HIGHWAY RESEARCH RECORD

Number 465

Air Pollution Controls for Urban Transportation

8 reports

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FOREWORD

This RECORD contains eight papers that deal with problems of air quality and air pollution controls relating to urban transportation.

In the first paper, Bellomo discusses the process for incorporating air quality considerations into the transportation planning and decision-making processes. The paper emphasizes the need for closer cooperation between those responsible for air quality control and those responsible for transportation planning because air quality problems are a combination of factors including vehicle technology, weather, traffic flow, and reduction of pollution concentrates.

Venezia addresses the impact on transportation of new federal air pollution controls. The paper first gives a brief summary of the federal clean air acts as they affect transportation. The paper points out some of the problems in developing and measuring the adequacy of the control strategies required of the states. Environmental management strategies for dealing with pollutants include process modifications such as alternative power sources for motor vehicles, source controls such as catalytic connectors, and adjustment to the assimilative capacity of the environment through transportation and land use planning and control.

Revis looks at short-term air pollution control strategies for transportation. Inspection-maintenance-retrofit, conversion to gaseous fuels, traffic flow techniques, bypassing through traffic, improvements in public transportation, motor vehicle restraints, and work-schedule changes are compared as control strategies. This paper is concerned with the carbon monoxide emissions from motor vehicles and concludes that a reduction of at least 50 percent from existing levels will be required to meet the national ambient air standards for 1975-77. The paper reports on the EPA-sponsored "six-city study" research project. Using Washington, D.C., one of the six cities, as a case study, Revis examines inspection and maintenance, traffic flow control, and combined strategies.

Wickstrom discusses the need to integrate air quality considerations into the long-range transportation planning process. Eight recommentations for incorporating air quality planning into the transportation and land use planning process are discussed. The problem of air quality must be solved on a regional rather than on a project basis and should consider various scales and time frames with the benefits and impacts clearly stated.

Skog, Shirley, and Ranzieri present a description of meteorological ambient air quality field measurements and traffic data that are necessary to write an environmental impact statement. A mathematical model is presented for calculating emission concentrations and dispersions from a line source. The procedures for analyzing highway impact on air quality are set forth, and the variables that affect emission factors are described. The paper also considers the use of motor vehicle restraint systems.

Rocco describes a procedure for determining whether detailed air quality studies are warranted for proposed transportation corridor alternatives. Capacity curves and planning criteria, presented in the paper, describe maximum average daily traffic volumes that can be tolerated under generalized "most adverse" meteorological conditions before exceeding national ambient air quality standards.

Myrup states that the process by which air pollution from moving vehicles is dispersed by atmospheric turbulence and transported downwind is central to the problem of air quality. He concludes that the microclimate in highway air quality is important because it determines the ability of the atmosphere to disperse air pollution, the Richardson number should be part of any air quality measurement program, and more comprehensive measurement programs are of greater need than are more complex air quality models.

Moon and Ludwig present an urban air diffusion model that includes variables such as speeds, volumes, distances on network links, and meteorological data to forecast concentrations of carbon monoxide. The model includes a technique to compute carbon monoxide concentrations in urban street canyons. The models have been tested in St. Louis, Missouri, and San Jose, California.

PROVIDING FOR AIR QUALITY AND URBAN MOBILITY

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The process of incorporating air quality considerations in planning, the basic relations between transportation and air pollution, techniques for achieving air quality, and the institutional difficulties of implementing transportation control techniques are discussed in this exploration of ways in which air pollution considerations might be incorporated in the decision-making process. The air quality problem related to transportation is not solely a function of vehicle emissions, and the planner must understand how factors such as direction and speed of wind, time of day, and physical barriers affect the problem. Primary and secondary air quality standards established by federal and state governments are discussed and tabulated. The relation of vehicle technology and the effects of speed, travel mode, and operation mode on the emission of pollutants are set forth. Techniques of air quality control are grouped into programs oriented toward vehicles, traffic flow, and reduction of pollution concentration. There is a need for improvement of communications between DOT and EPA, and obstacles that may arise are noted. The report shows that transportation control techniques may be used to achieve air quality (some of these may infringe on mobility goals and others may not). It is suggested that short-term actions aimed at ameliorating air pollution must aim at fostering communication among responsible agencies. Long-term actions require research and more analytical information.

•RESIDENTS of urban America have a variety of social goals, all of which may be desirable but many of which may be conflicting. One such conflict within the present state of technology and controls is that between urban mobility and an air-pollution-free environment.

Mobility goals require that a transportation technology and system be available to provide safe, rapid, convenient, and economical linkages between different land uses for all segments of our society. In the past these goals have been achieved by using conventional transit systems and the automobile. These transportation decisions have resulted in our present level of mobility. In addition, the resulting transportation technologies and systems have affected the urban and economic structure of our metropolitan areas and have contributed to air and noise pollution, water pollution, and loss of social amenities.

Environmental goals, on the other hand, relate to the air we breathe, the water we drink, and the land on which we live. It is clear that these goals were not addressed seriously in the past. This was due in part to a lack of knowledge about the pollution problem, that is, to a lack of understanding of the effects of transportation decisions on the environment. Today there is sufficient evidence to see how actions to achieve mobility goals may create a pollution problem. Conversely, attempts to achieve environmental standards may create mobility problems for segments of our population and have serious economic effects on business, industry, and even personal income.

The objective of this paper is to explore ways in which air pollution considerations might be incorporated into the decision-making process. This objective may be achieved by incorporating air quality considerations in transportation planning. In this paper, the basic relations between transportation and air pollution will be set forth, and

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techniques for achieving air quality will be described. With this information, the institutional difficulties of implementing transportation control techniques to achieve air quality will be set forth. Finally, conclusions will be set forth on short- and long-term directions that might be taken.

INCORPORATING AIR POLLUTION CONSIDERATIONS IN TRANSPORTATION DECISIONS

Figure 1 shows how air quality considerations can be incorporated into the planning process. As indicated, transportation alternatives produce air pollutant emissions, generally as a line source. These emissions, when combined with current background air pollution levels, spread or diffuse in the atmosphere and result in certain levels of air pollution that either meet or exceed the air quality standards for that area. If the standards are exceeded, the air pollution might then be reduced by modification of the transportation or land use plan and by direct controls on the emission sources.

Because the air quality problem related to transportation is not solely a function of vehicle emissions, the planner must understand how the immediate problem may be aggrevated or relieved by certain factors such as wind speed, wind direction, time of day, physical barriers, and other elements that tend to affect the dispersion of pollutants. If, because of adverse meteorological and site characteristics, pollutants tend to concentrate in a given area, factors other than emissions must also be considered in the introduction of transportation and air quality goals. It then becomes a question of the amount and location of mobility or the quality and location of pollution control. Thus, air quality is a prime consideration of overall urban mobility and must be included in the process described.

Based on provisions of the Clean Air Amendments of 1970, the Environmental Protection Agency (EPA) has formulated emission standards for individual groups of vehicles and air quality standards for a geographic region. The emission standards are, of course, the core of a control program aimed at reducing air pollution. The motor vehicle in 1969 accounted for an estimated 60 percent of the total carbon monoxide (CO) from all sources, about 50 percent of the hydrocarbons (HC), and about 35 percent of the nitrogen oxides (NO_x) (1). The other major gaseous pollutants, oxides of sulfur (SO_x), are developed primarily from power plants, such as those used to power urban electric systems, and other stationary sources. Thus, urban transportation severely affects the urban air environment.

Minimum air quality standards are established by the federal government for certain pollutants. The various states, however, may set more stringent standards if they so desire.

Primary ambient air quality standards were developed to protect the public health, and secondary standards were set to protect the public welfare. National primary and secondary ambient air quality standards are given in Table 1. Each standard specifies an averaging time, frequency, and concentrations. The standards specify that the maximum concentrations are not to be exceeded more than once per year. The responsibility for attaining the ambient air quality standards is with the states and local air quality control agencies.

BASIC RELATIONS AND EFFECTS

Many factors affect the air pollution generated by transportation facilities: emission control and technology, vehicle speed, operation mode, traffic mix, topography, altitude, wind speed, wind direction, and local meteorology. The basic relations needed to estimate air pollution from transportation policies vary by the type of pollutant and the state of the art.

Control Technology and Emission Factors

The basic cause of automobile air pollution is the technology of the vehicle itself. EPA has promulgated certain requirements to reduce vehicle emission levels. A timetable for achieving reduced vehicle emission levels was included in the 1970 Clean Air

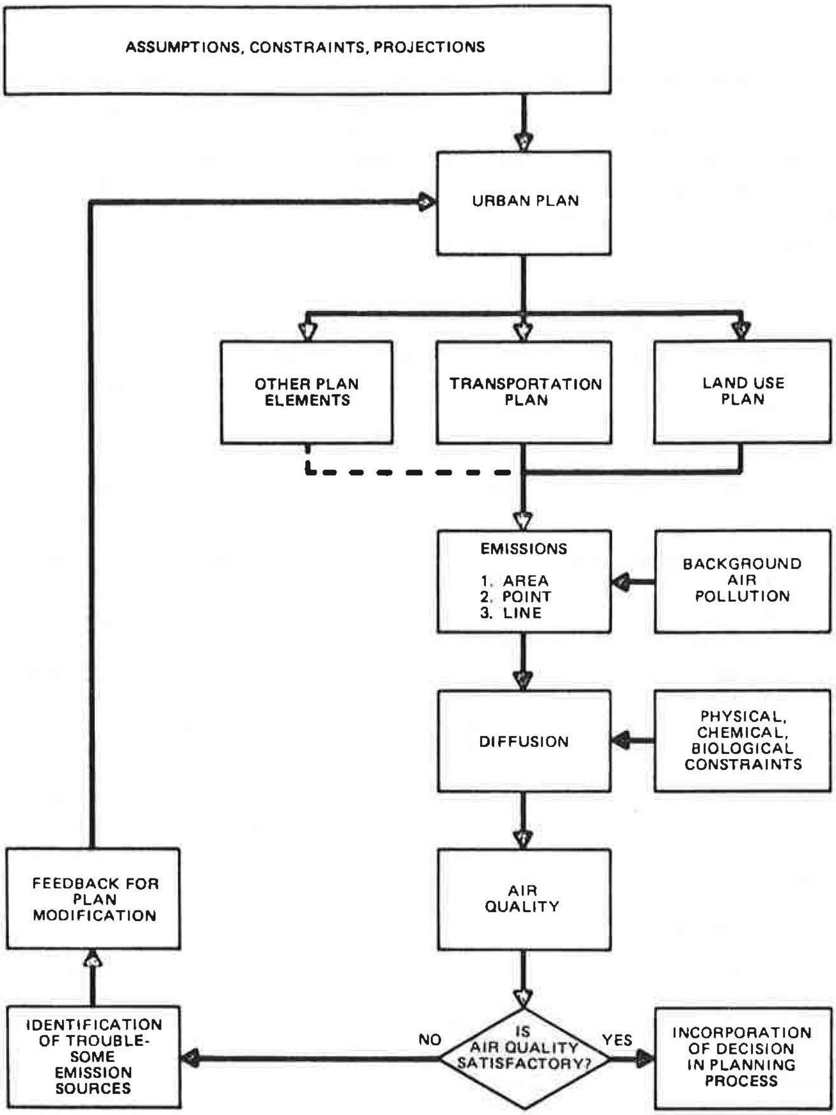


Figure 1. Air quality considerations in the planning process (8).

Table 1. Primary and secondary ambient air quality standards (2).

Pollutant	Standard	Averaging Time	Frequency Standard	Concentration	
				µg/m	ppm
Carbon monoxide	Primary and secondary	1 hour	Annual maximum[a]	40,000	35
		8 hours	Annual maximum	10,000	9
Hydrocarbon (nonmethane)	Primary and secondary	3 hours (6 to 9 a.m.)	Annual maximum	160[b]	0.24[b]
Nitrogen dioxide	Primary and secondary	1 year	Arithmetic mean	100	0.05
Photochemical oxidants	Primary and secondary	1 hour	Annual maximum	160	0.08
Particulate matter	Primary	24 hours	Annual maximum	260	—
		24 hours	Annual geometric mean	75	—
	Secondary	24 hours	Annual maximum	150	—
		24 hours	Annual geometric mean	60[c]	—
Sulfur dioxide	Primary	24 hours	Annual maximum	365	0.14
		1 year	Arithmetic mean	80	0.03
	Secondary	3 hours	Annual maximum	1,300	0.5
		24 hours	Annual maximum	260[d]	0.1[d]
		1 year	Arithmetic mean	60	0.02

[a] Not to be exceeded more than once per year.

[b] As a guide in devising implementation plans for achieving oxidant standards.

[c] As a guide to be used in assessing implementation plans for achieving the annual maximum 24-hour standard.

[d] As a guide to be used in assessing implementation plans for achieving the annual arithmetic mean standard.

Amendments requirements for new motor vehicles. These standards include a reduction of 90 percent (from 1970 levels) in hydrocarbons and carbon monoxide emitted by 1975 vehicles and a reduction in oxides of nitrogen of 90 percent to be achieved by 1976. Table 2 gives the effect of these standards on reducing the rate of emissions of various pollutants from automobiles and light-duty trucks (3). In addition to control technology, vehicle speed, and operation mode, the mix of vehicle types and ages can affect the emission rate and hence air pollution. The factors given in Table 2 represent the vehicle mix for the calendar year shown.

Vehicle mix includes passenger automobiles, light-duty trucks, and gasoline-powered heavy-duty vehicles including buses. Each vehicle class is weighted by number of vehicles by age to account for deterioration of vehicles with age and mileage and by the higher control standards for new vehicles established by federal regulations.

As indicated, the standards imposed on gasoline-powered vehicles and the controls designed to achieve those standards will do much to reduce the pollution level and achieve the ambient air quality standards.

However, many parties speculate that the automotive emission standards may not be achieved:

1. The automobile manufacturers have emphasized strongly that they would not be able to develop the requisite technology in time to meet the 1975-1976 standards.
2. Because a pollution-free engine may not be developed for a reasonable price within the near future, chances are that some kind of mandatory inspection system will be required. However, the technology for measuring emissions quickly and cheaply does not yet exist.
3. The prospects of replacing the internal-combustion engine with unconventional power systems are minimal in the foreseeable future.

These factors reinforce the need to plan transportation facilities and programs to reduce air pollution emissions, concentrations, and human exposure to air pollution. A balanced and comprehensive approach to solving the air pollution problem is the most effective way to achieve the standards.

Effect of Speed

For the emission factors given in Table 2, certain basic relations exist between the emission rate and average network speed. Figures 2 and 3 show the relation between emission rates and speed for highway vehicles for CO and HC by year. This relation represents urban driving conditions and assumes an inherent mode of operation, including a cold start (3). The average speeds are for passenger automobiles and light-duty trucks in proportion to their use. Allowance is made for deterioration and scrapping of vehicles as they age and are replaced by new (controlled) vehicles.

Figures 4 and 5 show the speed-emission relations for rural driving conditions where a hot start is assumed (3). It should be noted that these curves represent the information available to the author in August 1972. More precise information should be made available in the last quarter of 1972. These figures show a negative relation between speed and CO and HC emissions because these emissions are influenced by the air-fuel ratio supplied to the engine. Concentrations tend to decrease as this ratio increases with higher speeds (3).

The speed-emission relation is not so certain for oxides of nitrogen. It appears that there is a positive relation because NO_x formation is influenced by combustion temperature and the amount of oxygen available for interaction with nitrogen, which is not necessarily a concomitant of speed (3).

Figure 6 shows this relation as determined from tests of automobiles for both a steady-state speed and an average speed under actual driving conditions (4). These tests support the conclusion that nitric oxide emissions do tend to increase at higher speeds. Other work has shown similar results (5).

The quandry posed by these relations is the issue of speed being positive in reducing HC and CO but working in an opposite manner in the case of NO_x. There is a need for more adequate data on these basic relations, particularly with regard to NO_x emissions.

Table 2. Emission factors for gasoline-powered motor vehicles (grams per vehicle-mile) (3).

Emission	1960	1965	1970	1971	1972	1973	1974	1975
Carbon monoxide								
Urban	120	120	95	90	85	80	75	60
Rural	70	70	60	55	50	45	40	35
Hydrocarbons								
Evaporation	2.7	2.7	2.7	2.3	2.3	1.8	1.8	1.4
Crankcase[a]	4.1	2.7	0.9	0.45	0.45	0.32	0.22	0.22
Exhausts								
Urban	16	16	12	11	9.5	8.5	7.2	6
Rural	10.5	10.5	8	7	6.5	6.0	5.0	4
Nitrogen dioxide (NO_x as NO_2)	6.6	6.6	6.63	6.47	6.17	5.75	5.55	4.90
Particulates[b]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1
Sulfur oxide[c] (SO_2)	0.18							
Aldehydes (HCNO)	0.36							
Organic acids	0.13							

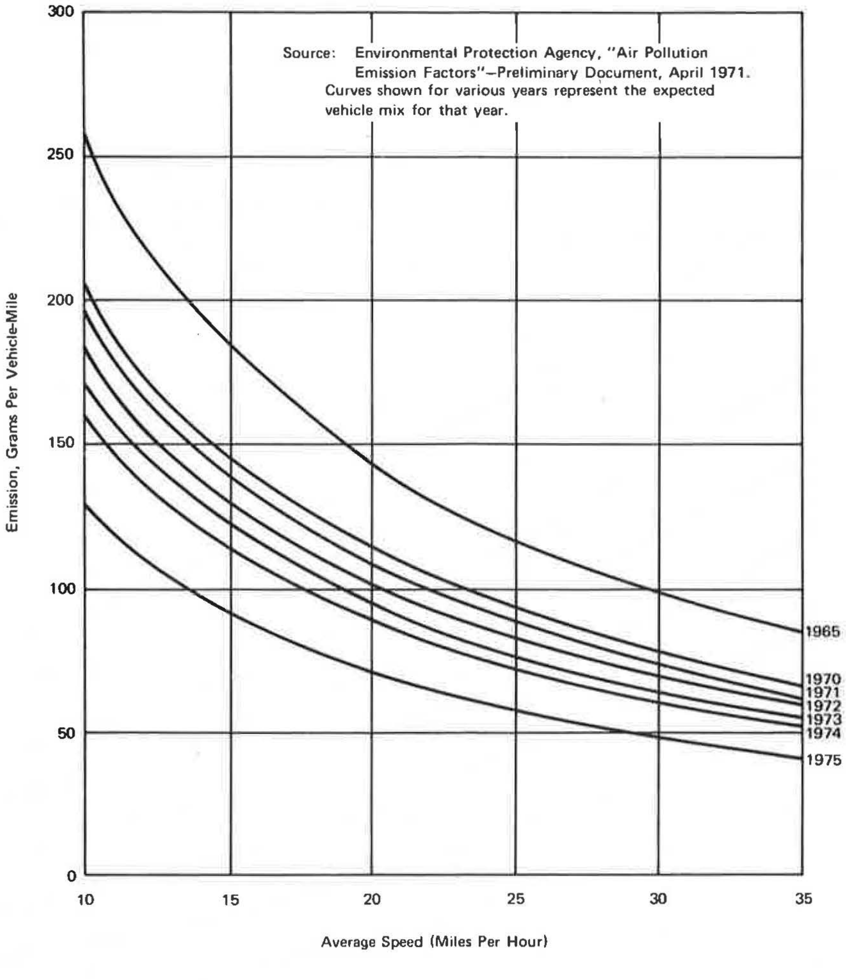
Note: Average urban speed of vehicles is 25 mph; average rural speed is 45 mph.

[a] Crankcase emissions for vehicles after 1962 are negligible. These data are based on pre-1962 vehicles left in the vehicle population.

[b] Urban factor = rural factor.

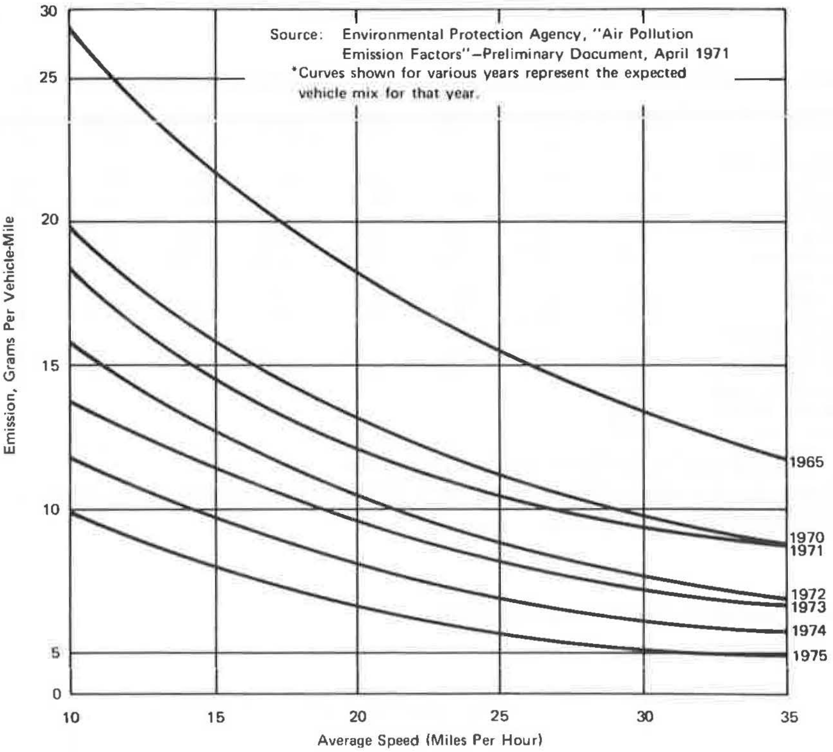
[c] Based on sulfur content of 0.04 percent and a density of 6.17 lb/gal.

Figure 2. Carbon monoxide emissions (urban).



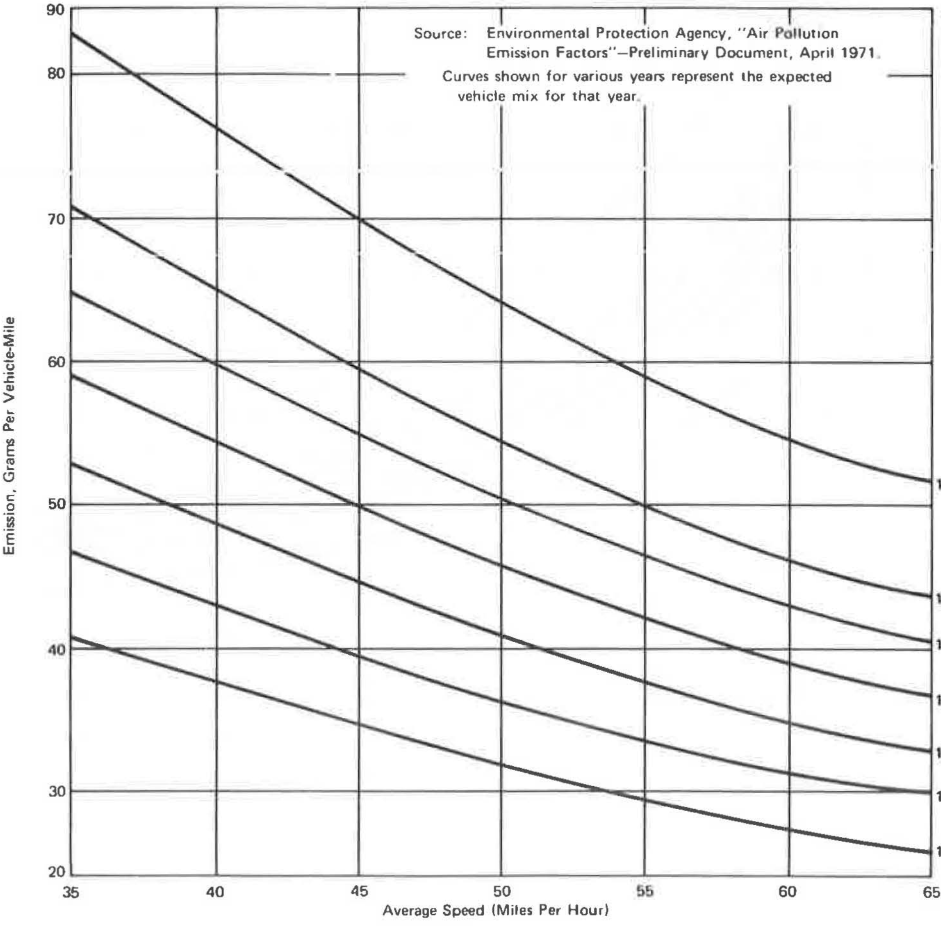
Source: Environmental Protection Agency, "Air Pollution Emission Factors"—Preliminary Document, April 1971. Curves shown for various years represent the expected vehicle mix for that year.

Figure 3. Hydrocarbon emissions (urban).


Source: Environmental Protection Agency, "Air Pollution Emission Factors"—Preliminary Document, April 1971

*Curves shown for various years represent the expected vehicle mix for that year.

Figure 4. Carbon monoxide emissions (rural).


Source: Environmental Protection Agency, "Air Pollution Emission Factors"—Preliminary Document, April 1971.

Curves shown for various years represent the expected vehicle mix for that year.

Figure 5. Hydrocarbon emissions (rural).

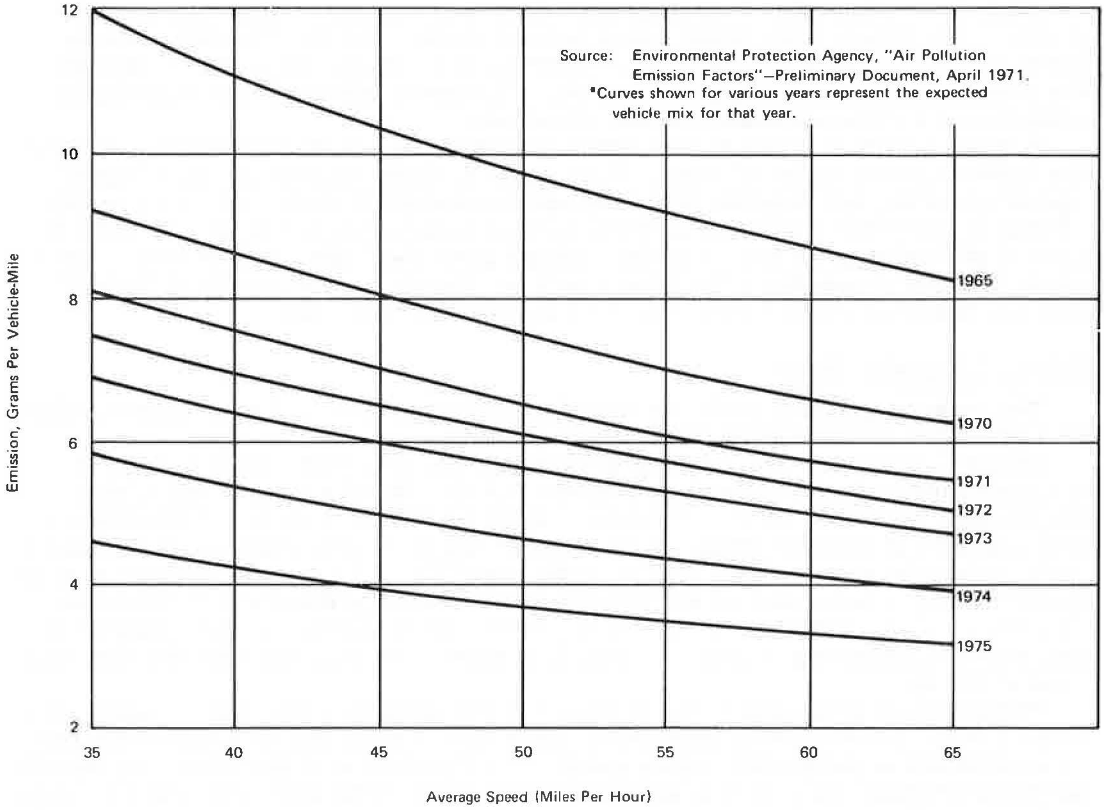
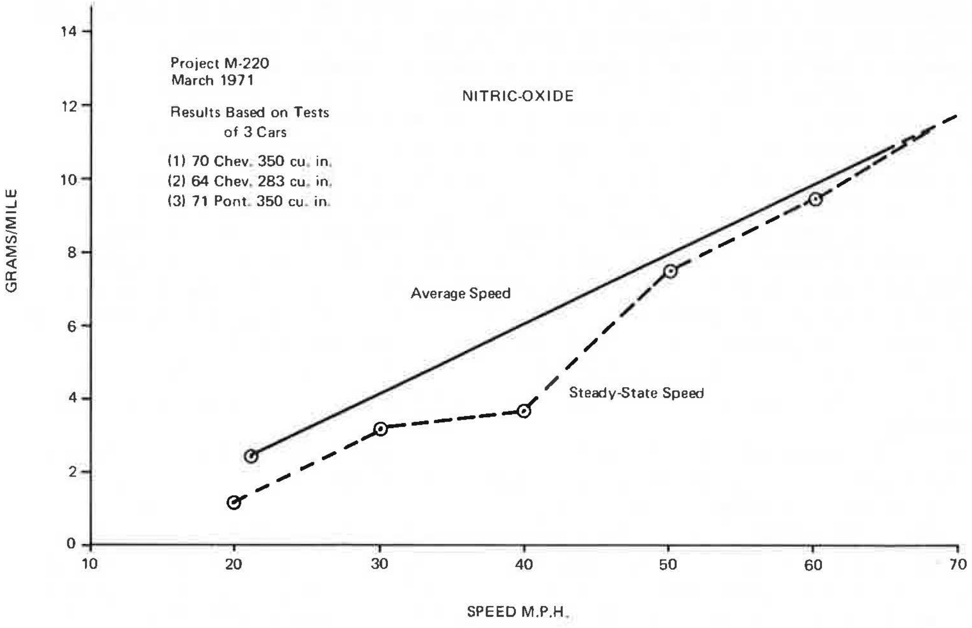


Figure 6. Nitric oxide emissions (4).



