might address the strategy of reducing emissions or preventing their release through such tactics as streamlining traffic flow. In contrast, a public health official might be concerned with strategies that make people healthier and therefore less susceptible to the ill effects of urban air pollution (e.g., smoking reduction, diet and exercise to reduce susceptibility to cardiovascular disease) or that prevent the contact of air pollutants with the lungs (e.g., gas masks for persons who work in zones of high pollution).

1.
In the city of Boston, for example, transportation accounts for 94 percent of the carbon monoxide emitted within the city.

2.
A study of the exposure of Boston policemen to carbon monoxide found that carbon monoxide levels within patrol cars over an eight-hour period exceeded EPA standards.

3.
These approaches are similar to those available to prevent human or economic loss from other hazards, a subject that has been well studied. See, for example, Haddon, 1970.

To date, the range of approaches that have been implemented to reduce transportation-related air pollutants and human exposure to them has been rather narrow. These actions may not be sufficient in some cities to meet national air quality standards (Horowitz, 1982); and even if standards for ambient levels are met, levels in some locales may still be high.

There is mounting evidence that local concentrations of air pollutants are greatly affected by the form of the city, but there has been relatively little attempt to enhance street-level air quality through the manipulation of urban form. Urban design, especially if integrated with other measures, could play an important role in enhancing dispersion of street-level air pollutants and in limiting human exposure in areas where pollutants are highly concentrated. Such an approach is hampered by the fact that few urban designers have an understanding of the factors that affect the generation and dispersion of air pollution and that few air quality specialists have an appreciation for the potential contribution of urban design to air quality. This report is intended as an initial effort to remedy that situation. It discusses the major transportation-related air pollutants, their health effects and exposure standards. It describes spatial and temporal distribution of air pollutants and the factors that contribute to their concentration and dispersion at street-level. It provides a checklist for identifying potential problem areas and describes a range of urban design strategies. Finally, it reviews how such strategies can be integrated in a single city and identifies future directions for action and research.

This report differs from others in its emphasis on the contribution of urban design to air quality management. While it recognizes the importance of other approaches such as emission controls and traffic management measures, it devotes little space to these strategies, since they have been treated in detail elsewhere.

A Framework

This study is based on a review of the literature on air pollution exposure standards, health effects, and monitoring; on urban air pollution modelling, including both physical and mathematical models; on air flow in urban environments; on air pollution sinks; and on air quality management and urban planning and design.[4] With the exception of an early review article by Rydell and Schwartz (1968), the literature review identified

4.
This literature review was the subject of a previous report (Spirn and Batchelor, 1985).

no source that dealt in a comprehensive way with air pollution and urban form.

From this literature that information most relevant to urban design was distilled. This report presents the results of that distillation: a framework based upon the processes of production, dispersion, concentration, and filtration of transportation-related air pollutants and the variable sensitivity of the human population to exposure. Within this framework, the significant factors that influence the quantity of air pollutants emitted, and how, when, and where they are likely to be concentrated or dispersed are identified. Six design situation classes encompass combinations of these variables, and appropriate urban design strategies are identified for each. Each design strategy is illustrated by several examples. These examples demonstrate how designs at a particular scale of concern can be tailored to a specific factor. They are intended to be illustrative, not exhaustive.

Both the framework and the illustrative models are presented here in the hope that they may encourage urban design that is responsive to air quality, and that they may serve as a bridge between urban designers and planners, on the one hand, and air pollution specialists, meteorologists, and public health experts, on the other. The framework has exposed areas that require further research; and it should be sufficiently flexible to incorporate the results of that research. Some of the strategies designed by the author, although based upon data derived from empirical studies (wind tunnel modelling and air pollution monitoring), are hypotheses that should be tested by experimentation. A logical next step would be to use the framework presented within this report, applying it to a particular case, a portion of downtown Boston, for example. This report is a first step in what promises to be a rich area of research. It is the author's hope that it may lead to new collaboration between urban designers and individuals in other fields concerned with air quality management.

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II. MAJOR TRANSPORTATION-RELATED AIR POLLUTANTS

Health Effects and Exposure Standards

Carbon monoxide, hydrocarbons, nitrogen oxides, ozone, and particulates, including lead, are the major transportation-related air pollutants. The EPA has established ambient air quality standards for each of these pollutants.

Carbon monoxide (CO) is a colorless, odorless gas whose principal source is the incomplete combustion of organic fuels (such as occurs in automobiles driven in stop-and-go traffic). When inhaled, it combines with hemoglobin in the blood stream, reducing the ability of the blood to carry oxygen; in high doses it is fatal. Although the urban atmosphere does not contain fatal concentrations of CO, it may contain concentrations sufficient to aggravate cardiovascular disease and impair psychomotor functions. Studies of Los Angeles commuters driving two hours a day in morning and afternoon traffic, for example, found that drivers are exposed to enough CO to elevate blood levels to a "serious" level, a level sufficient to impair alertness, vision, and physical coordination (Haagen-Smit, 1966). In Boston, where transportation accounts for 94 percent of CO emissions (Horowitz, 1982), the EPA eight-hour standard for CO is currently in violation, and there may be local pockets that are in violation of the one-hour standard.

Hydrocarbons (HC) are chemical compounds of carbon and hydrogen, produced by internal combustion engines of automobiles as well as other sources. Motor vehicles account for 61 percent of the HC emissions in Boston, for example (Horowitz, 1982). In quantities found in the urban atmosphere, HC are not directly harmful, but they play an important chemical role in the creation of nitrogen dioxide and ozone.

Nitrogen-dioxide (NO_2) is a brownish gas with a strong odor, and is the compound responsible for the brownish haze of the urban skyline. It is a secondary pollutant, meaning that it is not produced directly by a given source, but is derived from another reactive compound released into the atmosphere, in this case nitric oxide, which is emitted by automobiles. Nitrogen dioxide is an irritant to the lungs, increasing the risk of respiratory infection and disease.

Ozone (O) is a colorless gas with a strong odor. Like NO_2, it is a secondary pollutant and is formed by the combination of hydrocarbons and nitrogen oxides which react with sunlight to create ozone and other compounds that are collectively known as "photochemical smog."

6 Particulates (TSP) are solid particles suspended in the air, including dust, chemical aerosols, microscopic droplets, and pollen. The health effects of these particulates varies depending on their type and size. Although most particulates in the urban atmosphere are produced by industrial emissions, those emitted by trucks, cars, and buses are of special concern since they are emitted at street-level and include highly toxic elements like lead. Lead causes damage to the nervous system, kidney, and blood, and is particularly dangerous to very young children. The main source of lead particulates is from combustion of leaded fuels. The dust and soil along heavily traveled streets exhibit high concentrations of particulate lead (Smith, 1976). When play areas are located along such streets, small children risk lead poisoning from inhalation or ingestion of dust. Although leaded fuels are being phased out, street-side soils remain contaminated and automobiles continue to present a potential health hazard.

Of the above pollutants, carbon monoxide and toxic particulates are of particular concern here. They are primary pollutants (i.e., emitted directly from the source), their chief source is the automobile, and they are highly poisonous. Their distribution is closely linked to the local environment of the street, and is directly affected by the manipulation of urban form in the roadside environment. In contrast, the effect of secondary pollutants like nitrogen dioxide and ozone is often felt several hours later far from the site where their components were originally emitted (Godin et al., 1972).

Monitoring Air Pollutants

Both stationary and mobile monitors are used to measure specific air pollutants. The standard practice is to locate a few stationary monitors at strategic sites throughout the city. In Boston, for example, the EPA uses a stationary monitoring system for CO that consists of four monitoring stations.[5] Boston is not unusual in the relatively few CO monitoring sites it has; from 1977 to 1978, CO data were collected at twelve sites in Philadelphia, nine sites in Washington, D.C., and two sites in Pittsburgh (Horowitz, 1982).

Such a system may contribute to an understanding of ambient air quality throughout the city, but it does not provide an accurate picture of the variation in local air quality at street level. Studies in several

5.
Kenmore Square, Washington and Essex Streets, Kneeland and Essex Streets, and Brenman Street in East Boston.

cities, including Boston, have demonstrated that roadside readings are consistently higher than those measured at the stationary monitors. A study of CO exposure in Boston, for example, found that the persons studied were exposed to maximum CO concentrations 40 percent greater than the one-hour average concentration measured at the fixed monitoring stations, while the eight-hour concentrations to which the same individuals were exposed were 35 percent less than those measured at the downtown monitoring stations (Cortese and Spengler, 1976). Ott and Eliasen reported pedestrian CO exposures (eight-hour average) of from three to ten times the values at stationary monitors (Ott and Eliasen, 1972). Such findings demonstrate that while stationary monitors may indicate that air pollution levels fall within national air quality standards, pedestrians at street level, especially people who must work in close proximity to the street, may be exposed to air pollution concentrations that exceed the standards.

Mobile monitors are useful in obtaining measurements at multiple locations throughout the city: at intersections and midblock; from within automobiles; in tunnels and parking garages. Carbon monoxide is frequently the pollutant measured in such studies. The technology for CO monitoring is relatively accurate, and since CO is both a non-active gas and a primary pollutant, it is a good indicator of pollutant concentration and variability. Recently experimentors have measured the air pollution exposure of individual persons as they move through the city in their daily routines through the use of mobile "personal exposure monitors" (PEMs). The findings have matched expectations; the highest exposure levels are in parking garages, tunnels, parking lots, and automobiles in heavy traffic (Hartwell, et al., 1984).

Despite their limitations, stationary monitors offer several advantages: they collect data over the course of the year, thereby affording comparison of pollutant concentrations under varied traffic and climate conditions, and they provide more accurate, quantitative data than do mobile monitors. Ideally, a city should employ a system that combines stationary and portable monitors, exploiting the accuracy of the first and the flexibility of the latter.

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III. STREET-LEVEL AIR POLLUTION: PATTERNS OF DISTRIBUTION AND EXPOSURE

Air Pollution Dispersion Models

Transportation-related air pollutants and their spatial and temporal distribution differ greatly from spot to spot within a city, a function of commuting patterns, traffic volume and speed, meteorological conditions, the topography of urban form, and the material of which the city is composed. Pollution levels often vary by a factor of six from one street corner to another, and may differ by a factor of ten.

The prediction of how air pollutants will disperse within the city is therefore a difficult and complex task. Dispersion models have been developed to provide an economically feasible means to predict where, when, and to what extent air pollution concentrations will occur, given a certain situation. Models can also assist the urban planner in assessing the effectiveness of alternative transportation plans and in selecting locations for pollution-generating and pollution-sensitive land uses. There are two types of modeling approaches: physical and mathematical.

Wind tunnel simulations are physical models that use a scaled representation of existing and/or proposed structures. This approach can identify wind stress and building wake areas, but does not quantify air pollution concentrations. Wind tunnel simulations also do not fully characterize the thermal turbulence in the atmosphere. They do, however, provide a means of identifying local areas that are poorly ventilated and therefore prone to the build-up of pollutants.

Mathematical models are of two varieties. One variety is based on empirically derived algorithms appropriate to a particular situation. Street canyon models and building wake models are examples of equations derived from such study. Other models are based on mathematical simulations of atmospheric processes affecting plume rise and pollutant transport and dispersion. These models are used to estimate the impact of industries, roadways, parking facilities, transportation facilities, and power plants. A variety of conditions and design options can be tested relatively inexpensively. Most mathematical models, as currently constructed, are most useful in large-scale decisions concerning location of new land uses, like a highway or housing project, but are of limited value in small-scale urban design decisions concerning the size and shape of a building or building complex.

Although stationary monitoring networks and large-scale mathematical models do not give a precise picture of urban air pollution at street-level, it is possible to achieve an understanding of the factors that influence the distribution, concentration, and dispersion of air pollutants at this scale. This report presents an alternative, but complementary, approach to mathematical and wind-tunnel modelling, one that permits the identification of places of concern and the factors that contribute to their formation. The following pages summarize the factors that influence the distribution of air pollutants at street-level and pedestrian exposure to those pollutants. Many, but not all, of these variables are incorporated into most mathematical and physical models. Here these factors are related directly to the form of the city, its open spaces and buildings, the materials of which it is composed, and the location of various uses and activities, both pollution-generating and pollution-sensitive.

Factors

Emission Levels

The quantity of pollutants emitted varies from street to street and even from spot to spot along the same street, a function of traffic volume and speed. The greater the number of vehicles traveling along a street, the greater the quantity of pollutants that are emitted. Vehicles emit fewer air pollutants at even speeds, when engines operate more efficiently, and emit greater quantities in stop-and-go traffic and while idling at stoplights. Under calm conditions, the concentration of air pollutants can therefore vary significantly along a single street or between two streets a block apart. CO emissions, for example, tend to peak at intersections, where concentrations may be ten times higher in the intersection than at a point eighty meters further down the road (Horowitz 1982). In calm weather, there are even variations within an intersection; pollution levels tend to be higher, for instance, along stopping or queuing lanes. The quantity of pollutants emitted by a vehicle is also influenced by thermal conditions; engines starting up in cold weather, for example, emit more pollutants.

Proximity to the Roadway

Under calm conditions in flat, open terrain, air pollution concentrations tend to be highest near the roadway and to decline with increasing distance from it. One study along a highway in Los Angeles found that CO dropped by more than a factor of ten between the center of the road and points 300 to 450 feet away on either side (Horowitz 1982). Atmospheric concentrations of particulate lead have been found to drop by a factor of two at a point 50 meters away from the road and by a factor of four at a point 100 meters away (Smith, 1976). However, variation in meteorological and topographic conditions can modify this distribution.

Air Circulation

Meteorological and topographic conditions can either enhance the dispersion of street-level air pollutants or permit their build-up. Several conditions affect air circulation at street-level: the degree to which winds and breezes penetrate the city, the presence of inversion conditions, and degree of spatial confinement.

Regional weather patterns and the modification of those patterns by the city's physiographic context and its overall form, as well as local topographic variation, all contribute to the patterns of air circulation at a given spot within the city. Plans to address air circulation, whether at the scale of the city or the street corner, should always be framed within the context of these three scales: the regional, the city—wide, and the micro.

Regional climate, which varies significantly from city to city, influences prevailing wind directions and the relative frequency of different wind speeds and their seasonal variation. The occurrence of stationary high-pressure areas that may lead to reduced air circulation is also determined by regional climate.

Variations in a city's physiographic setting, the presence of hills and valleys, for example, or large bodies of water, modify regional climate and may produce pronounced differences in air circulation in cities with similar regional climate.

Local topographic variation such as that caused by the height and shape of buildings can also influence air circulation in a given locale. Buildings of varying height, lining streets of varying width, interspersed with open plazas and landscaped parks, together create an urban form with a complex topography. Just as the topography of hill and dale, field and forest, and canyon and peak contribute to the creation of multiple, contrasting microclimates in the countryside, so does the complex man-made, urban topography create a mosaic of different microclimates in the city. Urban form can deflect or channel winds; thus windy street corners and stagnant air pockets may occur side by side. Pollutants emitted within a well-ventilated situation may be quickly dispersed, whereas pollutants trapped within the wakes of buildings can become concentrated, resulting in increased street-level pollution and even, if entrained into the building, in increased pollution within building interiors.

Even in cities with a relatively windy climate, the speed and penetration of wind may be reduced at ground level. The city has a very "rough" profile, when compared with the relatively smoother surface of lakes and fields. This rough profile tends to slow the wind as it moves over and around the city. The orientation and continuity of open spaces like streets and parks influence whether regional winds are channeled into and through the city, or whether they are deflected from the interior. Large open spaces and isolated towers, however, may permit winds to reach ground level (Gandemer and Guyot, 1976).

As wind moves around an obstacle (whether a city, a single building, or a row of trees), its direction and speed are modified. Typically there will be both a zone of accelerated speed and, on the lee side of the obstacle, a protected zone with reduced ventilation. When pollutants are emitted within this leeward wind "shadow" or building "wake" their dispersion may be retarded. In addition, these areas may also be prone, under certain conditions, to downwash from chimneys.[6] The dimensions, orientation, shape, porosity, and surface roughness of an obstacle influence the occurrence, size, and shape of such wind shadows.

Dispersion is generally enhanced by increased wind speeds, but concentrations tend to be higher on the downwind side of the roadway than the upwind side, unless the roadway is enclosed, as in a street canyon. Studies of urban street canyons have demonstrated that both their orientation and geometry have a significant effect on local patterns of air movement and concomitant distribution of air pollutants. When a street canyon is perpendicular to the wind direction, a

6. Though not within the scope of this report on transportation-related air pollutants, stack emissions are another very important source of street-level air pollution.

helical air flow may be created, causing a concentration of pollutants on the upwind side of the street. The CO concentration on upwind sidewalks may be two to three times higher (Johnson, et al., 1973; Wright, et al., 1975). The physical shape of an urban street canyon also has a significant effect on the dispersion of air pollutants. Regardless of wind direction, a street canyon lined with buildings of varied heights interspersed with open areas tends to disperse pollutants and produce fewer areas of stagnation than a street canyon lined solidly with buildings of similar height (Wedding, et al., 1977).

For visualizing air flow within the complex topography of urban form, wind tunnel modeling is quite useful. It physically represents the intricacies of air flow through a specific location in the city, enabling the identification of areas where air movement is accelerated and areas where it is stagnant. The results obtained when alternative building proposals are submitted to such study yields valuable data to the urban designer.

The city of Boston is considering the adoption of a pedestrian wind ordinance that would require wind-tunnel testing of proposed downtown development to verify that certain pedestrian-level winds speeds will not be exceeded. Although these studies are designed primarily to identify uncomfortably windy conditions, they could also be used to identify potential stagnant areas in building "wakes." There are several techniques for wind-tunnel modeling; the use of hot-wire anemometers permits quantification of specific local wind speeds, while flow-visualization techniques permit a better qualitative appreciation for wind movement in both two and three dimensions. The combination of these techniques, as currently employed by some researchers (Durgin and Chock, 1982), affords the ability to describe both quantitatively and graphically the size, shape, and location of building "wakes" with reduced air circulation.

Although most cities experience winds blowing at one time or another from most points of the compass, not all wind directions are equally significant for the dispersion of urban air pollutants. It is best to seek the advice of a meteorologist in determining which wind conditions are critical: the prevailing wind direction for all speeds, for example, or the prevailing direction under conditions of reduced speeds or during a specific season.

In some cities, a sea breeze or hillside-to-valley breeze may be more significant than regional winds. These breezes form in calm, clear weather, as warm air rises over a heated surface, and cooler air is sucked in to replace it. Breezes may disperse pollutants or, if blocked, may concentrate them against an obstruction. The continuity and orientation of open spaces is thus particularly important in determining how far these breezes penetrate the city. A sea breeze, for example, may penetrate a mile or more inland (Landsberg, 1981).

Under certain conditions, the volume of air available to dilute air pollutants can be reduced by a lowered mixing height (the distance above the ground over which pollutants are mixed and diluted). Such is the case in a thermal inversion, whether at the city-wide or microscale. Normally air temperature decreases with height above the ground. A thermal inversion exists when the temperature increases with height. This can occur aloft, suppressing vertical mixing. Such thermal inversions may occur across an entire city and may last for days. When inversions occur at the surface, under conditions of radiational cooling at night, cool air off the ocean or lakes or cool air drainage into valleys does not rise into the warmer air above, and pollutants emitted at the surface are usually trapped. In valley cities or cities in undulating terrain with enclosed low spots, micro-inversions may occur overnight and extend into mid-morning.