Effect of Travel Mode

Table 3 gives the exhaust pollutant emissions in grams per vehicle-mile for automobile (1972 vehicle mix), diesel bus, diesel locomotive, and electric rail. Although these data are based on information currently being revised by EPA, they do indicate the relative differences among travel modes. The speed relation is not available for emission data on modes other than the automobile.

A useful methodology has been devised by Scheel (6) to relate emissions by mode on the basis of person-miles of travel. This study has made assumptions about speed, operating cycles, and emission standards and concludes that the impact on air quality of transit under 1971 conditions is slight and that future impacts will depend on the degree of utilization of the transit mode. Table 4 gives the findings of this study. However, it should be noted that this table should not directly be compared with Table 3 because different emission factors and other assumptions were used.

Effect of Operation Mode

The mode of operation is also an important factor in the amount of automotive pollution generated and the concentration of that pollution.

Figure 7 shows the carbon monoxide emissions related to the operating cycle as measured along a length of roadway in Great Britain. Readings were taken of three automobiles traversing an 800-ft section of road; the motion cycle represents the vehicle stopping at a traffic signal, idling, accelerating to 30 mph, operating at that speed, and decelerating for a stop at the next traffic signal (7). This type of operation is most typical on city streets, causing concentrations of emission pollutants at intersections or other locations where the idle and acceleration phases occur. Another analysis of this effect on emissions is given in Table 5, in which emissions are related to a vehicle-mile of travel.

The effects on emissions of the variations in the operating cycle are, of course, reflected in new vehicle testing procedures and in the emission factors used to calculate concentrations of pollutants in urban areas. The significance of this effect may readily be observed; thus, one goal is to endeavor to reduce the peaking effects caused by stop-and-go operation.

TECHNIQUES FOR ACHIEVING AIR QUALITY

Many techniques can be used to achieve air quality standards or reduce further degradation of the air: programs oriented to vehicles, techniques to reduce traffic, techniques to improve traffic flow, and techniques to reduce pollution concentration.

The federal emission standards for new motor vehicles will reduce automotive pollutants. A large percentage of automobiles on the road in 1975, however, will not be controlled by the standards. State or local governments can develop programs to modify or correct in-use vehicles through inspection and maintenance, retrofit, or gaseous fuel fleet conversion. An inspection and maintenance program aimed at air pollution control devices will work toward ensuring that all devices are performing maximally. Retrofit can also be used for pre-1968 cars. The technology for post-1968 and pre-1974 vehicles, however, needs further testing before it can be effectively used. Conversion of vehicle fleets to other types of gaseous fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG), and liquefied natural gas (LNG) can also be applied. These programs oriented to source control on the vehicle must be carefully assessed from funding, administrative, and legal viewpoints prior to plan completion and implementation.

Emission controls on the vehicle supplemented by the programs oriented to vehicles identified previously may not be sufficient to meet ambient air quality standards. Therefore, other transportation control strategies need to be considered. Techniques to reduce traffic will reduce vehicle-miles of travel and, hence, vehicular emissions. Reductions in vehicular emissions will improve air quality. Techniques to reduce vehicular traffic can be grouped broadly into four categories: regulation, pricing policy, land use control, and transit operations. References that suggest techniques to reduce traffic are given in Table 6.

Table 3. Exhaust emission factors for various travel modes (grams per vehicle-mile) (3).

Pollutant	Automobile[a]	Diesel Bus[b]	Diesel Locomotive[b]	Electric Rail[c] Coal	Electric Rail[c] Gas	Electric Rail[c] Oil
Carbon monoxide	85.00	20.41	6.35	0.91	Negligible	0.01
Hydrocarbons	9.50	3.36	4.54	0.37	Negligible	1.09
NO_x	6.17	33.57	6.80	37.19	0.05	35.38
SO_x	0.18	2.45	5.90	13.97	0.02	27.21
Particulates	0.30	1.18	2.27	29.30	0.73	3.44

[a] 1972 emission factors based on 25 mph and cold-start operation.
[b] Based on fuel consumption estimate of 5 mi/gal.
[c] Expressed as grams per train mile where one train is comprised of four cars, in married pairs, i.e., two power units per train.

Table 4. Relative effects of emissions from different vehicles.

Pollutant	Automobile, 1970	Automobile, 1975	Bus (diesel-arterial)	Gas Turbine	Commuter Train (turbocharged)	Rail Transit
Carbon monoxide	0.24	0.02	0.02	0.003	0.004	0.00
Hydrocarbons	1.56	0.14	0.10	0.012	0.08	0.002
NO_2	3.27	1.63	3.50	0.97	0.58	0.72
SO_2	0.18	0.18	0.52	0.52	0.10	3.40
Total equivalent without particulates[a]	5.25	1.97	4.14	1.50	0.76	4.12
Particulates	0.25	0.25	2.08	2.08	0.33	1.54[b]
Total equivalent[a]	5.50	2.22	6.22	3.58	1.09	5.66

Note: Relative effect = gram per vehicle-mile x relative effect of air quality standards concentration/persons per vehicle.

[a] Measured in grams per vehicle-mile.
[b] Based on 7,250 g/ton of coal, 10 percent fly ash, and 80 percent collection efficiency on control equipment (on person-mile basis).

Figure 7. Relative emissions of carbon monoxide during vehicle operation (9).

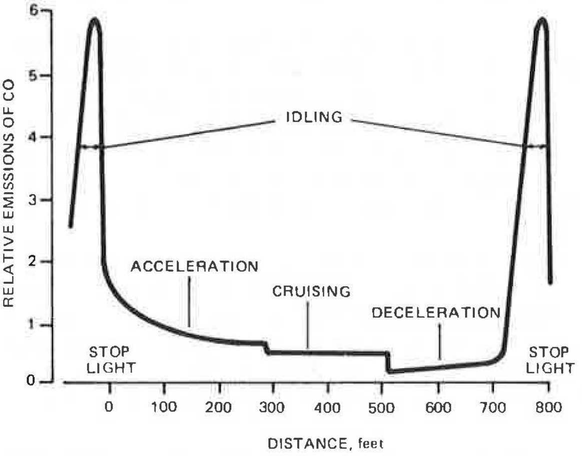


Table 5. Percentage of pollutants emitted per mile for different engine operations.

Engine Operation	Gross Hydrocarbons	Carbon Monoxide	Oxides of Nitrogen
Idle	5.9	7.5	0.03
Cruise	14.1	14.3	21.4
Acceleration	56.2	62.2	78.5
Deceleration	23.7	16.1	0.17

Techniques to improve traffic flow may also be applied to reduce emissions and hence improve air quality by reducing unnecessary idling and stop-start driving conditions. Techniques to reduce concentrations can also be utilized to eliminate "hot spots" of air pollution. Table 7 gives some of the techniques that could be utilized to reduce the concentrations of air pollution. For ease of exposition, these techniques are grouped into freeway operations and design, arterial improvements, traffic distribution, and staggered work hours. Appropriate references have also been indicated.

Application of these techniques to alleviate a mobility or air pollution problem requires that a balance be maintained between the net user benefit-cost (a measure of mobility) and improvement in air quality (reduction in concentration, dosage, or emissions). Figure 8 shows a framework for such a trade-off process using data obtained from a number of metropolitan areas where transportation control strategies have been applied (14). The y-axis indicates a reduction in carbon monoxide emissions. The x-axis indicates net present benefits or costs per person for the agency responsible for implementing the action and for the user. User benefits reflect net user savings in travel time, vehicle operating costs, and accidents.

The techniques to reduce air pollution shown in Figure 8 have been combined to produce maximum emission reduction and net user benefit per person. By application of such a procedure, the user cost and air pollution effectiveness of various techniques to achieve air quality and urban mobility can be assessed. Use of this tool coupled with other devices to assess social, economic, legal, funding, and administrative factors can provide a base for the formulation and evaluation of transportation control strategies aimed at achieving air quality and other societal goals.

HOW TO ACCOMPLISH MOBILITY AND AIR QUALITY GOALS

The previous section suggested transportation actions and techniques that could be applied in some combination toward achieving air quality and urban mobility. Air pollution implementation plans prepared for various Air Quality Control Regions have called for the application of some of these transportation actions and techniques. Programs related to cleaning up the engine through technology may not reduce pollution levels adequately. The problem may become particularly acute for certain metropolitan areas in the short range prior to the development and deployment of pollution-free vehicles in the traffic stream.

Therefore, the problem of the planner may be more related to the "how" than to the "what" of needed short-range transportation strategies. Because time is relatively short (now until 1980), the strategies must be clearly communicated and agreed to by the organizations that plan, build, own, operate, and design transportation. We cannot depend on political innovations to achieve air quality goals by 1980. There is not enough time or money to make such changes in the next 5 to 10 years. Therefore, we need to remove the barriers to clear communications between DOT and EPA and obtain the necessary agreements to achieve the actions.

In many urban areas, the desired transportation actions should be communicated through the transportation planning process to the agency within the metropolitan area that needs to take the action: a highway department, a city traffic engineering department, a parking authority, a toll or turnpike commission, or a federal agency that might own or operate the facility. The action needs to be communicated so that it is clear what needs to be done. The costs for the action, in turn, have to be related to available funds at the disposal of the agency.

Once communication is achieved, then the strategies must be agreed to and implemented by the concerned agency. Such agreements are not always easy. Some obstacles that will emerge are as follows:

1. Insufficient funds on the part of the agency to carry out the action;
2. Insufficient time to develop the plans and details to carry out the action;
3. Insufficient manpower and skills within the agency to do the job;
4. Conflicts between the air quality goals and other goals such as noise pollution, water pollution, and level of traffic service; and
5. Political resistance—business or industrial interests objecting to a regulation if it affects their economic parameters.

Table 6. Techniques to reduce traffic.

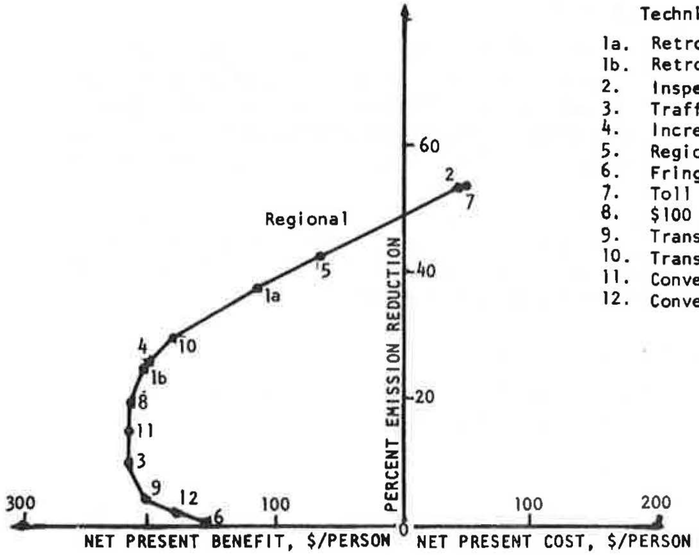
Item	Reference Number
Regulation	
Parking bans	4, 8, 9, 10
Automobile-free zones	4, 8, 9, 10
Gasoline rationing	4, 8, 9, 10
Idling restrictions	4, 8, 9, 10
Four-day, 40-hour week	4, 8, 9, 10
Favor priority traffic	4, 10, 12, 13
Pricing policy	
Parking price policy	4, 8, 9, 10, 12, 13
Road user tax	4, 8, 9, 10
Gasoline tax	4, 8, 9, 10
Car pool incentives	4, 8, 9, 10
Land use control	
Control of parking supply	13, 15
Planned unit development	8, 9, 15
Density control	8, 9, 15
Transit operations	
Bus lanes on highways	4, 8, 9, 12
Service improvements and cost reductions	4, 8, 9, 10

Table 7. Techniques for improving traffic flow and reducing concentrations.

Item	Reference Number
Freeway operations and design	
Reverse lane operations	8, 9
Ramp control	8, 9
Interchange design	8, 9, 13
Cross section design	8, 9, 13
Alignment	8, 9, 13
Arterial improvements	
Widen intersections	4, 8, 9, 11
Parking restrictions	4, 8, 9, 11
Signal progression	4, 7, 8, 9, 11
Reversible lanes	4, 8, 9, 11
Reversible one-way streets	4, 8, 9, 11
Cross section design	4, 8, 9, 11
Alignment	4, 8, 9, 11
Traffic distribution	
Traffic responsive control	4, 9, 9, 11
One-way street operations	4, 8, 9, 11
Loading regulations	4, 8, 9, 11
Pedestrian control	4, 8, 9, 11
Staggered work hours	4, 8, 9

Note: Many of the items listed fall in the Traffic Operations Program to Increase Capacity and Safety.

Figure 8. Average costs and effects for transportation control strategies.



Technique

1a. Retrofit of pre-1975 light duty vehicles
1b. Retrofit of pre-1975 gasoline heavy duty vehicles
2. Inspection and maintenance
3. Traffic flow improvements
4. Increase downtown parking rates
5. Region-wide auto user charge of 50¢ per trip
6. Fringe parking
7. Toll into CBD of 50¢
8. $100 "Bounty" on pre-1968 vehicles
9. Transit service improvements
10. Transit fare reduction
11. Conversion of taxis to LPG
12. Conversion of fleet vehicles to LPG

Source: MVMA-Reference 14

Cities used as bases for calculation of average costs and effects:
Baltimore, Boston, Pittsburgh, Seattle, & Spokane

It will take concerted technical and political leadership and effort in the next few years at the federal, state, and local levels to achieve the needed communication and agreements to bring about air pollution reductions through transportation strategies.

CONCLUSIONS

As the cases presented here have shown, transportation control techniques can be applied to achieve air quality. Some of these payoffs can be realized without infringing on mobility goals. Others, however, will require some trade-offs on an individual level, e.g., sacrifice of the private automobile for car pooling or mass transit and restriction of urban travel mobility through traffic restraints or pricing.

The greatest difficulty in the short run (5- to 10-year period) will be in overcoming the obstacles to the agreement and implementation of transportation actions needed to reduce air pollution, particularly those that are a drastic departure from present programs and that require additional funding or legislation. Massive new transportation programs aimed solely at reducing air pollution will probably never overcome the funding, administrative, legal, and political barriers standing in the way.

For short-term transportation actions aimed at ameliorating air pollution there is a need to

1. Foster communication among the responsible agencies and elected officials at the federal, state, and local levels;
2. Provide information on the interrelations of air pollution reduction and transportation actions and provide case studies on cause, effect, and costs;
3. Focus on cost-effective techniques that work toward reducing air pollution caused by transportation sources and minimize infringement on mobility;
4. Apply traffic restraint and control improvements to areas that are highly polluted (these actions will require the most in terms of administrative, legal, and funding effort and should work toward minimizing reductions on urban mobility);
5. Work with, build on, or combine existing transportation institutions rather than attempting to build new institutions focused solely on air pollution; and
6. Have political leadership at the federal, state, and local levels involved in expediting agreements aimed at those transportation strategies that reduce air pollution and can be adequately funded and administered.

For long-term transportation and land use actions aimed at achieving air quality, there is a need to have research and analysis tools that provide information on the air pollution impacts of future transportation and land use policies in the light of a dynamically changing technology and society and to effectively communicate these impacts to decision-makers so that needed policies and institutional changes can be evaluated and implemented.

Given the problems and opportunities, the planner, the air pollution official, and the decision-maker need a process to bring all interests together. The constraints are primarily institutional, political, and economic in nature: The technology to reduce air pollution exists, but wide support will be required to implement it.

ACKNOWLEDGMENTS

The author wishes to acknowledge the diligent help of Ms. Sally Liff, who offered critical suggestions on the structure and content of the paper.

REFERENCES

1. Environmental Trends: Radiation, Air Pollution, and Oil Spills. Mitre Corporation, MTR6013, May 1971.
2. A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards. U.S. Environmental Protection Agency, Nov. 1971.
3. Compilation of Air Pollutant Emission Factors. U.S. Environmental Protection Agency, AP-42, Revised, Feb. 1972.

4. Evaluating Transportation Controls to Reduce Motor Vehicle Emissions in Major Metropolitan Areas. Institute for Public Administration and Teknekron, Inc., for the Environmental Protection Agency, March 1972.
5. U.S. Secretary of Health, Education and Welfare. Second Report to U.S. Congress. 1965.
6. Scheel, J. W. A Method of Estimating and Graphically Comparing the Amounts of Air Pollution Emissions Attributable to Automobiles, Buses, Commuter Trains, and Rail Transit. Automotive Engineering Congress, Society of Automotive Engineers, SAE Paper 720166, Jan. 1972.
7. Cars for Cities. Great Britain Ministry of Transport, 1967.
8. Air Quality Consideration in Transportation and Urban Planning—A Five-Year Program Guide. Alan M. Voorhees and Assoc., Inc., and Ryckman, Edgerley, Tomlinson and Assoc. for Environmental Protection Agency, 1971.
9. A Guide for Reducing Automotive Air Pollution. Alan M. Voorhees and Assoc., Inc., and Ryckman, Edgerley, Tomlinson and Assoc. for Environmental Protection Agency, 1971.
10. Reducing Motor Vehicle Emissions Through Traffic Controls and Transportation Policies. Organization for Economic Co-operation and Development, 1971.
11. Leonard, J. H. Benefits From TOPICS—Type Improvements. Jour. Civil Engineering Div., Proc. ASCE, Feb. 1971.
12. Boston Transportation Planning Review, Northshore. Alan M. Voorhees and Assoc., Inc., et al. Draft Environmental Impact Statement, May 1972.
13. Woo, W., Bellomo, S. J., and Calcagni, J. Strategies to Reduce Air Pollution—The Boston Experience. Presented at 66th Annual Meeting of the Air Pollution Control Assn., June 1973.
14. An Analysis of the Economic Impact of Motor Vehicle Use Restrictions in Relation to Federal Ambient Air Quality Standards. Alan M. Voorhees and Assoc., Inc., for Motor Vehicle Manufacturers Assn., March 1973.
15. A Guide for Reducing Air Pollution Through Urban Planning. Alan M. Voorhees and Assoc., Inc., and Ryckman, Edgerley, Tomlinson and Assoc. for Environmental Protection Agency, Nov. 1971.

IMPLICATIONS FOR TRANSPORTATION OF NEW FEDERAL AIR POLLUTION CONTROLS

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A concise legislative history of federal air pollution control efforts terminating with the Clean Air Amendments of 1970 provides the basis for a discussion of the implications of compliance with federal ambient air quality standards. A major implication is the need in numerous urban areas for transportation controls, control mechanisms not addressed by most of the state implementation plans submitted to the Environmental Protection Agency in January of 1972. A review of the rollback methodology used in predicting future air quality attendant with projected emission reductions is presented. Inherent data base uncertainties and basic technological and socioeconomic assumptions employed are discussed. The use of a comprehensive systems analysis approach for evaluating the externalities of selected implementation plan control strategies is strongly endorsed.

•THE growing recognition of the potentially adverse environmental impact of transportation systems is well documented by 15 years of federal legislation. Legislative history reflects increasingly stringent corrective policies to minimize adverse environmental impacts.

In terms of transportation legislation, there has been a growing concern that the planning process itself be truly "continuing, comprehensive, and coordinated" and that environmental objectives, including air pollution abatement, be given due consideration. Moreover, the necessity to provide a viable alternative to the automobile through acceptable mass transportation is gaining emphasis in policy objectives and financial commitment. As given in Table 1, however, federal subsidies for mass transit remain meager in comparison to highway and aviation subsidies.

Federal air quality legislation was first enacted in 1955 to establish a national commitment to research for air pollution abatement. Research was expanded in the early 1960's to include the study of air pollution from automobiles. Responsibility for air pollution abatement remained totally with the states until 1963 when Congress authorized federal intervention primarily in air pollution problems of an interstate nature. By 1965, Congress determined it necessary to establish national emission standards for new automobiles. The 1967 Air Quality Act, although significant in the evolution of air quality legislation, did not specifically address pollution from transportation sources. In contrast, the most recent federal legislation, the Clean Air Amendments of 1970, impacts directly on the design and operation of transportation systems through several provisions including revised emission standards for motor vehicles; state air quality implementation plans that, if necessary, must include land use and transportation controls to achieve national standards; fuel additive regulations; inspection, maintenance, and retrofit programs for in-use motor vehicles; and emission standards for aircraft.

A major concern is the emission standard provision. The amendments stipulate that motor vehicles manufactured in 1975 must emit 90 percent less carbon monoxide and hydrocarbons than those made in 1970. By 1976, emissions of oxides of nitrogen must

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be reduced 90 percent from the 1971 model level. These reductions must be maintained for the useful life of the vehicle, defined as 5 years or 50,000 miles, whichever occurs first.

The amendments stipulate that, by January 30, 1972, each state is required to submit to EPA an air quality implementation plan showing how the national ambient air quality standards will be achieved. Implementation plans include emissions limitations, compliance timetables, and other measures that may be necessary to attain or maintain primary (related to health) and secondary (related to welfare) ambient air quality standards including, but not limited to, land use and transportation controls.

Primary standards must be achieved by 1975 and secondary standards within a reasonable time period. The degree to which land use and transportation controls actually will be necessary to achieve and maintain air quality standards will be a function of three factors: the degree to which the automobile industry can produce and market a "clean" automobile, the time period for which the automobile will actually remain clean, and the accuracy of vehicle use projections and future operating characteristics in urban areas.

The Clean Air Amendments of 1970 and the Federal-Aid Highway Act of 1970 exhibit a noteworthy mandate for the interface between EPA and DOT on the question of air pollution from transportation. Section 109(j) of the highway act requires the DOT Secretary, after consultation with the EPA Administrator, to develop and promulgate guidelines to ensure that the highways are consistent with the state's air quality implementation plan. Section 210(2) of the 1970 Clean Air Amendments directs that grants for developing and maintaining vehicle inspection systems shall not be made to states unless the DOT Secretary has certified to the EPA Administrator that such an inspection program is consistent with any highway safety program. Furthermore, this transportation and environment interaction at the federal level will necessarily stimulate the cooperation of transportation and air quality agencies on the state and local levels as well as promote research of transportation and air-quality relations.

In addition to specifying transportation and air quality objectives, federal legislation has mandated the coordination of single-objective programs and policies to reduce overlap and conflict (Demonstration Cities and Metropolitan Development Act of 1966 and Intergovernmental Cooperation Act of 1968). The National Environmental Policy Act of 1969 further called for the alignment of all major proposed federal legislation, plans, and programs with a national commitment to environmental quality. For any proposed federal action significantly affecting the environment, a detailed environmental impact statement must be made addressing both the short- and long-run effects in an effort to minimize adverse impacts.

The National Environmental Policy Act of 1969, the Clean Air Amendments of 1970, and portions of the Federal-Aid Highway Act of 1970 represent significant points in the evolution of legislation aimed at protecting the environment from adverse impacts of transportation. Together, these acts establish a framework for the inclusion of environmental objectives in the transportation planning process for the next few years. With such a complex task, no single piece of legislation can be viewed as static.

The necessity for readapting our approach is fully contemplated in the amendments, which require the revision of state implementation plans and air quality standards when appropriate.

Mobile sources are significant contributors to the air pollution problem. More than 92 percent of the carbon monoxide (CO) emissions in 11 urban regions is caused by mobile sources. Mobile sources in these regions also account for at least 67 percent of the hydrocarbon (HC) emissions; in four regions, this value is 90 percent or more. Mobile source contribution to nitrogen oxide (NO_x) emissions ranged up to 88 percent in two regions. Passenger automobiles account for the greatest percentage of all mobile source emissions. Therefore, air pollution abatement strategies in many urban areas must clearly concentrate on reducing automobile emissions either by making the automobiles cleaner or by curtailing automobile use.

The amendments direct that states will formulate an implementation plan that will demonstrate how the air quality standards will be achieved by 1975. The amendments provide for a 2-year extension where "technology or alternatives" will not be available soon enough to permit full implementation; this could extend the compliance date to 1977.

However, the data given in Table 2 show that transportation controls are being considered seriously in many states.

The Appendix gives air quality control regions requiring transportation-land use controls or 2-year extensions or both by EPA to attain carbon monoxide and photochemical oxidant standards.

ANTICIPATED ADEQUACY OF 1972 CONTROL STRATEGIES

The state implementation plans submitted January 30, 1972, should effectively improve air quality and achieve the ambient air quality standards by 1975 or 1977. The ultimate efficacy of the control strategies advanced in the 1972 implementation plan will determine the need and the severity of transportation controls. Therefore, the basis for the 1972 control strategy, that is, the methodology of projecting future air quality and emission reductions, must be evaluated.

GENERAL REVIEW OF ROLLBACK

Rollback technique for calculating future air quality is a first-generation control strategy design tool. The rollback calculation is based on the assumption that regional air quality will improve in proportion to a rollback of regional emissions.

Regional emissions are rolled back on the basis of the air quality reading measured at the highest pollution point, which may vary among pollutants. The adequacy of a regional control strategy is therefore dependent on the representativeness of the sampler location. It is apparent that this technique lacks spatial sensitivity. The rollback technique also lacks temporal sensitivity. Regional emissions are indiscriminately rolled back from a 1- or 8-hour maximum of air quality sample. Therefore, the eventual adequacy of a regional control strategy is dependent on two related factors: the degree to which a 1- or 8-hour air quality measurement at one point consistently fluctuates in proportion to 1- or 8-hour emission rates over the entire region and the degree to which a control strategy brings about a proportional reduction in these 1- or 8-hour emissions. If emission rates increase (during rush hour, for example) or emissions are transported to the sampler from elsewhere in greater quantities, then the maximum concentration measured during one season or year may be exceeded in subsequent years.

The inherent uncertainties concerning spatial and temporal insensitivity in the rollback technique outlined previously advance the case for contingency transportation controls in addition to exhaust controls because they determine regional vehicle-miles traveled (VMT); spatial distribution of VMT, particularly at points of congestion; temporal distribution of VMT, particularly during rush hours; and spatial and temporal distribution of actual route speeds and idling times throughout the region.

All these factors determine emissions. Therefore, the transportation system determinants of emissions must be planned and controlled if ambient air quality standards are to be achieved and maintained.

Basic rollback inputs are averaged urban factors for emissions tested according to the federal emission test procedure, deterioration rate of the exhaust device, projected growth of urban VMT, vehicle age distribution, and annual mileage per model year.

Averaged values for the preceding factors were used in making the curve shown in Figure 1.

Figure 1 shows future decreases in automobile emissions based on the replacement of older cars with new clean cars. Understandably, these assumptions are needed to make a complicated, unwieldy prediction more manageable; however, each of these averaged factors represents a potential error in determining when the air quality standards will be attained. If states had data that were deemed to be better than those on which Figure 1 is based, the states were permitted to use them. Taken singly or in combination, the possible errors can be described as follows: The federal exhaust test procedure has been modified several times to measure automobile emissions more accurately. The driving cycle that is based on an average route speed has been adjusted to simulate the average urban driving pattern more closely. But experts recognize that "conditions to which an emission-control system would be exposed by the driving public are more

Table 1. Federal funding of transportation modes (3).

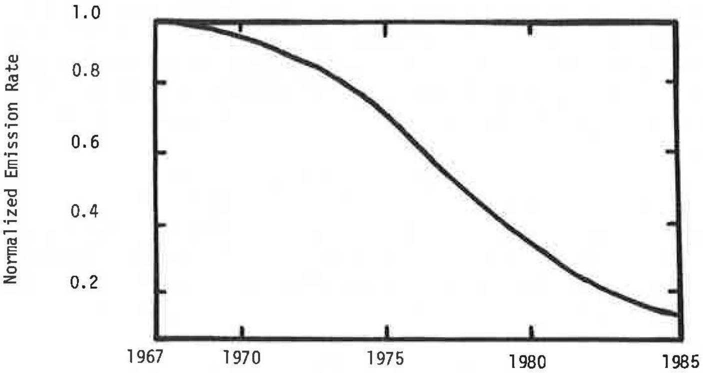
Transportation Mode	Fiscal Year (dollars × 10^6) 1955	1960	1965	1970	1971
Highway	636	2,978	4,069	4,642	4,588
Aviation	122	508	756	1,252	1,636
Urban mass transit	0	0	11	158	280
Railroad	0	3	3	21	23

Table 2. Transportation controls in state implementation plans, February 1972.

Area	Traffic Controls	Parking Restrictions	Retrofit Systems	Testing and Inspection	Gaseous Fuel Systems	Public Transportation Improvements	Work Schedule Changes	Land Use Controls
Illinois (Chicago)				x				x
Wisconsin (Milwaukee)				+				
New Jersey (all)				x				
New York (New York, New Jersey, Connecticut)		0			0	0		
Maryland (Baltimore, Washington, D.C.)	0	0	0	0	0	0	0	0
Pennsylvania (Philadelphia)	0							
Washington, D.C.	+			+	+	+		
Virginia (Washington, D.C.)	+							
Massachusetts (Boston)	0	+		+		+		
Arizona (Phoenix, Tucson)	+	0		+	+		0	
Nevada (Clark, Mohave, Yuma)	x		+	+		x		
California				+		+		
South Coast	+	+	x	+	+	+	+0	+
San Francisco Bay Area	x	+	x	+	+	x	+	+
San Diego	+	+	x	+	+	+	+	+
San Joaquin			+	+				
Sacramento			+	+				
Texas (all)				+				
Alaska (Fairbanks)	0		0		0	0	0	
Oregon (Portland)	0	0		0		0		
Colorado (Denver)	0	+	+		0			
Washington (Puget Sound)							0	
Utah (Wasatch Front)	0			0		0		
Minnesota (St. Paul)	x	0		0		x	0	
Ohio (Dayton)	0	0	0	0		0		

Note: 0 = considered, + = proposed, and x = adopted.