Generally, the more spatially confined a location is, the smaller the volume of air available to dilute air pollutants. Unless vented, enclosed spaces like tunnels or parking garages afford little opportunity for the dispersion of air pollutants. In calm weather, pollutants tend to accumulate against a wall or embankment adjacent to the roadway; against a highway embankment, for example, or along building walls lining an urban street canyon (General Electric Co., 1973). Of particular concern are recently built downtown hotels where air pollutants emitted under covered entrances may be sucked into the lobby or atrium space. When confined spaces like tunnels and parking garages are vented, the vents themselves may be a source of considerable air pollution. In unvented tunnels, the air movement set up by the motion of traffic pumps air pollutants out the tunnel, creating highly concentrated pollution sources at each end.

Air Pollution Sinks

Air pollution concentrations are a result of a dynamic balance among emissions, dilution, and removal. Removal mechanisms include chemical reactions, surface deposition, and impaction and absorption on surfaces. The latter mechanisms can be thought of as filtration, since they result in removal of particles and gases as they come into contact with vegetation, structures, cloud droplets, or precipitation.

Plants are probably more effective at filtering particulate pollution than they are at taking up gaseous pollutants. Smith (1978) has identified several factors which enhance a plant's ability to capture particulates: the presence of rough leaves, dense leaves, and twigs; large stomatic pores; and a tolerance for compacted soil, drought, and pollution. Optimally, planted areas should be fairly large, and plants should be of diverse height, in order to increase turbulence and impaction collection of airborne particulates. Plants are unlikely to have a significant effect on the reduction of particulate pollution at the city-wide scale. They can, however, if planted as a buffer reduce particulate pollution somewhat.

The absorption of gaseous pollutants by plants is less well understood. Since solubility is an important factor in plant uptake, plants absorb insoluable gases like CO and NO slowly or not at all. Plants should probably not be considered as an effective means of removing gaseous air pollutants.

Pollution-Sensitive Uses and Activities

Some people are more susceptible to injury or ill health from air pollution than others. Young children, the elderly, and persons with resiratory and cardiovascular diseases are especially vulnerable to air pollution. Smokers are particularly affected by elevated carbon monoxide levels, as are pregnant women and the fetuses they carry. Places used regularly by such individuals, like playgrounds, school yards, and sitting areas, should therefore be located in zones of low pollution. The duration and frequency of exposure to air pollution is also of concern. Those who regularly work, play, or live in zones of high pollution are at greater risk than individuals who spend little time in such areas.

Street-level air pollution may also be sucked into building interiors if building doors, windows, and intake vents are poorly placed. A study of one office building in Toronto, for example, compared interior carbon monoxide levels with levels measured on the sidewalk outside. Levels of CO on the first floor were only 28 percent less than those measured on the sidewalk; CO levels on the third floor were only 37 percent less, and on the fifty-fourth floor were 60 percent less (Godin, et al., 1972).

Current land use practice and recent downtown building projects demonstrate that designers and planners have little appreciation for the significance of the public health problem posed by air pollution along streets. Playgrounds for small children, for example, are frequently located along major streets and sitting areas are placed on traffic medians in busy intersections.

Summary Charts: Patterns of Distribution and Exposure

The charts on the following pages summarize the factors that influence the emission and distribution of street-level air pollution, as well as sensitivity of pedestrians to exposure. Places and uses of particular concern are identified.

Factors

Factor 1. Emission Levels

Factor 2. Proximity to Road

Factor 3. Air Circulation
- A. Winds
  1. Isolated Obstacles
  2. The Street Canyon
  3. The City
- B. Breezes
- C. Inversions
- D. Spatial Confinement

Factor 4. Sinks

Factor 5. Pollution-Sensitive Uses and Activities

FACTOR 1. Emission Levels

Principle

Traffic patterns have a direct bearing on the quantity of air pollutants emitted by motor vehicles.

Variables

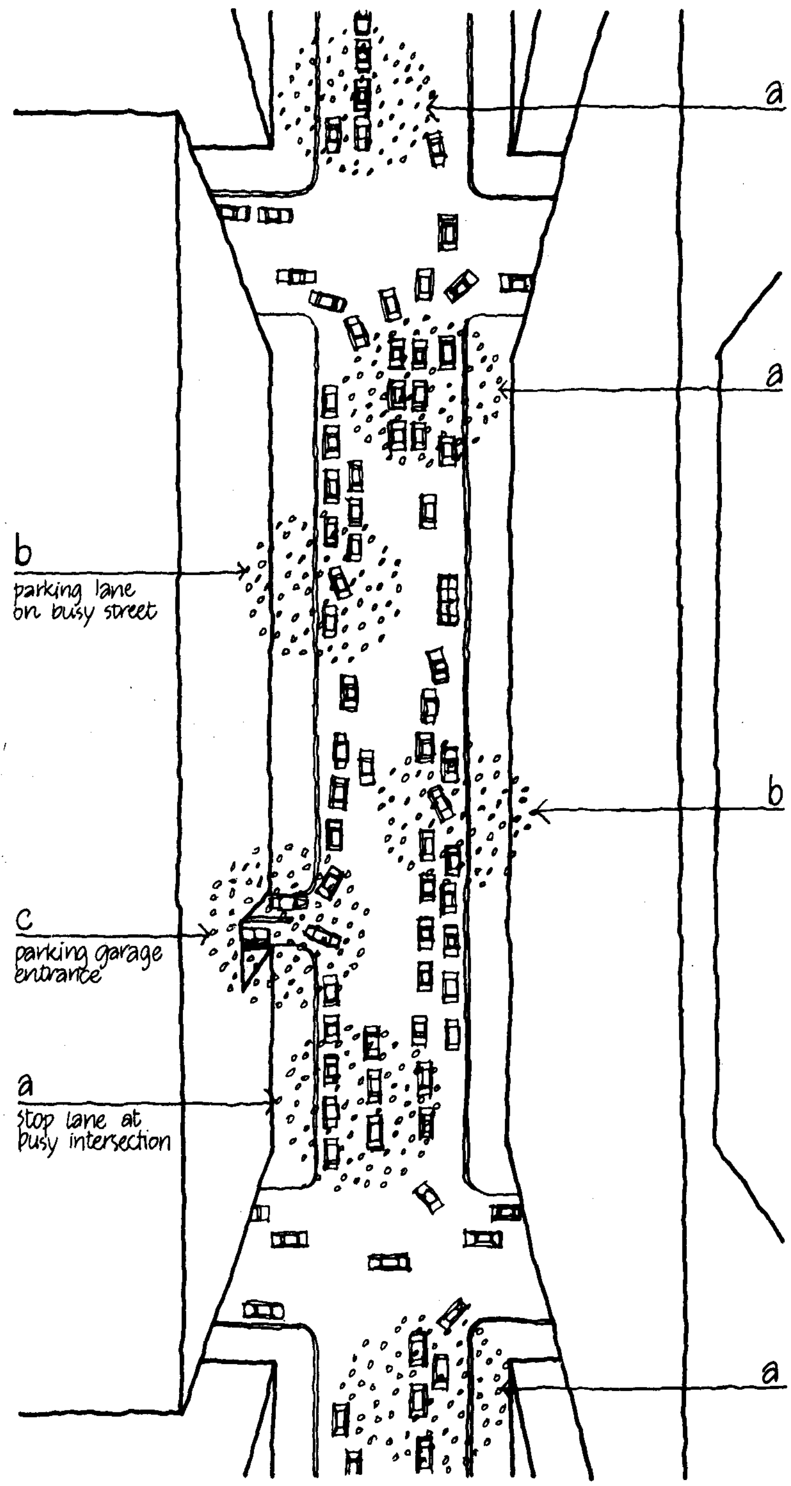
The quantity of pollutants emitted by motor vehicles is influenced by:

- Traffic volume. The more traffic, the more pollutants emitted.
- Traffic speed. Idling vehicles and vehicles in stop-and-go traffic emit more pollutants than vehicles traveling at even speeds. At intersections, highest emissions are in areas where cars are slowing or idling. Corners at stop lanes tend to have higher concentrations of pollutants (under calm conditions).

Places of Concern

The following places may therefore have relatively high emissions of pollutants:

- Major streets and highways (particularly those with parking lanes)
- Busy intersections (especially stop lanes)
- Taxi stands
- Bus depots
- Parking garage entrances and exhaust vents
- Tunnel entrances and exhaust vents



PLACES OF CONCERN : HIGH EMISSIONS

FACTOR 2. Proximity to Road

18 Principle

There is a direct correlation between the level of air pollution and distance from the roadway.

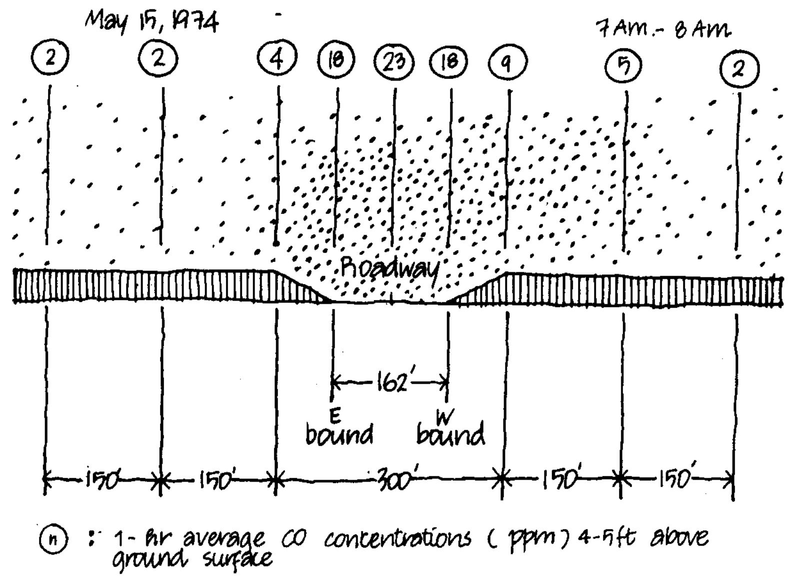
Variables

- Proximity to roadway. In flat, open terrain, under calm conditions, air pollution levels are highest adjacent to the road and decrease with distance from it.

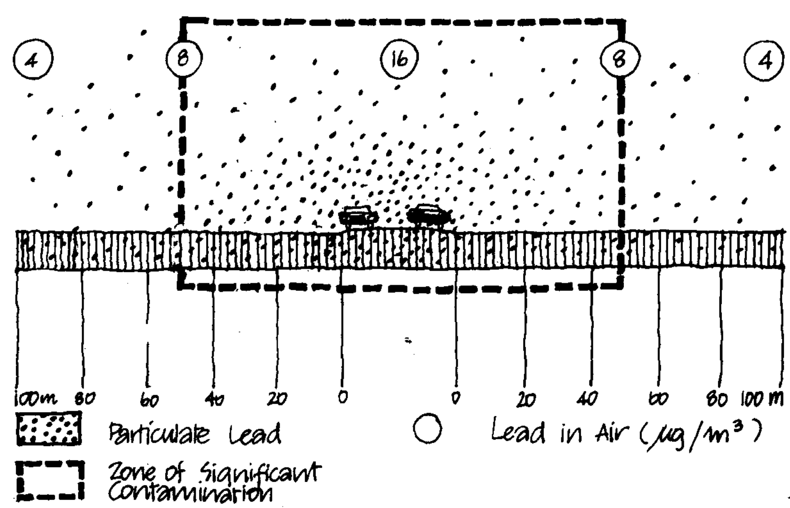
Places of Concern

The following places are adjacent to the road and may therefore have relatively high levels of air pollutants:

- Median strips
- Traffic islands
- Curbsides
- Roadside zone (width varies with traffic volume)



PROXIMITY TO ROAD : CARBON MONOXIDE
(Source : Horowitz, 1982)



PROXIMITY TO ROAD : PARTICULATE LEAD
(Source : Smith, 1976)

FACTOR 3. Air Circulation

Principle

There is a direct correlation between the level of air pollution and the pattern and degree of air circulation. When air circulation is inhibited, opportunity for dispersion is limited, and pollutants emitted may build up.

Variables

The interaction of variables at the regional scale, the city-wide scale, and the microscale produces great variation in the degree of air circulation from spot to spot within the city:

- Regional weather patterns. Overall wind direction and speed, and the occurrence of stationary high pressure areas are determined by regional climate.
- Macroclimate. The city's physiographic context and its overall form produce modifications to the regional climate that are felt city-wide and locally.
- Microclimate. The topography of built form influences wind direction and speed at a given spot.

Places of Concern

Areas downwind of major air pollution source and areas with low air circulation (see Factors 3A1, 3A2, and 3A3. Winds; Factor 3C. Inversions; and Factor 3D. Spatial Confinement).

FACTOR 3A1. Air Circulation: Winds Around an Isolated Obstacle

20 **Principle**

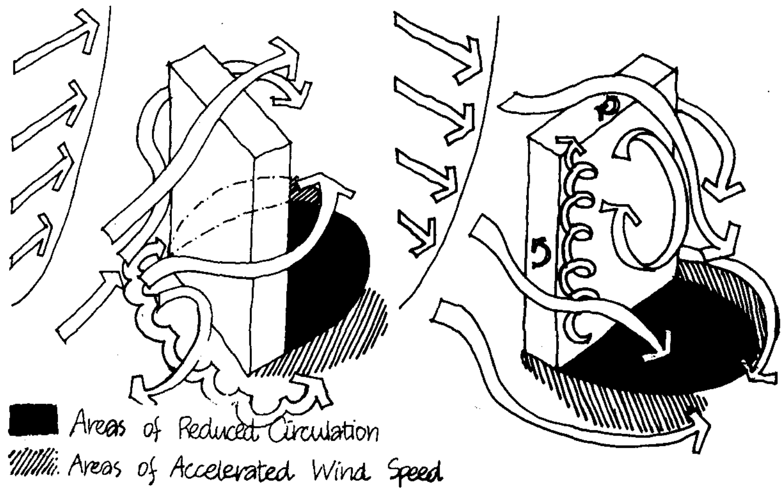
Wind speed and direction are altered as wind flows around an obstacle, creating updrafts, downdrafts, and swirling eddies, zones of accelerated wind speeds and zones of reduced air circulation (wind shadows).

The form of an obstacle, its density, and its placement relative to wind direction all influence the pattern of air flow around it.

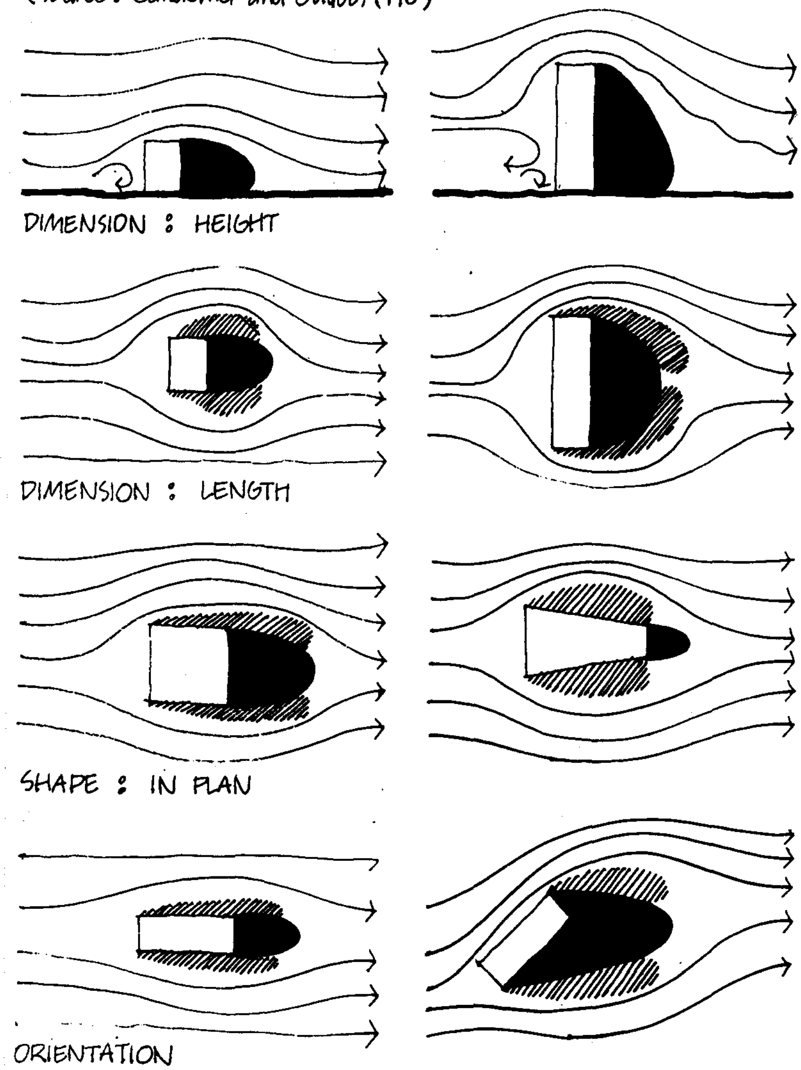
Variables

Air flow around an isolated obstacle (e.g., building, wall, hedgerow) on a flat plane is well understood. Such a situation rarely occurs in the city, but it is helpful to understand the variables at this simpler level. Patterns of air movement around an obstacle are influenced by its:

- Dimensions (height, width, length) influence the size of the wind shadow at ground level and the volume of air within it. The higher and wider the building, the larger the wind shadow it casts. A solid, rectangular obstacle casts a wind shadow approximately four times its height.
- Shape (in plan and profile) An obstacle of pyramidal shape tends to create a smaller wind shadow and less corner effect than one of rectangular shape.
- Orientation (in relation to wind direction)

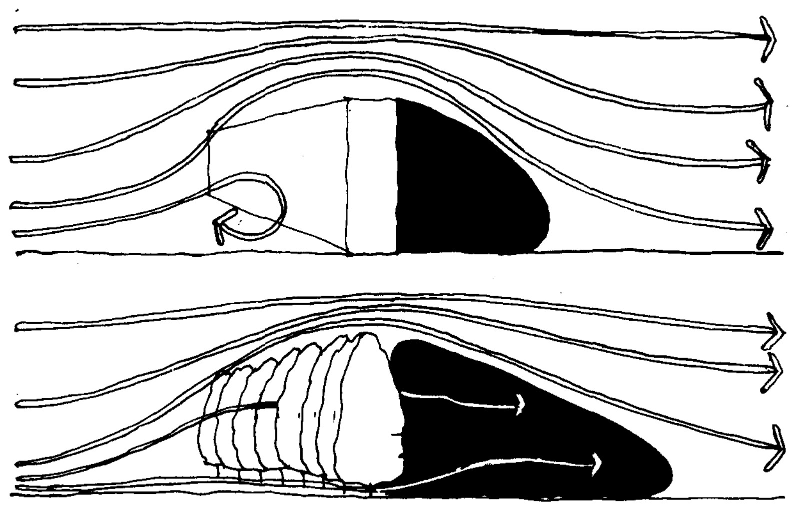


AIR FLOW AROUND SINGLE OBSTACLE
(source: Gandemer and Guyot, 1976)



VARIABLES INFLUENCING WIND SHADOW

- Porosity (including size and location of openings. The denser the building material, the more pronounced the wind shadow. A semi-porous obstacle will produce a wind shadow that is less pronounced, but which extends over a greater area and permits some air circulation.
- Surface roughness. A multi-faceted or deeply indented facade may slow winds slightly through increased friction.