Figure 1. Urban vehicle carbon monoxide emission rates.



variable and extreme than those to which it would be exposed during the emission test" (1). Therefore, exhaust device deterioration and emissions are likely to be greater than those currently calculated. How much greater these emissions will be can only be determined after 1975 and then only if the "spatial and temporal distribution of actual route speeds and idling times" is known.

There are uncertainties about the exhaust control device relating to its deterioration rate and about additional research into catalysts and manufacturing lead times. In addition there are administrative problems concerning mandatory inspection.

Projected urban VMT can vary from city to city. It was assumed that VMT per vehicle would remain constant at an average of 9,800 miles per year per vehicle. The average annual mileages of various model year automobiles according to Bostich and Greenbalgh (2) vary from 13,200 for automobiles less than 1 year old to 5,700 for automobiles 10 to 11 years old.

In areas of increasing urban sprawl and of populaces with increasing leisure time, it has been noted that persons make more frequent and longer trips. Apparently, the improved highway systems required to service urban areas stimulate a latent trip demand. Because traveling is easier and quicker, people travel longer distances more frequently. VMT per year may also increase at a rate greater than currently calculated if total area vehicle populations grow more rapidly than expected.

Vehicle age distribution and hence mileage per model year for specific urban areas can differ significantly from the national average. Therefore, proper determination of urban vehicle age distribution is necessary before establishing the need and severity of transportation controls.

AN IMPLEMENTATION APPROACH: SYSTEMS PLANNING

Possible strategies for altering existing transportation systems in urban areas at this time to achieve air quality standards are indeed limited, both in feasibility of implementation and in potential for emission reduction. It is crucial, however, that strategies selected now for their short-term emission reduction potential not be detrimental in the long run by inducing more or longer trips, for example. Further, longer range planning must begin now on a systematic basis.

Good transportation system design necessitates analyzing transportation as a forceful component in the entire urban development arena. This necessity has long been recognized but has yet to be implemented. Previously, transportation design criteria were limited to factors of technological and economic efficiency. Developing criteria for evaluating the social cost of a transport network is indeed complex. Ambient air quality standards, nevertheless, do offer a quantified criterion for designing future transportation systems with respect to environmental or social objectives.

Air quality standards serve as a useful criterion, however, only if transportation decisions are evaluated in a truly systematic fashion. That is, evaluation must not be limited to the primary impact of a system on air quality. The secondary and tertiary impacts of transportation on land use and activity patterns are crucial to a thorough system analysis. Shifts in land use and activity patterns may intensify the air quality impact of a proposed transportation system beyond that originally predicted. Similarly, land use decisions must consider the potential impacts on activity patterns and subsequently on transport networks.

Environmental management strategies for dealing with pollutants may be classified in three categories: process modifications such as substituting an alternative power source for the internal-combustion engine, source controls such as adding a catalytic muffler, and assimilative capacity of the environment through use of planning land use and transportation systems. Currently, most research is directed toward the first two approaches. The potential of the third approach, however, has been recognized and is being increasingly studied.

In the long run, the assimilative capacity of the environment and the limitations thereof must be the central factor in environmental management. Our society operates in a multiple objective framework including social, economic, and environmental goals; however, the assimilative capacity of the environment poses some definite constraints on any objective societal function. Nevertheless, there are ways in which societal activities can be reorganized to achieve objectives within these environmental constraints. Although we do not now possess perfect technical capabilities for assessing and utilizing this assimilative capacity, our understanding of the relation of land use and transportation to air quality is growing steadily, and this new knowledge must be used in making urban development decisions. Transportation systems can be designed to meet social and economic objectives without adversely affecting the environment, but this will require a radical departure from current concepts of urban land use and travel characteristics. It is rather doubtful that social, economic, and environmental objectives will be achieved if trends continue as projected in the automobile-dominated transportation systems of urban areas.

REFERENCES

1. Semi-Annual Report by the Committee on Motor Vehicle Emissions to EPA. National Academy of Sciences, Jan. 1, 1972.
2. Bostich, T. A., and Greenbalgh, H. J. Relativity of Passenger Car Age and Other Factors to Miles Driven. Bureau of Public Roads, U.S. Department of Commerce, Jan. 1967.
3. Schultze, C. L. Setting National Priorities. In The 1971 Budget, Brookings Institution, 1970.

APPENDIX

State	EPA Region	Air Quality Control Region	Transportation and Land Use Controls Required for	Two-Year Extension (7/75-7/77) Granted for	Justification for Extension[a]
Massachusetts	I	Metropolitan Boston, interstate	CO, O_x	CO, O_x	Stationary source regulations (significant only for O_x) Transportation controls
		Hartford, New Haven, Springfield, interstate		CO	FMVCP alone needs until 1977 to make standards
New Jersey	II	New York, New Jersey, Connecticut, interstate	CO, O_x	CO, O_x	Transportation controls (inspection and maintenance)—already accepted by the Administrator
		Metropolitan Philadelphia, interstate	CO, O_x	CO, O_x	Transportation controls (inspection and maintenance)—already accepted by the Administrator
New York	II	Central New York		CO	FMVCP alone needs until 1977 to make standards
		Genesee, Finger Lakes		O_x	FMVCP alone needs until 1977 to make standards
		New Jersey, New York, Connecticut, interstate	CO, O_x	CO, O_x	Stationary source regulations (significant only for O_x) Transportation controls
District of Columbia	III		CO, O_x		
Maryland	III	Metropolitan Baltimore	CO	CO	Stationary source regulations Transportation controls
		National Capital, interstate	CO, O_x	CO, O_x	Stationary source regulations Transportation controls
Pennsylvania	III	Metropolitan Philadelphia, interstate	CO	CO	Transportation controls
		Southwest Pennsylvania	CO	CO, O_x	Stationary source regulations (significant only for O_x) Transportation controls (required for CO)
Alabama	IV	Metropolitan Birmingham		CO, O_x	Stationary source regulations
		Mobile Pensacola, Panama City, southern Mississippi, interstate		O_x	Stationary source regulations
Indiana	V	Metropolitan Indianapolis		CO, O_x	Stationary source regulations (EPA will promulgate those for O_x)
Illinois	V	Metropolitan Chicago, interstate	CO		
Minnesota	V	Minneapolis-St. Paul	CO	CO	Transportation controls (state needs time to complete auto study and submit results)
Ohio	V	Metropolitan Cincinnati, interstate		O_x	Stationary source regulations
		Metropolitan Dayton	O_x	O_x	Stationary source regulations Transportation controls
		Metropolitan Toledo		O_x	Stationary source regulations
Kansas	VI	Metropolitan Kansas City, interstate		CO	Regulations for catalytic crackers and gray iron cupolas
Texas	VI	Austin-Waco	O_x		
		Corpus Christi Victoria	O_x	O_x	State regulation V—control of air pollution from volatile organic compounds and CO and transportation controls
		Metropolitan Houston-Galveston	O_x	O_x	State regulation V—control of air pollution from volatile organic compounds and CO and transportation controls
		Metropolitan Dallas-Ft. Worth	O_x		
		Metropolitan San Antonio	O_x		
		El Paso-Las Cruces, Alamogordo, interstate	O_x		
Louisiana	VII	Southern Louisiana Southeast Texas, interstate		O_x	Stationary source regulations
Missouri	VII	Metropolitan Kansas City, interstate		CO	FMVCP alone needs until 1977 to make standards
Colorado	VIII	Metropolitan Denver	CO, O_x	CO, O_x	Transportation controls
Utah	VIII	Wasatch Front	CO	CO	Transportation controls
Arizona	IX	Phoenix-Tucson	CO, O_x	CO	Transportation controls
California	IX	San Francisco Bay Area	CO, O_x	O_x	Stationary source regulations Transportation controls
		Metropolitan Los Angeles	CO, O_x	O_x	Transportation controls (EPA will promulgate plan)
		San Diego	CO, O_x		
		Sacramento Valley	CO, O_x	CO, O_x	Stationary source regulations Transportation controls
		San Joaquin Valley	CO, O_x		
		Southeastern Desert		O_x	(This extension was not requested. EPA granting extension because air quality in this region is greatly influenced by air quality in Los Angeles.)
Nevada	IX	Clarke-Mohave, interstate	CO, O_x		
Alaska	X	Northern Alaska	CO		
Oregon	X	Portland, interstate	CO, O_x		
Washington	X	Eastern Wash.-Northern Idaho, interstate	CO	CO (extension until 6/77)	Transportation controls
		Puget Sound	O_x	CO, O_x (extensions until 6/77)	Transportation controls (required for O_x)

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[a] Local control measures (in addition to the nationwide Federal Motor Vehicle Control Program) need until 1977 to effect the required reductions in emissions.

SHORT-TERM TRANSPORTATION CONTROL STRATEGIES FOR AIR POLLUTION CONTROL

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Seven short-term transportation control strategies are identified as likely candidates to provide for short-term reductions in carbon monoxide emissions for motor vehicles and attainment of primary standards for carbon monoxide for the 1975 deadline: inspection, maintenance, and retrofit; conversion to gaseous fuels; traffic flow techniques; bypassing through traffic; improvements in public transportation; motor vehicle restraints; and work schedule changes. For each of these candidates, the paper describes the air pollution control potential, the maximum feasible emission reduction, and the institutional feasibility. The findings are based an an EPA-sponsored study of Chicago, Denver, Los Angeles, New York, San Francisco, and Washington, D. C. Emphasis was placed on identifying transportation controls that could be available within a period of 3 years, realistically subject to implementation by state and county governments and institutionally and technically feasible. In addition, three of the control strategies (inspection, maintenance, and retrofit; traffic flow controls; and motor vehicle and public transport improvements) were tested through simulation methods applied to each of the six cities. The paper summarizes the preliminary results of these tests as isopleths of pollution concentration for carbon monoxide, hydrocarbons, and oxide of nitrogen for the 1- and 8-hour periods of maximum VMT for a base year projected to 1977 under both uncontrolled (no transportation control strategy) and controlled conditions.

•IN August 1971, the Institute of Public Administration, Teknokron, Inc., and TRW Systems Group [under contract to the Environmental Protection Agency (EPA)] initiated a six-city study to evaluate the potential of transportation controls for reducing motor vehicle emissions in major metropolitan areas. Section 110 of the Clean Air Amendments of 1970 states (with respect to state air quality implementation plans):

> The Administrator shall approve such plan, or any portion thereof, if he determines... that it includes... such other measures as may be necessary to insure attainment and maintenance of such primary or secondary standard, including, but not limited to, land-use and transportation controls....

The purpose of the study was to provide assistance in the preparation of the transportation component of state plans through intensive study of six metropolitan areas (New York City, Washington, D. C., Chicago, Denver, San Francisco, and Los Angeles). The most promising transportation controls were evaluated in detail for their pollution reduction potential and implementation difficulties. These controls included inspection, maintenance, and retrofit; gaseous fuel conversions; traffic flow improvements; increased mass transit use; motor vehicle restraints; and work schedule changes. In evaluating the pollution reduction potential and implementation difficulties of these transportation controls, two efforts were mounted: First, a major examination was undertaken of all potential transportation control candidates; second, selected strategies were tested in each of the six cities. The major focus of this paper will be on the first effort, though some consideration will be given to the preliminary results of the testing of specific strategies.

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STUDY GUIDELINES

Before examining the results of these two efforts, it is essential to spell out the criteria provided to the study by EPA:

1. The project would be concerned essentially with carbon monoxide emissions from motor vehicles although the problems of other motor vehicle emissions (e.g., nitrogen oxides and hydrocarbons) would be kept in mind throughout the study.
2. The project was to focus on attainment by 1975 (later extended to 1977) of primary standards for carbon monoxide although it was expected that recommended transportation controls would also serve to assist in achieving the secondary standards.
3. The measures must be available and must be expected to take effect within the next 3 years. A major alteration in metropolitan land use and urban design, for example, would not meet this criterion because, unless major efforts are already under way (e.g., the Washington, D.C., Metro system), these factors must be considered fixed for at least a decade.
4. The measures must be available locally, i.e., realistically subject to manipulation by state and local governments. A measure that would require basic alterations by automobile makers of the internal-combustion engine, for example, would not be a locally available measure.
5. The measures must be institutionally feasible. For example, measures that are politically unacceptable or administratively unworkable would not meet this criterion.
6. The measures must be technically feasible. For example, a measure that requires retrofit devices that are beyond the state of the art would not be technically feasible.
7. The study focused on light-duty vehicles as defined by EPA, generally stated as commercial vehicles with a rating of up to 6,000 lb or passenger vehicles with capacity of up to 12 passengers.
8. Primary attention was given to automobile air pollution problems arising from travel into, out of, and within the central business district (CBD) during the peak rush hours of workdays.

Within the guidelines, the task of the project (in its first phase) was to identify major transportation control candidates, their potential for pollution reduction, and the difficulties that might be encountered in their implementation. An intensive literature search was undertaken of the existing ideas and experience relevant to transportation controls. As part of this effort (as well as for the second phase), reconnaissance trips were scheduled to each of the selected cities. The purpose of the reconnaissance trips was to obtain information and pertinent documents (e.g., local budgets, transportation plans, and air pollution control statutes) and to interview central city, regional, and state officials having responsibility for both transportation and air pollution control in order to ascertain institutional feasibilities, special economic problems, and specific circumstances in each city with regard to each of the strategies. The interviews and field trip work in each of the cities provided the basic data for both phases of the study as well as the insight for making decisions on potential pollution impacts where data were not available.

From the initial phase of the six-city study emerged an interim report (1) that considered the impact of seven short-term transportation control strategies considered to be the most likely candidates for implementation within the time available to the cities: inspection-maintenance-retrofit, conversion to gaseous fuels, traffic flow techniques, bypassing through traffic, improvements in public transportation, motor vehicle restraints, and work schedule changes. For each strategy, the air pollution control potential was analyzed, the maximum feasible emission reduction was estimated, and its institutional feasibility was explored. The report contains a considerable data base, specific data analyses, and the recording of all relevant experience with each of the controls. The section that follows provides a summary of the findings and conclusions of that report with respect to each transportation control strategy examined.

SHORT-TERM TRANSPORTATION CONTROL STRATEGIES: FINDINGS

Inspection, Maintenance, and Retrofit

Broadly defined, the programs of inspection, maintenance, and retrofit as discussed in the study involved (a) the inspection of in-use vehicles; (b) the identification of high emitters and, hopefully, the provision of some diagnostic information; and (c) some requirement for subsequent corrective action (whether at inspection stations or garages). Conceivably, some corrective actions could be required without inspection. For example, spark plugs or breaker points could be replaced on the basis of their expected life. Corrective action might also be required on the basis of records kept for the federal new car warranty program. Nevertheless, inspection appears to be a necessary prerequisite to corrective action for in-use vehicles on two counts: to determine what corrective action needs to be taken and to reduce possible underservicing or overservicing. For these reasons, it was assumed that inspection should be an integral part of any effective program involving maintenance or retrofit (2).

At the present time, enforcement of federal new car emission standards is the principal public policy to control motor vehicle emissions. Its effectiveness depends on in-use vehicle conformance (i.e., mileage accumulation without a substantial deterioration of exhaust control systems). Under the federal Air Quality Act, authority to regulate emissions from in-use motor vehicles is retained by state and local governments; however, states are required to provide for periodic inspection and testing of in-use vehicles to the extent "necessary and practicable." The same legislation also authorizes federal funding for "effective" inspection, maintenance, and retrofit programs.

Preliminary indications are that regulation of in-use vehicle emissions will be necessary in several large metropolitan areas to meet national ambient air quality standards. But the practicability and effectiveness of inspection, maintenance, and retrofit cannot be precisely established at this time. For example, the time required to physically implement a statewide emission inspection program (whether state owned and operated, state regulated, or operated by the private sector) is probably small (on the order of 6 months to 1 year). This "physical implementation time" would include the time required for constructing facilities, acquiring staff, and training professional personnel and would, of course, depend to some degree on the testing procedure selected. However, the "real implementation time," which includes total elapsed time from consideration of program initiation by the policy-makers until actual program operation, will probably be considerably longer, among other things because of the political problems involved (i.e., resistance to programs on the part of strong rural interests in some state legislatures, opposition from automobile owners associations, and so forth).

Even if such a program could be implemented, estimating the effectiveness of inspection, maintenance, and retrofit over time is impossible at present because of inadequate information (e.g., with respect to deterioration of maintained vehicles between inspections) and inherent uncertainties (e.g., as to post-1975 exhaust control systems). For any area's vehicle population, the potential emission reductions consist of both the initial reduction achieved at the time of maintenance and retrofit and the reduction over time. (Actual on-the-road reductions are significantly less than initial reductions because of the deterioration of emission control equipment efficiency with accumulated mileage—referred to here as reduction "over time.") The potential for initial emission reductions will depend on the accuracy of the test procedure and the level at which emission standards are set (which in turn determines the test rejection rate). Preliminary indications concerning rejection rates seem to indicate that for most states these rates should not exceed 20 to 40 percent so as to prevent a critical overload of commercial repair facilities and to eliminate heavy burdens on the inspection program that occur because of demand for retest (3, 4). The probability of adverse public reaction to high rejection rates should also be a central consideration when inspection programs are developed.

Unfortunately, present knowledge does not permit a determination of the deterioration rates of maintenance and retrofit. Deterioration over time will depend on a number of unknowns, such as the reliability of post-1971 emission control systems (not to mention the uncertainty attached to post-1975 emission control systems, with potentially more sophisticated technology). Deterioration rates for inspection and maintenance are shown in Figure 1. As indicated, an initial emission reduction (from e_3 to e_1) is achieved at the time of inspection and maintenance (t_1). Reductions over time depend on the slope of the deterioration curve. With an early substantial deterioration (curve d), fully half of the initial reduction would be dissipated within 2 months; with linear deterioration (curve d^1), the same initial reduction would return to half its premaintained level within 6 months; with late substantial deterioration (curve d^2), half of the initial reduction would disappear after 9 months. (These deterioration curves and time periods, it should be stressed, are solely for purposes of illustration; further empirical research is required to determine actual deterioration rates over time.)

Different deterioration rates, in turn, require different intervals between inspections. If, for example, initial reductions are dissipated rapidly, frequent inspection would be necessary to maintain vehicles below a given level. With a target emission level at e_2 (Fig. 1), the appropriate interval between inspections would be determined by that point in time at which emissions returned to the target level. Whether the time to t_2 is 2 months (t_1 - t_2') or 6 months (t_1 - t_2''') has an obvious bearing on the costs and feasibility of any exhaust emissions inspection program. Acquiring the additional information needed to make for effective inspection programs will probably take another 6 to 12 months for experimentation in pilot projects. These lead times imply that most federally funded inspection, maintenance, and retrofit programs will probably not be in place until at least 1975.

Without this information, it is nevertheless possible to arrive at a rather broad range of initial emission reductions that can reasonably be expected. On the basis of research performed by TRW, Inc. (5), Northrop Corporation (2), and the state of New Jersey (6), as well as information from EPA officials in the Bureau of Mobile Source Pollution Control, it appears that the most likely initial reduction in aggregate carbon monoxide emissions would be on the order of 10 to 25 percent. (By aggregate we mean the carbon monoxide attributable to light-duty motor vehicles in any given area. To the extent that other motor vehicles or stationary sources contribute importantly to an area's emissions, the reduction possible from inspection and maintenance would be less than estimated here.) However, it appears that values in the upper range (particularly 20 to 25 percent) are decidedly less likely than those in the lower range (particularly 10 percent). It should also be stressed that these values represent a definite upper bound for the air pollution control potential of inspection and maintenance because subsequent deterioration of maintained vehicles (in the interval between inspections) would lessen the effectiveness of this control.

With respect to retrofit, currently available "industry-type" devices appear able to reduce emissions by 20 to 25 percent for precontrolled vehicles. Aggregate emission reductions, therefore, depend on any area's proportion of precontrolled vehicles and their associated vehicle-miles traveled (VMT), bearing in mind that older cars are driven less than newer cars.

If at least 3 years would be required for legislation and the certification and installation of equipment, it appears the earliest date for completion of a retrofit program would be 1975. Based on this assumption (and using vehicle age distribution and VMT by age data), it was possible to calculate the upper bound of possible carbon monoxide reductions for any area. It was concluded that only modest emission reductions are possible especially for the light-duty vehicle population as a whole (1). It was also concluded that retrofit did not warrant further consideration as a control with widespread application. The possibility of new, more effective technology may, of course, alter the situation. Other more sophisticated technology (e.g., catalytic convertors, thermal reactors, and exhaust gas recirculation) is currently being tested and may hold more promise, particularly if it is applicable to controlled vehicles as well.

Gaseous Fuel Systems

Within the next 5 years, only three types of gaseous fuels can be seriously considered as alternatives to gasoline for powering motor vehicles: liquefied petroleum gas

(LPG), compressed natural gas (CNG), and liquefied natural gas (LNG). These fuels are inherently cleaner burning (produce fewer heavy hydrocarbons) than gasoline because of their lower molecular weight and carbon content. In addition, gaseous fuels ignite more rapidly, and the combustion process proceeds more nearly to completion, leaving less unburned fuel in the exhaust stream.

Modification to gaseous fuel requires the installation of a special carburetor, special fuel tanks (pressure tanks for LPG and CNG and cryogenic tanks for LNG), pressure-regulating devices, shutoff valves, and fuel lines. This is generally regarded as "simple" conversion as opposed to more sophisticated (and costly) modifications that may include installation of a special venturi carburetor (to allow for lean air-fuel mixtures at low power levels and enriched mixture at high power operations), refined adjustment of engine variables, exhaust gas recirculation, exhaust air-injection thermal reactor system, and a catalytic convertor. Vehicles modified to this extent, however, would probably have emission levels similar to those required by 1975 and 1976 for gasoline-fueled operations (and therefore would be of little advantage from a pollution control point of view). Consequently, the following discussion is confined to simple conversion. For simple conversion, the cost of modifying an in-use light-duty vehicle to CNG or LPG ranges from \$350 to \$500, whereas conversion to LNG may cost from \$800 to \$1,000.

It was the conclusion of the study that the conversion of large numbers of motor vehicles to gaseous fuels would be impractical or unwarranted in most major metropolitan areas for the following reasons:

1. Natural gas is currently in short supply, and no major expansion in capacity is anticipated in the near future. Low supplies of LPG combined with preferential treatment for heating customers have already caused a reduction in conversions and loss of sales.
2. Conversion of large numbers of vehicles and implementation of an adequate fuel distribution system would be extremely expensive.
3. Adequate supplies of conversion equipment are currently not available. Consequently, at least 2 to 3 years would elapse before significant numbers of vehicles could be modified (7).
4. Considerable efforts are currently under way to meet stringent 1975 federal emission standards through modification of conventional gasoline engines. If successful, these efforts would obviate the need for gaseous-fueled vehicles, which would be unable to meet the preceding standards without engine modifications and substantial supplemental equipment.

In some metropolitan areas, however, fuel supplies, distribution systems, and conversion equipment may be adequate for small-scale conversions (e.g., commercial fleets) in highly polluted downtown or densely developed districts. Aside from the possible technical difficulties, the principal institutional problems in implementing small-scale conversions may consist of present safety regulations at both state and local levels that discourage or preclude gaseous fuels for motor vehicle use, the considerable costs and risks for fleet owners and operators of converting to natural gas or LPG, and the limited legal authority of municipalities over large vehicle-fleet owners and operators.

Conversion of gasoline-powered motor vehicles to gaseous fuels should be considered only for large centrally maintained fleets that account for a high proportion of total VMT and operate in severely polluted areas. Medallion taxicabs in the Borough of Manhattan are one such example. Emission reductions achievable through conversion to gaseous fuels are highly variable. However, for pre-1975 motor vehicles, significant reductions in carbon monoxide and hydrocarbon emissions and some reduction in nitrogen oxides emissions can be expected.

New car federal emission standards for 1975 and later are below levels that can be achieved through simple conversion. Consequently, conversion would be an interim measure, assuming 1975 emission standards are achieved. However, diversion of natural gas from power production or space heating to motor vehicle use would be counterproductive from a pollution abatement point of view. Furthermore, as noted previously, implementation problems loom large even for the limited case of converting fleet vehicles. Specific economic and/or regulatory incentives would be required to induce fleet owners to convert to gaseous fuels in view of the capital investments required, the logistics of fuel supply, reduced drivability, new maintenance requirements, and the loss of manufacturers' warranties implicit in conversion.

Traffic Flow Techniques

As used in the study, "traffic flow techniques" refer to those traffic engineering measures that have as their principal objective a reduction in delays, idling periods, and stops and starts that, in turn, would tend to increase average vehicle speeds on the existing street network. In terms of air pollution control potential, simply stated, motor vehicle exhaust emissions are lower in freely flowing traffic than in congested, stop-and-go conditions. However, there is some evidence that NO_x emissions increase with increased vehicle speeds. Consequently, consideration of traffic flow techniques requires careful evaluation of pollutant trade-offs, especially in those areas where nitrogen oxides appear to be the primary problem. Assuming an established relation between emissions and speed, what increases in average vehicle speeds and accompanying carbon monoxide reductions can be anticipated from traffic control and flow improvements? Straightforward as this question may seem, a simple answer is not easily given because of a number of complicating factors.

To begin with, from a pollution viewpoint, the degree of potential improvement depends in large measure on the baseline speeds prior to implementation of traffic flow techniques. For example, increasing average vehicle speeds from 5 to 10 mph is much more important from an air pollution control point of view than increasing average vehicle speeds from 25 to 30 mph. In turn, baseline speeds depend on factors such as the physical characteristics of the urban street network under consideration, the existing traffic volumes and available capacity, anticipated growth, and so forth. All of these factors vary by city.

Second, any accurate evaluation of the impact of traffic flow improvements must take into account network (system) repercussions, i.e., those repercussions that extend beyond the specific facility being improved. Unfortunately, however, most available data as to the impact of potential improvements are for specific facilities and not for entire networks. It may be highly misleading to consider an improvement strictly in terms of the specific facility. For air pollution control purposes, improvements need to be studied in terms of impact on the entire street network. In addition, longer time periods (perhaps several years in some cases) would be needed to allow all secondary and tertiary repercussions and adjustments to be worked out. For example, it is well established that increased travel speeds (and therefore shorter trip times) eventually generate longer trips. Therefore, a consequence of improved traffic flow (without motor vehicle restraints) could well be higher VMT with accompanying greater (though perhaps more dispersed) emissions.

Finally, in the short run of 3 to 5 years, the available street capacity is relatively fixed in most large urban areas and saturated during peak hours. Improvements in either added or existing capacity could result in higher speeds or shorter travel times or both; the latter, in turn, could release latent demand, a result of peak-hour capacity saturation, and generate new trips, until once more congestion acts as a constraint on the use of the automobile. The rapidity with which traffic builds up in response to new or improved facilities will depend on many factors including the existing traffic density on the present street network. However, even where capacity saturation is found, overall traffic volume in most U.S. metropolitan areas (and certainly for the cities of Chicago, Washington, D.C., San Francisco, and Los Angeles) will continue to grow—probably at a rate of about 2 to 4 percent a year. Thus, from a pollution viewpoint, both long-term traffic trends and induced travel tend to limit the air pollution control potential of traffic flow improvements in the medium- and long-term period. In most metropolitan areas, the additional capacity afforded by traffic flow improvements would tend to be "used up" within 2 to 4 years because of the higher volumes that would be attracted.

Impact of Traffic Improvements on Speed

Appraisal of the network impact of traffic flow improvements on speed requires a data base currently not available. To begin with, there is no comparability for existing data, all of which relate to specific traffic flow techniques implemented in specific cities at specific sites. The site-specific nature of traffic flow improvements has already been discussed. Second, even if (judgmentally) comparable experience were examined, the data typically available do not include observations over a period long enough to enable evaluation of major repercussions; only the most immediate impacts are usually measured. Furthermore, traffic flow improvements at one point of the street network frequently result in deterioration in traffic conditions at other points; often these network-wide trade-offs are not considered.

Despite the difficulties of developing network averages of the impact on speed of implementation of various traffic flow techniques, an effort was made in the study to evaluate the evidence and estimate the relative orders of magnitude of speed impacts that might be expected. Recent comprehensive research carried out under sponsorship of the National Cooperative Highway Research Program (8) provided a major source of information. The project provided information based on actually demonstrated methods of improving traffic flow on complex networks of city streets as compared with the usual information available for only spot or arterial improvement. Dozens of traffic engineering improvements were implemented and evaluated in Newark and Louisville. A network analysis was conducted to evaluate various models for use in the analysis of downtown area traffic flows. Work of the NCHRP study represents one of the most comprehensive efforts to evaluate the impact of various traffic engineering techniques and provided the major source for evaluating the magnitude of the impact of major traffic control improvements on speed.

The experiments undertaken in Newark and Louisville were reviewed, and all observations in which there were positive increases in speed were assembled and analyzed. Traffic flow control experiments with negative speed results were not taken into account. It was assumed that any speed losses not offset by substantial gains in dominant traffic streams would not be continued. In addition, our purpose was primarily to show the upper bounds of emission reductions that would be possible with successful traffic control and flow techniques.

Based on these before and after results, it was found that, of the 43 instances in which average travel speeds increased after implementation of traffic flow techniques, approximately two-thirds of the speed improvements fell between the class intervals of 5 to 10 percent at the lower bound and 35 to 40 percent at the upper bound. Our experience in the six cities indicated that, at least for the six cities in the study, the improvement in speed was anticipated to be somewhat in the range of 10 to 15 percent (clearly closer to the lower bounds).

Assuming an increase in average vehicle speed along an urban arterial of 10 to 15 mph, emissions might be reduced by about 20 percent, at best. However, these emission reductions would be short-lived unless accompanied by some form of restraint. At worst, emissions could be significantly greater than if no "improvements" had been implemented at all.

It was concluded that traffic flow techniques, unless accompanied by motor vehicle restraints, could well be counterproductive from an air pollution control point of view. Furthermore, many traffic flow techniques would render public transport (especially bus) less attractive relative to the automobile. Finally, implementation of traffic flow improvements on a network-wide basis would be a costly measure, particularly when weighted against the short-lived effectiveness of these controls.

Bypassing Through Traffic

In large central cities, through traffic can account for about 5 to 20 percent of total traffic volumes, even at peak hours. From an air pollution control viewpoint, bypassing through traffic would shift VMT away from already congested central city roadways and smooth traffic flows by a separation of through and local traffic in the areas affected. Both results would reduce emissions in high pollution areas of the central city, the first by redistributing emissions elsewhere and the second by bringing higher average vehicle speeds, fewer stops and starts, less idling, and emission reductions associated with these improvements.

Several possibilities are available to bypass through traffic, including the use of circumferential routes, inner-city barriers, and directive signs or signals.

An important example of bypassing technique, using inner-city barriers, was implemented in Gothenburg, Sweden, in 1970 (9). The city's CBD was divided into wedge-shaped quadrants. Physical barriers were constructed between these quadrants, thus making traffic through the CBD impossible (except to emergency vehicles such as fire and ambulance and public transit). In effect, each quadrant became a self-contained precinct with only local circulation allowed. All other traffic was required to use a ring road, entering and leaving each quadrant at designated locations (Fig. 2).

The success of the barriers in decreasing through traffic in Gothenburg can be clearly seen. After 8 weeks of operation, traffic on one of the main arterials (Oestra Hamngatan) was decreased by some 70 percent. As Figure 2 shows, traffic has shifted to the peripheral streets. Barriers have not been used in large scale anywhere in the United States as yet, and the size of the experiment in Gothenburg (whose population numbered slightly more than 444,000 in 1971) does not provide adequate evidence that a similar strategy can be easily and quickly transferred to any major United States city. Even the comparatively small Gothenburg experiment entailed a planning period of 7 years. In fact, given the size and extent of vehicle ownership in most major cities in the United States, it is doubtful that a similar experiment could be implemented before at least 2 or 3 years of planning. To the extent that similar measures depend on new construction, they are not likely to be implemented in less than 5 years.

If other measures, such as directive signs or signals, are used and are designed specifically to attract and divert vehicles away from central cities, some emission reduction may occur and more rapid implementation may be possible. It was the best judgment that the reductions that could be achieved in the short term—within 5 years—would not exceed 5 percent for most central cities. More substantial reductions would require motor vehicle restraints to discourage through trips. Given the substantial share of through traffic in some central city areas (a third or more of total traffic is typical in the CBD), this possibility appears to merit more attention that it is now receiving. However, construction of major highway facilities including circumferential routes is not likely to be feasible by 1977. In urban areas where circumferential facilities are already under construction, some bypassing of through traffic might be possible by 1977. But where no plans exist, at least 8 to 10 years would be required. Even with an accelerated effort, it is unlikely that major construction of circumferential facilities could be achieved in less than 5 to 8 years.

Improvement in Public Transportation

In the study, mass transit was considered as conventionally defined (rail and bus systems) as well as including a number of other means of conveyance such as the taxicab, demand-responsive systems, car pools, and people movers. Improvements in public transportation could, conceivably, reduce motor vehicle emissions in the short run by attracting motorists away from their automobiles and in the long run by encouraging high-density development and more efficient land use.

Before proceeding, however, a caveat is in order concerning the role of public transport improvements in the context of air pollution control. Extensive review of recent experience with public transport improvements reveals that these improvements alone hold little promise for attracting motorists out of their automobiles. Modal diversion to public transport, moreover, does not necessarily reduce motor vehicle traffic. Of all public transport improvements in recent years, the Philadelphia-Lindenwold line has often been cited as a great modal diversion success. However, special analysis undertaken as part of this study did not establish that any significant reduction in motor vehicle traffic had occurred. The best judgment is that public transport improvements would be unlikely to reduce the VMT of light-duty vehicles (and hence emissions) by more than 5 percent in any major metropolitan area. Improve-

Figure 1. Hypothetical deterioration rates for inspection and maintenance.

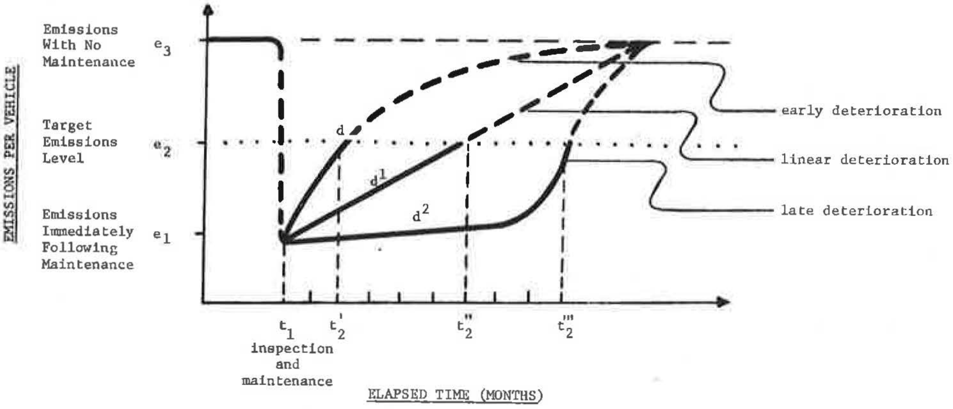
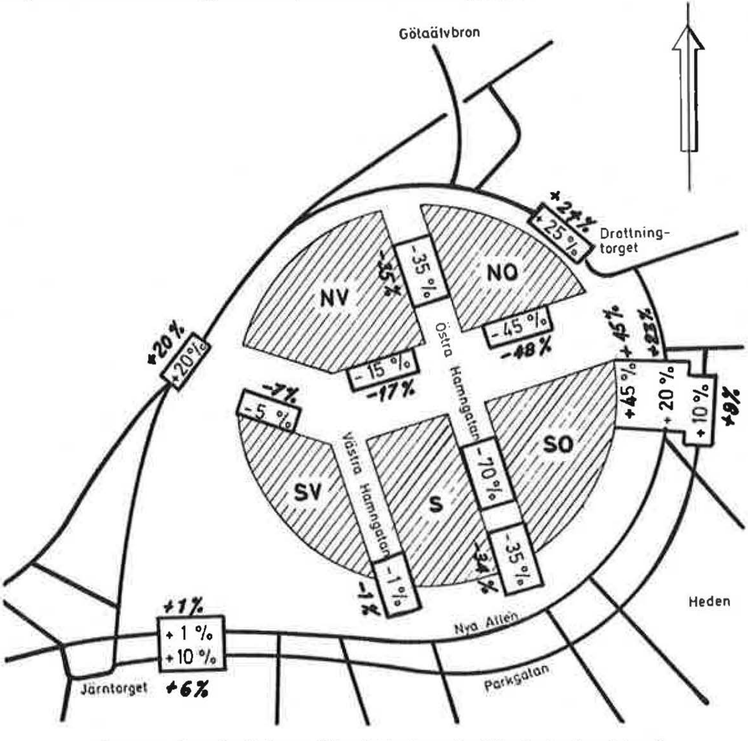


Figure 2. Gothenburg, Sweden, traffic restraint system.



Source: Curt M. Elmberg, "The Gothenburg Traffic Restraint Scheme" (Paris: Organization for Economic Cooperation and Development, May 1971), p. 22.

Note: Hatched areas are quadrants; lines represent major arterials. Numbers refer to percentage change in vehicle volumes along central area routes two weeks and eight weeks (figures in boxes) following introduction of scheme in August 18, 1970.

ments in public transport, therefore, are a necessary but not sufficient condition for reducing motor vehicle emissions. They are necessary because reducing motor vehicle use in high pollution areas will require substantially improved public transport to provide an alternative means of making trips. They are not sufficient, however, because public transport improvements, unaccompanied by motor vehicle restraints, will reduce motor vehicle traffic only modestly, if at all. Indeed, as a result of some improvements, especially rail, emissions may actually increase where they are currently worst, in the downtown and other densely developed areas. Historically, the effect of good transit has been to encourage the economic development of the CBD it serves. When a new transit system is installed, development tends to take place around the downtown stations of that line. Development is especially intense at the node points—where two or more lines cross. Because ground rents are high, the new office buildings also tend to be high. As a result, more people tend to work in the downtown than was previously possible. Although a large number of new workers probably ride the new, convenient transit system to work, some percentage will use motor vehicles. The proportion of new motorists may be small relative to transit users, but their absolute numbers are important, particularly at peak hours.

Capital Costs—Of considerable importance in connection with public transportation is the issue of costs of improvements. Within the time available to complete the study, preparation of detailed estimates of the investment costs required to substantially improve public transportation was not possible. However, preliminary estimates were prepared of potential investments in public transport between 1970 and 1980 to allow identification of the overall orders of magnitude implied. The estimates included a mix of short-lived or off-the-shelf items (buses, transit cars, and so forth) and very long-lived or custom-built items (new rights-of-way, including track and structures for high-capacity rapid transit and commuter rail). Not included were demand-responsive transit systems and generally untested technology. The estimates include substantial unmet demands (at 1971 population levels) that are expected to be fulfilled or initiated before 1980.

The basic approach was to estimate rail transit on the basis of work under way and plans in process and bus transit on the basis of industry replacement cycles, population growth, rate of urbanization, and changes in real per capita income. These estimates do not include the scope of changes (i.e., substantial improvements in public transport services) that apparently are needed to meet national air quality standards by 1975, and in that context they must be considered conservative. Table 1 gives the estimates for the six cities focused on in this study. The estimates indicate that about $13.8 billion will be required for investment if the existing plans plus some moderate improvements (such as people movers) are implemented.

The estimates should be considered within the context of severe financial difficulties facing most transit systems across the United States. Most systems cannot cover operating costs let alone finance improvements. Consequently, federal funding would be required. However, if (as provided for in the Urban Mass Transportation Assistance Act of 1970) the federal government provided two-thirds of the $13.8 billion investment needs estimated previously, more than 90 percent of federal funds obligated for the entire country would be expended on just the six cities of New York, Chicago, Washington, D.C., Los Angeles, San Francisco, and Denver. Clearly, if even modest improvements in public transport are to be made, a much greater federal commitment will be required.

Operating Costs—In addition to capital investment requirements, improved public transportation will generate increased operating costs. Again, estimates for the six cities are not possible at this point in the study. Moreover, the orders of change will of course depend on the specific operating characteristics of each city's transportation system. However, estimates have been prepared for Washington, D.C., for the year 1975. The estimates must be considered as rough orders of magnitude. The following assumptions were made:

1. The Metro (the new rail transit under construction) will not be in operation by 1975, and all bus services will be used;

2. There would be about a 10 percent passenger diversion to bus transit by suburbanites and a somewhat smaller diversion for trip-makers within the District of Columbia;
3. No cost increases would be required for off-peak service—only for increased demands during the peaks;
4. No change in labor practices would be needed;
5. No fare change would be established until 1975 and thereafter a 12 to 15 percent increase would be made; and
6. Only moderately improved services would be forthcoming.

Table 2 gives the results of these estimates.

The data given in Table 2 show that the overall system deficit would be in the order of $15 million in 1975, if no fare increases were provided, and about $5 million with a fare increase of about 15 percent. Thus, the deficit would increase sharply from the 1969 level without any fare changes and would probably decline slightly with a moderate fare increase. However, even a deficit of $15 million annually by 1975 would not represent an insurmountable cost obstacle (in contrast, perhaps, to the capital investment requirements) for expansion of the service needed, especially if parking taxes are imposed to restrain motor vehicle use. Revenues from such a tax would undoubtedly go a long way toward covering such deficits.

Operating Deficit for the United States—In 1970, for the United States as a whole, the total operating deficit for transit operators amounted to about $288 million (a large part of which was accounted for in large cities such as New York, Boston, San Francisco, and Philadelphia where air pollution problems are at their worst). If no improvements are made in existing public transport services, the deficit (conservatively estimated) can be expected to double by 1975 (and is probably more likely to be closer to $600 million). If major improvements were instituted, operating deficits would be even greater, particularly if fares were not increased.

Motor Vehicle Restraints

In the context of the six-cities study, motor vehicle restraints were considered to be those measures that could reduce to some degree motor vehicle use in high air pollution areas. These measures consist of controls over parking or road use or both by administrative action or pricing policy and are summarized in Table 3. Subsequent sections discuss the air pollution control potential of these motor vehicle restraints and their institutional feasibility (10).

For many transportation controls to be effective, motor vehicle restraints will be required. These restraints could consist of parking regulations or imposition of higher parking prices, regulation of road use (pedestrian malls or vehicle-free zones), or road pricing (toll collection or the use of a congestion pass in high pollution areas). None of these measures will be politically popular, and intense opposition can be expected from those whose direct interests are involved (road users, automobile owners' associations, downtown businessmen, parking garage owners, and others).

This suggests that, for motor vehicle restraints to be at all acceptable to the public, and hence workable and effective, the quality and quantity of public transport must be importantly and visibly improved. Improvements should be made in conjunction with any strategy to reduce motor vehicle use.

The most promising restraint, at least for the short term, would be to intensify control over the location, amount, and use of parking space, both on- and off-street. The most desirable method of control appears to be through municipal taxation, particularly where local revenues will be required for improved and expanded public transport. The effectiveness of parking controls, however, will be limited by several factors. First, through traffic and internal circulation will not be affected; indeed it would probably be encouraged if a lower volume of local traffic results from parking controls in some areas. Second, comprehensive parking controls, particularly over already existing space provided by private firms and government agencies, would be difficult to enforce and would probably require new legislation. In many downtown areas, such space constitutes more than half of existing storage capacity.

To the extent that it is practical, road pricing would be a more effective motor vehi-

Table 1. 1980 investment estimate for urban transport (in millions of dollars).

City	Rail Rapid	Suburban Rail	Buses	CBD People-Movers	Total
New York	2,833.1	2,223.2	587.3	250.0	5,893.6
Chicago	1,011.2	240.9	162.3	12.0	1,426.4
Washington, D. C.	2,970.0[a]	—	—[b]	6.0	2,976.0
Los Angeles	2,162.3	—	—[b]	24.0	2,186.3
San Francisco	427.7[c]	—	—[b]	16.0	443.7
Denver	852.6	—	—[b]	4.5	857.1
Total	10,256.9	2,464.1	749.6	312.5	13,783.1

[a] Approximately $200 million is now under contract or in active bidding.

[b] Estimates for buses are not given except for New York and Chicago where bus investment plans were specified separately as part of comprehensive multimodal plans. However, our estimates for bus investment needs for all metropolitan areas of more than 1 million population (excluding New York City, Chicago, Boston, Philadelphia, and Cleveland–all of which include buses as an intergral part of multimodal plans) amount to less than $119 million. Washington, D.C., San Francisco, and Denver represent a relatively small percentage of this total.

[c] Represents 30 percent of the full cost. About 70 percent is complete, and 30 percent is under contract.

Table 2. Bus transit estimated revenues and expenses for Washington, D.C., area.

Year	Revenue (millions of dollars)	Cost (millions of dollars)	Deficit (millions of dollars)	Passengers (millions)	Deficit per Passenger (cents)
1969	50	58	8	150	5
1975 (no fare change)	65	80	15	186	8
1975 (12 to 15 percent fare increase)	75	80	5	186	3

Table 3. Motor vehicle restraints.

Restraint	Description	Experience[a]	Results
Regulating parking	Reduce by administrative action motor vehicle storage capacity, off-street or on-street parking or both in or near high pollution areas.	Some large cities have moved to control the construction of additional parking garages in downtown areas. However, other off-street parking (e.g., spaces in commercial buildings made available to employees) are usually outside of municipal control. On-street parking has been controlled in relatively few areas, except during peak hours.	Would reduce motor vehicle use in high pollution areas and, to some extent, travel to and from them. This reduction, particularly if combined with controls over on-street parking, could also significantly improve traffic flow. However, through and circulating traffic would not be reduced and might even be encouraged.
Pricing parking	Impose parking prices for off-street or on-street parking or both in or near high pollution areas.	Increased off-street parking charges have occurred in virtually all metropolitan areas because demand exceeded supply. However, nominal charges (well below those for off-street parking in the same vicinity), are still in effect for most on-street parking. Moreover, most off-street spaces are still allocated outside the market mechanism (e.g., to employees and residents). Parking meters are still the major method of charging for on-street space.	
Regulating road use	Reduce by administrative action road network used (e.g., through pedestrian malls or vehicle-free zones) in or near high pollution areas.	Some 24 U.S. cities have introduced such schemes (mostly on an experimental basis) in recent years.	Would reduce or eliminate motor use in high pollution areas and, to some extent, travel to and from them. However, would create host of transportation problems (e.g., fringe parking, goods delivery, improved access, and internal circulation) and possible greater congestion and accompanying motor vehicle emissions on immediately adjacent local streets and arterials.
Pricing road use	Impose charges for motor vehicle use of selected portions of urban street networks in or near high pollution areas.	Toll collection facilities in and around Baltimore, Boston, Chicago, Jacksonville, Kansas City, Miami, New York City, and Philadelphia. Other techniques for imposing road pricing are currently available, as summarized in text, but have only been tried in limited applications or not at all.	

[a] Most experience with motor vehicle restraints has been motivated by objectives other than air pollution control (e.g., reducing congestion, minimizing motor vehicle-pedestrian conflicts, enhancing the aesthetic and commercial appeal of central city areas, and, in the case of parking charges and toll collection, raising revenues). However, particularly in some large cities, growing concern about automobile air pollution has given rise to increasing public support for curbing motor vehicle use.

cle restraint for purposes of air pollution control. This potential, as well as other ancillary benefits, argues strongly for further exploration of the concept to determine whether (and how) such a system could be implemented. Some measures (e.g., toll collection or a congestion pass approach) show promise for near-term application although substantial increases in enforcement may be required. The mechanics of imposing these controls, however, are less of a problem than gaining public acceptance to limit"freedom of the roads" in areas of high air pollution. The feasibility of these measures will, of course, vary widely in different metropolitan areas, depending on such factors as geography of the city, size of the central area, availability of public transport, shape of the street network, urgency of the local air pollution problem, and—probably most importantly—the local attitudes toward air pollution control and the degree to which public officials are willing to propose politically unpalatable measures to achieve air pollution control.

If motor vehicle restraints are to be effective, dramatic departures from previous practice would appear necessary (e.g., tripling or quadrupling parking rates for many areas of the city or tolling off major portions of the downtown). Restraints this severe could cause profound social, economic, and land use effects, many of which may be highly undesirable from other standpoints. For example, severe motor vehicle restraints in some areas of the central city would cause employment centers to shift to the suburbs, an undermining of the city property tax base, and particularly adverse economic effects on low-income residents.

An extensive review of the literature was undertaken to identify the potential impact of motor vehicle restraints. This review indicated that there was little evidence available as to the potential pollution reduction impact of restraints. Based on the little evidence later available and our judgment, and assuming parking controls or some other form of road pricing, the range of reductions in VMT reported in the interim report was estimated to be between 5 and 25 percent with 25 percent being the upper limit of any practical action that might be taken within the time frame of the study, 1977.

As the study progressed toward completion, additional evidence developed—some from reconnaissance trips in the six cities and intensive examination of their respective "implementation plans" and some from evidence obtained (and analyzed) too late to be included in the interim report. All these sources confirmed the difficulty of implementing motor vehicle restraints and suggested that the most likely reduction achievable by the period 1975 to 1977 was closer to 5 to 10 percent.

Modal split models examined for Washington, D.C., Baltimore, and Minneapolis substantiated the fact that substantial changes would be required in parking rates (in the case of Washington, D.C., doubling and tripling of rates were implied) before major diversions in motor vehicle use would occur, e.g., in the range of 20 to 25 percent.

Data available for the Bay Area Rapid Transit System (BART) in San Francisco provided estimates of the reductions expected in motor vehicle use for 1975. These estimates indicated that, in four counties of Alameda, Contra Costa, San Francisco, and San Mateo, the number of trips diverted from motor vehicles to BART by 1975 would reduce the VMT per day by 2.1 percent. In specific important line-haul corridors where transit is more competitive, the diversion factors (for example, San Francisco Bay Bridge) were as high as 8.1 percent, but in general the estimates ranged well below 10 percent when all corridors were taken into account.

Reconnaissance of the six cities substantiated the difficulty of implementing motor vehicle restraints. In fact, with only minor exceptions, the trend appeared to be toward considerable political resistance against any kind of motor vehicle restraint. This does not necessarily suggest that restraints may not come into effect or that, in time, they may not be accepted. However, within the framework of attempting to achieve emission standards by 1977, there appears to be considerable opposition to be overcome. For example, in San Francisco where a 25 percent parking tax has been in effect on commercial space, the study was informed that there had been little or no impact on motor vehicle use with the possible exception of some shift to on-street parking. There has been no change in transit ridership, and there is considerable pressure to remove or substantially reduce the parking tax from 25 to 10 percent. There is indication that such a reduction might be successfully implemented.

Again, in San Francisco, the use of car pool experiments suggested that it was going to be very difficult to achieve the limited goals of diversion of 3,000 vehicles per day to car pools, hardly an overwhelming support for motor vehicle restraints.

In New York City, restraint on motor vehicle use has been an important element in the city's policy for dealing with congestion, particularly in view of the long history of congestion. A number of vehicle ban proposals have been suggested; however, in general, they have been politically unacceptable. For example, efforts to develop the Madison Avenue Mall have been generally deterred, and it appears likely that only limited implementation of the mall will occur.

In Los Angeles, the need for regional controls in order to solve the pollution problem (as described in the interim report) indicated that reductions of 20 percent VMT would have to be undertaken throughout the area because reductions in the CBD alone would not be particularly helpful. The uniformity of the distribution of emissions and the difficulty of implementing them in the Los Angeles area (given the multiplicity of governments and the general importance of the automobile in the daily traffic movements) suggest extraordinary difficulty in implementing any kind of major restraint effort.

In Washington, D.C., it was proposed to provide an all-day parking tax of $1 a day to be implemented as part of the effort to reduce VMT. Estimates ranged from 8 to 16 percent reduction in trips; overall reductions were in the range of 4 percent. Major opposition resulted in postponement of the issue to 1973, and it appears very unlikely that even a small tax of a dollar a day (which would not, perhaps, result in more than a 4 to 5 percent reduction) will be passed, if at all, before 1974—too late to be of any significant value for the target year of 1977.

The Chicago plan indicated that no motor vehicle restraints were contemplated. Emphasis was placed on the automobile manufacturers providing the necessary reduction through changes in engine design or the use of control devices and improvements in traffic flow controls or both. Reconnaissance made it quite clear that there was opposition on the part of city government to any policy of motor vehicle restraint that, in any case, the city felt would not be necessary in Chicago if the automobile manufacturers were made to meet the standards set by EPA.

Finally, in Denver one study of the problem indicated that only small reductions may be expected from any kind of motor vehicle restraint program. Although four proposed parking garages were recently defeated by environmentalists, we were informed that actually all that changed was whether the parking facilities would be built under public control or private enterprise. The city administration is strongly in favor of the construction of the garages and would be opposed to any attempts to stop the private sector building the garages (assuming that it would be legally possible to stop such construction). The city is even more opposed to any kind of motor vehicle restraint; the administration has no present plans for motor vehicle controls and does not intend to implement any. We were further advised that the automobile is an important and basic element in the life of residents in the city of Denver, and no one anticipates any major restraints.

The reluctance and resistance to even limited use of motor vehicle restraints in any form was readily apparent in the implementation plans of the six cities. It is only in San Francisco and Los Angeles that any estimates are provided for reductions through motor vehicle restraints. In both cities, a 20 percent reduction is provided; however, these are values estimated by the state, and there is no evidence provided that such reductions could be achieved. Furthermore, there is no plan provided as to how such reductions could be achieved or whether it is realistic. For example, the San Francisco plan notes that, through public transportation, car pooling, and changes in working schedules, it is hoped that emissions will be reduced. It is pointed out, however, that "the level of achievement of these measures cannot be closely estimated. The goal, which is set on the optimistic side, is to reduce traffic by 20 percent" (1). Nothing is indicated as to how this 20 percent would be realized or the basis on which it is estimated. In the Los Angeles plan, the same 20 percent is used, and, in fact, the language used to describe the plan is exactly the same as that used for San Francisco with no further evidence.

For the other cities reviewed, the possibilities were unspecified with the exception of Washington, D.C., where a number of limited parking facility proposals are provided (including a ban on on-street parking, sharp increases in commercial parking lot fees, and other potential control devices). In all cities, there is considerable reluctance to indicate any form of motor vehicle restraint or to specifically identify the way in which reductions would be achieved.

In view of the reconnaissance experience—the review of implementation plans, the findings of the interim report, and other evidence reviewed—the following conclusions emerged:

1. It would appear at the present time that it is not politically feasible to achieve any major program of motor vehicle restraint in any of the six cities under review. Though minor programs could emerge in the way of price increases for parking, no significant impact is likely to have any major effect by 1975 and only slightly more by 1977. This is likely to be true for other large cities as well.
2. The only possibility that might negate this conclusion appears to be if it is conclusively demonstrated that there is a serious health hazard effect associated with emissions. At the present time, that does not seem to be a likely prospect, at least by 1975-77.
3. The conclusion of 5 to 20 percent air pollution reduction indicated in the interim report, though within the realm of possibility, must be considered to represent broad ranges. For the six cities in the study at least, based on an evaluation of opinion in those cities, 20 percent appears to be in the very upper limits of what is realistically feasible and seems to be a very unlikely possibility for any of the six cities.
4. A strategy of motor vehicle restraint will have to be accompanied by very substantial improvements in transit involving fairly substantial sums of investment from the federal government.
5. The most feasible restraint appears to be some form of pricing policy—perhaps increases in parking costs or possibly toll roads or some other forms of road pricing. These appear more feasible because of the somewhat more subtle characteristics of the impact, which might reduce public opposition to the motor vehicle restraint. Major vehicle bans and frontal assaults of a similar nature are likely to encounter fierce opposition.
6. For the range of possibilities, all assumptions about reductions of VMT must be considered optimistic in the light of a target for 1977. For purposes of testing a motor vehicle restraint strategy, the range of reductions in VMT anticipated from motor vehicle restraints in the six cities was optimistic (5 percent), moderately optimistic (10 percent), and very optimistic (15 percent). Thus, after careful consideration of all of the evidence and recognizing that a considerable amount of judgment is involved, it was considered that none of the six cities is likely to achieve even a 15 percent reduction in VMT by 1977.

Work Schedule Changes

Recent experience with work schedule changes in the United States and abroad suggests that these measures are feasible. Two measures for changing work schedules were considered: work staggering and the 4-day workweek. Work staggering involves making small systematic shifts in work hours of employees so that currently underutilized travel times to the CBD are more adequately used. Conceivably, this could result in decreased peak-hour congestion, higher average vehicle speeds, and reduced emissions. The 4-day workweek has the same potential effect. Because the workweek is shortened, each workday will be lengthened and thus "out of phase" with traditional peak hours (at least at one of the peaks).

Of the two measures, the 4-day workweek goes further toward reducing motor vehicle emissions than staggered hours because its effect is twofold, both reducing the total number of commuting trips by 20 percent and shifting workers away from peak-hour travel. If this measure were introduced, and working days were spread over a 6-day period, daily VMT for the journey to work could be reduced by as much as one-third. Assuming 30 percent of motor VMT is accounted for by the journey to work, and 25 percent of the labor force would be on a 4-day workweek by 1977, a maximum reduction of 2.5 percent in daily VMT could be achieved [(0.33) (0.30) (0.25) = 2.5 percent]. All of these assumptions, however, appear highly optimistic. Moreover, increased leisure would undoubtedly result in additional

VMT for recreational and other trips (although these are likely to be at off-peak periods and in relatively less polluted areas).

The profound social and economic implications of a large-scale shift to the 4-day workweek suggest that this measure should be considered from a broader perspective than congestion relief or air pollution control alone. Such an examination of the 4-day workweek, though beyond the scope of this study, was considered a priority area for further research.

OVERALL CONCLUSIONS

Based on the findings discussed in the previous sections, a number of conclusions were reached. Because of the range of judgments involved and the complexity of the subject, it must be recognized that such conclusions are at best tentative. However, they are significant in assessing emission reduction timetables and strategies.