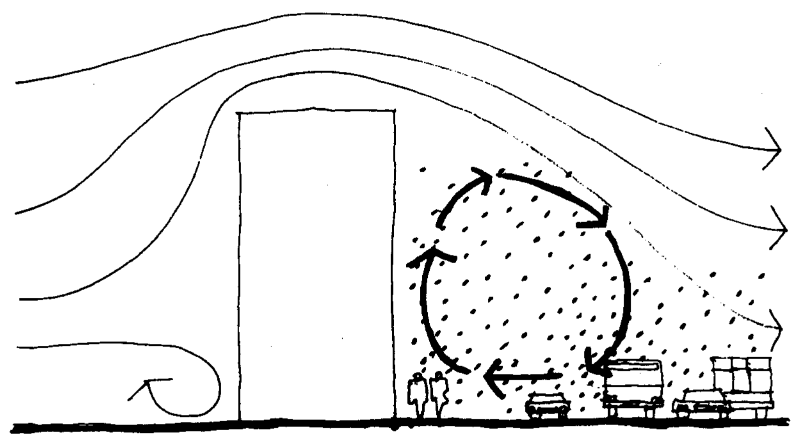
POROSITY

VARIABLES INFLUENCING WIND SHADOW

Places of Concern:

The following places have reduced air circulation and pollutants emitted within them may tend to build up:

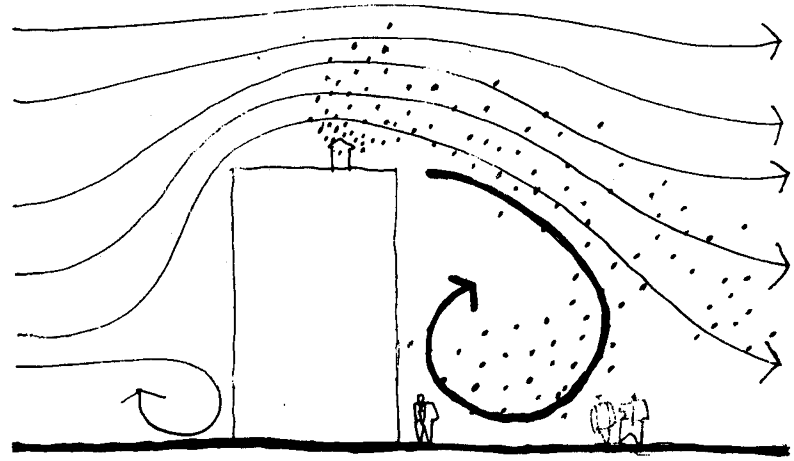
- Wind shadows at leeward base of buildings. In the city, buildings rarely occur in isolation. Certain areas may therefore lie in the wind shadow of different buildings as wind direction varies. Such spots can be identified in wind tunnel studies (See also Factors 3A2 and 3A3).
- Also of concern, though outside the scope of this study of transportation-related air pollution, are areas where smoke from chimney stacks may be blown down to street-level)



PLACE OF CONCERN : WIND SHADOW TO LEEWARD OF BUILDING

The following places may have relatively high pollution concentrations:

- Areas downwind of pollution source (see Factor 1. Emissions).



PLACE OF CONCERN : WIND SHADOW AND STACK DISCHARGE

FACTOR 3A2. Winds in the Street Canyon

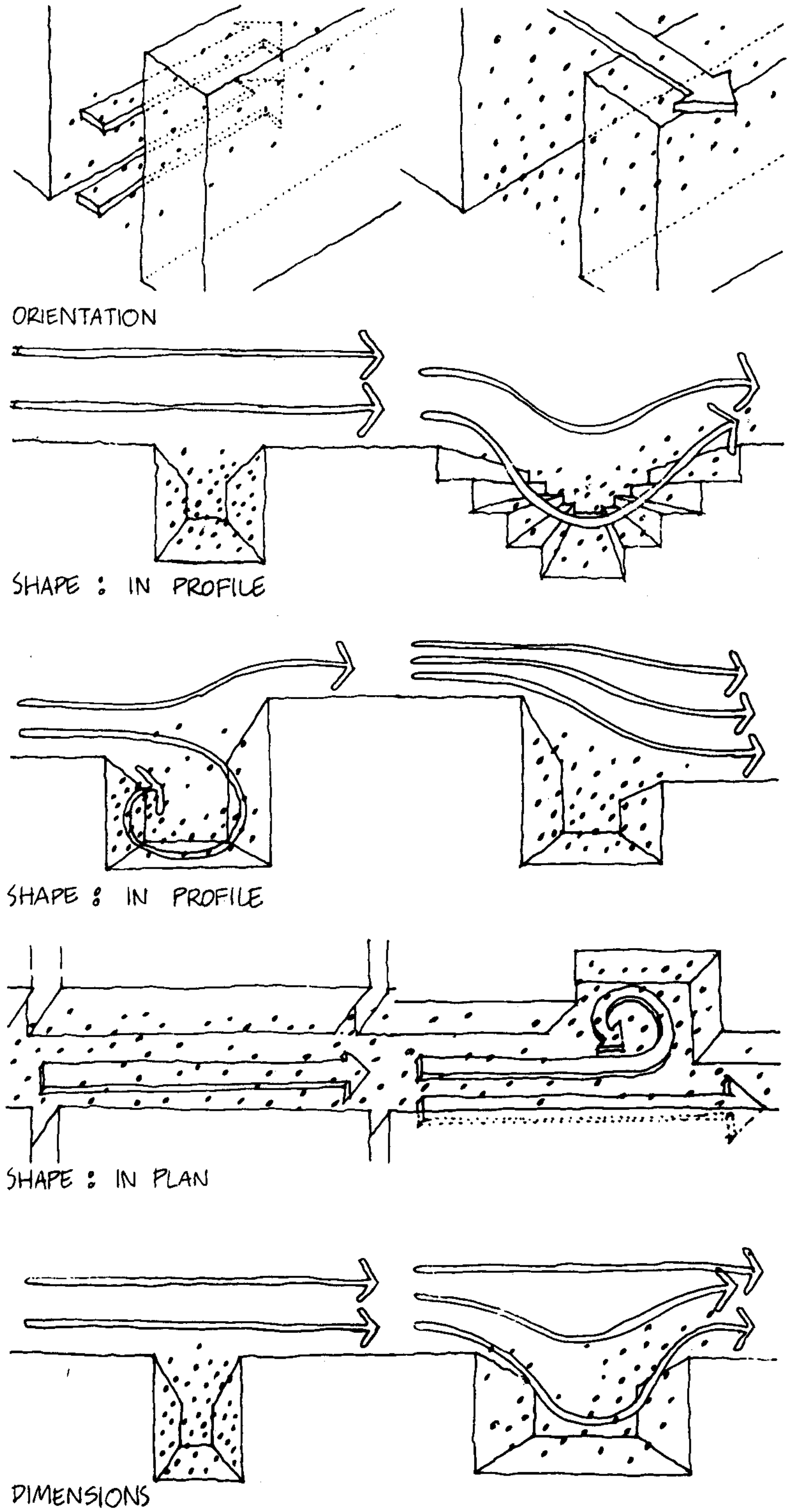
22 Principle

The same principles that influence the patterns of air circulation around an isolated obstacle also apply to the street canyon. The form of a street canyon, its porosity, and its orientation relative to wind direction all influence the pattern of air flow within it.

Variables

The variables that influence patterns of air circulation within the street canyon are the same as those that influence air flow around an isolated obstacle:

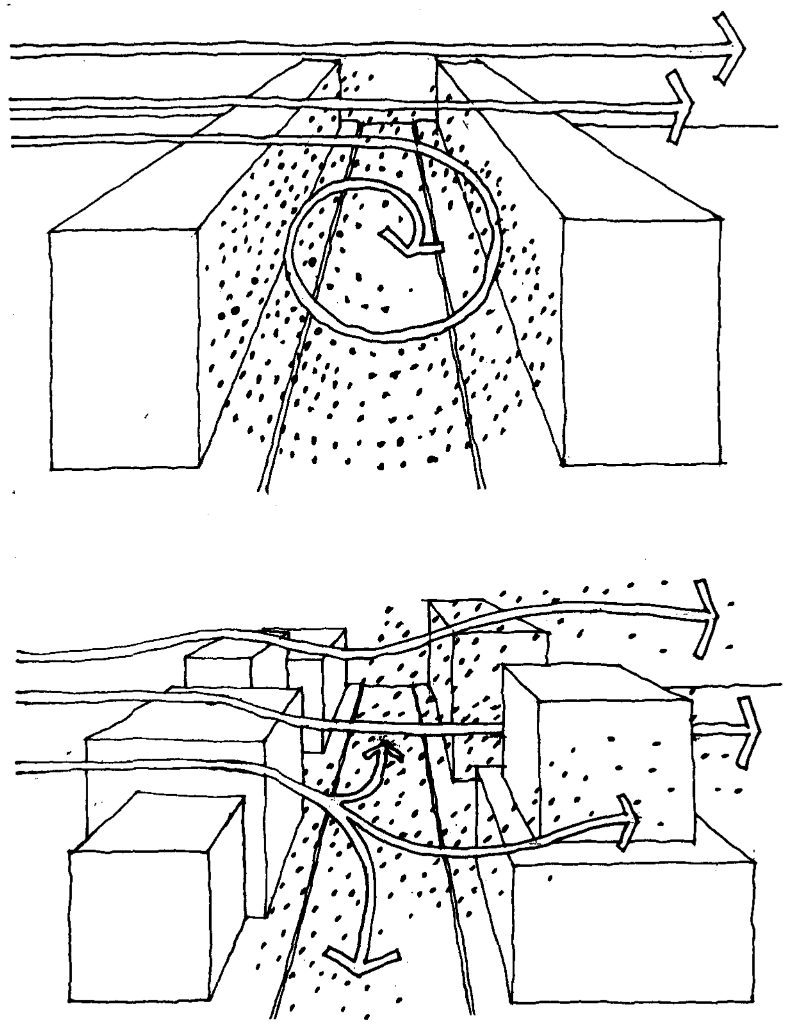
- Orientation (in relation to wind direction)
- Shape (in plan and profile). In street canyons with a rectangular cross-section oriented perpendicular to wind direction, pollutants will tend to concentrate on the windward side of the street.
- Dimensions (height, width, length).
- Porosity (dimensions and locations of openings, including plazas and intersecting streets)
- Surface roughness (heights and shapes of buildings in relation to each other). The more abrupt the changes in building heights and the more open areas around them,



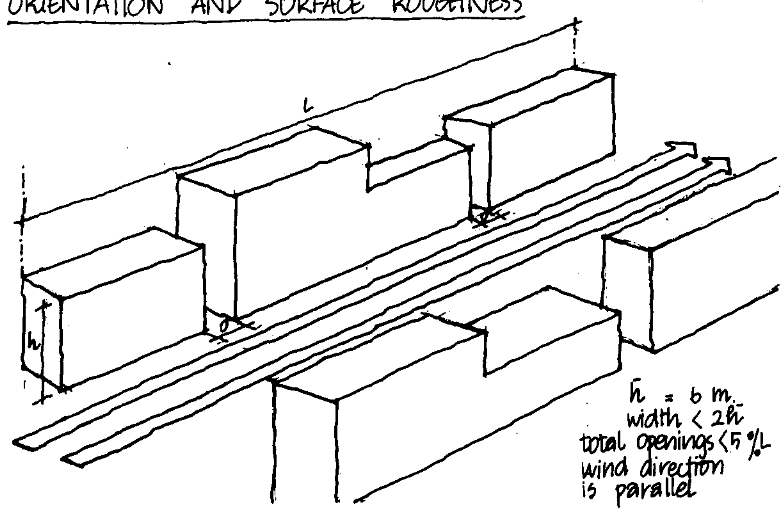
VARIABLES INFLUENCING AIR CIRCULATION IN STREET CANYON the rougher the surface posed to the wind and the greater the turbulence created. Street canyons lined with buildings the same height tend to have poorer air circulation than street canyons lined with buildings of different heights or that are interspersed with open areas.

These variables combine in multiple ways to produce the following effects:

- Channelization effect. Winds may become channeled when street canyons are oriented parallel to the wind direction. The occurrence of this effect is a function of total length, width, openings, and average height of the canyon. Channelled winds may be uncomfortable to pedestrians, but will disperse air pollutants generated at street level.
- Venturi effect. When winds are funneled through a relatively small opening, speeds are accelerated. When combined with a channelization effect, accelerated speeds may prevail along the entire length of the street canyon. Although this may serve to disperse air pollutants, it can also produce uncomfortable conditions for pedestrians. The Venturi effect is a function of the width, total length, average height of the sides, and the size of openings.



VARIABLES INFLUENCING AIR CIRCULATION: ORIENTATION AND SURFACE ROUGHNESS



CHANNELIZATION EFFECT
(Source: Gandemer and Guyot, 1976)

24 - Bar effect. When air flows over a street canyon oriented at a 45 degree angle to the wind, an area of accelerated wind speed may occur on the leeward side. The bar effect is a function of the width, total length, average height of the sides, and the size of the openings.

The following variables also influence the pattern of air movement in street canyons:

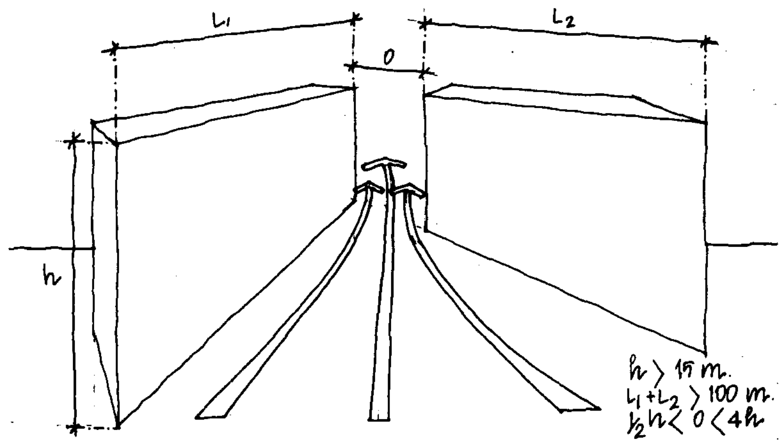
- Orientation, dimensions, shape, and porosity of obstacles upwind (e.g., buildings, walls, hills, woods). See also Factor 3A3.
- Orientation, dimensions, and continuity of open spaces upwind (e.g., streets, parks, parking lots).

Places of Concern:

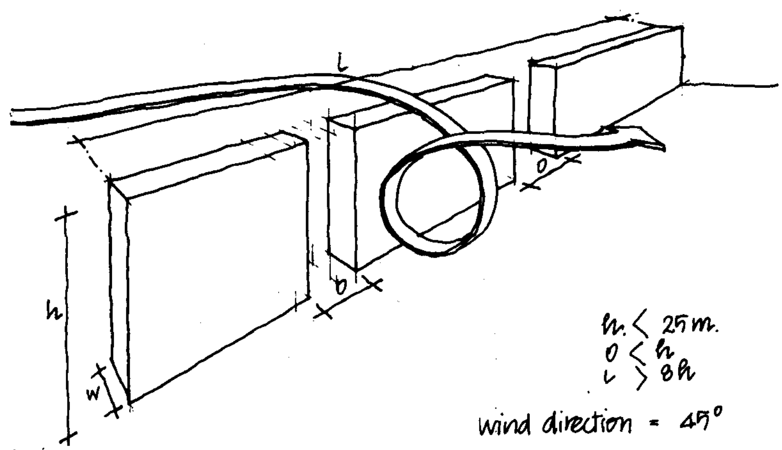
The following street-canyon types may have reduced air circulation and pollutants emitted within them may tend to build up.

- Deep, narrow street canyons oriented perpendicular to prevailing winds, with long blocks and buildings of similar height
- Short street canyons blocked at both ends

Poor air circulation may also occur in local spots along other types of street canyons, but may be difficult to identify without the use of a modeling technique like a wind tunnel study.



VENTURI EFFECT
(Source: Gandemer and Guyot, 1976)



BAR EFFECT
(Source: Gandemer and Guyot, 1976)

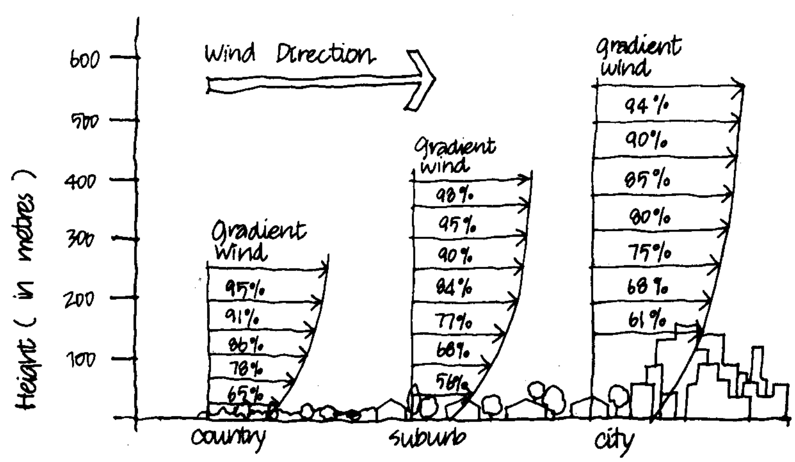
Principle

The city is essentially a very large obstacle with an extremely complex form. As wind moves over and through the city, its speed is reduced and it is channeled into some areas and deflected from others. There is a correlation between urban form and the extent to which wind penetrates the city. The more wind penetrates the city, the greater the opportunity for dispersion of pollutants emitted within it.

Variables

Wind patterns vary from city to city and are influenced by:

- Regional climate. Prevailing wind directions and relative frequency of different wind speeds may change seasonally. Certain seasons may therefore be more prone to air pollution problems than others. See also Factor 3C.
- Physiographic setting. The presence of hills and valleys or large bodies of water can modify regional winds (e.g., a city in a valley may be protected from winds, while a city adjacent to a large lake may be more exposed to winds). See also Factor 3B.
- Surface roughness of the city's profile. The rougher the profile (e.g., the more abrupt the changes in building height), the more winds are slowed.

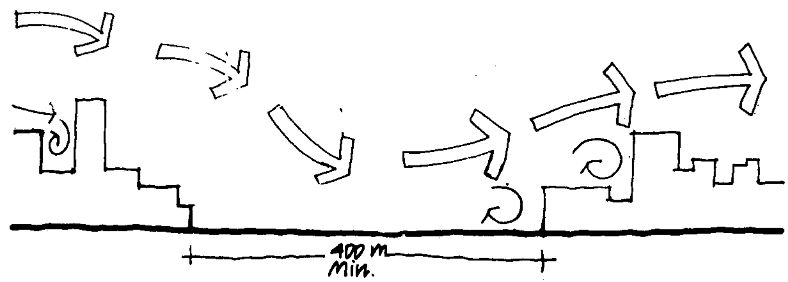


SURFACE ROUGHNESS AND WIND SPEED

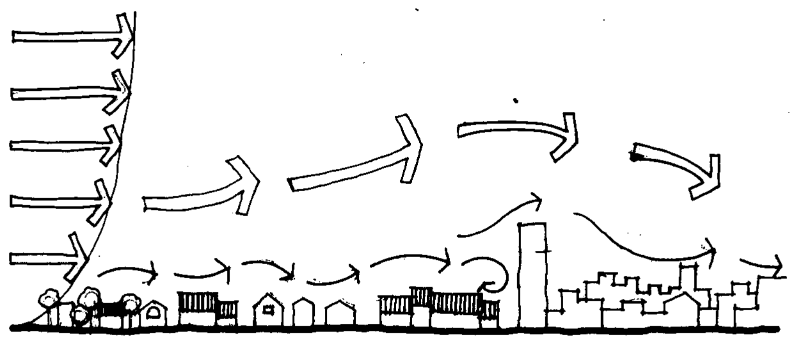
(Source : Davenport, 1965)

26 The degree to which winds penetrate the city at street level is influenced by:

- Orientation and continuity of open spaces. Continuous streets and parks oriented parallel to the wind direction will tend to channel winds.
- Dimensions and shape of open spaces. Large open areas, even if not continuous, may permit winds to reach street level.
- Building topography. Abrupt changes in building height may result in the deflection of winds to ground level.