1. In most of the metropolitan areas in the study, overall emission reductions of at least 50 percent from existing levels appear required to meet the national ambient air standards for carbon monoxide for 1975-77. These required reductions are substantially higher in some central city areas (e.g., 80 percent in midtown Manhattan).
2. Measured against this scale, most transportation controls that are capable of being introduced in the next few years offer the potential for only modest reductions (Table 4).
3. Even those controls that are easiest to implement will take several years to develop and put into effect. All controls will entail very substantial implementation costs (although in some cases, such as an increase in parking rates, these costs can be recouped from revenues), will involve complicated impacts, and will generate considerable opposition from motor vehicle users.
4. The legal authority to effect transportation controls for reduction of air pollution cannot be quickly established in most states. With the exception of some traffic flow improvements, there is essentially little or no experience with the use of the transportation controls required to achieve the air quality standards.
5. In the absence of more empirical data and computer simulations, estimates for potential reductions must be considered approximations. One difficulty is that some of the transportation controls (notably motor vehicle restraints) could have additive effects by reducing VMT and, thereby, improving traffic speeds. Even if emission-speed relations were known with confidence, additive effects of motor vehicle restraints would result in substantially greater emission reductions than those estimated in our findings.
6. Some of the transportation controls tend to generate additional new traffic (e.g., improved speeds from traffic flow control) and may be counterproductive to achieving and maintaining the air quality standards.
7. Because of the counterproductive character and limited effectiveness of most of the transport controls and the "additive" effects of motor vehicle restraints, such restraints are not likely to be required in many major metropolitan areas (such as the six under study) to reach and maintain national ambient air standards for carbon monoxide by 1975. In addition, motor vehicle restraints would have to be accompanied by important improvements in public transport if serious social and economic repercussions are to be avoided.
8. Assuming substantially improved public transport, the implementation of some forms of motor vehicle restraints would appear technically feasible within 5 years. However, the basic question these measures raise is the extent to which it is politically possible to deprive people of some of the convenience of their cars in return for cleaner air. Changes in the prevailing travel pattern—commutation by private passenger car—and the provision of public transport cannot be brought about overnight. The automobile is intricately related to almost all aspects of community life; the social and economic consequences of changing these established relations are likely to be profound.
9. In the light of all these factors, it would appear that, when motor vehicle restraints are to be recommended, they should be made part of a comprehensive effort and that they should be considered as more than short-term measures for air pollution control. Motor vehicle restraints may be warranted over a longer term and on other grounds (e.g., reducing noise and relieving congestion) than air pollution control.

TESTING OF THREE STRATEGIES: PRELIMINARY RESULTS

In the second phase of the work, three specific strategies (inspection, maintenance, and retrofit; traffic flow control; and motor vehicle-public transport improvements) were tested for their emission reduction impact using urban transportation demand models that provided (by fine-grained zones) data on VMT and speed. These two key inputs of VMT and speed were transferred to a grid system (of 1 mile or 1 kilometer square), and VMT speed data were converted to vehicle emissions based on available information on speed-emission relation in combination with the Hanna-Gifford diffusion model (11).

The resulting concentrations are shown as isopleths on a map of the metropolitan area (the pollutants considered were carbon monoxide, hydrocarbons, and oxides of nitrogen—with carbon monoxide being of primary interest). Concentrations (and isopleth maps) are calculated for the 1- and 8-hour periods of maximum VMT (therefore emissions) for a base year projected to 1977 under both uncontrolled (no transport control strategy) and controlled conditions for the three transportation control strategies in each of the six cities in the study. Examples of the isopleth maps (for the 1-hour maximum for carbon monoxide) are shown in Figures 3 and 4.

In connection with this approach, it must be noted that, because of variation in the transportation demand nodels used (as among the six cities), the detail data base developed by each city for its transportation model, the number of zones used for the analysis, and the reliability of the original statistical base (e.g., origin-destination study, traffic counts, etc.) for any one city, it is not possible to make comparisons among the cities. The approach does, however, provide a means for evaluating for each city the range of impacts that might be anticipated from the respective control strategies tested.

Because of the voluminous nature of the outputs of this phase of the work, and the fact that the final report is still under review by EPA, a complete summary of findings and conclusions cannot be presented. However, a summary of results for Washington, D.C., is presented as an indication of some of the outputs generated by the model.

The diffusion model and transport data were applied to the Washington, D.C., metropolitan area for four meteorological conditions: summer wind at 5.5 m/sec, winter wind at 6.6 m/sec, nominal (typical) wind at 5.0 m/sec, and worst case wind at 2.5 m/sec. The three transportation conditions were current conditions (as close to conditions as transportation data allow for Washington, D.C., 1968), projected conditions for 1977 (assuming no transportation restrictions beyond internal automotive emission controls), and projected conditions for 1977 (with estimations of the effects of various transportation controls). Figure 5 shows the grid system of Washington, D.C., utilized in the model. Figures 6, 7, and 8 show the worst wind condition for the three strategies tested for carbon monoxide. Specifically, the following strategies are shown in the isopleth maps for the 1- and 8-hour periods of maximum emissions:

1. Strategy 1B, inspection and maintenance—A 10 percent reduction in CO emissions was applied as the most likely impact of this strategy (Fig. 6).
2. Strategy 2, traffic flow control—Average speeds within each of the speed rings in the original data were increased to indicate the impact of this strategy (Fig. 7).
3. Strategy 3, combined strategies—The impact of strategies 1B and 2 were combined with a VMT reduction due to vehicle restraints to produce the most optimistic pattern of emission reductions (Fig. 8).

Table 5 gives the maximum emissions and maximum concentrations predicted for carbon monoxide, hydrocarbons, and nitrogen oxides for each of the applied control strategies and the uncontrolled cases. The maximum concentrations predicted are given for the worst case (defined by a wind speed of 2.5 m/sec).

Carbon Monoxide

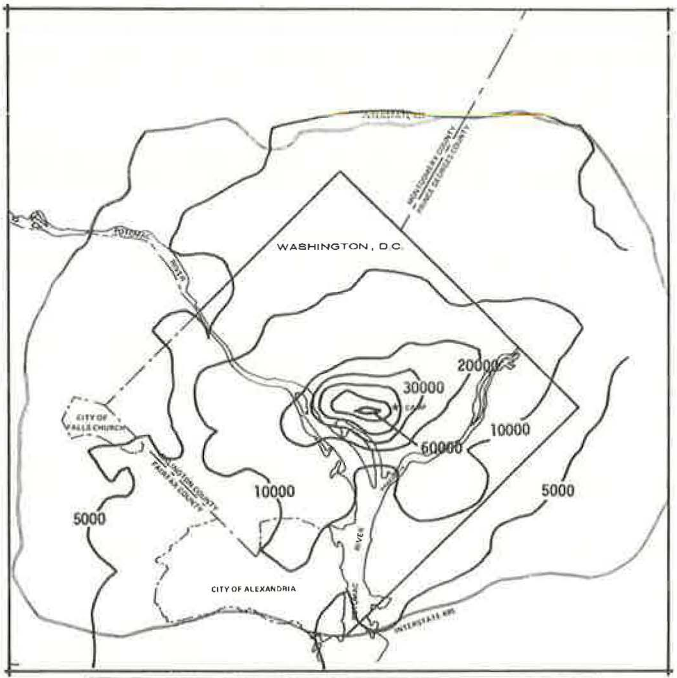
The maximum concentration for all cases occurs near the center of Washington, D.C., in the immediate vicinity of the area of greatest traffic density (Fig. 9). Because there were no major stationary sources of CO in the immediate vicinity of this maximum con-

Table 4. Impact of transportation controls on travel patterns and motor vehicle emissions (carbon monoxide from light-duty vehicles).

Transportation Control Candidates	Impact on Travel Patterns	Impact on Motor Vehicle Emissions
Short Term (2 to 5 years)		
Inspection, maintenance, and retrofit	No changes in modal mix, trip generation, or origin-destination patterns.	Ten to 25 percent. Upper range (particularly 20 to 25 percent) decidedly less likely than lower range (particularly 10 percent).
Gaseous fuel systems	No changes in modal mix, trip generation, or origin-destination patterns.	Less than 15 percent. Appropriate only for large, centrally maintained fleets that account for a relatively high proportion of total VMT (e.g., taxicabs in borough of Manhattan).
Traffic flow techniques	No changes in modal mix. Possible increase in trip generation as a result of improvements in traffic flow. No changes in origin-destination patterns, at least for the short term.	Less than 20 percent. However, emissions appear to decrease for only the year immediately following implementation, after which time emissions may increase above original levels due to growth in traffic volumes. To control traffic volumes, motor vehicle restraints would be required.
Bypassing through traffic	No changes in modal mix. Possible increase in trip generation as a result of improvements in traffic flow. No changes in origin-destination patterns, at least for the short term.	Less than 5 percent. Measures requiring new construction (e.g., circumferential routes) not implementable within 5 years. Modest bypassing may be possible through use of directive signs or signals or both. More substantial bypassing will require motor vehicle restraints.
Medium Term (5 to 10 years)		
Improvements in public transportation	Changes in modal mix by improvements in public transport, no change in trip generation or origin-destination patterns at least in the short term.	Less than 5 percent. Improvements in public transport are a necessary but not sufficient condition for reducing motor vehicle emissions. To have an appreciable effect on emissions public transport, improvements must be combined with motor vehicle restraints. Restraining or restricting motor vehicles, however, would require substantial public transport improvements to provide an alternate means of making trips.
Motor vehicle restraints	Changes in modal mix by improvements in public transport and motor vehicle restraints. Only minor changes in trip generation or origin-destination patterns at least in the short term.	Five to 25 percent. Potential emission reductions depend on the severity of restraints. Several motor vehicle restraints are administratively feasible. However, the mechanics of imposing motor vehicle restraints are much less of a problem than gaining public acceptance to limit "freedom of the road."
Long Term (10 to 20 years)		
Work schedule changes	Changes in modal mix, possible reduction in trip generation (particularly for the journey to work), and changes in origin-destination patterns due to additional recreational trips.	Less than 3 percent. Work trips would be reduced but increased leisure time would probably generate additional recreational trips (although these are likely to be primarily at off-peak periods to and from areas outside the central city).
Land use controls	Change in modal mix, change in origin-destination patterns, and change in trip generation.	Could not be implemented with any appreciable effect on emissions in the short term. Medium- and long-term effects not known.

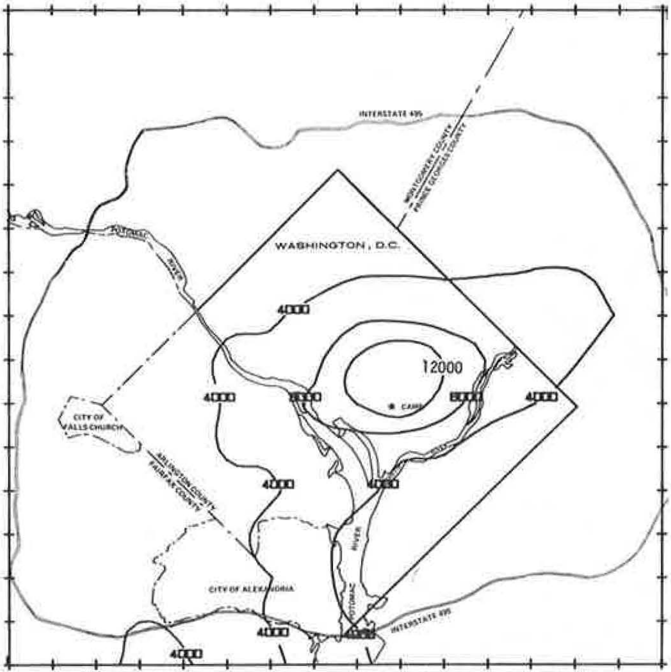
Note: A more complete explanation of the data in this table is given elsewhere (1).

Figure 3. Pollutant concentration, 1968.



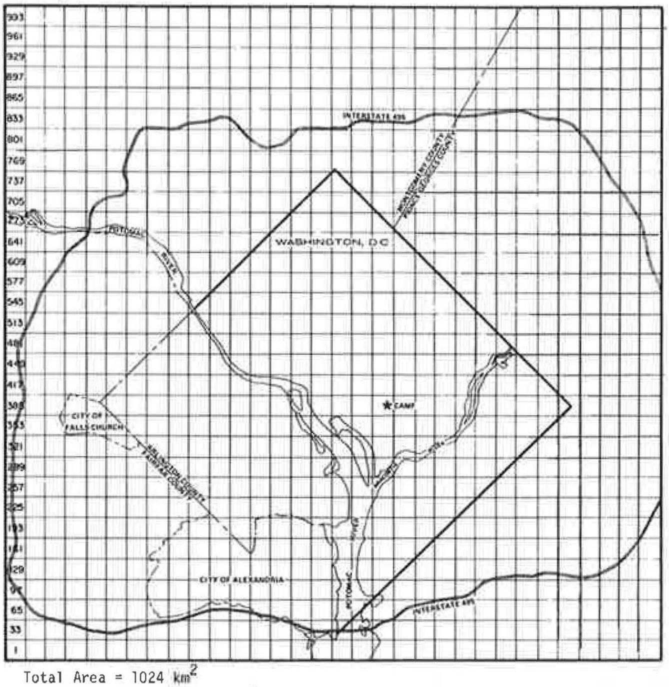
City Washington, D.C. Year 1968 Strategy Uncontrolled
Pollutant CO Case 4 Time Period 1 Hr. Total
Units $mg/m^3 x 10^3$ Federal Standard 40 mg/m^3

Figure 4. Pollutant concentration, 1977.



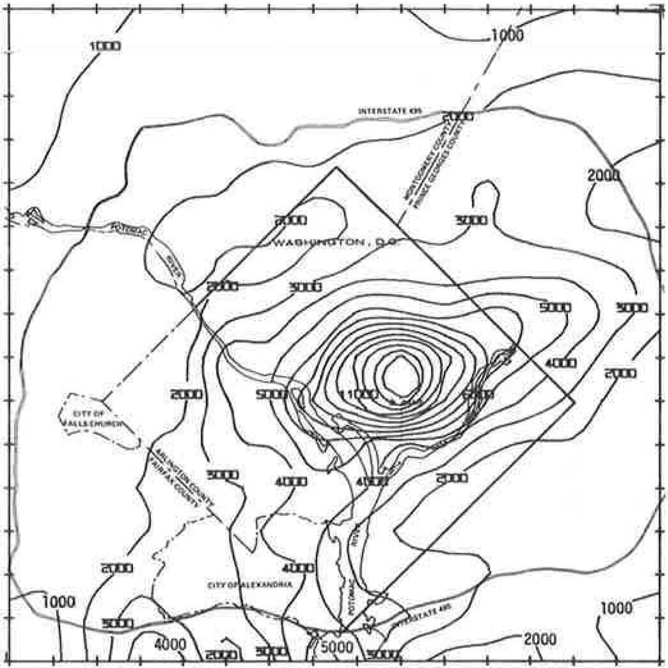
City Washington,D.C. Year 1977 Strategy Uncontrolled
Pollutant CO Case 4 Time Period 1 Hour Total
Units mg/m^3x10^3 Federal Standard $40\ mg/m^3$

Figure 5. Washington, D.C., grid system.



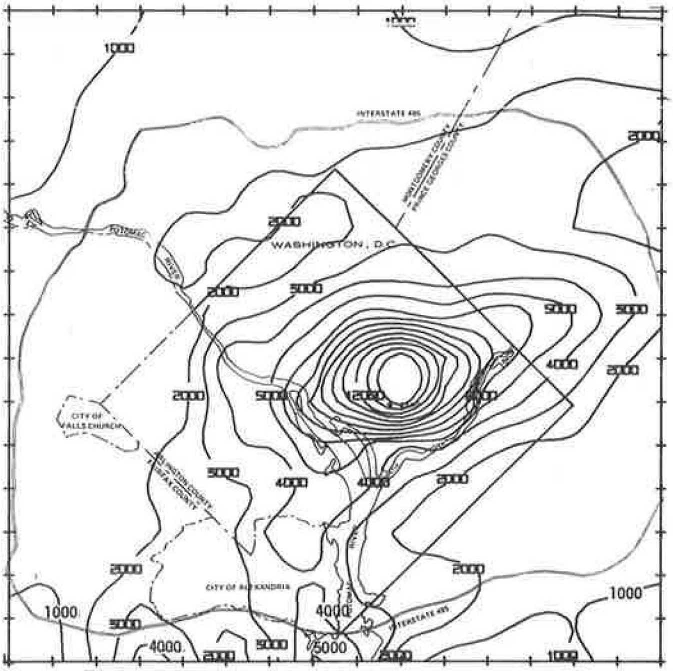
Total Area = 1024 km^2
Individual Grid Area = 1 km^2

Figure 6. Strategy 1B.



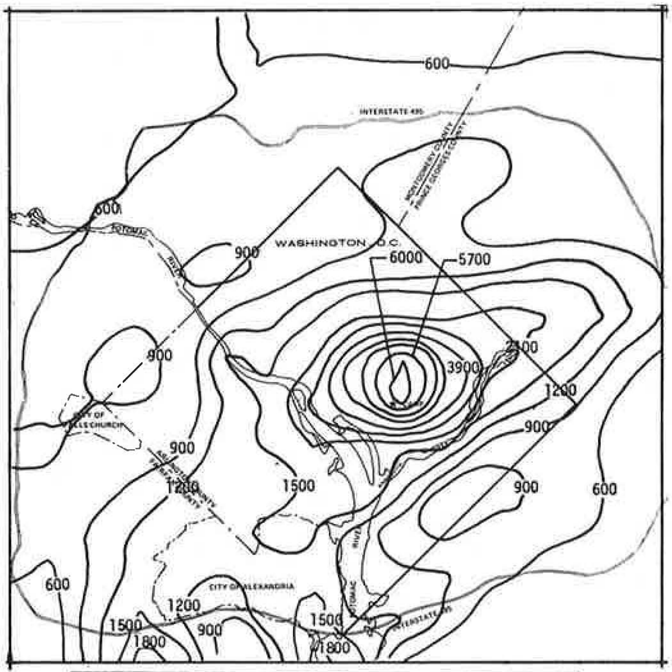
City Washington,D.C. Year 1977 Strategy 1B
Pollutant CO Case 4 Time Period 1 Hour Total
Units mg/m^{3}x10^3 Federal Standard 40 mg/m^3

Figure 7. Strategy 2.



City Washington,D.C. Year 1977 Strategy 2
Pollutant CO Case 4 Time Period 1 Hour Total
Units mg/m^{3}x10^3 Federal Standard 40 mg/m^3

Figure 8. Strategy 3.



City Washington,D.C. Year 1977 Strategy 3
Pollutant CO Case 4 Time Period 1 Hour Total
Units mg/m^3x10^3 Federal Standard 40 mg/m^3

Table 5. Maximum emissions and concentrations, Washington, D.C.

	Maximum Emissions (tons/year)		Maximum Concentrations (mg/m^3)	
Pollutant	Total	Mobile	8 Hours	1 Hour
Carbon monoxide				
1968	12,589	12,589	28.4	59.1
1977	4,513	4,513	10.6	22.1
Strategy 1A	3,384	3,384	7.9	16.6
Strategy 1B	4,061	4,061	9.5	19.9
Strategy 1C	4,287	4,287	10.1	21.0
Strategy 2	4,412	4,412	10.3	21.2
Strategy 3	3,687	3,687	8.4	17.2
Hydrocarbons				
1968	2,015	1,773	4.1	8.3
1977	1,862	490	2.9	3.1
Strategy 2	1,859	482	2.8	3.1
Strategy 3	1,854	428	2.8	3.0
Nitrogen oxides				
1968	6,022	439	7.2	7.5
1977	6,005	271	7.2	7.3
Strategy 3	6,001	241	7.2	7.3

centration area (as shown by the difference between the mobile and total emission), the maximum concentrations are a result of mobile source emissions only.

The 1977 predictions show the estimated effect of manufacturers' emission control devices alone on the maximum 8-hour and peak-hour concentrations. It indicates that the 1968 maximum concentrations would be reduced by nearly two-thirds without the application of any further transportation controls.

Strategy 1 illustrates the potential additional reductions in CO emissions by implementing an inspection and maintenance program for the Washington, D.C., region. This strategy would allow a reduction in CO emissions from 5 to 25 percent, with 10 percent (strategy 1B) being the most likely possibility. A 10 percent reduction in CO emissions would bring the 8-hour concentration maximum slightly below the federal standard of 10 mg/m^3.

Strategy 2, the traffic control strategy, would, in effect, increase the traffic speeds in the downtown area. This would, in turn, decrease the emissions and result in a 5 percent decrease in the 8-hour maximum concentration over and above the predicted 1977 concentrations. However, without additional traffic controls, this 5 percent decrease would probably disappear within 1 year because of induced traffic volume increases.

Finally, strategy 3 shows the effect of combining inspection and maintenance (10 percent CO reduction), traffic flow control, and vehicle restraints (10 percent reduction in VMT). The estimate assumes that the full benefit of all strategies would be achieved in 1977. The resulting maximum 8-hour concentration is approximately a 20 percent improvement over the predicted uncontrolled 1977 concentrations and would bring the 8-hour maximum concentration below the federal standard.

Hydrocarbons

The location of the maximum emissions and maximum concentrations for hydrocarbons (Table 5) are shown in Figure 10. It should be noted that peak-hour concentrations are given although federal standards are suggested only for a 3-hour (6 to 9 a.m.) average. Transportation data given did not allow estimation of concentrations for this specific time period; therefore, care must be taken in comparing predicted values with federal standards.

It can be seen by the difference between total and mobile source emissions for hydrocarbons (Table 5) that the maximum concentration values are greatly affected by stationary sources for which no transportation or other controls were considered. For the purpose of analyzing the effect of transportation controls, it may be more appropriate to consider the relative reduction in mobile source emissions rather than the reduction in predicted maximum concentrations. The 1977 uncontrolled mobile emissions are approximately 70 percent less than base-year emissions. Whether this reduction alone would be sufficient to bring actual air quality within the federal guidelines would be dependent on the impact and control of the major stationary sources. The traffic flow control strategy (strategy 2) would have very little effect, by itself, on mobile source emissions; however, by combining traffic flow control with vehicle restraints as given by strategy 3, an additional 12 percent reduction in mobile emissions might be achieved.

Oxides of Nitrogen

Figure 11 shows the location of the areas of predicted maximum concentrations for each transportation control condition for NO_x.

It can be seen from Table 5 that the predicted maximum concentrations are a result of emissions from large stationary sources included in the data base. Maximum concentrations resulting from the maximum mobile source emissions given in the table would be approximately 60 percent less, or about 3.0 mg/m^3 for the 8-hour maximum concentration. As in the case of hydrocarbons, for the purpose of analyzing the effect of transportation controls, it is more appropriate to consider the relative reduction in mobile source emissions rather than the relative reduction in predicted maximum concentrations, which are so grossly affected by stationary source emissions.

Figure 9. Locations of maximum concentration of carbon monoxide for conditions given in Table 5.

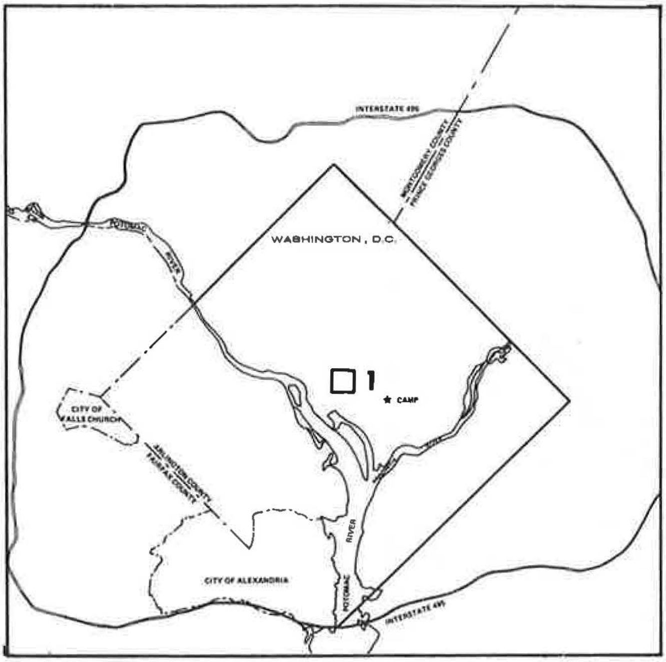


Figure 10. Locations of maximum concentration of hydrocarbons for conditions given in Table 5.

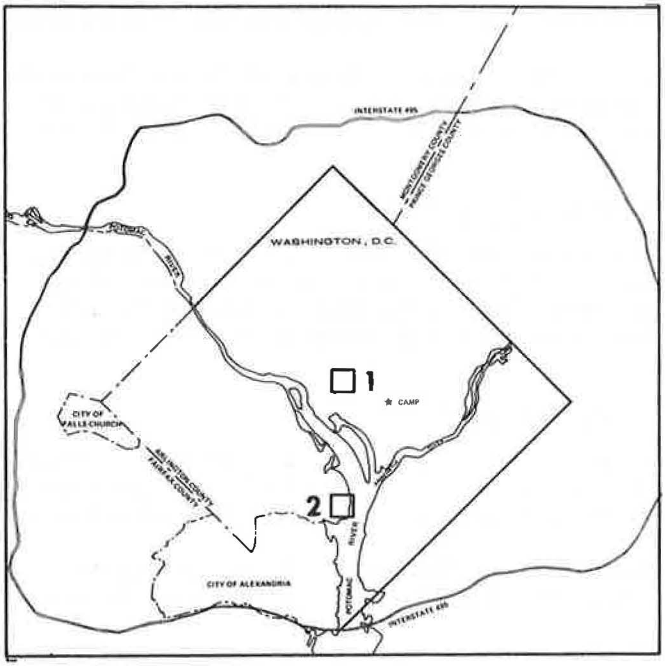
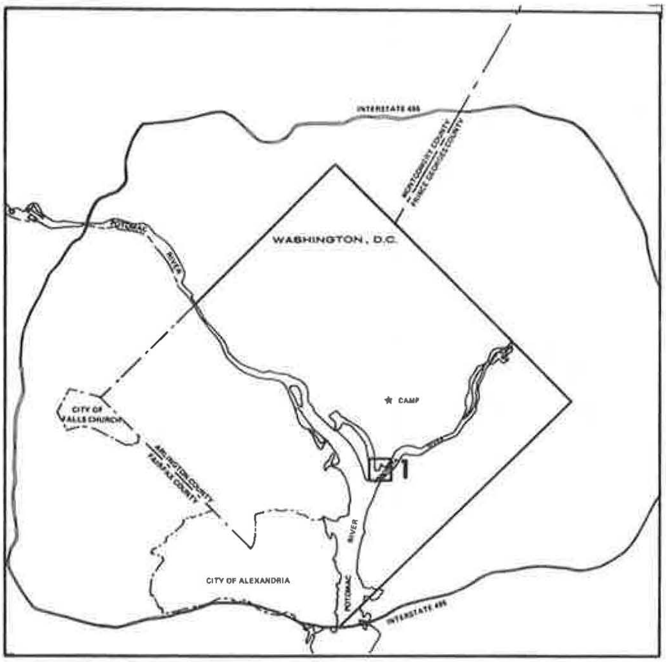


Figure 11. Locations of maximum concentrations of nitrogen oxides for conditions given in Table 5.



The 1977 uncontrolled mobile emissions are, at most, approximately 40 percent less than base-year mobile emissions, largely due to direct automotive emission controls. Whether this reduction alone would be sufficient to bring actual air quality within the federal guidelines would be dependent on the impact and control of the major stationary sources.

Strategy 3 (combined emission and traffic control strategies) is the only transportation control strategy with a direct impact on NO_x emissions. The approximately 10 percent additional reduction in mobile emissions is a result of reduced VMT due to vehicle restraints.

ACKNOWLEDGMENT

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REFERENCES

1. Evaluating Transportation Controls to Reduce Motor Vehicle Emissions in Major Metropolitan Areas: A Draft Interim Report. Institute of Public Administration and Teknokron, Inc., for Office of Land-Use Planning, Environmental Protection Agency, Dec. 23, 1971.
2. Mandatory Emission Vehicle Inspection and Maintenance, Volume I: Summary. Northrop Corp. in association with Olson Laboratories, Inc., Anaheim, Calif., 1971.
3. A Study of Selected Hydrocarbon Emission Controls. Ernst and Ernst for U.S. Department of Health, Education and Welfare, July 1969.

4. Chew, M. F. Auto Smog Inspection at Idle Only. For Society of Automotive Engineers, No. 690505, 1969.
5. Emission Factors for Motor Vehicles. TRW Systems Group, TRW, Inc., Oct. 21, 1971.
6. Motor Vehicle Tune-Up at Idle—The New Jersey Repair Project. Bureau of Air Pollution Control, N. J. Department of Environmental Protection.
7. 1969 LP-Gas Market Facts. National LP-Gas Assn., 1970.
8. Optimizing Flow on Existing Street Networks. NCHRP Rept. 113, 1971.
9. Elmberg, Curt M. The Gothenburg Traffic Restraint Scheme. Organization for Economic Co-operation and Development, Paris, May 1971.
10. Governmental Approaches to Automobile Air Pollution Control. Institute of Public Administration, 1971.
11. Hanna, S. R., and Gifford, F. A., Jr. Urban Air Pollution Modelling. Presented at 1970 Internat. Air Pollution Conf., Internat. Union of Air Pollution Prevention Assns., ATDL Contribution 37.

AIR POLLUTION: IMPLICATIONS FOR TRANSPORTATION PLANNING

G. V. Wickstrom, Metropolitan Washington Council of Governments

The paper discusses the need to integrate air quality considerations into the long-range transportation planning process. Eight recommendations for incorporating air quality planning into the transportation planning process are given by using illustrations from the Washington, D.C., metropolitan area: Because air quality is a regional problem, solutions must be sought and implemented on regional and local scales, the kind of solution will vary depending on the time frame considered, the interaction between transportation and land use must be considered fully if correct solutions are to be found, central area parking policy should become an integral part of the transportation planning process, the benefits of alternative actions should be stated clearly and the impacts to private and public groups estimated, alternative land use policies and alternative transportation policies should be examined, a planning process that is responsive to evaluating alternative courses of action is required, and continuing process improvements, monitoring, and feedback are essential.