LARGE, OPEN AREAS AND WIND PENETRATION
(Source: Gandemer and Guyot, 1976)



BUILDING TOPOGRAPHY AND WIND PENETRATION
(Source: Gandemer and Guyot, 1976)

Places of concern

Cities with relatively low average wind speeds may have poorer air circulation than windier cities. However, even in relatively windy cities, the following places may have relatively poor air circulation due to reduced wind penetration:

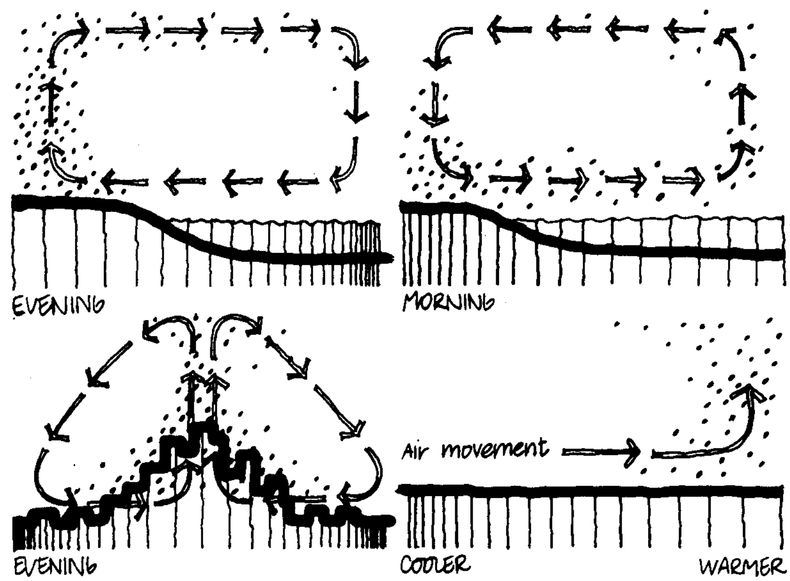
- Urban districts with narrow streets, even building heights, and long blocks with few openings.
- Urban districts with an irregular street pattern.

The following places may have relatively high pollution concentrations:

- Urban districts downwind of a major pollution source (see Factor 1. Emissions: Places of Concern).

Principle

In calm, clear weather, breezes (e.g., sea breeeze) may be initiated by the temperature differential between adjacent surfaces. As warm air rises over a heated surface, cooler air is sucked in to replace it. These breezes may disperse pollutants or, if blocked, may concentrate them against the obstruction.



FORMATION OF SEA AND URBAN BREEZES

Variables

The occurrence and strength of such breezes is influenced by:

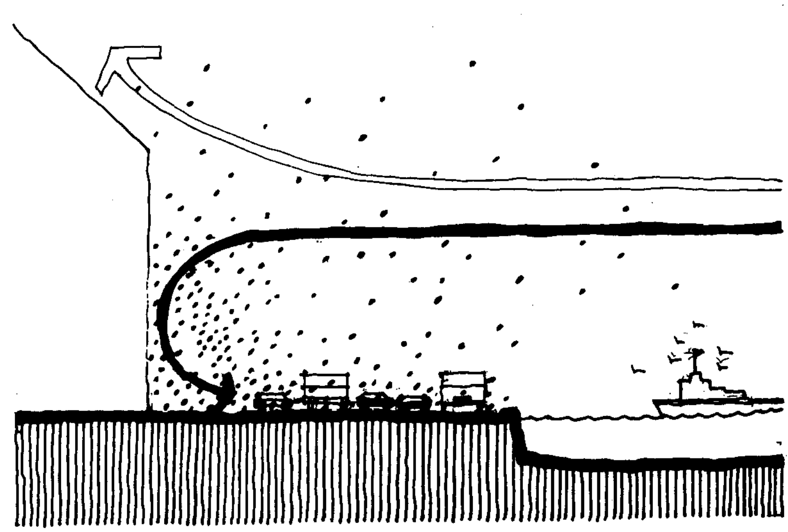
- Physiography. The presence of hills and valleys, lakes and oceans.
- Temperature differential between adjacent surfaces. The greater the temperature difference, the stronger the breeze.

The extent to which breezes penetrate the city is influenced by:

- The continuity and orientation of open spaces. Such breezes are weak and are easily blocked.

Places of Concern

The same places of concern identified in Factors 3A1, 3A2, and 3A3. These may be of even greater concern, given the relative weakness of these breezes.

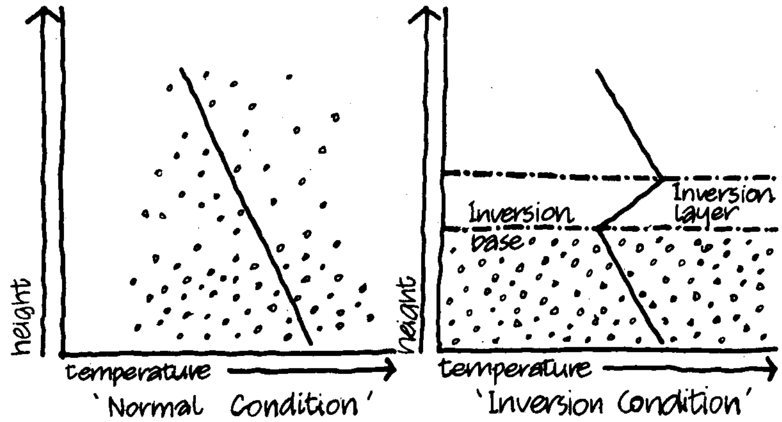


PLACES OF CONCERN: WINDWARD BASE OF OBSTRUCTION TO BREEZE

FACTOR 3C. Air Circulation: Inversions

28 Principle

Normally air temperature decreases with height above the ground. A thermal inversion occurs when the temperature increases with height. Such inversions can inhibit vertical mixing of air, thus slowing the dispersion of air pollutants. The formation of inversions can be a function of regional weather patterns and/or local physiography.

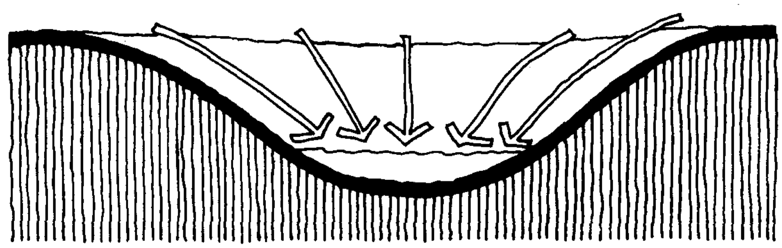


INVERSIONS AND DISTRIBUTION OF POLLUTANTS
(Source: Horowitz, 1982)

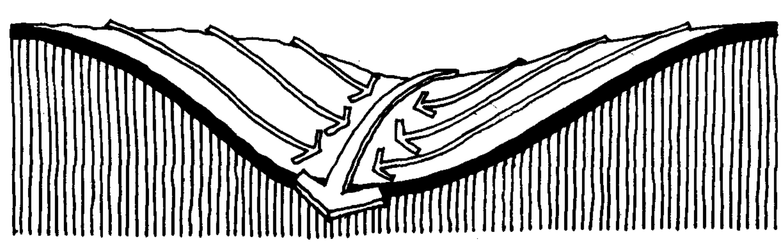
Variables

The occurrence and duration of inversions are influenced by:

- Regional weather patterns. Inversions may occur across an entire city and may last for days. They frequently occur more often during certain seasons, and they may be associated with weak winds from a predominant direction.
- Physiography. On calm, clear nights, cool air blows onto land off lakes or ocean and flows down hillsides into valleys. This cool air near the ground may trap pollutants until midmorning sun warms the air near the surface. (See also Factor 3B. Breezes)



PONDING OF COOL AIR IN VALLEY BOTTOM



COOL AIR FLOW DOWN VALLEY

INVERSION FORMATION AND PHYSIOGRAPHY

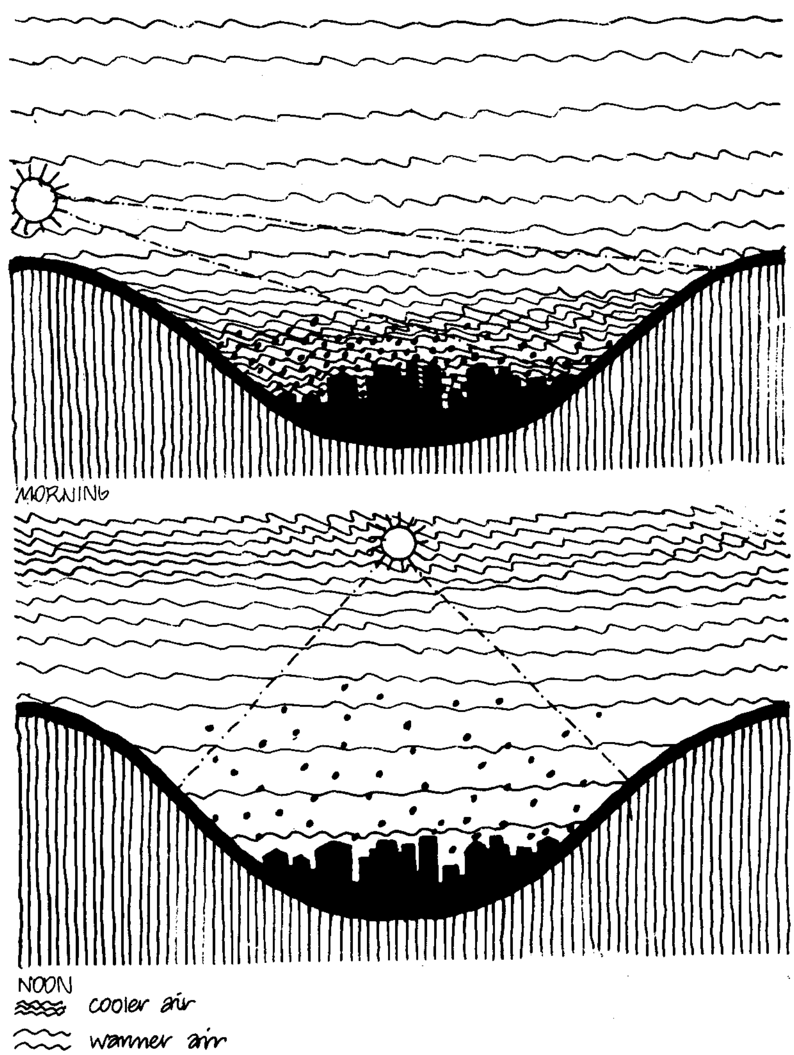
Places of Concern

The following places may have reduced air circulation during the night and early morning in calm, clear weather:

- Valley bottoms (especially bowl-shaped, as opposed to horseshoe-shaped valleys)
- Deep, narrow street canyons oriented north-south (especially those with long blocks or in topographic low spots)

The following places may have both reduced air circulation and higher air pollution levels during inversions:

- Places downwind of major pollution source. (See Factor 1. Emissions: Places of Concern)



PLACE OF CONCERN : VALLEY BOTTOM

FACTOR 3D. Air Circulation: Spatial Confinement

30 Principle

The more enclosed a space is by buildings, walls, embankments, or canopies adjacent to or over the roadway, the less opportunity pollutants within that space have to disperse, and the more likely that they will build up. Conversely, opportunity for dispersion is greatest in open terrain.

Variables

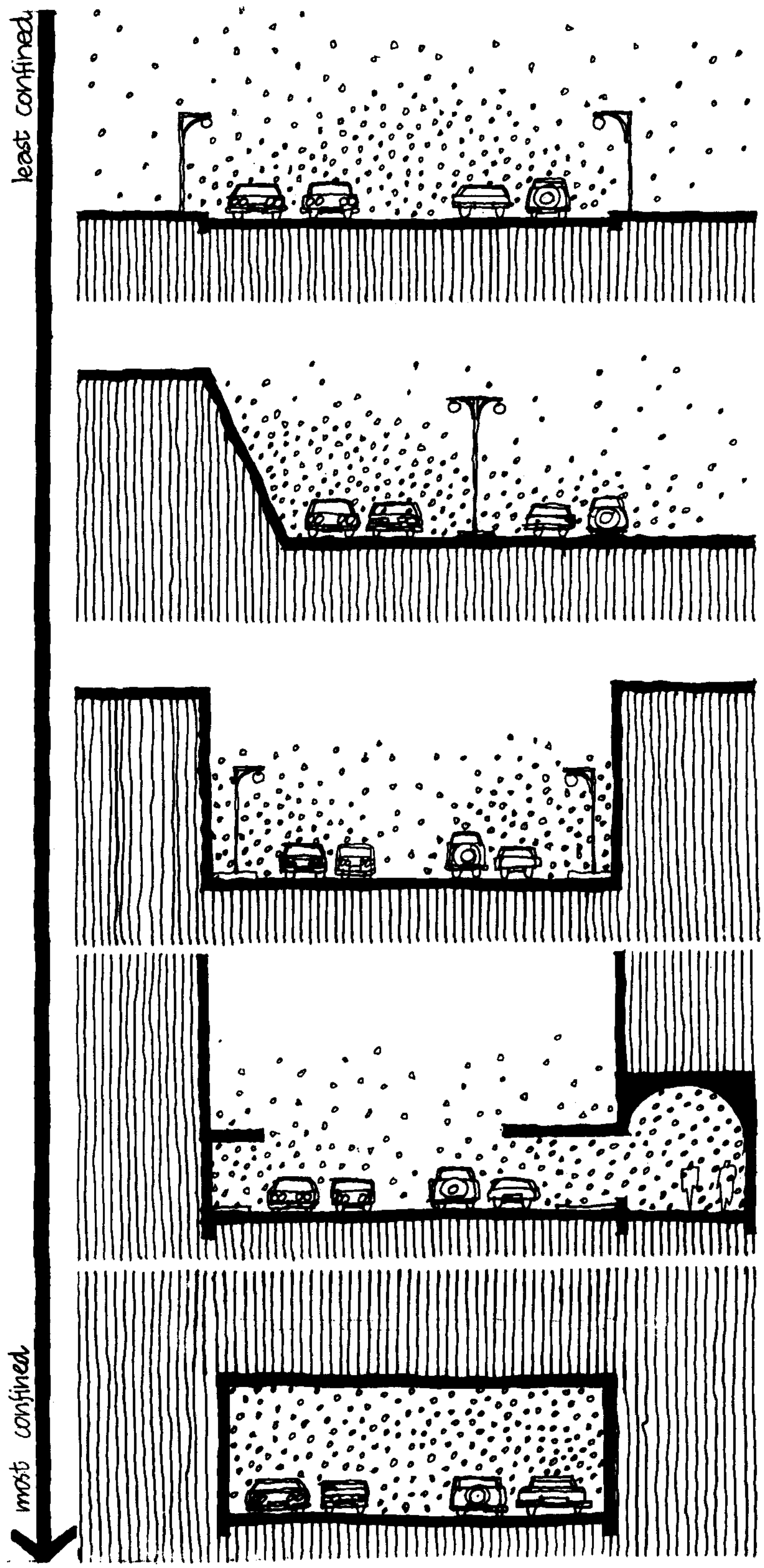
Degree of confinement is influenced by:

- Number of sides enclosed: The more sides enclosed, the less opportunity for air circulation.
- Height of confining elements: The higher the walls and the lower the canopy, the less opportunity for air circulation.
- Length of confining elements: The longer the walls or canopy, the less opportunity for air circulation.

Places of Concern

The following places may therefore have reduced air circulation:

- Street canyons, especially deep and narrow, (See also Factor 3A2).
- Arcades, especially with low canopy
- Bus shelters
- Interior atriums
- Tunnels
- Parking garages



SPATIAL CONFINEMENT AND DISTRIBUTION OF POLLUTANTS
(Source: Kurtzweg, 1973)

FACTOR 4. Sinks

Principle

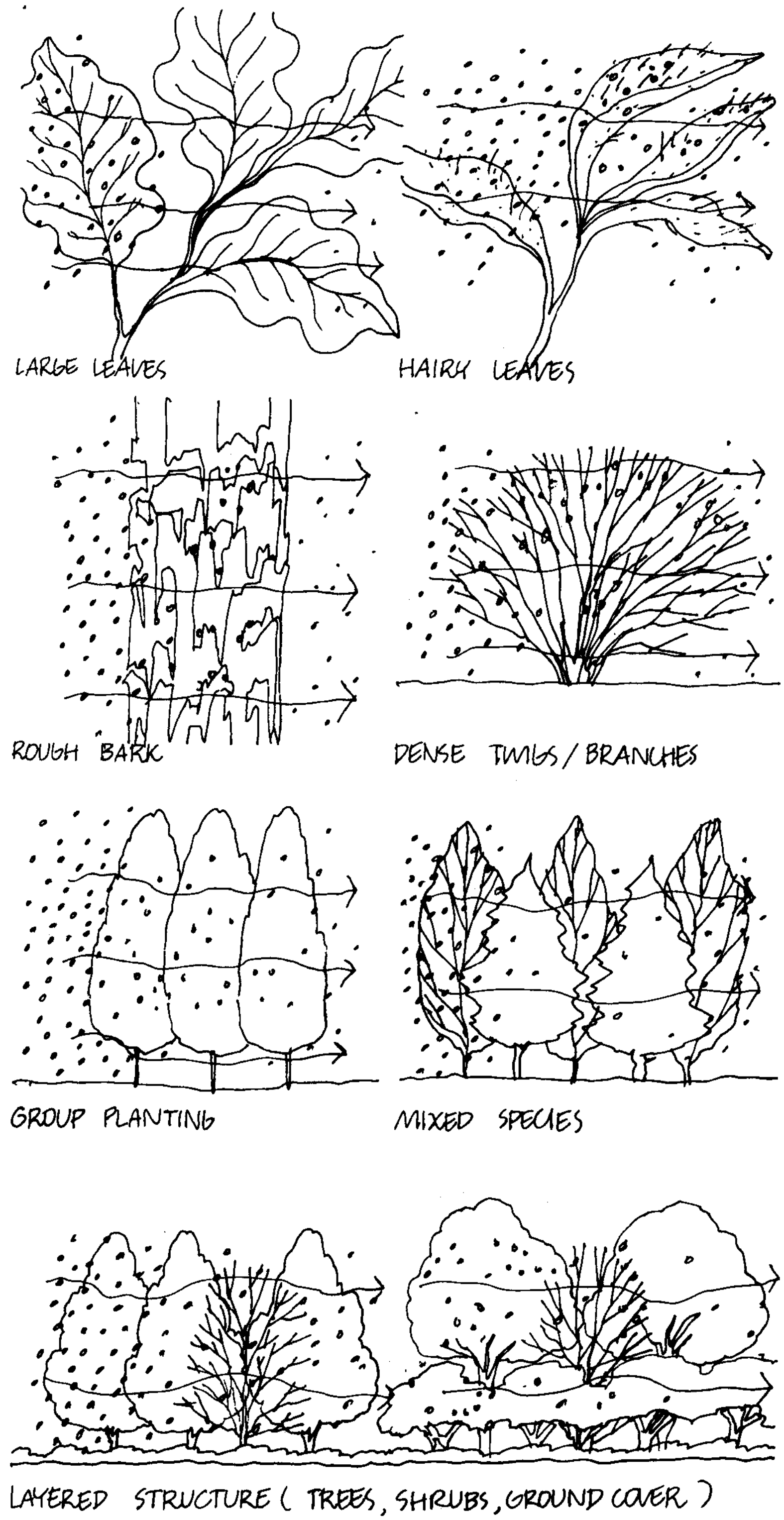
Under some conditions, plants may act as "sinks" for certain air pollutants. Plants, for example, can filter particulate pollutants.

Variables

Both the characteristics of individual plant species and the manner in which they are grouped are important. The following characteristics will increase the potential of plants as effective sinks for particulate pollutants:

- Hardy species
- Large leaf circumference
- Hairy leaves
- Leaves with large surface area
- Dense twigs
- Planting in groups
- Mixture of species (coniferous and deciduous)
- Layered structure (trees, shrubs, groundcover)

Note: Plants are most effective as filters in very large plantations. The filtering effect of a row of street trees, for example, is insignificant compared to that of a large, wooded park.



VARIABLES INFLUENCING PLANTS' EFFECTIVENESS AS SINKS FOR PARTICULATES
(Source: Smith and Staskawicz, 1977)

FACTOR 5. Pollution-Sensitive Uses and Activities

32 Principle

Certain uses or activities are particularly sensitive to air pollution and should therefore receive an extra measure of protection from exposure to high pollution levels.

Variables

The degree to which a particular activity or use may be deemed sensitive to air pollution is influenced by:

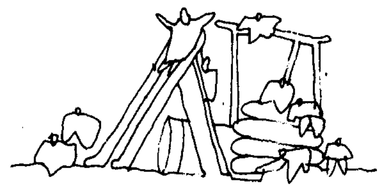
- Age and health of users. Young children, the elderly, and persons with respiratory and cardiovascular diseases are particularly vulnerable to air pollution.
- Duration of activity. The longer a person remains in a particular place, the longer the potential exposure to air pollution.
- Frequency of use. The more frequently a person uses a place, the greater the potential cumulative exposure to air pollution.
- Intensity of use. The more intensely a place is used, the greater the number of individuals exposed to air pollution.
- Voluntary vs. involuntary use. Obligatory activities or uses (e.g., bus stop, place of work, schoolyard) afford no opportunity for avoidance.

- Timing. Activities which must take place at a given time (e.g., lunch hour, commuting hours), afford diminished opportunity for avoidance.

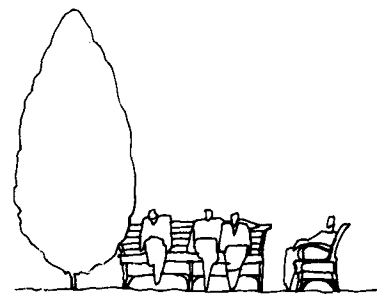
Places of Concern

The following places are particularly sensitive to air pollution due to the uses they serve:

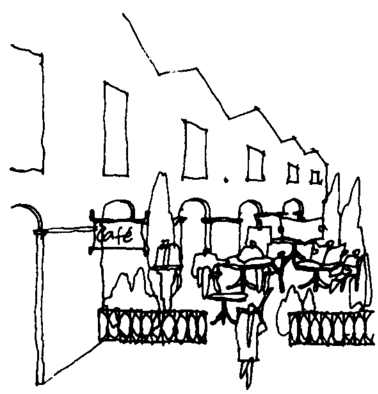
- Playgrounds and school yards
- Sports fields
- Sitting areas (especially those that will be used frequently by the same individuals, or for a long period of time, or by senior citizens and convalescents)
- Outdoor cafes
- Bus stops
- Building entrances, windows, and intake vents



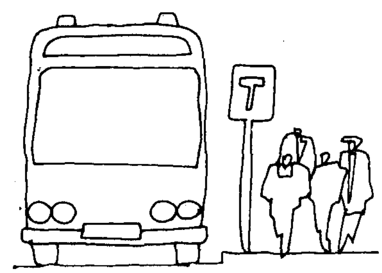
PLAYGROUNDS / SCHOOLYARDS



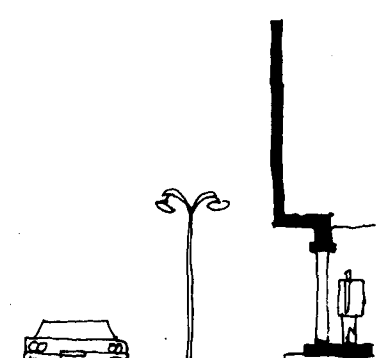
SITTING AREAS



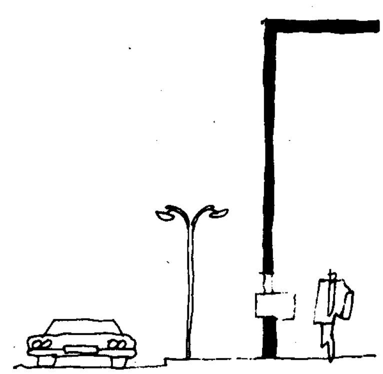
OUTDOOR CAFÉS



BUS STOPS



BUILDING DOORS & WINDOWS



BUILDING INTAKE VENTS

PLACES OF CONCERN : POLLUTION-SENSITIVE USES

The Design Situation

This chapter has reviewed the factors that influence the quantity of air pollution emissions, the dispersion or concentration of these emissions, and the sensitivity of various human activities to air pollution. For the sake of clarity, these factors were considered separately. Air quality at any given spot within the city, however, is rarely determined by a single variable, but is most often a result of several variables, whose overlap creates a distinct situation to which the urban designer must respond.

The Places of Concern Checklist[7] summarizes those places prone to air pollution that were identified on the charts in this chapter. It is organized by four major categories: quantity of emissions; proximity to the road; air circulation; and pollution-sensitive uses. The checklist is intended as both an analytical and a predictive tool; it permits the description of a location in terms of the factors that influence emissions, dispersion, and pollution sensitivity, and also the prediction of potential problems and opportunities that arise with certain combinations of factors. By tabulating the overlap of conditions in a single location, for example, potential "hot spots" can be identified and then evaluated empirically. If conducted at a district or city-wide scale, such a tabulation could be utilized to design an air quality monitoring network.

The Places of Concern checklist has been employed here to classify design situations, each of which represents a different combination of variables, and each of which poses opportunities or constraints for urban design. These are ranked from one to six, the first affording the most opportunity and the sixth posing the most constraints. Class One, with low or no emissions, outside the roadside zone, and with good air circulation has the least potential for transportation-related air pollution, whereas Class Six, with high emissions, within the roadside zone, and with poor air circulation has the greatest potential. Classes One and Two present an opportunity for locating pollution-sensitive uses, whereas Classes Four, Five, and Six pose constraints for such activities. Each design situation class also entails an appropriate constellation of strategies for reducing human exposure to street-level air pollution.

7.
This checklist is an initial attempt to identify places of concern. It may be expanded or modified as new research and empirical data warrant.

STREET-LEVEL AIR POLLUTION: PLACES OF CONCERN CHECKLIST

High Emissions
- Major street or highway (especially with parking lanes)
- Busy intersection
- Taxi stand
- Bus depot
- Parking garage entrance and exhaust vents
- Tunnel entrance and exhaust vents

Proximity to the Road
- Median strip
- Traffic island
- Curbside
- Roadside strip

Poor Air Circulation: Winds
- Wind shadows at leeward base of buildings
- Short street canyons blocked at both ends
- Long street canyons perpendicular to prevailing winds
- Urban districts with narrow, irregular street pattern

Poor Air Circulation: Breezes
- Locations upwind of pollution source
- Windward base of obstruction to breeze

Poor Air Circulation: Inversions
- Valley bottom
- Street canyon bottom

Poor Air Circulation: Spatial Enclosure
- High, narrow street canyons
- Arcade
- Bus shelter
- Interior atrium
- Tunnel
- Parking garage

Pollution-Sensitive Uses
- Playgrounds and schoolyards
- Sports fields
- Sitting areas used frequently or for a long period of time by same individuals
- Sitting areas used by elderly or convalescents
- Outdoor cafes
- Bus stops
- Building entrances, windows, and intake vents

STREET-LEVEL AIR POLLUTION: DESIGN SITUATIONS AND APPROPRIATE DESIGN STRATEGIES

	Opportunity for Pollution-Sensitive Uses	Constraint for Pollution-Sensitive Uses	Appropriate Design Strategies
<u>Class One</u> - Low or no emissions - Outside roadside zone - Good air circulation			
<u>Class Two</u> - Low or no emissions - Outside roadside zone - Poor air circulation			2A,2B,2C 2D
<u>Class Three</u> - Low to moderate emissions - Within roadside zone - Good air circulation			3A 4B,4C
<u>Class Four</u> - Low to moderate emissions - Within roadside zone - Poor air circulation			2A,2B,2C,2D 3A 4A,4B,4C,4D
<u>Class Five</u> - High emissions - Within roadside zone - Good air circulation			1A 3A 4A,4B,4C,4D
<u>Class Six</u> - High emissions - Within roadside zone - Poor air circulation			1A 2A,2B,2C,2D 3A 4A,4B,4C,4D

IV. DESIGN STRATEGIES TO REDUCE PEDESTRIAN EXPOSURE

Urban Design Strategies

The objective of this report is to suggest the range of strategies available to urban designers in order to encourage comprehensive designs that are tailored to the scale of concern and specific design situation. This is not to imply that urban design strategies are more important than other considerations, nor that urban designers have a more significant role to play than public health officials, air quality managers, or transportation engineers. Urban design strategies are the subject of this report, because they have been neglected elsewhere.

Of the potential design strategies to reduce pedestrian exposure to street-level pollution, these have been distilled here to four: the prevention or reduction of emissions; the enhancement of air circulation; the removal of pollutants from the air; and the separation of pedestrians from zones of high pollution. These are all strategies that involve the manipulation of urban form and the location of land uses.

Strategy One: Prevent or Reduce Emissions. The reduction of vehicular emissions can be addressed on multiple levels, from those that deal with the individual vehicle to those affecting city-wide traffic patterns. One tactic is to prevent emissions either through the removal of traffic from an entire street or district (1A1, 1A2) or by removing high emission uses like a taxi stand (1A3). A second tactic is to reduce emissions by limiting the number of vehicles (e.g., by restrictions on private cars or by or through improved public transit) or by improving engine efficiency (e.g., traffic-flow improvements such as bus lanes and on-street parking controls). A third tactic is to reduce peak emissions (e.g., staggered work hours); and a fourth tactic is to modify their spatial distribution (e.g., concentrated or dispersed traffic). Of particular concern to urban designers is the potential designation of pedestrian districts and streets (see 1A1, 1A2) and the siting of high emission uses (see 1A3).

Strategy Two: Enhance Air Circulation to Disperse Air Pollutants. The second strategy addresses the dispersion of air pollutants after they have been emitted. The aim here is to enhance ventilation and thereby to increase the volume of air available to dilute pollutants. Promoting the penetration of winds and breezes (2A1, 2A2, 2A3, 2B1, 2B2), inhibiting local inversions (2C1), and reducing spatial confinement (2D1 and 2D2) are all means of accomplishing this objective.

Strategy Three: Remove Pollutants from the Air. A third strategy is to remove pollutants from the air, through the use of plants to filter particulates, for example (3A1, 3A2). This strategy is limited in its potential effectiveness, due to the large volume of air that must be filtered. It may be an effective strategy at the microscale in a confined situation with limited air circulation, but it is unlikely to be a feasible city-wide strategy, unless the introduction of very large forested reserves or belts are contemplated.

Strategy Four: Protect Pollution-Sensitive Uses. The physical separation of pollution-generating and pollution-sensitive uses is often the most effective means of limiting pedestrian exposure to air pollution. This can be accomplished by spatial separation (4A1, e.g., location of playgrounds outside zones of high emissions), by temporal separation (4D1,4D2, e.g., lunchtime bans on automobile traffic), or by the interposition of a barrier (4C1, e.g., a wall between street and plaza).

Not all strategies are equally appropriate to every design situation. The accompanying chart is intended to identify strategies applicable to each class of design situation in order to facilitate their combination. For Class Two, for example, the concern is poor air circulation, and the design strategy should be to improve air circulation. For Class Three, the main concern is proximity to the road, and design strategies should therefore be aimed at filtering pollutants and separating pollution-sensitive uses from the road, either through distance or a barrier. All four design strategies are appropriate for Class Six, which is characterized by a combination of high emissions, proximity to the roadway, and poor air circulation.

The implementation of measures to improve air quality in one locale should always take cognizance of the potential impact on another locale. Transforming a poorly-ventilated, narrow, busy street into a pedestrian zone, for example, may improve the situation locally, while increasing traffic and pollution on adjacent streets. Changes in traffic patterns should therefore always be made within the larger transportation context, even if the change is localized. Attempts to improve air quality at the microscale should be part of a more comprehensive plan to improve air quality at the city-wide scale, and vice versa. For each of the design strategies, illustrations are given at multiple scales, from street corner to district or city-wide.

Sometimes strategies to improve air quality may conflict with other social objectives, such as comfort, security, or commercial vitality; at times they may be complementary. For example, increasing air circulation could result in uncomfortable pedestrian winds; and the reduction of pedestrian winds could, in certain circumstances, lead to poor air circulation. On the other hand, stepped-back building facades and landscaped buffers between street and sidewalk (as illustrated in strategies 2A2, 2C1, 2D1, and 4C1) could result in improved micro-climate at street-level (i.e. increased solar access and reduced pedestrian-level winds). Urban design to improve street-level air quality should always be integrated with other urban design issues.

40 Strategies

Strategy 1. Prevent or Reduce Emissions

A. Remove source of emissions
B. Prevent release of pollutants
C. Improve engine efficiency
D. Improve traffic flow
E. Reduce number of vehicles
F. Reduce peak emissions

Strategy 2. Enhance Air Circulation

A. Promote penetration of winds
B. Promote formation and penetration of breezes
C. Inhibit inversions
D. Avoid spatial confinement

Strategy 3. Remove Pollutants from the Air

A. Plant landscape filters

Strategy 4. Protect Pollution-Sensitive Uses

A. Locate pollution-sensitive uses outside high pollution zones
B. Locate high-emission uses judiciously
C. Buffer pollution-sensitive uses from high emission uses
D. Regulate time of time of use to separate pollution-sensitive and pollution-generating uses

STRATEGY 1. Prevent or Reduce Emissions

Various measures have been implemented to prevent or reduce emissions. These have involved six major strategies:

1A. Remove Source (e.g., pedestrian zones)

1B. Prevent Release of Pollutants (e.g., vapor recovery, controls on extended vehicle idling)

1C. Improve Engine Efficiency (e.g., inspection/maintenance programs, alternative fuels and engine design, extreme cold start emission reduction program)

1D. Improve Traffic Flow (e.g., on-street parking restrictions, exclusive bus and carpool lanes, street and intersection improvements)

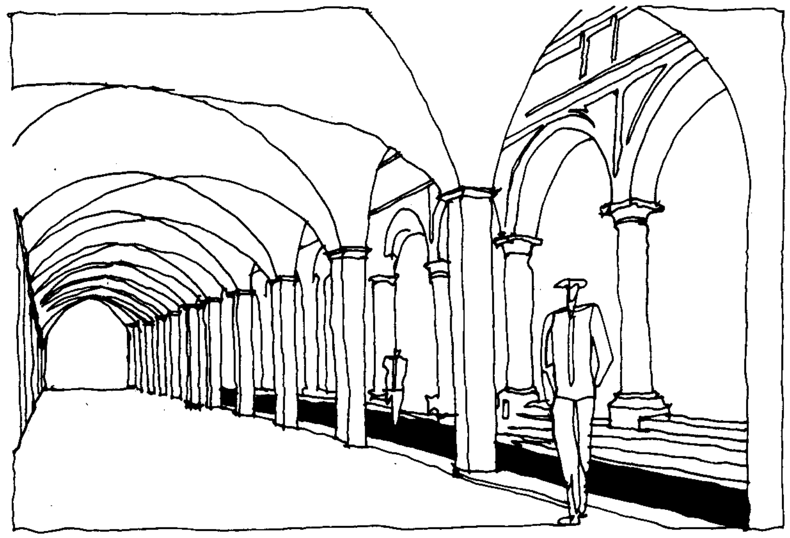
1E. Reduce number of vehicles (e.g., private car restrictions, carpool programs, bicycle and pedestrian programs)

1F. Reduce peak emissions (e.g., improved public transit, park-and-ride programs, staggered work hours

Many of these strategies do not fall within the domain of urban design. The designer should be aware of all, however, in order to achieve an integrated, comprehensive solution to street-level air pollution.

STRATEGY 1. Prevent or Reduce Emissions
A. Remove Source of Emissions

Removing the emission source (whether it be the motor vehicle itself or a use like a taxi stand that generates high emissions) is an effective way to reduce or eliminate transportation-related air pollution in a particular location.



BOLOGNA. NARROW, ARCADED STREET

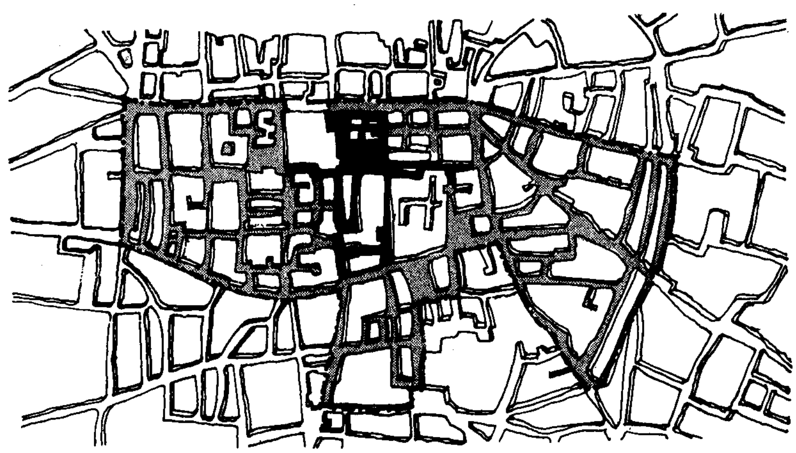
The decision to create a car-free zone should always be made at the district level; for removing traffic from one street may increase emissions on another street. In certain cases, it may be best to set aside an entire district as a pedestrian zone a single pedestrian street. In other cases, removing high emission uses and activities may reduce emissions to acceptable levels.

Removing the motor vehicle entirely is rarely feasible, but under certain circumstances, it may be the most attractive alternative.

1A1. <u>Designate Pedestrian Districts</u>.

Urban districts with narrow streets, relatively even building heights, and long blocks with few openings or with a highly irregular street pattern may be good candidates for designation as pedestrian zones with restricted vehicular access.

The center of Bologna, Italy, has many narrow streets lined by buildings with deep arcades that trap pollutants emitted on the street. Bologna designated part of this area as a pedestrian zone and part as a zone with restriced vehicular access.