•THIS paper will discuss and illustrate, by using examples from the Washington, D.C., area, the need to integrate air quality considerations into the long-range transportation planning process. It is the central theme of this paper that air quality considerations are compatible with sound land use and transportation planning and that a viable planning process can be described that fully considers air quality as well as other social, economic, and environmental impacts. Such a process does not exist at the present time, but the framework for such planning has been established at the regional scale by land use and transportation planning programs required in urban areas and supplemented through A-95 review procedures.

AIR POLLUTION CONTROL OBJECTIVES

National objectives for the control of air pollution as pointed out in the Air Quality Act of 1967 are

1. To protect and enhance the quality of air,
2. To initiate and accelerate a national research and development program in this area,
3. To provide technical and financial assistance to states and local governments to achieve the preceding, and
4. To encourage and assist in the development and operation of air pollution control programs.

Studies have indicated that the motor vehicle is responsible for more than three-quarters of carbon monoxide emissions, more than half of hydrocarbon emissions, and nearly half of nitrogen oxide emissions. In addition, some pollutants combine to produce more harmful effects than the original emissions.

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Recently, plans for continued construction of urban freeway systems have been criticized on the basis that such facilities contribute to air pollution. Evaluating the need for such freeway facilities (PPM 20-8, DOT) requires that social, economic, and environmental effects be considered and that such environmental effects include consideration of air pollution. In addition, the National Environmental Policy Act requires that a study of the environmental impact of any federally funded action be included as part of any major action significantly affecting the quality of the environment. Such a study would include

1. Measurement of the environmental impact of the proposed action,
2. Identification of unavoidable adverse impacts,
3. Identification of alternatives, and
4. Study of the relation between short- and long-term uses of the environment.

A description of the kinds of studies needed to determine the effects of transportation system alternatives on air pollution follows.

GENERAL CONSIDERATIONS

Transportation system alternatives can include proposals for construction of freeways to provide more capacity and faster travel, improvements to existing facilities through reconstruction and traffic control, or alternative modes of travel such as improved bus service or construction of rail transit facilities. Alternatives may also contain more than one of these solutions.

In addition, and particularly in the short run to meet air quality standards by 1975, automobile restraints and pricing policies are being discussed.

The effect of transportation alternatives on air pollution can be properly measured by estimating the amount of emissions for each alternative proposed. Such an estimate should include the effect of alternative future emission standards such as those proposed by Congress. In addition, consideration must also be given to weather conditions, diffusion of pollution in the atmosphere, air quality standards, and number of people and kinds of property exposed to such emissions. At the present time, a comprehensive study considering all these factors has not been made in any urban area. Figure 1 shows the relation between alternative transportation systems and the effects on air pollution.

POLLUTION CONCENTRATIONS

Different amounts of pollution concentrations are formed at different scales of measurement. For example, the first scale at which any investigation of air pollution effects should be made is at the street level. Concentrations of pollutants at this level can be severe, with the intensity of pollution varying significantly with small changes in time or distance. At this scale, these concentrations are greatly influenced by facility design and location and traffic operation characteristics. Such effects are felt most in downtown areas, where large concentrations of people and vehicles exist throughout the business day. The effects of alternative transportation systems on air pollution in the central portion of the urban area are clearly of major concern.

A second scale would be that of the urban area as a whole. At this scale, the variation in effect occurs over many square miles and for hours, even days, at a time. Within the urban area, peak concentrations can occur in various parts of the region. These peaks within the region are caused by traffic concentrations on certain facilities and in certain areas and by meteorological characteristics. An important need in analyzing the effects of subregional pollution levels is to determine the distribution of the population exposed by time of day.

METHODOLOGY

Basic methodology for a study of the effects of alternative transportation systems on air pollution is shown in Figure 2.

Figure 1. Effect of transportation system on air pollution.

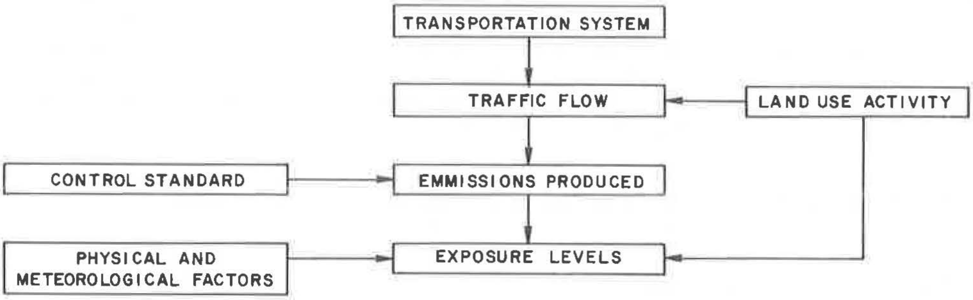
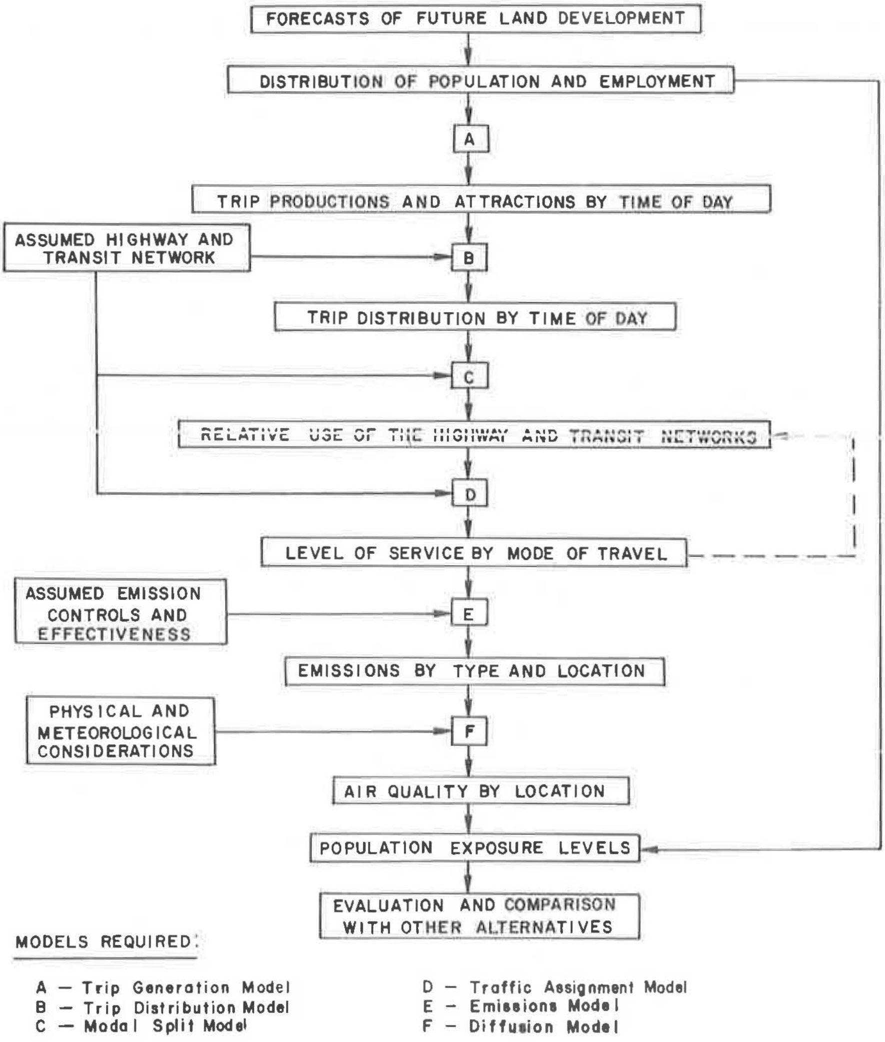


Figure 2. Methodology for study of effect of transportation system on air pollution.



It should be recognized that there are difficulties in both measurement and forecasting throughout the process and that many values are difficult to compute at the present time given the existing state of the art. These difficulties should not diminish the values of such a study, however, because each alternative tested would be subject to similar methodology.

As shown in Figure 2, land development and estimates of activity are converted to travel demands by time of day. Depending on the alternative transportation system being tested, the use of each part of the system is determined by forecasting both the distribution of travel and the use of each travel mode.

Comparisons of the amount of travel on highway facilities with capacity form a means to estimate system performance. Thus, performance measures (together with the use estimates by type of facility) form the required inputs to an emission model that determines emissions by type and area. Physical and meteorological considerations are then taken into account resulting in a determination of pollution levels by area. These levels, together with population distributions, are then used to determine the exposure levels under the different transportation plan alternatives tested. These exposure levels are then compared with acceptable standards.

The preceding paragraphs have described a more or less "ideal" technical process. Suffice it to say that such a methodology could be developed and integrated into an ongoing land use and transportation planning process. However, such a method would be expensive and time-consuming, and the results might not be available in time to influence decisions. Much is known already about these relations, however. Given the current state of the art, there may be other ways to integrate air quality considerations into the planning process in the short run. Existing data, forecasts, and methods could be used to provide policy guidance to decision-makers.

RECOMMENDATIONS

Eight recommendations for incorporating air quality planning into the land use and transportation planning process follow:

1. Because air quality is a regional problem, solutions must be sought and implemented at a regional as well as local scale.

Although EPA has required the states to prepare air quality implementation plans for urban areas, the problem is a regional one, requiring home-grown solutions. Thus, in the Washington, D.C., metropolitan area, it came as no surprise that one jurisdiction found no problem at all, another asked for a 2-year extension in meeting the standards, and the third recommended an immediate action program to reduce pollution by up to 55 percent. An analysis of the local situation reveals that the concentration of slow-moving traffic at high density in the region's core causes automobile emissions that are many times greater than the regional average. Further analysis quickly discloses that two out of every three vehicles bound for the CBD in peak hours originate in the suburbs.

It should be obvious that a regional approach must be taken if effective solutions are to be found. The suburbs also have an air pollution problem. The highest regional levels of oxidants have been recorded in Hyattsville, downwind from Washington, D.C. These levels have reached the "alert" stage all too frequently in past months.

2. The kind of solution will vary depending on the time frame considered. Both short- and long-range solutions are required.

It has been estimated that the 1970 level of carbon monoxide emissions from motor vehicle travel in the District of Columbia must be reduced by 55 percent in order to meet air quality standards by 1975. A recent study (1) has indicated that, even with fully effective control devices on new vehicles, this level of reduction could not be achieved by that time without major improvements to public transportation service. As more vehicles are equipped with emission control devices and as a large regional rail transit system becomes available, the chances of meeting air quality standards are enhanced.

Control strategy options available for meeting standards in the short run include retrofitting all vehicles with emission control devices or providing constraints or deterrents to automobile travel or both.

Substantial differences in the level of effort required to meet air quality standards exist even between 1975 and 1977.

In the short run, emission control devices coupled with improved transit services and equitable CBD parking charges may well meet the needs by 1977, if not by 1975. In the long run, however, a reduction in the rate of trip-making and travel by automobile might also be required as regional growth continues.

3. The interaction between transportation and land use must be considered fully if correct solutions are to be found.

No one can deny that the automobile is a major contributor to air pollution. Persons and agencies concerned with air quality have called for reduction in the use of the automobile, a halt to freeway construction, institution of automobile-free zones, and creation of vastly improved public transit systems. Are such solutions indicated? Would the public accept such actions? Would they have the desired effect?

To obtain answers to these questions, we must understand why the majority of people today travel by automobile and what types and magnitudes of change are required to reduce this travel. Also required is an understanding of the interaction between transportation and land development.

As shown in Figure 3, the number of daily person- and vehicle-trips made by a family residing inside the District of Columbia and Arlington (rings 1, 2, and 3) is much less than those made by families outside this area in the lower density suburbs. This points out that, although the total amount of travel generated is higher in high-density areas, the rate generated per family is less. Automobile ownership is also lower, and people can walk to destinations or use public transportation. Even when family size and income are taken into account, average automobile ownership is approximately one-half an automobile per household less in the District of Columbia. This lower level of automobile ownership results in less trip-making. Growth is now almost exclusively in the suburbs. Unless land use intensities and arrangements are created that approach those of the city, suburban travel and subsequent pollution will increase greatly. Creation of urban environments and reduction of automobile ownership and trip-making require that the suburban area be better served by public transportation and pedestrian systems.

In addition, mixed rather than segregated land uses are needed so that activities are closer together. New towns or communities having housing, shopping, recreational, and employment opportunities would contribute less total travel than would conventional suburban development.

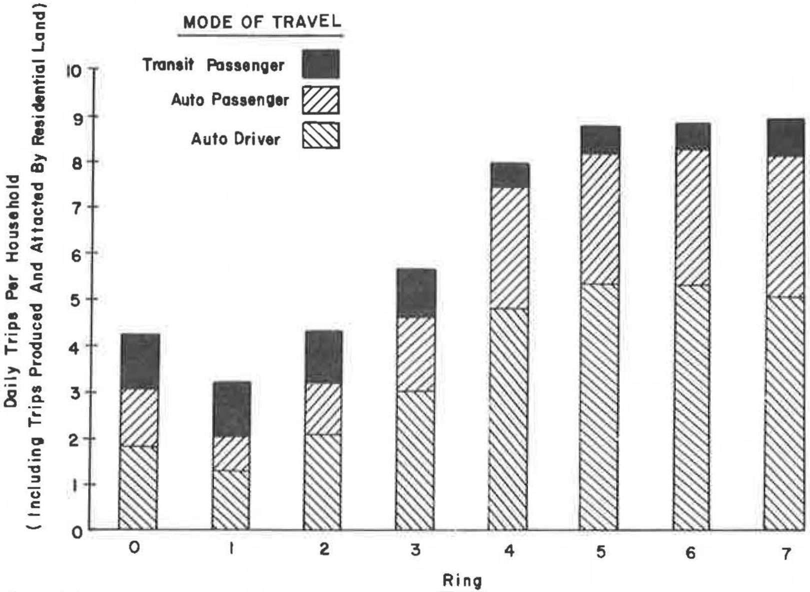
What about the question of improved highways?

It is generally believed that increases in the supply of highway facilities generate increased demands for automobile travel. Some claim that freeways increase travel faster than the new facility can absorb the increase, causing greater congestion than before. This view fails to take into account the fact that much of the so-called "generated" travel is really travel that has been removed from other routes and redirected away from other travel corridors. In addition, like transit facilities, freeways can channel land development, causing higher travel demands in the corridor. Must this necessarily be bad?

The effect of a major freeway on travel demands and on air pollution levels can be shown by forecasts of travel in the I-66 corridor in northern Virginia both with and without this freeway.

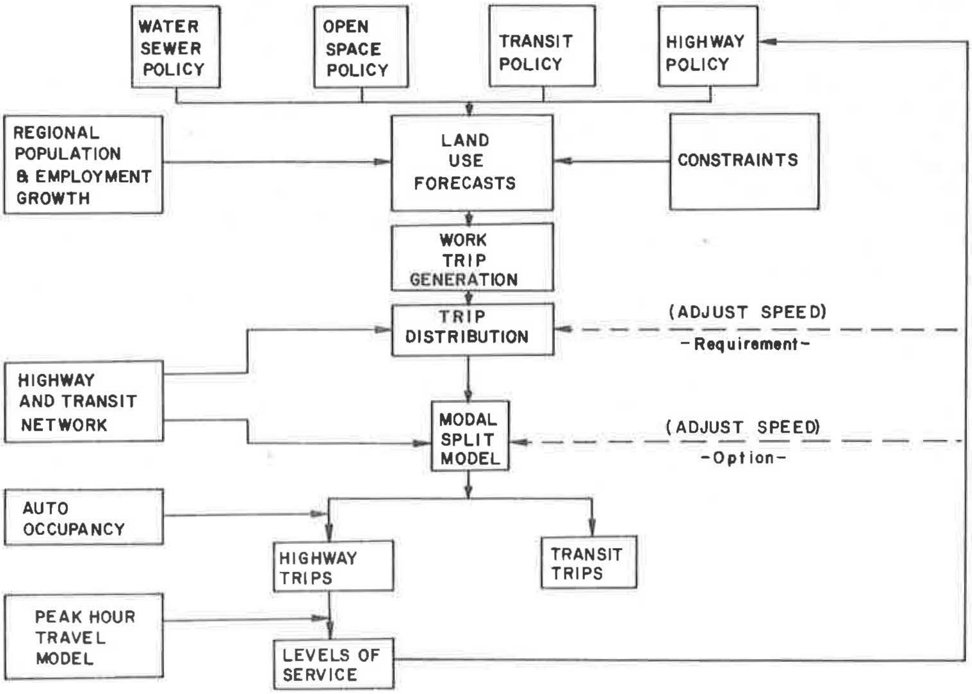
Forecasts of future travel demand by mode were made by using a series (or chain) of mathematical simulation models. The model system used is shown in Figure 4. Land activity forecasts by small area were made by inserting in the model a staged transportation alternative by time period. Other policies, such as water, sewer, and open space, were also introduced. The resultant distribution of land use activities was then converted to person work travel, distributed between origins and destinations, and split by mode (depending on the characteristics of the modal alternatives used). Automobile travel was converted to peak-hour travel demands and assigned to the highway network. The performance characteristics of the highway system were then determined, and the travel was redistributed between origins and destinations and among modes until a state of equilibrium was approximated. The results of this analysis indicated that the

Figure 3. Total person-trip ends per household, 1968.



Source: COG/TPB 1968 Origin Destination Travel Survey

Figure 4. Generalized traffic forecasting procedure (peak-hour travel).



provision of an interim transit facility in the right-of-way could absorb much of the increasing peak-period travel in the corridor in the short run and actually slightly reduce automobile travel in the corridor by 1976.

In the long run, the land use changes that would accompany the provision of the highway facility would also tend to encourage greater use of the parallel rail rapid transit line. This line also serves the corridor, and only moderate increases in automobile travel are forecast. The highway facility with its added capacity could then help relieve overcrowded conditions on parallel adjacent routes. Without the freeway, however, land use would be more dispersed, resulting in lower transit patronage. Although lower highway travel demands would also result, these demands would be accommodated at lower levels of service in the corridor with accompanying higher levels of automobile emissions. In addition, increased travel demand would occur, with little chance of increased public transportation, and regional air quality would suffer as well.

Major highway facilities, when accompanied by transit in the same corridor, may serve as a positive rather than a negative factor in reducing the amount of regional air pollution. Careful analysis of highway corridors, taking full account of the developmental effect of major facilities, should be undertaken.

4. Central area parking policy should become an integral part of the transportation planning process.

There is much talk about imposing automobile restraints or deterrents in the downtown area. So-called "modal split" or modal-choice relations developed from Washington, D.C., data have indicated that parking charges can have a substantial effect on the choice of travel mode. Such charges also affect the automobile occupancy rate and would encourage car-pool arrangements as well. Table 1 gives the percentage of people traveling to work who chose transit under differing levels of automobile and transit service for pay or free parking. The relative use of transit service from various distances is shown, for both pay and free parking. Based on the number of trips to the CBD from each area, Table 2 gives the total percentage of all CBD trips on transit in relation to pay and free parking. (The $1 average parking charge is actually created by nearly one-half the users paying up to $3 a day with the other half parking free.)

Because free parking attracts a larger percentage of automobile drivers, it can be shown that increases in the parking cost can influence drivers to use public transit if service is available. As shown, even assuming a minimal 5 percent increase in the modal choice percentages given in Table 1, the relative use of transit could increase from 36 to 41 percent with bus systems and from 46 to 51 percent with rail. These correspond to reductions in automobile use of 8 to 10 percent. A policy of improved transit and increased parking charges could have significant effects in reducing peak-period automobile travel to the CBD.

5. The benefits of alternative actions should be stated clearly and the impacts to public and private interests estimated.

The parking charge question, however, opens up other issues that should be explored. Why is there so much free parking in the downtown area? Why should government workers be subsidized to park in the area? Should the amount of parking spaces be reduced and zoning requirements changed? A rational, equitable parking policy could go a long way in shifting automobile users to public transit without increasing already high charges on those who do pay for parking. This will involve private as well as public interests. However, if parking charges are imposed or less parking is provided in the CBD, will not the CBD suffer and the alternative suburban development sites be benefited?

6. Alternative land use policies as well as alternative transportation policies should be examined.

The central area of Washington, D.C., is already substantially larger than most other U.S. cities. In 1968, the CBD contained nearly a quarter of the region's employment. If nearby Arlington is included, the core of the region contains more than one-third of the region's jobs. If pollution is a problem in the CBD, and if only one-half of all travel can be attracted to transit under the most optimistic forecasts, why continue to encourage employment to locate there? This question should also be raised when it is noted that most residential development is occurring outside the capital belt-

Table 1. Travel mode, time, and choice.

Distance From CBD (miles)	Equivalent Travel Time to CBD (min)		Work Trip Modal Choice (percent using transit)				
			Bus Versus Automobile		Rail Versus Automobile		
	Bus Versus Automobile	Rail Versus Automobile	$1 Parking Cost	Free Parking	$1 Parking Cost	Free Parking	Percentage of CBD Work Trips
4	+9	+6	45	30	50	35	50
8	+29	+9	30	20	45	30	30
12	+42	+16	25	15	40	25	15
16	+60	+22	20	10	35	20	5

Note: Equivalent travel time for walking, waiting, and transfer times weighted by a factor of 2½.

Table 2. Use of transit as related to parking costs.

Distance From CBD (miles)	Percentage of Trips to CBD Using Transit					
	Bus Versus Automobile		Rail Versus Automobile		Bus Versus Automobile, $2 Parking Cost	Rail Versus Automobile, $2 Parking Cost
	$1 Parking Cost	Free Parking	$1 Parking Cost	Free Parking		
4	22.5	15.0	25.0	17.5	25.0	27.5
8	9.0	6.0	13.5	9.0	10.5	15.0
12	3.75	2.25	6.0	3.75	4.5	6.75
16	1.0	0.5	1.75	1.0	1.25	2.0
Total	36.25	23.75	46.25	31.25	41.25	51.25

Table 3. Household and employment distribution by ring.

Ring	Existing Land Use Pattern (1968)		Future Land Use Pattern (1992)			
			Concentrated Employment Pattern		Decentralized Employment Pattern	
	Households	Jobs	Households	Jobs	Households	Jobs
0	1	19	—[a]	18	—[a]	13
1	5	17	1	13	1	13
2	16	14	7	11	7	11
3	20	11	11	8	11	9
4	30	19	20	15	20	17
5	15	9	17	10	18	12
6	9	8	20	13	20	13
7	4	3	12	7	12	7
8	—[a]	—[a]	11	7	10	5

[a] Less than 1 percent.

way, 10 to 12 miles away. Why continue to encourage such lengthy travel? Table 3 gives the imbalance between households and employment in each ring (rings are numbered outward from the center). With continued concentration in the region's core, it has been forecast that future highway travel will exceed current levels in that area, despite the completion of the rail system. In addition, future trip lengths will be substantially greater than they are today. Trip length and vehicle-miles of travel can be reduced by encouraging increased employment near the capital beltway. This decentralized employment pattern would redistribute 5 percent of regional employment out of the CBD and into satellite employment centers served by public transportation. A preliminary traffic analysis of this land use alternative shows significant reductions in trip length, travel time, and vehicle-miles of travel. Solutions to the air pollution problem can be found that are consistent with sound land use and transportation planning. The goals of such planning should be to minimize the number of vehicle-miles traveled and reduce traffic congestion.

7. A planning process that is responsive to evaluating alternative courses of action is required.

At a minimum, the planning process must be able to quickly produce forecasts of future conditions based on various land use and transportation alternatives and control schemes. These results should receive wide public distribution. Although the methods of determining these forecasts will necessarily vary, quantification of alternative courses of action is essential to sound decision-making.

8. Continuing process improvement, monitoring, and feedback are essential.

Although there is no shortage of traffic data, models, and forecasts (in Washington, D.C., if not in all U.S. cities), the corresponding data for automobile emissions and air quality are largely unavailable. Only a few control stations exist, and minimal ad hoc readings of pollutants are available. The conversion of vehicle-miles of travel and speed data to pollution values and the subsequent determination of air quality leave much room for continuing analysis and development. Monitoring and analysis, especially after control strategies are implemented, are essential to determine if standards are being met.

SUMMARY

Eight recommendations for incorporating air quality planning considerations into the land use and transportation planning process have been discussed. (Not discussed was the obvious need to consider the air quality implications of various land uses independently of traffic generation and resultant emissions.) A major need is to seek out transportation and land use planning strategies that can reduce the amount of vehicular emissions. It has been shown that the problem cannot be solved on a partial basis but that regional solutions must be sought and implemented. Public acceptance of such solutions can be attained if alternative courses of action are studied and evaluated.

These alternatives should consider various scales (CBD, corridors, and area-wide) and time frames (immediate, short range, and long range) with the benefit and impacts to the public clearly stated.

A planning process that can bring together affected groups and reconcile air quality, land use, and transportation (including central area parking policies) is needed. In most cities, it may be desirable to utilize the comprehensive transportation planning process for such work. The process should be responsive to meeting stated goals and objectives and evaluating the benefits and impacts of alternative policies and programs. Continuing monitoring and evaluation of strategies are essential to the process.

REFERENCE

1. Berwager and Wickstrom. Estimating Auto Emissions of Alternative Transportation Systems. For U.S. Department of Transportation, April 1972.

THE QUANTITATIVE AIR QUALITY REPORT

John Skog, Earl Shirley, and Andrew Ranzieri, California Division of Highways

A series of field observations and mathematical analyses are presented in an effort to answer certain questions posed in the preparation of an environmental impact statement. The significant primary pollutants (carbon monoxide, hydrocarbons, oxides of nitrogen, sulfur oxides, and particulates) produced from stationary as well as mobile sources are tabulated. Air quality standards based on results of investigations on the effects of pollutants are presented. The component parts of an air quality study are discussed. Transport and dispersion of pollutants depend on topography and meteorology, and the procedure to be adopted in their study is outlined. The use of a mathematical model in analyzing pollutant concentration in the microscale is described as is mesoscale analysis. Ambient air quality defines the background levels of pollutant concentration. Data gathering in ambient air quality studies is discussed. Guidelines on data presentation and summarization (written and tabular) and methods of graphical representation are provided. The need for research to quantify the various factors is stressed.

•CONCERN over the apparent deteriorating quality of the environment has resulted in the adoption of numerous new programs and requirements. In particular, the "environmental impact statement" requirements of the National Environmental Policy Act of 1969 are now familiar to those connected with the highway program. Further, in December 1970, Congress passed the Federal-Aid Highway Act of 1970, which directed that guidelines be prepared that will ensure that possible adverse economic, social, and environmental effects be considered on federal-aid highway projects.

Among other things, the Act stated that, "air, noise and water pollution be considered, and further, that all highways constructed under terms of the Act are consistent with implementation plans to attain ambient air quality standards for any air quality control region."

In order to properly evaluate the effects of air pollution from highways, one must perform necessary field studies and analyses leading to a quantitative air quality report. It is the purpose of this report to present an outline of the studies of the California Division of Highways in connection with the preparation of a quantitative air quality report.

AIR QUALITY PHENOMENA

Emissions contributing to air pollution are produced from stationary and mobile sources. The most significant primary pollutants from such sources are carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), sulphur oxides (SO_2), and particulates. Table 1 gives the estimated nationwide sources of the five major pollutants for 1968.

In the eastern United States, the most pervasive form of air pollution is a combination of sulfur dioxide and particulates derived from stationary industrial sources. Also, significant amounts of carbon monoxide, hydrocarbons, and oxides of nitrogen are emitted by mobile sources powered by internal-combustion engines.

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In the western United States, most large population centers do not have high sulfur dioxide levels but may be subjected to so-called photochemical smog that is composed of a large series of compounds derived from reactions of atmospheric oxygen with oxides of nitrogen and hydrocarbons in the presence of ultraviolet light. The conditions found in California, its cities built on flat lands surrounded by mountain ranges, a persistent inversion aloft, a large amount of sunlight (source of ultraviolet radiation), and a high concentration of automobiles in the principal urban areas, make it an ideal breeding ground for photochemical smog.

The principal factors affecting pollutant concentration are the downwind distance between the receptor and the source, the wind speed and associated turbulence, the source strength, and the mixing depth.

The greater the distance between the source and receptor is, the more chance there is for dispersion to occur and hence lessen the concentration. Higher wind speeds have the effect of increasing the amount of air into which the emitted pollutants are dispersed. In effect, this causes a greater dilution. Vertical turbulence, of course, promotes the dispersion of pollutants from a continuous line source such as a highway. The mixing depth directly affects the volume of clean air available to dilute the pollutants.

To properly define an air quality study for a highway line source, one must examine the manner in which the receptors perceive changes in air quality. It is convenient to look at these effects on two levels, microscale and mesoscale.

The receptor living immediately adjacent to the line source is affected when localized pollutant concentrations reach levels injurious to his health. This is the microscale effect, and it must be analyzed and quantified in terms of pollutant concentration. The mesoscale effect, as the term would imply, looks at the effect of the project over a much wider area than in the immediate highway corridor. A study of this level is quantified in terms of pollutant burden, that is, tons of pollutant per day per unit area of land surface. Pollutant burden, during episodic conditions, is directly related to ambient pollutant concentrations, and, although these concentrations never reach the levels of those found in the microscale situation, they may endure over a sufficiently long period to cause health problems in susceptible individuals.