Pedestrians only   Vehicular Access Restricted

1A1. PEDESTRIAN DISTRICT: BOLOGNA
(Source: Brambilla, 1977)

1A2. Designate Pedestrian Streets

In Copenhagen, Denmark, a pedestrian route through the dense city center links a series of narrow streets. "Stroget" connects important landmarks, institutions, public transit nodes, and shops and provides a convenient pedestrian route. It is intersected by major streets, but vehicles are not permitted on the pedestrian street itself, except during designated delivery hours.

The Denver Transitway is an attractive pedestrian mall with two bus lanes in downtown Denver. Transitways like the Denver Transitway and Downtown Crossing in Boston are more prevalent in the United States than zones that are entirely vehicle-free.

1A3. Remove High-Emission Uses

Even if the elimination of traffic from a district or street is not feasible, emissions at a particular spot may be significantly reduced by relocating uses that generate high emissions (e.g. taxi stands, bus depots, loading zones, and parking garage entrances and exhaust vents). Locate such sources in well-ventilated locations, away from pollution- sensitive activities (see Strategy 4B).

STRATEGY 2. Enhance Air Circulation

44 Air circulation can be enhanced by promoting the penetration of winds and breezes (Strategies 2A and 2B), inhibiting the formation of local inversions (2C), and avoiding spatial confinement (2D).

An understanding of the larger meteorological context is essential, whether one is concerned with promoting air circulation throughout the city or in a particular spot.

It is difficult, even impractical, to create a design or plan that responds equally well to all wind directions. It is therefore essential to determine what the most important wind directions are in a given city and whether there are seasonal variations. For example: The direction of prevailing winds under inversion conditions when vertical dispersion of pollutants is inhibited may be different than the prevailing wind direction for all weather conditions. If inversions are frequent phenomena, prevailing winds under these conditions may be the most significant.

STRATEGY 2. Enhance Air Circulation
A. Promote the Penetration of Winds

To be most effective, a design to enhance air circulation at any given spot should be framed within the larger context of street, district, and city. Failure to account for this larger context may nullify efforts at the local scale.

The most reliable way to predict air flow through the complex aerodynamic surface of a city is to test a scale model in a wind tunnel, manipulating the form of buildings and open areas to achieve adequate air circulation. The following recommendations are based upon wind tunnel studies (Gendemer and Guyot, 1976; Bosselman, et al., 1984).

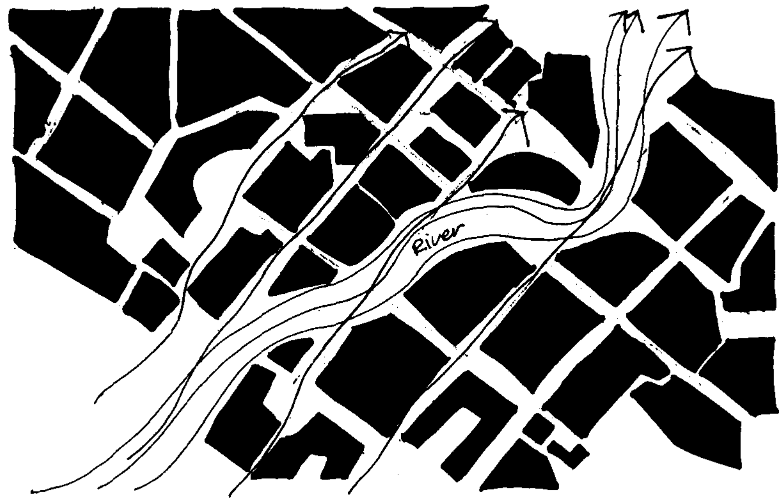
Note: The potential negative impact of increased winds should always be considered.

2A1. <u>Design major open spaces to enhance the penetration of winds into the city.</u>

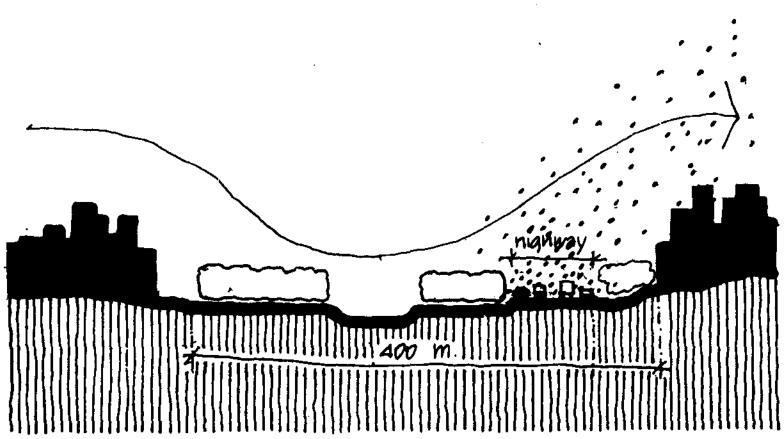
River and stream valleys, highways, parkways, railroad corridors, and linear parks are all potential channels for winds to move through the city at ground level. To exploit this potential:

- Create wide, continuous corridors oriented to channel winds from desired directions into and through the city.

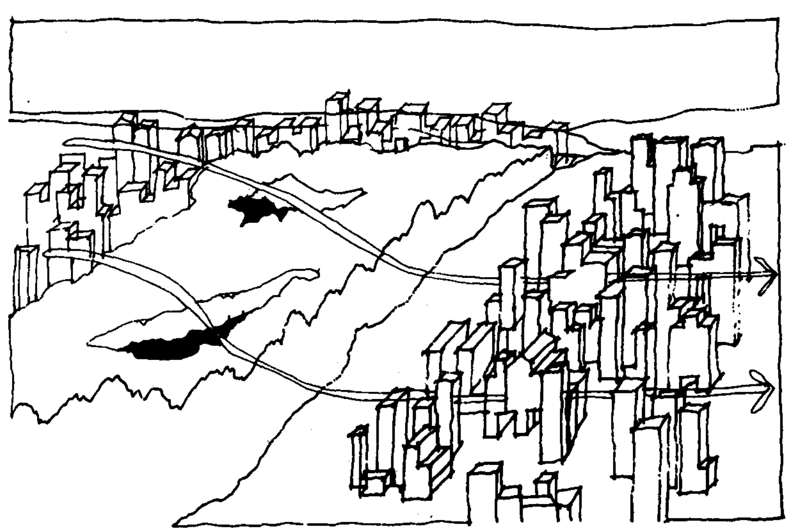
- Create large open areas (400 m x 400 m, optimally) to bring winds to ground level in densely built districts



2A1. ORIENT STREETS AND OPEN SPACE TO CHANNEL WINDS



2A1. CREATE LARGE, OPEN AREAS IN DENSELY BUILT DISTRICTS



2A1. CREATE LARGE OPEN AREAS IN DENSELY BUILT DISTRICTS

STRATEGY 2. Enhance Air Circulation
A. Promote the Penetration of Winds (cont.)

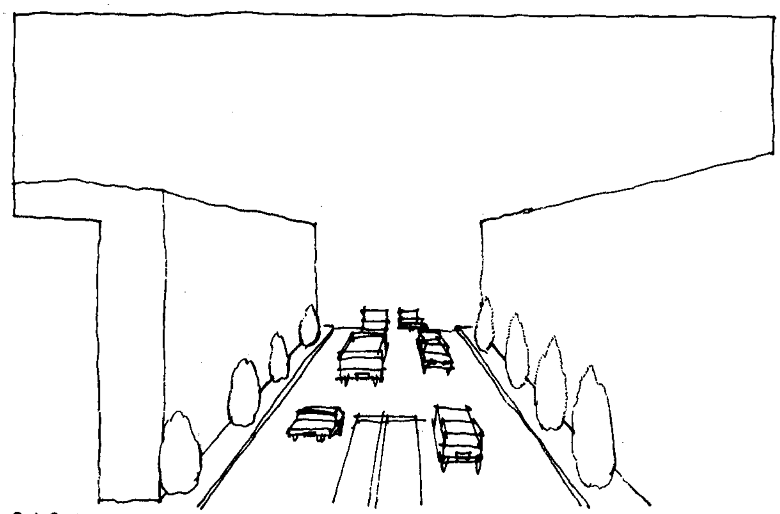
46 2A2. Design street canyons to promote the penetration of winds.

The following strategies may increase ventilation in street canyons perpendicular to the wind direction:

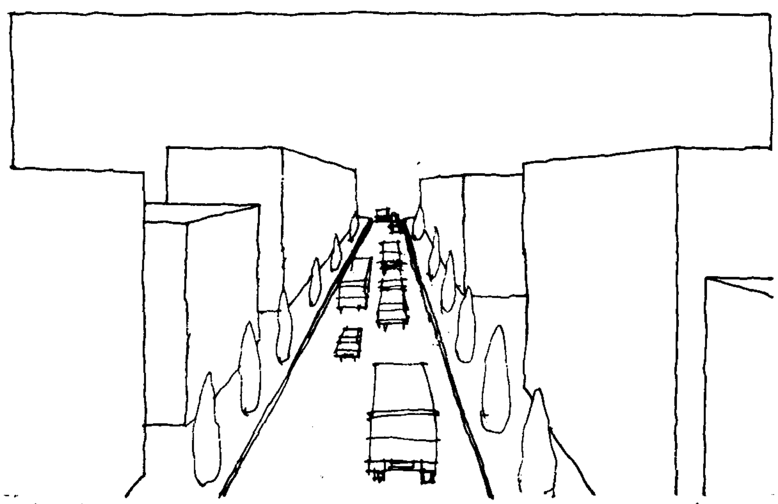
- Widen the street canyon
- Step buildings back from street
- Increase openings in the street canyon, either by frequent intersections or by the addition of open areas mid-block
- Design buildings of pyramidal or irregular shape
- Encourage uneven building heights
- Design intersections to deflect winds into the street canyons

Street canyons oriented parallel to wind direction will tend to channel winds, thereby dispersing pollutants, but may decrease pedestrian comfort. The channelization effect can be avoided or reduced by the first four strategies listed above and the following strategy:

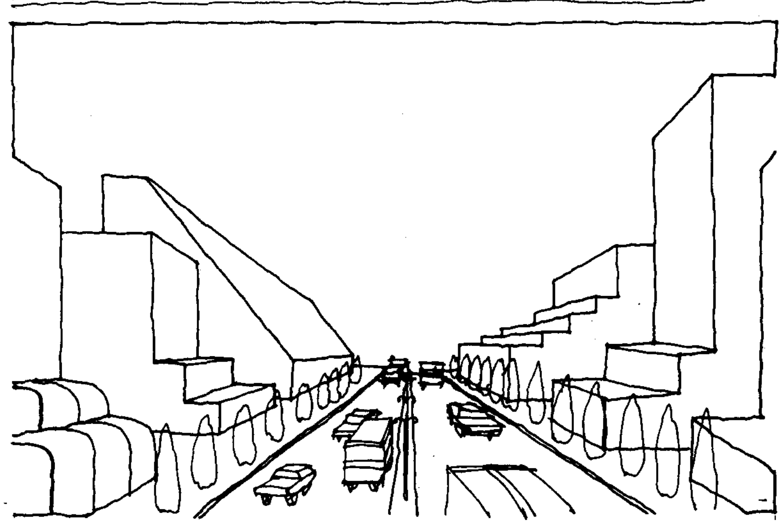
- Vary building setbacks to create a "rough," irregular profile.



2A2. WIDEN STREET CANYON



2A2. INCREASE OPENINGS AND VARY BUILDING HEIGHTS



2A2. STEP BUILDINGS BACK FROM STREET

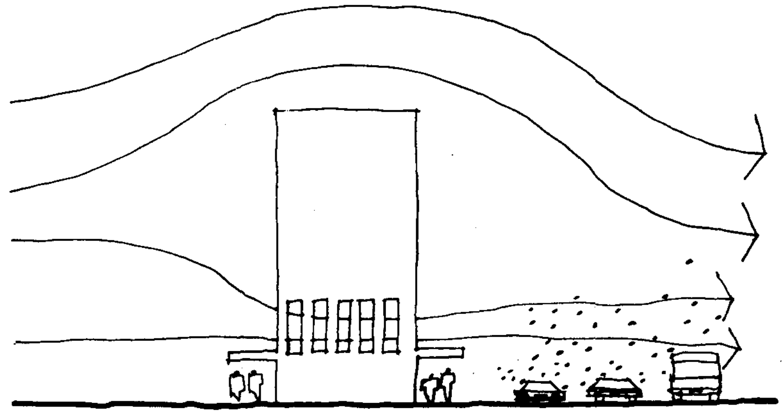
2A3. <u>Promote air circulation around the base of buildings and other obstacles.</u>

Wind shadows at the leeward base of buildings can be reduced:

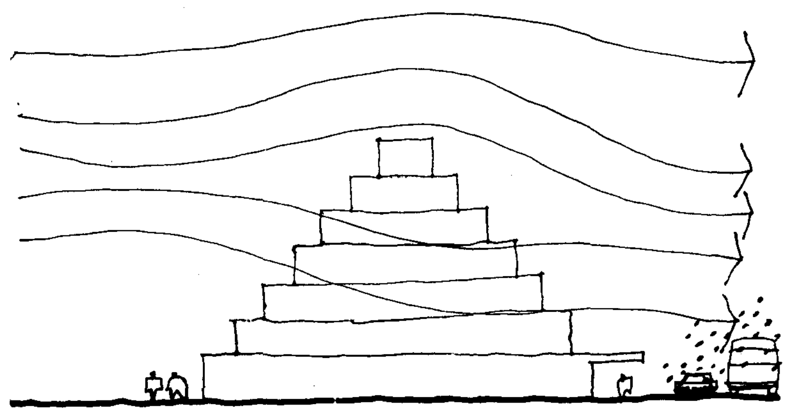
- Orient obstacle to pose minimum surface area to wind
- Design obstacle with pyramidal shape
- Use openings or porous building material to permit air flow
- Place another obstacle nearby to deflect and direct winds into wind shadow

Avoid creating uncomfortably windy areas by using canopies and permeable windbreaks to deflect winds from pedestrians.

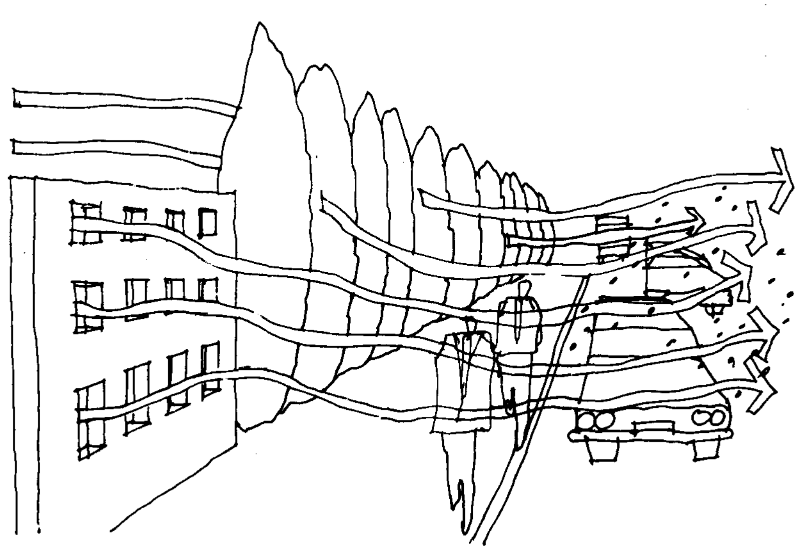
Zones of reduced winds may be desirable under certain conditions. A sun pocket, for example, is an outdoor space oriented south to southwest and protected from winds, thereby creating a place where people may sit comfortably on cool days. A sun pocket, however, should not be located adjacent to a source of air pollution emissions.



2A3. DESIGN OPENINGS TO PERMIT AIR FLOW



2A3. DESIGN BUILDINGS WITH PYRAMID SHAPE



2A3. USE POROUS WINDBREAKS TO PERMIT AIR FLOW

STRATEGY 2. Enhance Air Circulation
B. Promote the Formation and Penetration of Breezes

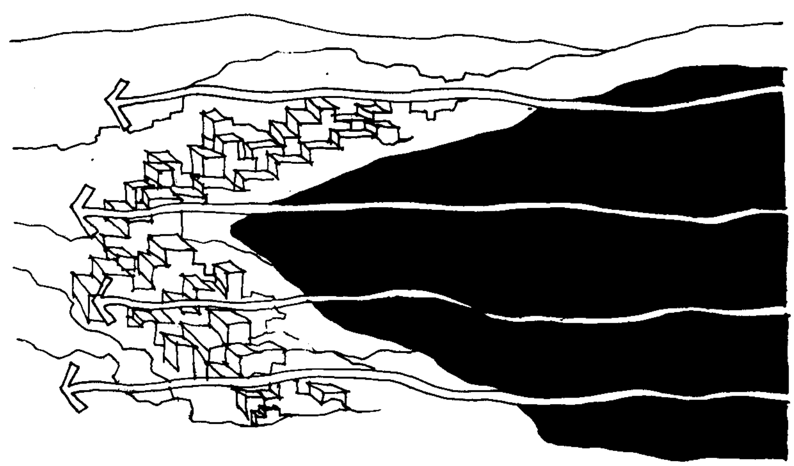
48 Cities that have a sea, lake, or hillside-to-valley breeze can exploit them to enhance air circulation.

2 B1. ORIENT STREETS AND OPEN SPACE TO FUNNEL VALLEY BREEZE

2B1. <u>Design major open spaces to enhance the penetration of breezes into the city</u>.

Establish wide, continuous corridors oriented to funnel breezes into and through the city. River and stream valleys, highways, parkways, railroad corridors and linear parks are potential breeze channels.

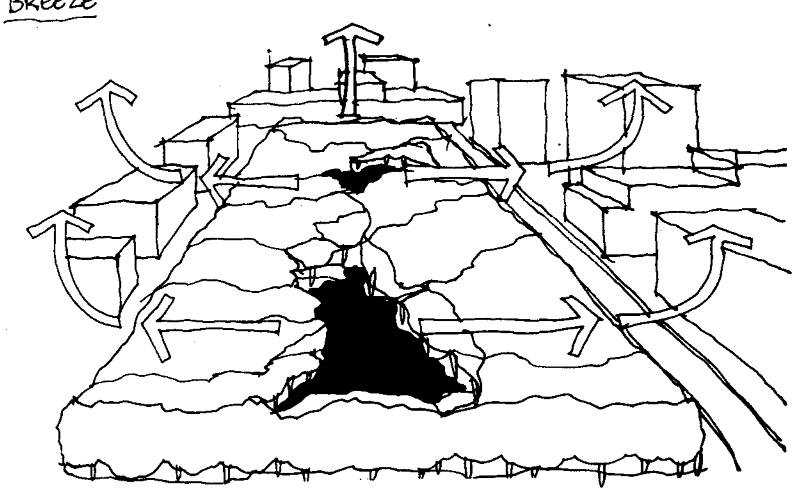
Stuttgart, West Germany, has implemented a system that links hillside parks, stairs, and terraces with boulevards and a linear park in the valley bottom. This system channels air flowing off the hillsides in the evening into and through the city (See Chapter V).



2 B1. ORIENT STREETS AND OPENSPACE TO FUNNEL SEA BREEZE

2B2. <u>Exploit the potential of large parks to initiate local breezes</u>.

When very large wooded parks, especially those that include a reservoir or large lake, are surrounded by an urban district, a local breeze may be initiated under calm conditions by the difference in ground-level air temperature between the park and adjacent streets. Such breezes might enhance air circulation in adjacent streets.



2B2. EXPLOIT LARGE PARKS TO INITIATE LOCAL BREEZE

STRATEGY 2. Enhance Air Circulation
C. Inhibit Local Inversions

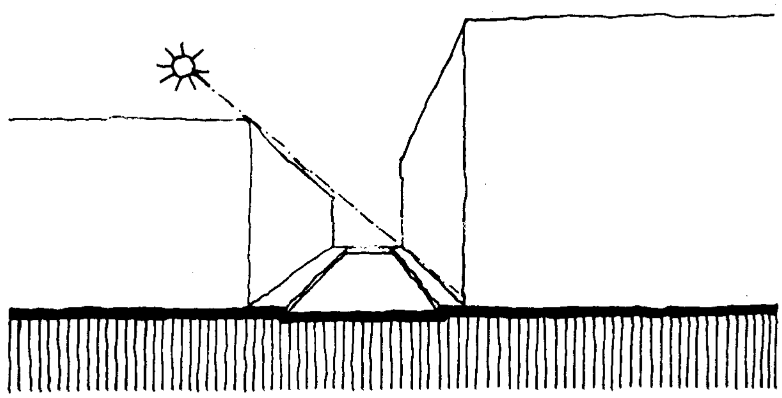
Shorten the duration of micro-inversions in enclosed low spots ("radiation inversions") by permitting the penetration of early morning sun at ground level.

Inversions can also be inhibited promoting the flow of breezes through the city to enhance air circulation during inversions (see Strategy 2B).

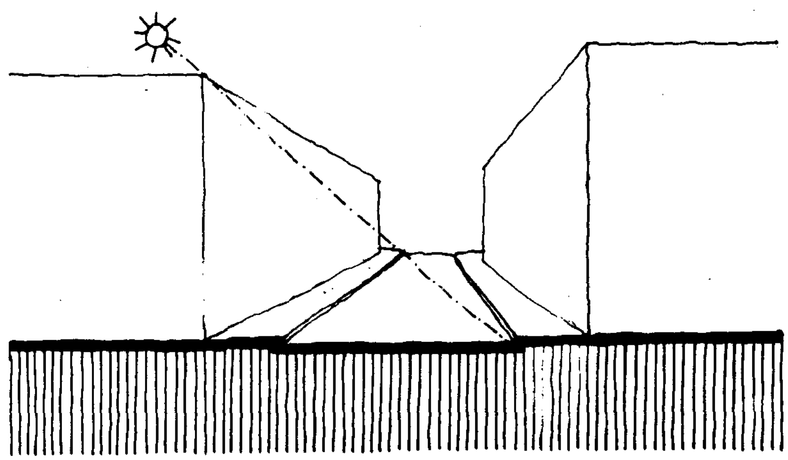
2C1. <u>Design street canyons to enhance solar access.</u>

Street canyons, especially when located in a topographic low spot, should be designed to permit sun to reach the ground relatively early in the morning. In streets oriented north-south:

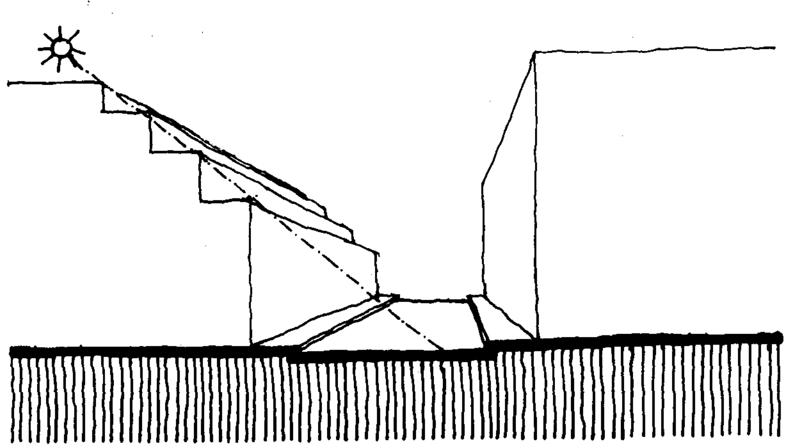
- Widen the street canyon
- Lower building heights
- Set buildings back from east side of street
- Step buildings back from east side of street



2C1. REDUCE BUILDING HEIGHTS ON EAST SIDE OF STREET



2C1. WIDEN STREET CANYON



2C1. STEP BUILDINGS BACK FROM EASTSIDE OF STREET

STRATEGY 2. Enhance Air Circulation
D. Avoid Spatial Confinement

50 Avoid spatial confinement in locations with relatively high air pollution emissions, such as heavily travelled streets. When this is not possible, as in tunnels and parking garages, ventilate the space and site exhaust vents judiciously. (See Strategy 4B.)

2D1. <u>Design Street Canyons to Reduce Spatial Confinement</u>

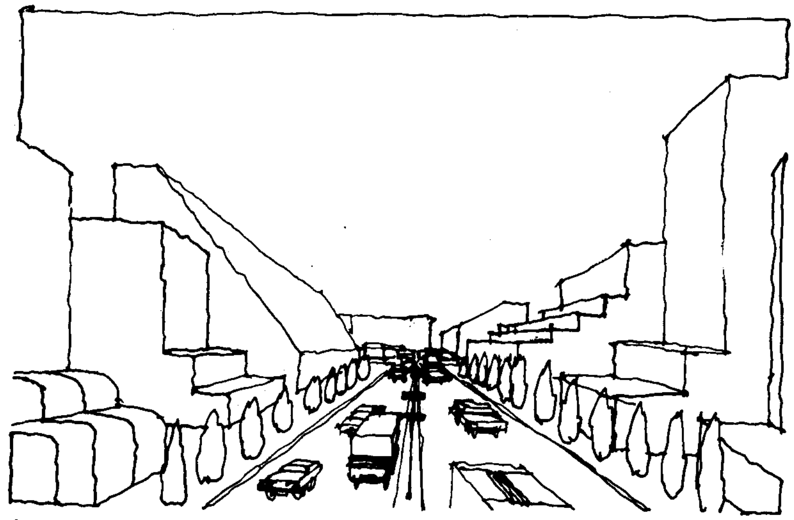
Reduce the degree of spatial confinement in street canyons:

- Widen the street canyon
- Increase openings in the street canyon by frequent intersections, or by adding open areas midblock
- Lower building heights
- Set buildings back from street
- Step buildings back from street

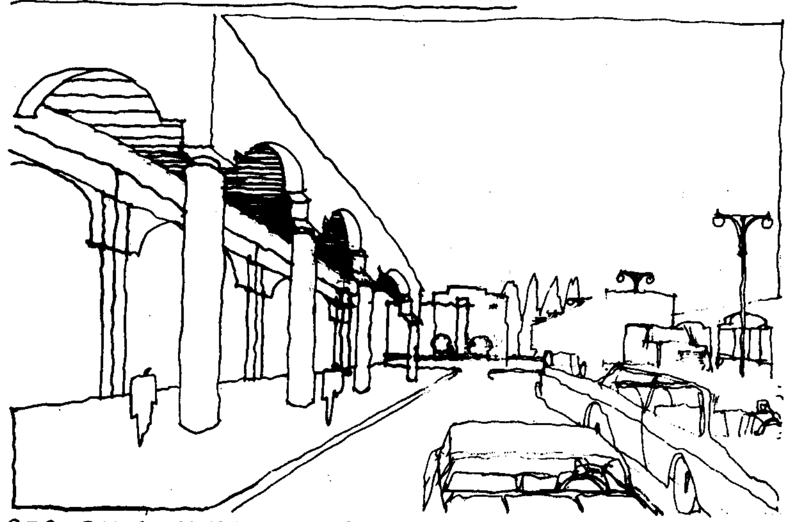
2D2. <u>Design Street-side Shelters to Reduce Spatial Confinement</u>

Design street-side arcades, bus shelters, and covered bus depots so as not to trap pollutants:

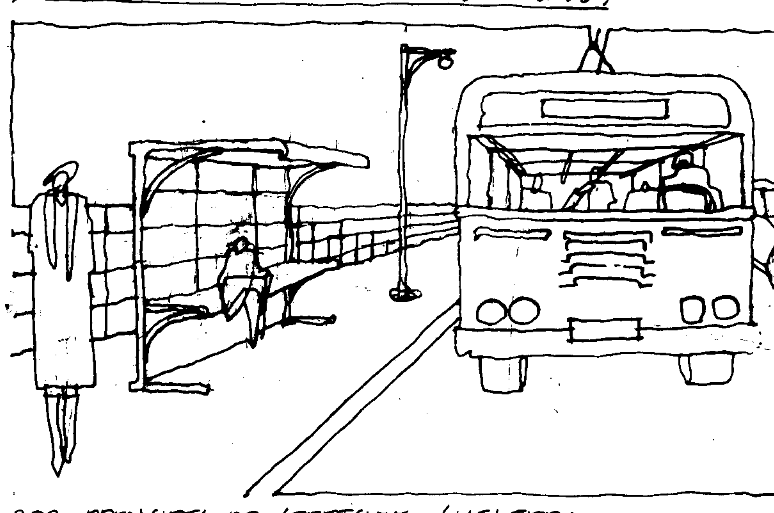
- Open side(s)
- Raise canopy or roof



2D1. STEP BUILDINGS BACK FROM STREET



2D2. RAISE CANOPY ON STREETSIDE ARCADES



2D2. OPEN SIDES OF STEETSIDE SHELTERS

STRATEGY 3. Remove Pollutants from the Air

Landscaped or wooded areas have a limited potential to filter particulate pollutants from the air. 51

Note: particulate pollutants removed from the air do not "disappear", but are merely transferred to the surface of leaves, branches, and bark. If leaves are raked, they will therefore pose a disposal problem; leaf-burning will return pollutants to the air. Such leaves should also not be composted and used as a soil amendment in vegetable gardens. It is best (though not always feasible) to design the roadside landscape as a relatively closed system, where leaves and twigs may remain where they fall.

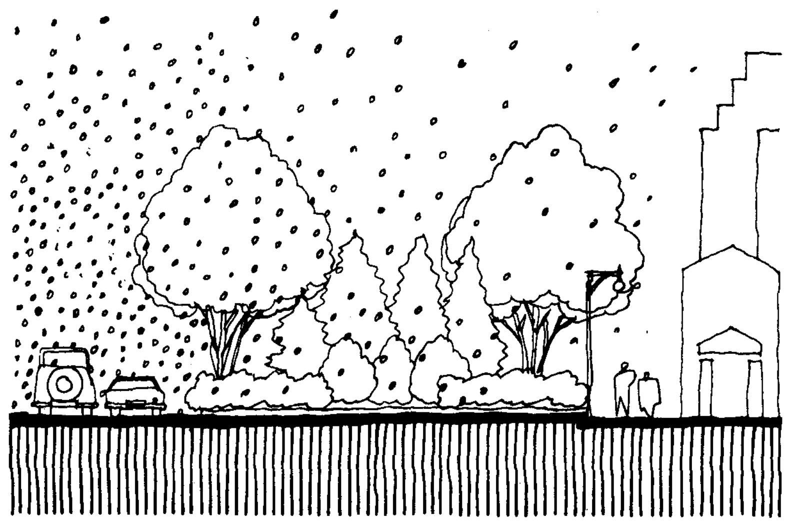
STRATEGY 3. Remove Pollutants from the Air
A. Plant Roadsides to Filter Particulate Pollutants

52 Plant the roadside zone to filter the air. The effectiveness of such "filters" can be enhanced greatly by design.

3A1. Design the landscape of major streets to filter particulate pollutants.

Design major streets with a roadside easement of sufficient breadth to accommodate a dense, layered plantation. Pedestrian protection will be enhanced if such strips are also designed as buffers (see Strategy 4C). Note: Street trees planted in a single row have an insignificant impact. The following strategies will enhance roadside strips as filters:

- Plant species with a dense branching and twig structure, rough bark, large and/or hairy leaves
- Plant both coniferous and deciduous species
- Plant a layered structure of trees, shrubs, and ground cover.

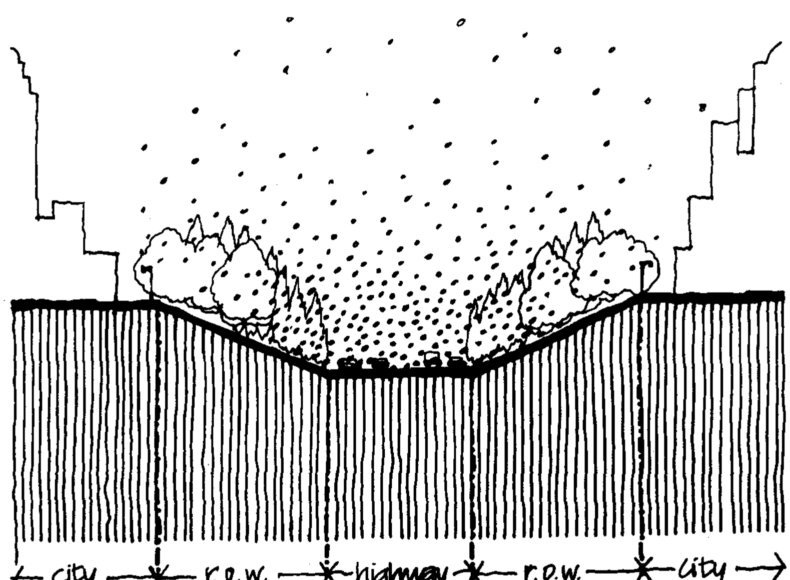


3A1. PLANT ROADSIDE STRIPS

3A2. Design the landscape within highway rights-of-way to filter particulate pollutants.

Grassy meadows with scattered trees possess little potential to filter particulates. The effectiveness of roadside vegetation as a filter can be increased by the above, as well as the following, strategies:

- Encourage the growth of woodland (leave a mowed strip next to road for safety)
- Line the roadway with a sloped embankment.



3A2. SLOPE HIGHWAY EMBANKMENTS AND ENCOURAGE WOODLAND GROWTH

It is neither feasible nor necessary to eliminate pedestrian exposure to air pollution. It _is_ important, however, to limit exposure of the most sensitive populations (e.g., young children senior citizens, convalescents) and to ensure that places used frequently and/or for extended periods of time by the same inidividuals have relatively low levels of air pollution.

The physical separation of pollution-sensitive uses is often the most effective means of limiting pedestrian exposure to air pollution. this can be accomplished by spatial separation (Strategies 4A and 4B), by temporal separation (Strategy 4D), or by the interposition of a barrier (Strategy 4C).

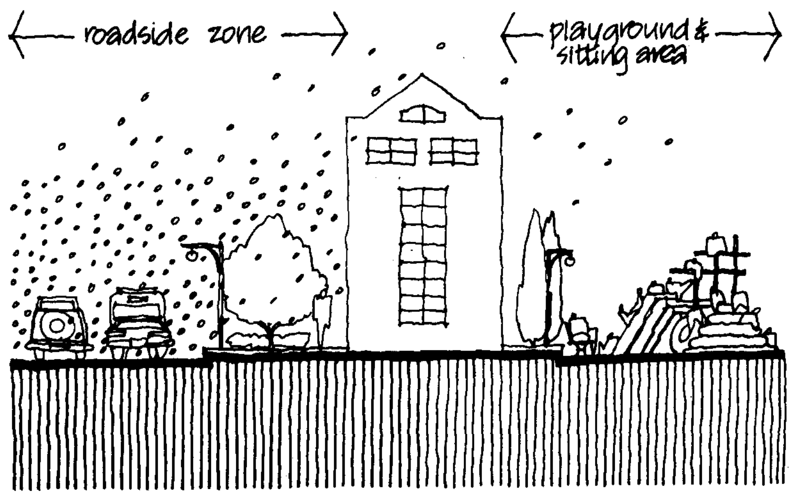
STRATEGY 4. Protect Pollution-Sensitive Uses
A. Locate Pollution-Sensitive Uses Outside High-Pollution Zones

54 Pollution-sensitive uses and activities (e.g., playgrounds and schoolyards, sitting areas, outdoor cafes, and building entrances and intake vents) should be located in zones with low pollution (see Design Situation chart, Classes One and Two) and away from high-pollution zones (see Design Situation Chart, Classes Five and Six).

4A1. Locate pollution-sensitive uses in areas of good air circulation, with low to moderate emissions, upwind of major pollution sources.

4A2. Maintain distance between pollution-sensitive uses and major streets and highways.

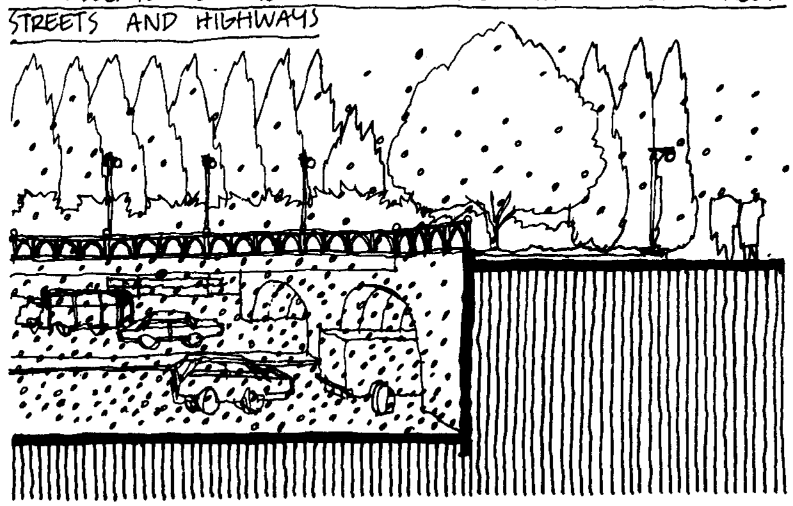
Separation from the roadway may be accomplished by either vertical or horizontal distance. Benches and bus shelters should be sited well back from the curb. Locate school yards, playgrounds, and outdoor cafes off major streets, especially if air circulation is limited.



4A2. LOCATE POLLUTION-SENSITIVE USES AWAY FROM MAJOR STREETS AND HIGHWAYS

4A3. Discourage the use of high-pollution zones for pollution-sensitive uses.

Do not place benches or play equipment adjacent to high emission uses, such as major streets and highways, parking garage entrances and vents, or near tunnel entrances. Discourage the use of such areas (e.g., by planting with dense shrubs and/or trees).


4A3. DISCOURAGE POLLUTION-SENSITIVE USES IN ZONES OF HIGH POLLUTION

STRATEGY 4. Protect Pollution-Sensitive Uses
B. Locate High-Emission Uses Judiciously

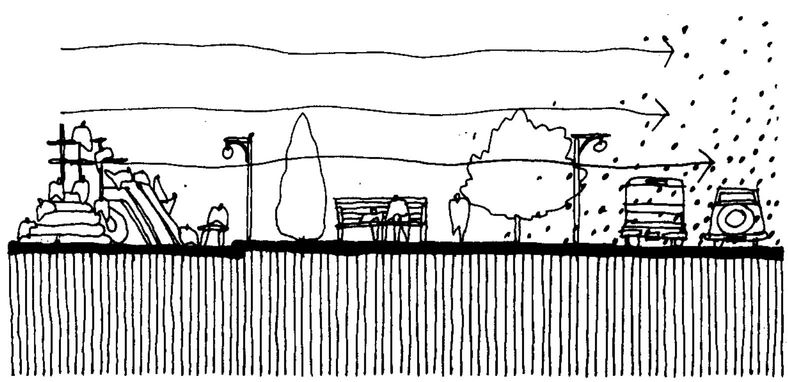
New uses that may generate high emissions should be located in order to both protect existing pollution-sensitive uses and to enhance dispresion of pollutants.