The effects of the various pollutants on man have been investigated and delineated by epidemiologists. As a result of these investigations, ambient air quality standards have been published by the California Air Resources Board and the Environmental Protection Agency. These standards are given in Table 2. It should be noted that these standards were developed to protect those people who are especially susceptible to the effects of air pollutants. These susceptible individuals are primarily the very old, the very young, those with cardiac insufficiencies and anemia, and respiratory cripples.

COMPONENT PARTS OF AN AIR QUALITY STUDY

Air quality predictions resulting from an air quality study should cover a time period that begins with the present situation and covers approximately 20 years subsequent to the estimated time of completion of the improvement. For this period, air quality predictions must be made for two conditions. The first condition assumes that the transportation project is built, and the second assumes that the project has not been built.

Determination of pollutant concentrations in the microscale area will be confined, initially, to carbon monoxide, lead, and total particulates. Hydrocarbon concentration will not be predicted because it is not considered by epidemiologists to constitute a health hazard. The primary reason for the inclusion of hydrocarbons in the ambient air quality standards was to effect a control on the formation of secondary pollutants. Oxides of nitrogen will not be predicted in the microscale analysis because of the lack of suitable emission factors showing the variation of these emissions with respect to speed.

Secondary pollutants will not be considered in the microscale analysis because even low wind speeds are usually sufficient to move the reacting pollutant out of the microscale area before sizable quantities of secondary pollutant can be formed. Indeed, recent study has shown that ambient ozone within the microscale area is involved in the

Table 1. 1968 estimated nationwide emissions (in millions of tons).

Pollutant	Transportation	Fuel Combustions in Stationary Sources	Industrial Processes	Solid Waste Disposal	Other	Total	Percentage of Total by Motor Vehicle
Carbon monoxides	64	2	10	8	17	101	63
Hydrocarbons	17	1	5	2	9	34	52
Nitrogen oxides	8	10	0.2	1	2	21	39
Particulates	1	9	8	1	10	29	4
Sulfur oxides	1	24	7	0.1	1	33	2

Table 2. Ambient air quality standards applicable in California.

Pollutant	Averaging Time	California Standards		Federal Standards[a]		
		Concentration[b]	Method[c]	Primary[d]	Secondary[e]	Method[f]
Photochemical oxidants (corrected for NO_2)	1 hour	0.10 ppm (200 μg/m^3)	Neutral buffered KI	160 μg/m^3[g] (0.08 ppm)	160 μg/m^3[g] (0.08 ppm)	Chemiluminescent
Carbon monoxide	12 hours	10 ppm (11 mg/m^3)	Nondispersive infrared spectroscopy	—	—	Nondispersive infrared spectroscopy
	8 hours	—		10 mg/m^3 (9 ppm)	10 mg/m^3 (9 ppm)	
	1 hour	40 ppm (46 mg/m^3)		40 mg/m^3 (35 ppm)	40 mg/m^3 (35 ppm)	
Nitrogen dioxide	Annual average	—	Saltzman	100 μg/m^3 (0.05 ppm)	100 μg/m^3 (0.05 ppm)	Colorimetric using NaOH
	1 hour	0.25 ppm (470 μg/m^3)		—	—	
Sulfur dioxide	Annual average	—	Conductimetric	80 μg/m^3 (0.03 ppm)	60 μg/m^3 (0.02 ppm)	Pararosaniline
	24 hours	0.04 ppm (105 μg/m^3)		365 μg/m^3 (0.14 ppm)	260 μg/m^3 (0.10 ppm)	
	3 hours	—		—	1,300 μg/m^3 (0.5 ppm)	
	1 hour	0.5 ppm (1,310 μg/m^3)		—	—	
Suspended particulate matter	Annual geometric mean	60 μg/m^3	High-volume sampling	75 μg/m^3	60 μg/m^3	High-volume sampling
	24 hours	100 μg/m^3		260 μg/m^3	150 μg/m^3	
Lead (particulate)	30-day average	1.5 μg/m^3	High-volume sampling, dithizone	—	—	—
Hydrogen sulfide	1 hour	0.03 ppm (42 μg/m^3)	Cadmium hydroxide stractan	—	—	—
Hydrocarbons (corrected for methane)	3 hours (6 to 9 a.m.)	—	—	160 μg/m^3 (0.24 ppm)	160 μg/m^3 (0.24 ppm)	Flame ionization detection using gas chromatography
Visibility reducing particles	1 observation[h]	—	—	—	—	—

[a] Federal standards, other than those based on annual averages or annual geometric means, are not to be exceeded more than once per year.

[b] Concentration expressed first in units in which it was promulgated. Equivalent units given in parentheses are based on a reference temperature of 25 C and a pressure of 760 mm of mercury.

[c] Any equivalent procedure may be used that can be shown, to the satisfaction of the Air Resources Board, to give equivalent results at or near the level of the air quality standard.

[d] The levels of air quality necessary, with an adequate margin of safety, to protect the public health. Each state must attain the primary standards no later than 3 years after that state's implementation plan is approved by EPA.

[e] The levels of air quality necessary to protect the public welfare from any known or anticipated adverse effects of a pollutant. Each state must attain the secondary standards within a "reasonable time" after implementation plan is approved by EPA.

[f] Reference method as described by the EPA. An "equivalent method" of measurement may be used but must have a "consistent relationship to the reference method" to be approved by the EPA.

[g] Corrected for SO_2 in addition to NO_2.

[h] In sufficient amount to reduce the prevailing visibility to 10 miles. Prevailing visibility is defined as the greatest visibility that is attained or surpassed around at least half of the horizon circle, but not necessarily in continuous sectors.

oxidation of nitric oxide to nitrogen dioxide, thereby reducing the ambient levels of ozone in the immediate vicinity. In the future, as suitable emission factors become available, determination of NO_x concentrations within the microscale area will be made.

For the mesoscale, or total burden analysis, predictions will be confined, initially, to the two gaseous pollutants, carbon monoxide and hydrocarbons. Again, oxides of nitrogen will not be estimated because of the lack of suitable emission factors relating emission of NO_x to speed. Effects of lead and other particulates are usually limited to the microscale area because these pollutants, except for some amount in the submicron size range, are acted on by gravitational forces and are also removed by impaction with surrounding objects. Hence, they will not be considered in the mesoscale analysis. Initially, secondary pollutants resulting from photochemical reactions will not be quantified in the mesoscale analysis because of the lack of a fully validated mathematical model to predict the photochemical reactions. Sophisticated models are now becoming available, and, as soon as the validation requirements are satisfied, this capability will be added to our procedures.

In the future, we should gradually proceed toward a systems approach because the ambient air quality is a function of the interaction among all the various freeways and the surface traffic network. This is the subject of scheduled research.

It should be recognized at the outset that air quality predictions are somewhat tenuous at best. The predictions resulting from an air quality study are based on statistical analysis of meteorological conditions, statistical analysis of ambient air quality, and statistical analysis of traffic data. These data are then extrapolated perhaps 25 years into the future and are used to make air quality predictions. It should be obvious that the reliability of these predictions is not precise. However, the predictions are made by using recognized methods and the best available data. For this reason, no apology need be made concerning the adequacy of the predictions.

PROCEDURES FOR ANALYZING HIGHWAY IMPACT ON AIR QUALITY

The following outline describes a procedure for analyzing highway impact on air quality (Fig. 1):

1. The project description should be a short narrative statement of not more than a few paragraphs describing the proposed improvement in sufficient detail to allow a reviewer to obtain a mental picture of the work to be done.
2. The conclusions are presented early in the report to enable a cursory review by the person who does not desire to dig through the details. In the conclusions, the first thing to be discussed should be the answers to the questions for the environmental impact statement. Secondly, the written and tabular data summaries should be presented. The final portion of the conclusions, the graphic data presentations, can be interspersed with the written and tabular data summaries if desired.
3. The background discussion should provide a resume of all the historical data that were researched for the study. These data should be presented under the following general topics: topography (including a copy of the map discussed later in this paper), historical meteorology, historical air quality, principal existing point and line sources, existing and future land use, existing and future sensitive receptors, and research (previous studies).
4. The field studies should be fully described including the instrumentation used, calibration of that instrumentation, dates and locations where observations were made, and a discussion of the setups at the various points. This section should be divided into two subsections: meteorology, including data reduction and results; and ambient air quality, including data reduction and results.
5. The source of traffic estimates should also be given if data sources other than the California Division of Highways were used. These estimates should also be tied in with the discussion of the existing and future land use.
6. A brief discussion of the derivation of the emission factors should be presented in this section.

7. Mathematical analysis should cover the use of the mathematical model to estimate microscale concentrations and the various mesoscale analyses that were made.
8. A bibliography should list the sources of historical data and other information used in the report.
9. If desired, the reduced meteorological and ambient air quality data from the field studies may be attached to the report in appendix form. The appendixes should be attached only to those reports going to interested agencies such as the Air Resources Board and the Department of Public Health. The average reviewer will be interested only in the data summary.

CHARACTERIZATION OF SOURCE STRENGTH

A highway represents a continuous line source of pollutant emissions. The strength of this line source is dependent on two factors: the volume of pollutants coming from each individual vehicle and the number of these vehicles on the highway at any given time (1, 2).

The emission factors used in this approach vary with (Fig. 2) vehicle model and year mix, percentage of heavy-duty vehicles in the traffic stream, speed of traffic, and vehicle operating model (this is, in the simplest sense, whether the vehicle is on the freeway system or on the surface network).

Traffic data for source strength calculations in the microscale area consist of speed and volume information at the point where the analysis is being made (Fig. 3). This information must be supplied for the critical hours of the day. The critical hours may be determined by peak-hour traffic or adverse meteorological conditions. For the mesoscale, or pollutant burden analysis, total daily mileage and associated average speeds are needed for both freeway traffic and surface traffic (Fig. 3).

TRANSPORT AND DISPERSION OF POLLUTANTS

The transport and dispersion of air pollutants depends on topography and meteorology. The very important first step in any study of transport and dispersion is that of laying out and examining, on a topographical map, all the features that might affect the air quality study. This procedure is as follows:

1. Plot the location of all air quality data sources;
2. Plot the location of all meteorological data sources;
3. Delineate natural and man-made features that might affect wind flow;
4. Plot the location of the most sensitive receptors such as hospitals, schools, and rest homes as well as the features of medium sensitivity such as residential areas;
5. Plot the location of existing and future point sources of pollution such as factories and power plants;
6. Plot the location of areas with susceptible agricultural crops that are downwind of the project in the area where secondary pollutants might be expected to form;
7. If sufficient data are available from the plotted meteorological stations, prepare wind rose plots and superimpose these on the topographic map;
8. If sufficient data are available, prepare overlays showing wind streamlines for the typical meteorological regimes; and
9. Examine the plotted data and locate the areas where field studies will be required to obtain additional desired meteorological and air quality data.

A meteorological study (3) is an essential element of any air quality analysis (Fig. 4). Only in this manner can the transport and dispersion of pollutants be estimated. The first step is to locate all existing data for the area under study. These data should be analyzed and wind roses developed. The desirable parameters for this analysis are wind direction, wind speed, stability for various regimes, inversion heights or mixing depths, and, if data are available, wind streamlines.

There will be a few cases where the existing data fully satisfy the data requirements for the project. Normally, data will have to be developed for each individual project. These data will be developed in distinct phases. The first step will be to obtain data, using mechanical weather stations at desirable locations, to characterize wind speed

Figure 1. Procedure for analyzing highway impact on air quality.

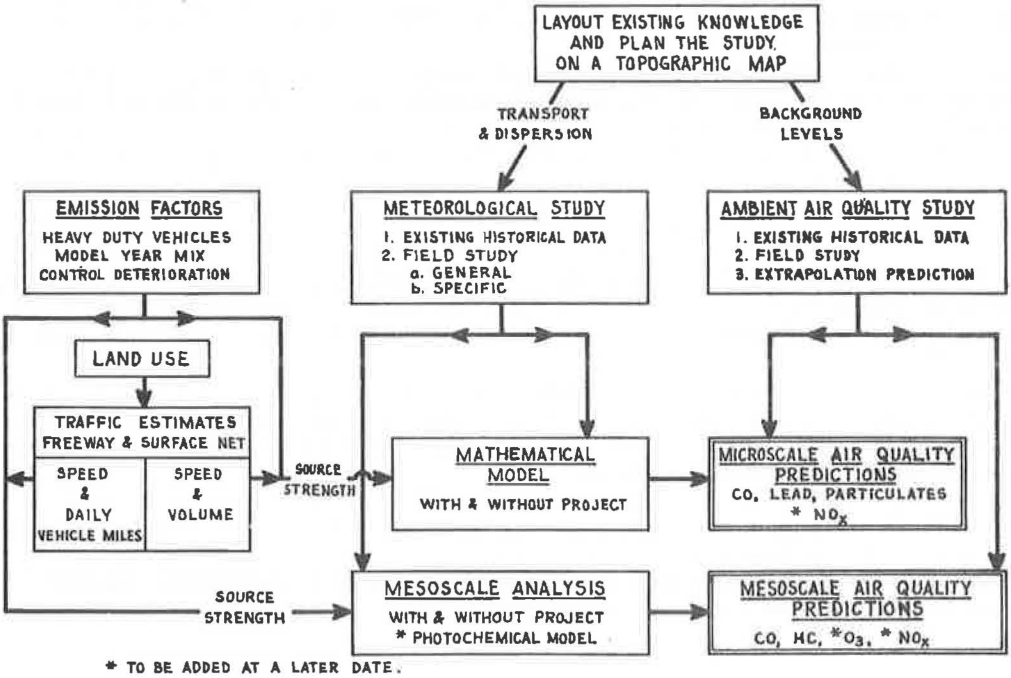


Figure 2. Emission factors.

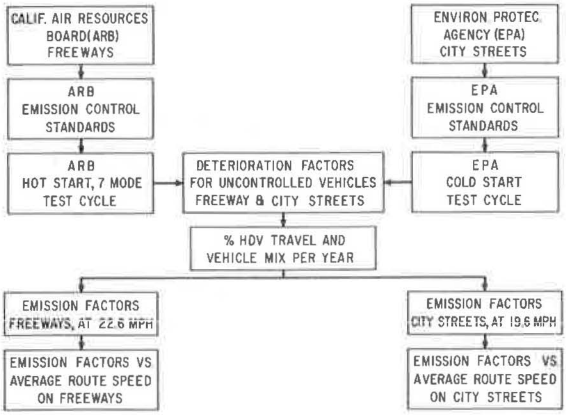


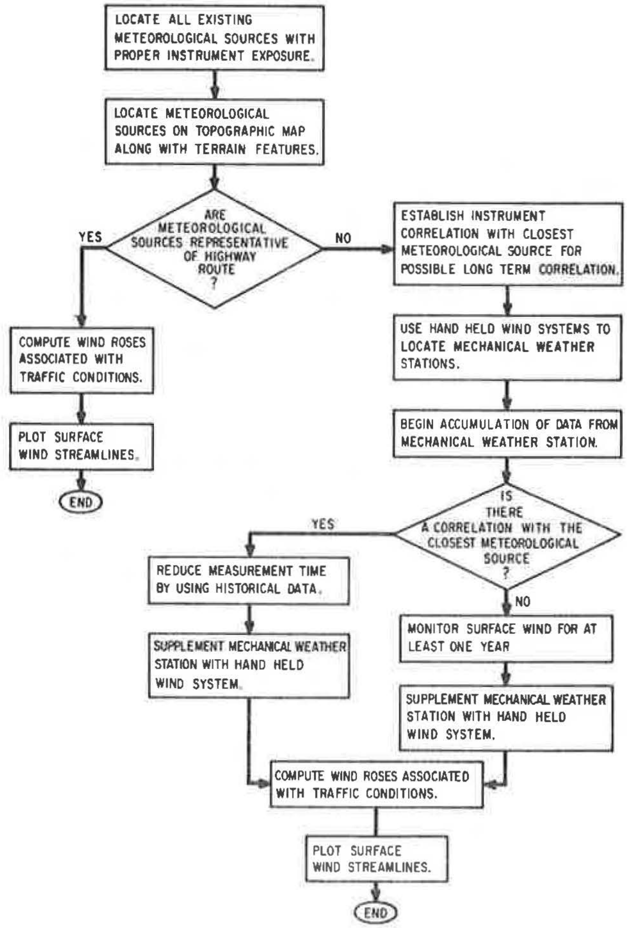
Figure 3. Traffic information matrix for air quality predictions.

TRAFFIC PARAMETERS		PROPOSED HIGHWAY FACILITY	SURFACE TRAFFIC*	
			WITH NEW FACILITY	WITHOUT NEW FACILITY
MESOSCALE AIR QUALITY	DAILY VEHICLE MILES	①②④⑤⑥ ⑦ ⑧ ⑩	②③④⑥ ⑦⑧⑩	② ④⑥ ⑦⑧⑩
	OVERALL SPEED	⑫ ⑬	⑪	⑪
MICROSCALE AIR QUALITY	PEAK HOURLY VOLUME	⑦ ⑧ ⑭ ⑮	⑯	
	SPEED AT PEAK HOURLY VOLUME	⑫		

*Surface traffic for the mesoscale analysis is that traffic from all streets in the feeder area - This represents a grid source of pollutants which affect the burden in the air basin.

①Attracted Traffic (use for new facility)
②Existing Traffic (use for improved facility)
③Diminished Traffic (use for surface streets)
④Normal Traffic Growth
⑤Generated Traffic
⑥Development Traffic (based on existing land use plane)
AASHO Definitions
⑦Change in Traffic Due to Future Land Use Changes
⑧Change in Traffic Due to Urban Mass Transit Facility
⑩Percentage of Heavy Duty Vehicles (HDV)
Daily Vehicle Miles
⑪Average Trip Speed
⑫Average Peak Hour Trip Speed
⑬Average Trip Speed for Free-Running Facility
Speed
⑭Daily volume
⑮Hourly % of Daily Volume
Volume
⑯This information is not usually available - It would define surface traffic from arterials parallel and immediately adjacent to the proposed facility which would be strongly influenced by that improvement. These represent a line source of pollutants which has an effect on nearby receptors.

Figure 4. Meteorological flow chart.



and direction. Collection of these data might take as long as a year. Where possible, inversion heights for the various meteorological regimes should be taken simultaneously with the other measurements. If instrumentation is available, twice daily flights from a nearby airport would satisfy this requirement. Calibration of any instrumentation used is essential.

The second phase for developed data involves an examination of the temperature structure and turbulence in the lower atmosphere. This can be accomplished by locating a meteorological tower on previously selected sites for short periods under the various meteorological regimes. The towers to be used by the California Division of Highways contain two sets of wind speed and direction instruments separated by a distance of 10 m to examine wind shear. They also have instrumentation for measuring temperature change over the same interval. This instrumentation is self-contained and capable of operating without support for more than a week at a time.

In any areas where wind flow patterns vary considerably because of topographical influences, it is desirable to obtain meteorological data that will allow construction of wind streamlines. For the microscale situation, these streamlines can be constructed with the use of hand-held anemometers and direction indicatoes. For the mesoscale situation, the use of balloons and theodolites is recommended.

Evaluation of meteorological information will involve the "most probable" and "worst case" meteorological conditions. The probabilities of occurrence of these conditions must be estimated. For each of these conditions, a wind rose and stability analysis must be made. These analyses must be correlated with hours of peak traffic flow and any anomalous traffic situation that may give rise to an increase in source strength. Conversely, traffic data must be collected for the worst case meteorological conditions. Analyses made in this manner enable the evaluation of the most critical conditions.

MATHEMATICAL ANALYSIS

Analysis of pollutant concentration in the microscale area is made using a mathematical model (Fig. 5). Inputs to this model consist of traffic data, meteorological data, and emission factors (4). The output from this model is presented in terms of concentration of the pollutant being analyzed for a particular meteorological regime and a certain traffic condition. To these predictions must be added the ambient concentration of the pollutant in question.

The mesoscale analysis (Fig. 6) is primarily concerned with the total pollutant burden resulting from changes in the traffic network that accompanies the initiation of a new traffic facility. The item of greatest importance in this analysis is the change in the total amount of daily vehicle mileage in the affected traffic network and the average operating speeds at which that mileage is generated. Another aspect of mesoscale analysis is the import of primary and secondary pollutants from distant upwind sources into the study area and the export of primary and secondary pollutants generated within the study area to distant downwind receptors. The final aspect of a complete mesoscale analysis is the examination of the time history of oxidant concentration and the prediction of future trends based on correlation with future pollutant burden estimates.

Beaton et al. (4) describe in detail the various aspects of the microscale and mesoscale calculations.

AMBIENT AIR QUALITY

A study of ambient air quality serves to define the background levels of pollutant concentrations in the project area (5). Like the meteorological study, an ambient air quality study must begin with the collection and analysis of the existing or historical data (Fig. 7).

Because it is highly unlikely that sufficient data exist to define ambient air quality along a proposed route, particularly in areas along the route containing sensitive receptors, it is mandatory to perform an on-site survey. The first level of sophistication in such a survey is to obtain bag samples of air for later analysis. The only gaseous pollutant for which values can be obtained without some degree of degradation is carbon

Figure 5. Microscale corridor analysis.

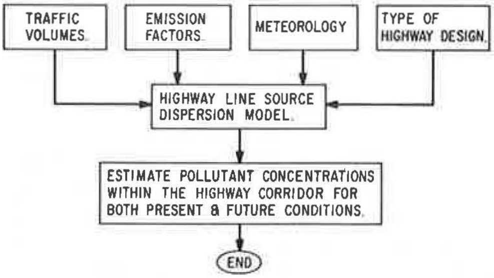


Figure 6. Mesoscale analysis.

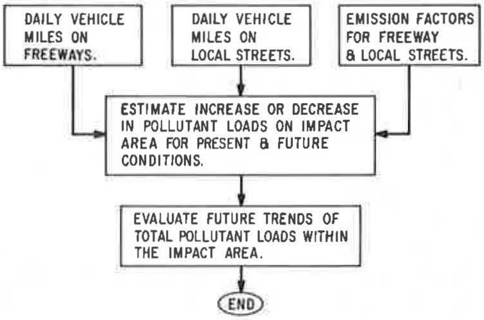
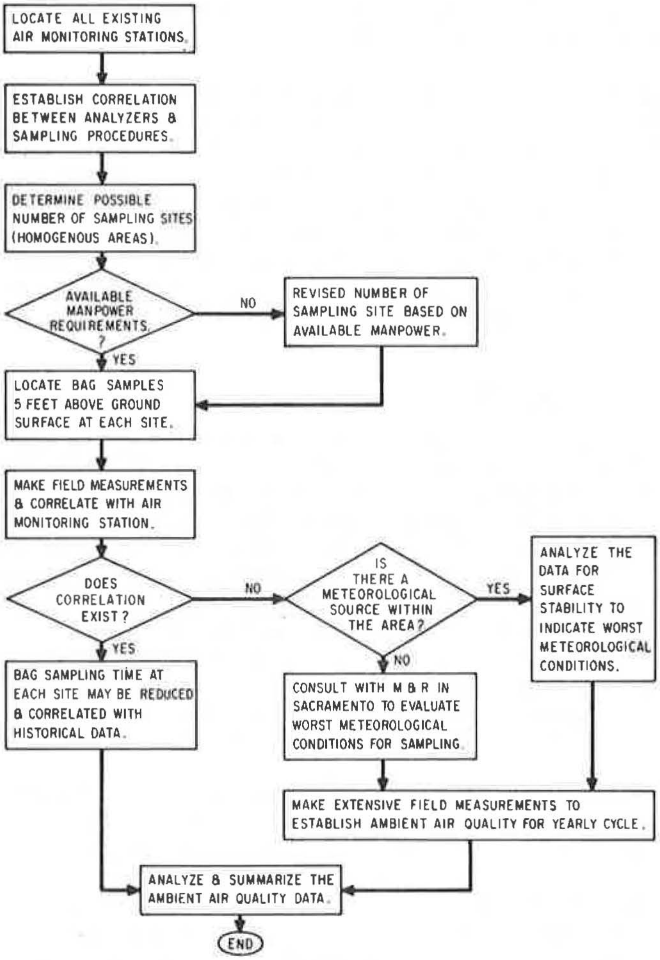


Figure 7. Flow chart for ambient air quality survey.



monoxide. The necessary equipment for this survey is a number of 12- by 18-in. Scotchpak bags, a battery-powered air pump, and a well-calibrated, sensitive, nondispersive infrared carbon monoxide analyzer. Lead and particulates can be sampled with a high-volume sampler, and subsequent analysis for lead can be performed with atomic absorption equipment. Continuous meteorological observations must be taken at the site during the gathering of any air samples.

The second stage of sophistication for an air quality survey involves the use of an instrumented van. The vans used by the California Division of Highways contain a long-path, nondispersive infrared analyzer for carbon monoxide, an ultraviolet absorption analyzer for ozone, a chemiluminescent analyzer for nitric oxide and nitrogen dioxide, and a high-volume sampler for lead and particulate samples. These minivans contain on-board power with a capability for connecting to house current. Each minivan has an on-board anemometer and wind direction indicator. Data are acquired graphically and on-board capability for calibration is maintained.

Data gathered during an ambient air quality study serve several purposes. The main purpose, naturally, is that of providing background air quality data. Secondary purposes involve the building of a data bank (this applies particularly to NO_x and O_3 data), mathematical model validation, and analysis of source strength predictions. Where NO_x and O_3 are traceable to upwind highways, traffic data should be obtained during sampling.

The periods during which ambient air quality data are gathered must be closely tied with the periods for the meteorological survey and the periods for which traffic data are estimated. Again, the object is to acquire data for the most probable conditions and the worst case conditions. Air quality data must be taken for periods corresponding with the various averaging times listed in the ambient air quality standards.

The final phase of the ambient air quality study is the prediction of future ambient air quality. This prediction can be based in part on an extrapolation of the correlation between historical pollutant burden and historical ambient air quality. To this extrapolation must be added the effects of future changes in land use and probable future point sources.

DATA PRESENTATION

One of the most difficult aspects of any report lies in the communication of the significant findings to other people. In the case of the air quality report, the findings will be incorporated into an environmental impact statement by another person. This statement will then be used as a basis for decision-making by still other people. It is very probable that the findings from the air quality study, in addition to being used in the environmental impact statement, will be used as a basis for discussions in a public hearing. It is, therefore, doubly important that the findings be communicated in a manner that promotes understanding and enables analysis by a reasonable layman.

It is entirely possible to address a report to two or three levels of understanding. The needs of the technically oriented person may be satisfied by presenting detail in the body of the report, whereas the reasonable layman, with the aid of written, tabular, and graphic data summaries, should be able to arrive at a full understanding of the findings.

The number of variables to be discussed in an air quality report taxes the ingenuity of the report writer who is attempting to communicate his findings. Air quality must be discussed in terms of the proposed project and without it. The most probable and worst case pollutant concentrations must be presented and the probabilities of their occurrence discussed. The time period for the study must begin with the existing situation and continue through the completion of the improvement and for 20 years thereafter. The effects of the pollutants must be discussed in terms of the distance between the receptor and the source. The pollutant concentrations must be discussed in terms of health standards; that is, the 1-, 8-, and 12-hour averages, yearly averages, and other averages as required must be presented for the pollutants to which they apply. Each pollutant requires a separate discussion, which increases the difficulty of the task.

WRITTEN AND TABULAR DATA SUMMARY

The following items should be presented in tabular form with sufficient written discussion for each item to fully explain the data (6).

1. Ambient air quality data should be shown in a form that will clearly indicate the existing air quality, the air quality at the end of the design life of the project, and the intervening trends. If the trends indicate a peak or a valley, both the poorest and the best air quality should also be indicated.
2. The pollutant burden and its variations over the same time period should be presented. A short discussion should cover the probability of episodic conditions and the effects of those conditions on the pollutant burden.
3. The import and export of pollutants, where applicable, should be discussed. The relative effect of these phenomena should be presented.
4. The oxidant trends with respect to time should be presented in terms of the number of adverse days, which might exceed the health standards, on a yearly basis over the period of the study.
5. Microscale pollutant concentrations should be shown for the most probable and worst case conditions. The respective probabilities of occurrence of these conditions should be indicated. Some detail should be presented with regard to areas where sensitive receptors are located. The data should also be presented in a manner that will indicate the variation in concentration with respect to the distance from the source.

VISUAL AIDS

One of the best avenues of communication between the engineer and the layman is that that utilizes visual aids such as charts, graphs, and sketches. This approach, however, is often abused and fails to achieve its purpose because of the amount of detail on any one chart that the eye is required to assimilate. Simple visual aids, with minimal detail and the bold use of color, are the epitome of good communication. The principal use of the visual aid should be to present trends and comparisons. The tabular and written summaries, discussed previously, are slightly more sophisticated and present some detail. The body of the report provides even finer detail and technical discussion for those who are interested.

Graphic presentation of trends, with time as the horizontal axis, can efficiently demonstrate changes in mesoscale pollutant burden, oxidant trends, and ambient air quality.

The mesoscale pollutant burden trends could be indicated with one color for the situation including the improvement and one color for the situation without the improvement. Horizontal limit lines could then be drawn with one line indicating the maximum acceptable pollutant burden under the most probable meteorological conditions and another limit line indicating the maximum acceptable burden under episodic conditions.

The trends in average ambient air quality can be indicated with a single line for each pollutant. However, because a comparison must be made with the averaging times specified by the health standards, several charts for each pollutant may be required. The applicable air quality standard should be indicated by a horizontal line on the appropriate charts.