4B1. <u>Site high-emission uses away from existing pollution-sensitive uses</u>.

New highways, bus depots, and parking garage and tunnel entrances should not be located adjacent to existing playgrounds, schoolyards, or small parks.

4B2. <u>Site high-emission uses in areas with good air circulation</u>.

4B3. <u>Site high-emission uses downwind of existing pollution-sensitive uses</u>.

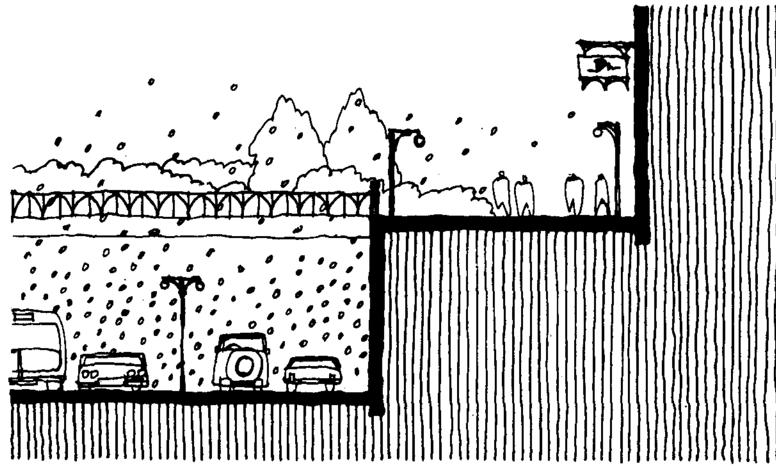


4B3. SITE HIGH-EMISSION USES DOWNWIND FROM POLLUTION SENSITIVE USES

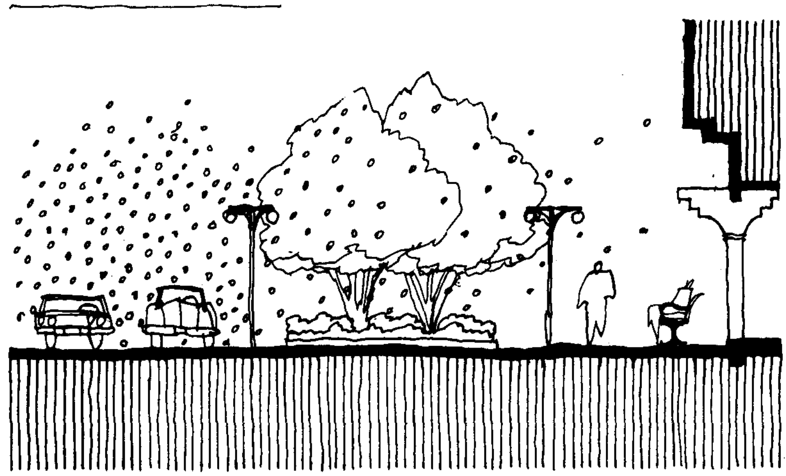
Pollution-sensitive uses must sometimes be located in zones of relatively high emissions. Commuters must use the street every day, for example, and busy streets are often exciting places to be. Pedestrians can be protected to some extent through physical buffers.

4C1. Use barriers to separate pollution-sensitive and pollution-generating uses.

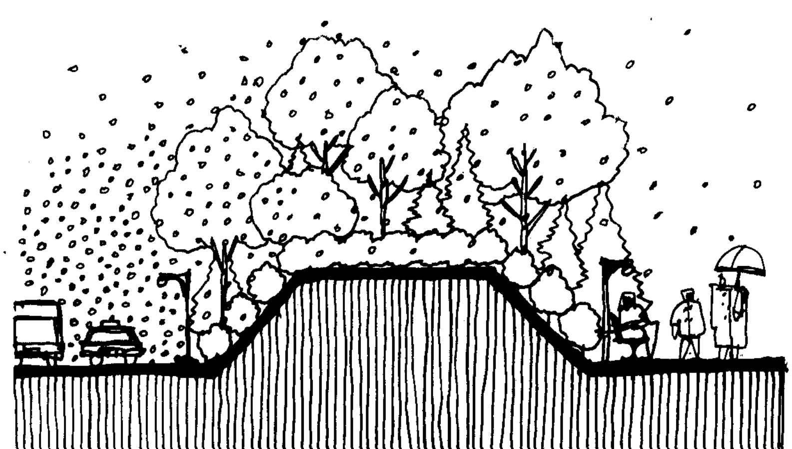
Walls, planters, and berms can all be used to protect pollution-sensitive uses like sitting areas and outdoor cafes. Planted berms will not only provide a barrier, but can also be designed to filter particulate pollutants (See Strategy 3A1).



4C1. SEPARATES USES WITH VERTICAL BARRIER: EMBANKMENT WALL



4C1. SEPARATES USES WITH HORIZONTAL BARRIER: PLANTED BUFFER



4C1. SEPARATES USES WITH VERTICAL AND HORIZONTAL BARRIER: PLANTED BERM

The use of the same space by pollution-sensitive and pollution-generating uses is sometimes unavoidable. In such cases a temporal separation may be the ideal solution to reducing pedestrian exposure to unacceptable levels of air pollution.

4D1. Establish vehicle-free time zones during intensive pedestrian use.

The time of most intensive pedestrian activity downtown is during morning and afternoon commuting periods and during the mid-day lunch hour. Traffic might be banned or restricted in some downtown districts between noon and two o'clock.

4D2. Restrict traffic during times of limited air circulation.

If local radiation inversions are a frequent morning occurrence, traffic might be restricted during that period. Deliveries, for example, might be limited to afternoon hours.

[redacted]

V. A COMPREHENSIVE APPROACH TO STREET-LEVEL AIR QUALITY

In the seventeenth century, John Evelyn described the air pollution of London and proposed a comprehensive plan to alleviate that problem. Evelyn's plan, outlined in Fumifugium: The Aer and Smoake of London Dissipated (1661), employed the four basic urban design strategies outlined in the preceding chapter. Evelyn recommended the prohibition of high-sulphur coal, the relocation of polluting land uses, like tanneries, from central London to outlying areas downwind, and the plantation of entire square blocks with trees and flowers, interspersed throughout the city, to sweeten the air. Rarely, since that time, has there been so comprehensive a proposal to improve urban air quality. Most programs in the United States today focus mainly on the reduction of emissions and ignore the potential of other strategies.

If an air quality program is to be effective and efficient, it is critical that it integrate multiple strategies and that it coordinate efforts at both city-wide and street-corner scale. The specifics of such a program will vary from city to city, depending on climatic setting, transportation patterns, and existing urban form. What works in one city may be inappropriate or impractical in another. Whatever its specifics, however, a plan to address air pollution should always acknowledge the issues of energy conservation and climatic comfort. Increased air pollution is often the by-product of profligate energy use and, in some cases, efforts to conserve energy have increased air pollution in building interiors. The promotion of climatic comfort in outdoor spaces may contribute to decreased air circulation and a build-up of air pollutants: for example, when sidewalks and building entrances are protected by deep arcades with vehicular access or when winds that might ventilate a space are deflected from it.

In devising an air quality management program, it is also important to assess the significance of the air pollution problem relative to other issues facing the city and to integrate air quality as part of an overall plan to improve environmental quality. The fragmentation of environmental concerns leads to plans that are inefficient, expensive, and that can precipitate additional problems, even as they solve the single problem for which they were designed. Plans designed to serve multiple purposes, on the other hand, may improve air quality, even as they help resolve problems of water quality, storm drainage, and flood, earthquake, or landslide hazards. Certain strategies or combinations of strategies may also be more feasible economically, culturally, or politically than others.

The Stuttgart Experience

Over the past several decades, Stuttgart, West Germany, has implemented a comprehensive program to manage its air quality and climate. Although air quality is one of Stuttgart's most important problems, the city has also incorporated other environmental concerns into its plan: the protection of water resources; the stabilization of landslide-prone slopes; management of forest resources; the provision of recreation opportunities; and the enhancement of the city's aesthetic image. Stuttgart is a city of 160,000; its center lies at the bottom of a horseshoe-shaped valley. The climate of Stuttgart is greatly influenced by this physiographic situation. Winds are generally weak, and inversion conditions occur two days out of three. Before the city devised a plan to alleviate the situation, industrial emissions, car and truck exhaust, and smoke from furnaces were trapped near the ground during these inversions.

Climatologists, air quality specialists, and urban planners and designers have worked together for several decades to monitor air quality, identify sources of air pollution, and to study patterns of air movement within the city. Together they have designed a multi-faceted air quality management program that applies that understanding. Stuttgart's program is exemplary, on many counts: for the way it exploits an understanding of the city's climate; for the way it coordinates multiple strategies to reduce air pollution; and for the way it integrates planning at the city-wide scale with incremental improvements at the microscale.

The city maintains a monitoring network comprised of both stationary and portable monitors, including a small van designed as a mobile laboratory. Industrial emissions, the smoke from thousands of individual furnaces, and vehicular exhaust were all identified as important sources of air pollution. The city has since reduced emissions significantly. Chimney stacks at the municipal incinerator and local industries were fitted with filters and were increased in height to enhance dispersion. The filtered material and cinder residue from the incinerator are now used as aggregate material in road construction. The incinerator was also converted to a power plant where burning garbage heats water that is piped to homes and businesses in the downtown and nearby residential neighborhoods. This provides both heat and hot water, thereby eliminating the need for furnaces in this entire area.

Other strategies have been employed to reduce emissions of air pollutants in poorly ventilated portions of the downtown. One narrow street, historically the city's most important route, was converted to a pedestrian street, with trolleys and buses placed below in an underground transitway. This street and transitway connect the main train station at one end of downtown with the old market square at the other end. New buildings and old, important institutions, offices, shops, and restaurants line the shaded pedestrian mall with its convenient transit stations.

Climatologists identified the daily pattern of hill-to-valley air movement and demonstrated its significance for city-wide ventilation. On calm, clear nights, cool air flows off the hillsides down small canyons to the valley floor where, if unimpeded, it pushes warmer, polluted air in the city center down the river valley. The city has therefore mapped these airflow channels and has ensured their continued effectiveness by incorporating them into a public open space system. A linear downtown park, several miles long and several hundred yards wide, was built in the valley between the Neckar River and the city center. At its downtown terminus, it is linked to a pedestrian street and is connected to hillside airflow channels by streets that run perpendicular to it. Thus have forests at the city's edge, wooded hillside canyons, a pedestrian mall, and a large central park been linked in a comprehensive system that ventilates the city, cooling and cleansing it. The pedestrian is well-served in Stuttgart. Hillside stairs step down the airflow channels providing shortcuts to downtown as well as sweeping views of the city. Even downtown, pedestrian routes are well separated by planted buffers from heavy traffic on major streets. Several major streets have been widened without increasing traffic lanes, thereby enhancing ventilation and providing more room for the separation of cars and sidewalks.

Stuttgart has integrated concerns for air quality, energy conservation, and climatic comfort. The same airflow that helps disperse pollutants also cools the city on hot summer nights, when the city would otherwise be considerably warmer than outlying suburbs. The conversion of the municipal incinerator to provide district heating has reduced energy consumption as well as air pollution emissions. The shady parks and walkways that funnel air through the city are far cooler than nearby streets and plazas and provide a pleasant place to be on hot summer days.

62 Stuttgart now employs several full-time specialists to monitor climate and air quality. But the original concept was worked out and implemented without the aid of the sophisticated monitoring system the city now maintains. The nightly pattern of downslope airflow was demonstrated during World War II, by smoke bombs that were discharged on the hillsides to hide the city from enemy aircraft. Based upon this experience, climatologists mapped probable airflow channels, and these have since been verified empirically. The broad outlines of the program were sketched in the 1950s and have been refined and augmented ever since. The early conceptual framework has guided both comprehensive and incremental improvements for several decades. The miles-long linear park, for example, was built in several stages; each stage was designed and built when Stuttgart hosted the German garden show, a time when there was great public support for major expenditures on park development. Even when pressures to develop the hillsides have prevailed, the city has usually been able to persuade developers to leave air flow channels open, either as streets, walkways, or private open space.

The Stuttgart experience is not equally applicable to all cities in its details. But in its broader concept, it is applicable to every city: in its incorporation of an understanding of climatic setting into a comprehensive program to reduce emissions, enhance ventilation, and reduce exposure to air pollutants; in its integration of concerns for air quality, energy conservation, and climatic comfort; in its balance of these with other urban issues; in its successful integration of small details that are consistent with the overall scheme; and in its evolution and staged implementation.

VI. THE LESSONS FOR BOSTON

Climatically, Boston's situation is quite different from that of Stuttgart; inversions are relatively infrequent, and windless days are rare. In fact, Boston is a windy city, and even on calm days, the sea breeze blows onshore in late afternoon and evening. Despite the generally favorable conditions, however, there are locations and even entire districts that have relatively poor air circulation. Combined with Boston's snarled traffic and attendant high emissions at street-level, there may well be ground for concern.

Places of Concern

The oldest parts of downtown Boston have an irregular pattern of narrow, winding streets. Prior to the construction of office towers in the past two decades, these narrow street canyons were rarely more than four or five stories high. New construction, however, particularly in the financial district, has transformed that pattern. These office structures have contributed to Boston's economic vitality, but have resulted in increased downtown traffic with an attendent increase in emissions and, in some places, in poor air circulation. The office workers that fill downtown streets and plazas during lunch in spring, summer, and fall compete with heavy traffic for street-level space and may be exposed during lunch hour to pollution levels that exceed the one-hour standards. Indoor air pollution levels (carbon monoxide, for example) may also be of concern in older buildings with window air conditioners or in some new buildings with large, enclosed atrium spaces. Where entrances of such atriums, for example, are sheltered by deep arcades with vehicular access, emissions could be entrained into the interior public space.

The central artery and entrances and exits to the Sumner and Callahan Tunnels are sources of high emissions in downtown Boston. When the sea breeze blows these emissions back into the city, nearby buildings upwind, especially if they pose a long, high obstacle to the breeze, may be exposed to relatively high pollution levels at their base. If plans to depress the central artery go forward, great care should be taken in the location and height of vents.

Boston is a windy city, and the many new tall buildings have sometimes created uncomfortable, even dangerous, pedestrian-level wind conditions. The city has wisely taken steps to arrest this problem. In reducing winds in public spaces, however, care should be taken not to create stagnant wind shadows in locations with high emissions.

There are many examples, in both public and private spaces where pollution-sensitive uses are located in inappropriate spots. Of special concern are playgrounds such as the one situated above the Callahan Tunnel entrance in the North End. Also of concern is the trend for restaurants like McDonalds and Burger King to build playgrounds adjacent to major streets and highways.

Opportunities

Boston possesses great opportunities to reduce pedestrian exposure to street-level air pollution both in existing parts of the city and through new development. The sunlight/air circulation project of which this study is a part provides an opportunity to integrate issues of climatic comfort and air quality. The fact that the results of this project have become available at a time when the city is undertaking a comprehensive open space plan for the downtown means that a concern for improving air quality can be incorporated into the redesign of existing open space and the design of future open space. Boston is currently experiencing a building boom, one that will influence the form of the city for many years to come. This is an opportunity to redesign portions of the city to address air quality as well as other environmental, social, and economic concerns.

In designing its open space plan and in guiding new development, Boston should seek to reduce emissions, especially in parts of the city with poor air circulation. Cultural and physical factors provide a favorable context for reducing vehicular emissions. There is already a strong constituency for public transportation. Boston is better served by public transportation than most American cities, and many residents already travel through, to, and from the downtown by bus or subway. It is therefore likely that improvements to that system, in combination with other incentives, could significantly decrease traffic. Bicycle and pedestrian programs are also more likely to succeed in Boston than many other American cities. Downtown Boston has a pedestrian scale; the entire downtown is approximately two miles across. Pedestrian streets linking major destinations and open spaces could form a convenient and pleasant pedestrian network. Given the high density of pedestrians downtown during the day, the creation of daytime pedestrian districts might be more acceptable and more feasible in Boston than in many other cities.

Given Boston's windy climate and the existence of open space channels like the Charles River and the Southwest Corridor, good air circulation can be maintained in most districts through careful deployment of new building, street, and open space construction. The Common, the Public Garden, and the Esplanade are also large public open spaces that probably function as sinks for air pollutants emitted nearby.

Next Steps

This study represents an initial piece of the groundwork necessary to incorporate air quality considerations into urban design for Boston. The following are some suggestions for continuation of this work:

1. Identify places of concern. This may not be feasible for the entire downtown area initially. The city might start with an area like the financial district or one in which intensive future development is likely. Places of concern and design situation classes should be identified and mapped for each district.

2. Assess significance of street-level air pollution. Portable monitors should be used to measure air pollution levels in the identified places of concern, especially where there are overlapping factors, as in design situation classes five and six. Previous studies have identified local "hot spots" that exceed standards to a significant degree. These findings should be compared with the places of concern maps to ascertain correlations. Both spatial and temporal (daily and seasonal) variation should be addressed. Public spaces in building interiors (atriums) should be included in the study. The contribution of non-transportation sources should also be considered. Air pollution monitoring should include one-hour exposure during times of most intensive pedestrian activity (e.g. 8:00 to 9:00 a.m., 12:00 to 2:00 p.m., 5:00 to 6:00 p.m.).

3. Use wind tunnel studies to identify existing and potential zones of poor air circulation.

When wind tunnel studies are conducted to measure pedestrian wind levels, areas of limited air circulation should be identified as well.

4. Incorporate air quality considerations into urban design plans for the downtown. Devise an approach appropriate to each district's urban form and use. Consider solutions that may extend beyond the district.

5. Implement air quality measures through incremental public and private development.

Boston's breezy climate and its legacy of convenient public transportation and generous open space are all resources that should be exploited to improve street-level air quality downtown. In its efforts to develop a new Open Space Plan for the Downtown, the BRA should give particular attention to the contribution of open space to air quality: as buffer between pollution-generating and pollution-sensitive uses; as pedestrian network separate from high pollution zones; as channel for airflow; as sink for particulate pollutants; as low-pollution oasis.

VII. FUTURE DIRECTIONS

This report has established a framework within which air pollution considerations can be addressed by urban designers and, hopefully, through which air pollution specialists can better visualize the contribution of urban design to the improvement of street-level air pollution. The strategies outlined in this report are based on the experimental literature, including both modelling studies of scaled or idealized urban conditions and measurements within actual urban settings. Further research is now needed to test, refine, and augment these strategies through empirical studies.

Several areas of potential future research promise to yield significant results. The effects of urban form on the dispersion of street-level air pollutants at both city-wide and project scales should be investigated. At the city-wide and district scales, the effects of varying size, geometry, and arrangement of buildings, streets, and open areas should be tested and compared. At the project scale, the manipulation of landform, planted form, and building form should be studied. Wind tunnel experiments to test and refine the proposed strategies would be particularly valuable if related to actual development projects. Measurements taken before and after construction could help verify the "truth" of these studies. The implementation of built models (or the identification of existing models) that incorporate the proposed design strategies would also afford the opportunity to assess their effectiveness through comparison with a control site. Since the most effective design solutions may involve intervention at multiple scales (city-wide, district, and street corner), work that integrates these scales is needed. Such research efforts will entail the collaboration between urban designers, wind engineers, and air pollution meteorologists and could yield substantial benefits for the health of city residents.

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