Oxidant trends with respect to time can be appropriately visualized by two different colored lines on a chart representing the situation both with and without the improvement.

Contour maps may be an effective way of visualizing microscale pollutant concentrations. This could be done by using a plan view of the project and the surrounding community with perhaps three colors representing ranges of pollutant concentrations. One chart could thus indicate spatial variations in pollutant concentrations for the combination of a particular meteorological regime and source strength. The color red could be used to indicate those concentrations that exceed the health standards.

The question of pollutant transport may be dealt with by a two-color presentation that indicates the relative amounts of transported oxidant and oxidant formed from pollutants generated within the area.

RESPONSE TO QUESTIONS FOR THE ENVIRONMENTAL IMPACT STATEMENT

Response to the questions to which the environmental impact statement must address itself should be made in the air quality study. The statements must be quantified insofar as possible. This may be done by listing the changes in air quality in terms of tons per day or parts per million.

The ultimate effect of air pollution, however, as it applies to human health, agricultural losses, wear and soiling of clothing and other fabrics in the home, corrosion and wear of metals, paints, and susceptible materials, extra-industrial maintenance, aesthetic losses, degradation in work performance, decline in property values, and visibility reduction is very complex and cannot be estimated. If the changes in quantities and concentrations of air pollutants are very small, it should be pointed out that the effects on the air environment would be small also. If, however, the changes are substantial, it is best to leave the evaluation of the effects of the change up to competent epidemiologists, plant pathologists, and other such experts.

SUMMARY

The quantitative air quality report consists of a series of field observations and mathematical analyses that answer certain required questions posed in the writing of an environmental impact statement. Detailed micrometeorological and ambient air quality field observations over relatively long periods of time must be obtained. The analysis of the information must be coupled with traffic data and vehicle emission factors in order to estimate emission concentrations and dispersion.

It should be stressed that the subject is in a continuing state of flux, and a great deal of research is still required to properly quantify the various required factors.

ACKNOWLEDGMENTS

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REFERENCES

1. Beaton, J. L., Skog, J. B., and Ranzieri, A. J. Motor Vehicle Emission Factors for Estimates of Highway Impact on Air Quality. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(2)-72-09, April 1972.
2. Beaton, J. L., Skog, J. B., and Shirley, E. C. Traffic Information Requirements for Estimates of Highway Impact on Air Quality. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(3)-72-09, April 1972.
3. Beaton, J. L., Skog, J. B., Shirley, E. C., and Ranzieri, A. J. Meteorology and Its Influence on the Dispersion of Pollutants From Highway Line Sources. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(1)-72-11, April 1972.
4. Beaton, J. L., Skog, J. B., Shirley, E. C., and Ranzieri, A. J. Mathematical Approach to Estimating Highway Impact on Air Quality. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(4)-72-12, May 1972.
5. Beaton, J. L., Skog, J. B., Shirley, E. C., and Ranzieri, A. J. Analysis of Ambient Air Quality for Highway Environmental Projects. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(5)-72-13, July 1972.
6. Beaton, J. L., Skog, J. B., and Shirley, E. C. A Method for Analyzing and Reporting Highway Impact on Air Quality. Materials and Research Dept., California Dept. of Public Works, Air Quality Manual CA-HWY-MR657082S-(6)-72-14, July 1972.

EVALUATION OF CRITICAL HIGHWAY PROJECTS IN THE AIR QUALITY PLANNING PROCESS

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With the increasing emphasis on environmental protection being manifested by the federal government and the general public, highway planning agencies are now required to assess in detail the impacts of proposed facility improvements and newly located roads on corridor ambient air quality. Experience on numerous projects throughout the nation has shown that such assessments generally require lengthy, comprehensive evaluations of corridor meteorology, preconstruction ambient air quality, post-construction traffic growth and redistribution effects, gross emission generation, and pollutant dispersion characteristics. The definition of the several elements required for a comprehensive highway air quality impact assessment must be undertaken at the earliest project planning stage so that all necessary studies and field surveys can be initiated in parallel with other aspects of the location study or environmental impact evaluation. This paper describes a novel procedure by which the transportation planner can determine whether detailed air quality studies are warranted for a proposed route alternate under consideration. The environmental capacity of critical average daily traffic of a given roadway is defined as a function of readily available highway planning parameters. A series of capacity curves and planning criteria are presented that describe maximum average daily traffic volumes that can be tolerated under generalized, most adverse meteorological conditions before the national ambient air quality standards for carbon monoxide and hydrocarbons will be exceeded at a given distance from the edge of the roadway. Use of this methodology has proved to afford a direct, valid means for structuring highway air quality studies and for direct assessment of air quality impact of proposed highways in suburban and rural environments.

•DURING the past several years, the federal government has supported extensive research and development programs directed toward the development of quantitative methodology for evaluating the impact of highway projects on ambient air quality. These efforts are now coming to fruition, bringing forth new technologies heretofore unknown in the highway planning process. As never before, transportation planning is becoming a marriage of conventional facility planning methodology with advanced state-of-the-art socioeconomic and technical environmental disciplines. In the area of highway air pollution technology especially, the body of knowledge related to planning processes is expanding at an exponential rate, thereby requiring that highway planning agencies expeditiously assimilate this information and adapt themseleves as necessary to implement these technically sophisticated procedures at the earliest possible date. Federal directives will soon require that state highway departments incorporate air quality considerations into their formal highway planning process as an essential criterion for their future highway projects to be eligible for federal-aid participation. Likewise, prudent development of environmentally sound highway systems warrants that equally comprehensive air pollution impact analyses be made integral components in the planning process for any future highway facility, regardless of its source of funding.

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*When this paper was written, Mr. Rocco was with the Tennessee Department of Transportation.

Realizing the importance of thorough air pollution treatment to the overall highway planning process and recognizing that it can be only through an intensive self-education program that the growing air pollution technology information gap can be spanned in the reasonably near future, several state highway departments have undertaken an aggressive program to ensure their competence in conducting highway air quality planning. Member states making up Federal Highway Administration Region IV (southeast United States) have attempted to capitalize on the broad and varied experience base within their several department staffs to form a regional environmental working group for the mutual identification, dissemination, and assimilation of the new environmental technologies for immediate application to the federal-aid highway planning process. Although the fields of noise and water pollution are also being treated in detail, special attention has been directed to the area of highway air quality planning. Under the direction of the FHWA regional staff, information exchange, technical workshops, and in-house seminars have become the main lines of communication and education in the most recent advancements in air pollution technology as applied to highways.

The experience and practical expertise gained as a result of this self-education program have led the member states to undertake the development of a series of generalized planning process guidelines for treating highway air pollution impact. In particular, Tennessee has developed a set of basic criteria by which highway planners can readily identify at the initial stages of location planning to what extent a proposed facility will adversely impact corridor air quality in violation of the Environmental Protection Agency's (EPA's) ambient air quality standards for two set 2 (automotive) pollutants, carbon monoxide (CO) and hydrocarbons (HC) (1). Using these criteria, the highway planner can determine the need for and extent of in-depth air quality studies at a time when they should be conducted in parallel with the other studies of the overall planning process. It is the intent of this paper to present the details of these air quality planning criteria and to describe their specific applicability to the overall transportation planning process.

IDENTIFICATION OF HIGHWAY PROJECTS CRITICAL TO CORRIDOR AIR QUALITY

The quantitative evaluation of the air pollution potential concomitant with a proposed highway project is a function of several independent variables, most of which, once identified, can be evaluated in the project planning stage. In developing a technically comprehensive yet administratively practical working procedure for transportation planners to employ in preparing environmental impact and section 4(f) statement air pollution analyses, the manifest objective is to establish a methodology that permits the reasonably accurate prediction of a proposed project's influence on ambient air quality both in the immediate project corridor and throughout its realm of influence. Planners must have facility in utilizing the best available technically accurate technique for predicting mobile pollutant emission rates as a function of traffic flow parameters and pollutant transport as a function of corridor micrometeorology and topography. Resultant estimates of highway-generated pollutant concentrations must then be coupled with background pollutant level estimates to yield a measure of the true impact of the facility on air quality. Because of the intersection of numerous man-made and natural variables affecting air pollution generation and dispersion, the technical treatment of highway air pollution must necessarily be a complex process, requiring detailed, interdisciplinary study.

The very nature of the gaseous set 2 pollutants, when released into the atmosphere, complicates the treatment of their impact on the environment. Their mobility and dispersion or mixing is a function of the meteorological stability and horizontal wind energy in the corridor. Their relative chemical activities further distort one's facility to predict their downwind effects. CO is slow to react in the atmosphere, whereas HC and the oxides of nitrogen once released are prime constituents in the formation of photochemical smog because of their sensitivity to sunlight and moisture. At present, technology has not given the transportation planner operational predictive techniques for quantifying the temporal and spatial distribution of secondary pollutants with confidence. In the alternative, the planner must treat them in their "as emitted" chemical state.

EPA has promulgated ambient air quality standards for set 2 (automotive) pollutants that transportation planners can use to measure the effect of pollution on the environment: carbon monoxide, 10 mg/m^3 (9 ppm) as a maximum 8-hour concentration not to be exceeded more than once a year and 40 mg/m^3 (35 ppm) as a maximum 1-hour concentration not to be exceeded more than once a year; hydrocarbons, 160 μg/m^3 (0.24 ppm) as a maximum 3-hour concentration (6 to 9 a.m.) not to be exceeded more than once a year; nitrogen oxides, 100 μg/m^3 (0.05 ppm) annual arithmetic mean; and photochemical oxidants, 160 μg/m^3 (0.08 ppm) as a maximum 1-hour concentration not to be exceeded more than once a year. The effects of these pollutants on man have been investigated and delineated by epidemiologists. It should be recognized that these standards were developed to protect that segment of the general population that is especially susceptible to the effects of air pollutants. These susceptible individuals are primarily the very old and the very young, those with cardiac insufficiencies and anemia, and respiratory cripples. These limits of pollutant concentration and exposure duration, above which human health and well-being are endangered, apply equally to all types of land use and activities, and their applicability is not abrogated by zoning distinctions. It is generally accepted that the presence of a proposed highway facility should not result in air pollution concentrations above these standards.

Once the highway planning agency gains technical competence in treating the several varied aspects of highway-generated air pollution prediction, it then faces the major problem of determining at the initial stages of the location planning process which projects will require detailed air pollution analyses and in what manner such analyses should be conducted to adequately quantify the air pollution potential of a proposed facility. A recent EPA position paper on the subject recommends as a general criterion that projects located in standard metropolitan statistical areas (SMSA's) and projects predicted to result in more than a 25 percent increase in annual traffic volume within the first 3 years of their use warrant in-depth consideration (2). Although this criterion is generally valid and prudent in that it tends to emphasize in-depth analysis for higher populated areas whose air quality is already likely to be poor, it is felt that, for rural states in which SMSA's often do not accurately describe the population density distribution and are not adequate indicators of high pollution potential, a more technically definitive set of criteria must be devised to describe which highway projects warrant close scrutiny of their pollution potential during the design period. In turn, these criteria should permit the highway planner to determine, using readily available location, predicted traffic flow, meteorological, and ambient air quality data, whether ambient air quality standards may be exceeded and which are the critical time periods for excessive air pollution potential during the design period. Once these essential determinations can be made, then the full air pollution impact analysis, if required, can be conducted in an orderly and technically comprehensive manner early enough to contribute to major location planning decisions to be made downstream.

Such a series of technically based criteria has been developed by the Tennessee Department of Transportation's Bureau of Planning. These criteria were structured to provide the transportation planner valid means for making the required initial technical judgments described previously. The basis for these criteria is shown in Figures 1 and 2. Using these figures, the planner can identify in terms of average daily traffic (ADT) those highway projects that will generate air pollution levels in excess of the EPA ambient air quality standards at some time during their construction period. These critical highway capacity curves represent that combination of available automotive emission factor data and highway-oriented pollutant dispersion prediction technique that yields the lowest allowable ADT as a function of peak-hour average vehicle-operating speed and design period year, above which the standards will be exceeded at a given reference distance downwind from the roadway's shoulder. EPA emission factors for gasoline-powered vehicles (3) and the at-grade highway line source dispersion model developed by the California Division of Highways (4) proved after extensive calculations and validation to afford the desired results.

The mathematical model developed and validated by the California Division of Highways under contract with FHWA is based primarily on the Gaussian diffusion equation. Concentrations of pollutants within the plume generated by highway user vehicles are

Figure 1. Critical ADT below which carbon monoxide ambient air quality standards should be maintained.

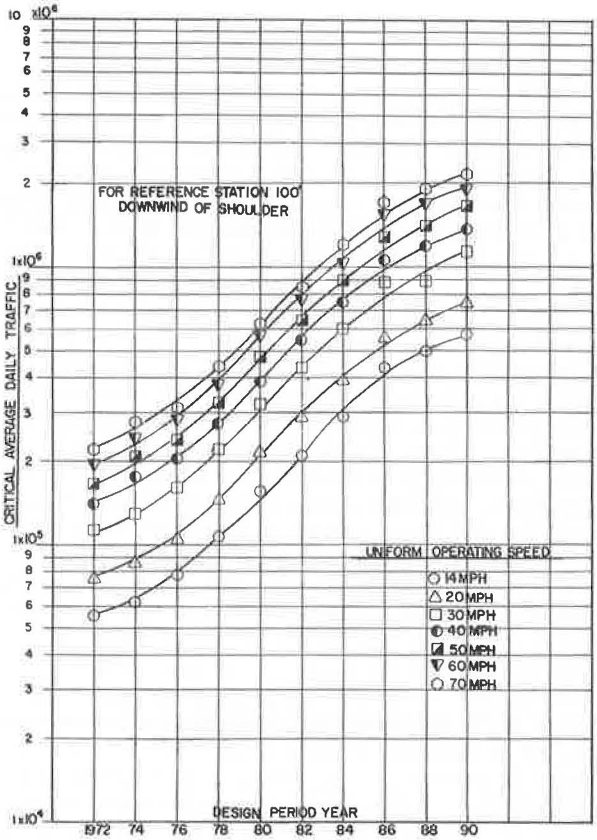
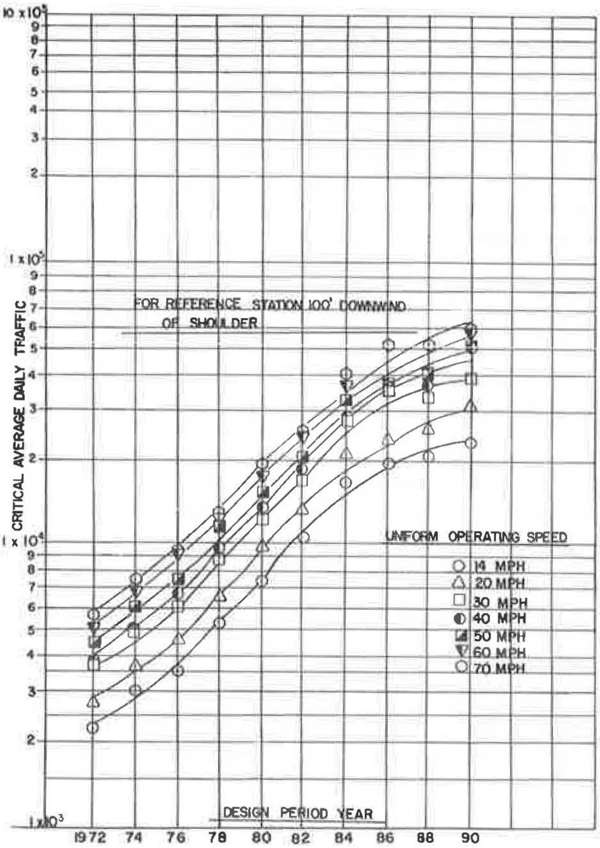


Figure 2. Critical ADT below which hydrocarbon ambient air quality standards should be maintained.



assumed to be distributed normally in both crosswind and vertical directions. Highway vehicles are treated as continuous emission sources for the time period analyzed. The surface stability classes of the atmosphere are determined from studies by Pasquill (5) and from an objective system of classifying stabilities from meteorological observations developed by Turner (6). In lieu of the conventional exhaust pipe line source used in several other highway dispersion modeling techniques, a mechanical mixing zone or cell is defined as the initial pollutant volume. This intense zone of mixing and turbulence caused by the motion of the vehicles exhibits pollutant concentrations that are independent of surface stability. A uniform wind flow field without wind shear is assumed to transport the pollutants generated within the mechanical mixing cell, unaffected by aerodynamic effects caused by air passing over structures, buildings, and other surface obstructions. The geometry of the highway dispersion calculation scheme is shown in Figure 3.

Utilizing the California model, critical ADT curves have been derived for generalized, yet assumed most adverse, corridor meteorological conditions. It should be recognized that certain project characteristics may result in "more critical" conditions than assumed in structuring this methodology. Pollutant concentrations resulting from depressed roadway sections or from winds parallel to the roadway may result in such situations; however, experience has shown that, with the limited meteorological and roadway design information available at the early stages of highway planning, the assumptions embodied in the "worst case" conditions used prove to be environmentally conservative for most highway planning applications.

Turner class F stability coupled with 1-mph average wind speed (essentially a calm condition) acting at 90 deg to the centerline of the roadway has been utilized in the calculations to evaluate what is generally considered an extremely adverse air pollution dispersion condition (7). Although many project corridors will exhibit this high pollution potential only a relatively small percentage of the year, the short averaging times inherent in the ambient air quality standards given in Table 1 demand that close scrutiny be given to these worst case conditions whenever they occur.

Critical ADT curves are presented for CO and HC only because the assumed most adverse meteorological conditions and traffic flow parameters used to derive them are valid for the 1- and 3-hour averaging times of these pollutants. The large variability of corridor meteorology and traffic flow over a 1-year averaging time precludes the realistic specification of a generalized, most adverse case for comparison with the oxides of nitrogen standard. Attempts to specify such conditions for this pollutant have repeatedly resulted in gross overestimates of pollution potential with concomitant unrealistically low critical ADT's when compared with actual air quality field measurements and traffic count correlations.

CORRIDOR ANALYSIS

Whether a given project or viable route alternative requires detailed or summary air pollution analysis can be determined by comparing predicted ADT throughout the entire design period with the critical values shown in Figures 1 and 2 for the peak-hour average vehicle-operating speed. Should the predicted ADT exceed the critical ADT for any set 2 pollutant at any time during the design period, the project should be considered as having a critical air pollution potential, and a complete technical analysis should be conducted to treat those years within the design period in which unacceptable pollutant levels are predicted to occur. However, should the predicted ADT compare favorably with the critical values for each pollutant, only a summary treatment of corridor air quality should be required unless there are overriding arguments to the contrary. It should be recognized that, in generating these curves, critical ADT has been calculated as a function of both peak-hour average operating speed and a generalized diurnal traffic volume distribution. As a result, critical ADT at any time in the design period is a direct function of peak-hour traffic conditions and assumed greatest average daily traffic volumes. It is only through this procedure that direct comparison of results with set 2 pollutant averaging times can be obtained (8).

Critical years to be emphasized in applying these criteria are the construction year, the design year, and the year shortly after construction during which traffic generation effects dominate traffic volume growth. Generated traffic is defined as the additional traffic above that that can be accounted for by diversion from other routes in the general vicinity of the project and by normal growth. Study of a number of actual projects has shown that generation on an urban limited-access highway normally ranges between 30 and 60 percent with an average of about 45 percent. The rural equivalent is approximately 15 percent (9). In most cases, this generation rate should be applied to the construction year ADT using the following formula:

$$\text{Stabilization year ADT} = (1 + \text{generation rate})(\text{construction year ADT})$$

The computed volume is assumed to occur at the year of stabilization, normally 2 to 3 years after a facility is opened.

Existing highway and nonhighway source background set 2 pollution levels must necessarily reduce the maximum average daily traffic that can be tolerated before ambient air quality standards are exceeded. Therefore, whenever background levels of set 2 pollutants are known to exist in the project corridor via aerometric measurements or mathematical predictive techniques, critical ADT's shown in Figures 1 and 2 must be adjusted downward because the curves so displayed assume no background. A simple mathematical relation has been derived to enable the planner to take into account such nonproject generated pollution concentrations. The "adjusted" ADT values obtained must be applied for all assumed operating speeds; i.e., for a given pollutant, the computed adjusted ADT obtained in the formula that follows must be used in lieu of any value obtained directly from Figures 1 and 2 for all years of interest within the design period of the proposed project.

$$ADT_{\text{adjusted}} = (1 - pX_B)ADT_{\text{critical}}$$

where ADT_{adjusted} is the critical value of ADT adjusted downward to account for existing or predicted background set 2 pollutant concentrations, X_B is the measured or predicted background set 2 pollutant concentration expressed in g/m^3, ADT_{critical} is the unadjusted critical capacity value obtained from Figures 1 and 2 for the assumed peak-hour average vehicle-operating speed and desired design period year, and p is a constant uniquely defined for each set 2 pollutant as follows: for CO, $p = 25\ g/m^3$ and, for HC, $p = 6.25 \times 10^3\ g/m^3$.

Should background levels already exceed ambient air quality standards, the preceding criteria should not be applied. In this case, the project should automatically be considered as critical from an air pollution standpoint, and a complete technical analysis should be conducted for that portion of the design period through which federal, state, and local emission controls on stationary and mobile sources are insufficient to reduce air pollution to within national ambient air quality standards.

In areas containing a relatively dense network of high-volume highway facilities, any new facility will generally cause major changes in the system-wide traffic distribution and operating characteristics with a resultant effect on background air pollution from these existing facilities. Adjustments should be made to corridor background set 2 pollutant levels whenever it becomes apparent that this phenomenon will occur after a proposed facility is opened for use. Both computerized and manual prediction technique have recently become available for treating system-generated background air pollution modifications (8).

As noted previously, the critical ADT curves shown in Figures 1 and 2 have been developed for a reference distance of 100 ft downwind of the highway shoulder using the California line source model. This permits ambient air quality standards to be met at distances greater than 100 ft downwind if the traffic volume is below the critical values shown. However, should intervening topography or land use dictate that a location farther downwind be considered as a basic reference point for minimally meeting standards, this can be achieved by using Figure 4. The curve shown in this figure provides the correction factors that can be applied to the critical ADT values for the 100-ft reference to convert them to reflect the effect of permitting a buffer zone to intervene between the roadway and the receptor greater than 100 ft in width. The resultant ADT represents the increased daily traffic capacity that can be tolerated if standards need

Figure 3. Geometry for the highway line source model and calculations.

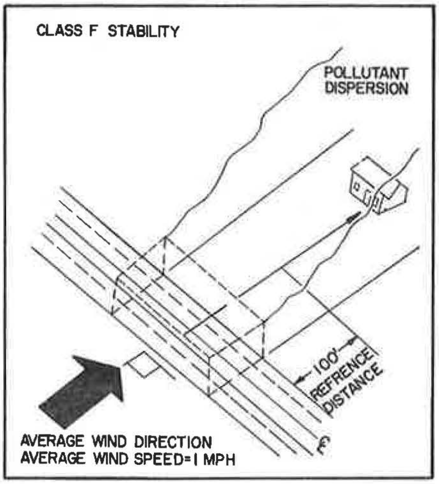
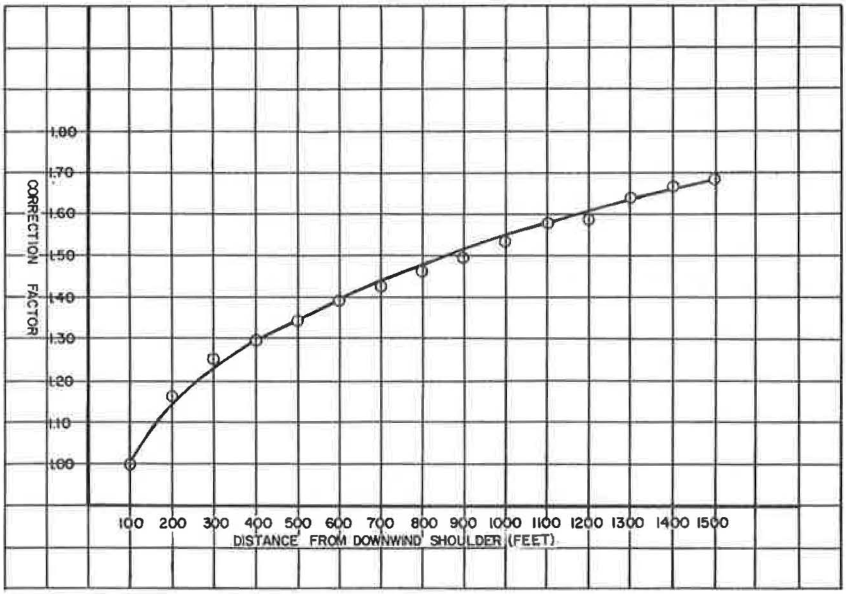


Figure 4. Critical ADT correction factor for receptor distances greater than 100 ft downwind from the highway shoulder.



not be met within the buffer zone. These correction factors allow such a zone to extend as much as 1,500 ft downwind of the roadway shoulder. Because of the universal nature of the ambient air quality standards, use of this correction is rarely justified unless federal approval is obtained and appropriate zoning restrictions are enacted to create a true buffer zone for the period before which federal automotive emission controls will reduce set 2 pollution to within acceptable levels.

RECOMMENDATIONS AND CONCLUSIONS

By utilizing the criteria discussed in this paper, a highway planning agency can identify which projects will require in-depth air pollution impact analyses and to what extent such treatment should be made. If these determinations are made early in the location planning stage, adequate preparations can be undertaken to evaluate several route alternates in terms of their individual air pollution potentials and to prepare a technically comprehensive and defensible impact statement for the alternate with best overall socioeconomic and environmental characteristics.

These criteria have not been devised to curtail the planning and eventual construction of new highway facilities but form the basis by which the highway planner can make responsible and prudent technical decisions affecting the impact of a proposed facility on the environment. It is only after he realizes that there is a problem and appreciates its extent that he can call on the other tools of the overall planning process to correct or mitigate the impact. This is the true role of the transportation system planner.

Despite the extensiveness of technology to be assimilated, highway planning agencies at all levels of government should realize that they must adapt now to face and master the environmental responsibilities concomitant with the advocacy of any new project. Experience has shown that, once these new responsibilities are shouldered, they can be mastered.

REFERENCES

1. National Ambient Air Quality Criteria and Standards. Federal Register, Vol. 36, No. 84, April 30, 1971.
2. EPA Review Guidelines for Highway Environmental Impact Statements. Region IV, U. S. Environmental Protection Agency, Atlanta, Aug. 1972.
3. Compilation of Air Pollution Emission Factors. Office of Air Programs, U. S. Environmental Protection Agency, Publ. AP-42, Feb. 1972.
4. Beaton, J. L., Ranzieri, A. J., Shirley, E. C., and Skog, J. B. Air Quality Manual, Volumes 1-7. Office of Research, Federal Highway Administration, Repts. FHWA-RD-72-33 through 39, April 1972.
5. Pasquill, F. Atmospheric Diffusion. D. Van Nostrand Co., Ltd., London, 1962.
6. Turner, D. B. In Jour. of Applied Meteorology, Feb. 1964.
7. Turner, D. B. Workbook of Atmospheric Dispersion Estimates. Office of Air Programs, U. S. Environmental Protection Agency, Publ. AP-26, Revised 1970.
8. Rocco, V. A. Predicting Highway Air Pollution: A Design Guide for Highway Planners. Res. and Planning Div., Tennessee Dept. of Highways, Nashville, May 19, 1972.
9. Guide for Forecasting Traffic on the Interstate System for the 1972 Cost Estimate. FHWA Highway Planning Program Manual, Transmittal 108, April 1971.

IMPACT OF HIGHWAYS ON AIR QUALITY

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A general survey is presented of the techniques by which the impact of highways on air quality may be measured and predicted. The processes by which air pollution emitted by moving vehicles is dispersed by atmospheric turbulence and transported by the wind are stated to be central to this problem. Application of micrometeorological theory and experience shows that the Richardson number is the most important parameter governing turbulent dispersion. The major existing theories available for the development of air quality models are discussed. An analysis is presented of a typical highway air quality impact study that included a measurement program and the development of a model to predict air quality in 1990. It is concluded that the measurement program was inadequate to verify the model and that little confidence could be placed in the future air quality projection. Four general conclusions are as follows: The microclimate is an important key to the problem of highway air quality because it determines the ability of the atmosphere to disperse air pollution and is closely related to land use patterns; the Richardson number should be a standard part of any air quality measurement program; better and more comprehensive measurement programs should have a higher priority than the development of more complex air quality models; and more attention should be paid to the inherent properties of the models.

•THE twentieth century has been a time of constantly increasing energy use in the United States and throughout the world. In the United States since 1925, the rate of increase has been about 3 percent per year. At the same time, there has been a major shift from coal to petroleum products as the major source of energy in this country and throughout the world. Pollution is inherent in the production and utilization of energy. With the second law of thermodynamics in mind, waste heat is the cleanest kind of pollution that can possibly be achieved. Of course, the relative efficiency of various kinds of energy production and use varies and is directly related to resultant pollution. In general terms, the most inefficient uses that we make of energy resources are the conversion process to electric power and transportation by means of the internal-combustion engine. In terms of waste heat and pollution, power generation and transportation lead all other categories.

The subject of this paper is pollution associated with transportation, in particular that emitted by motor vehicles traveling on highways. The processes that lead to a specified air quality level in the air that we breathe are complex. Figure 1 shows the kind of perspective that is useful in considering this problem. The diagram suggests that meteorological influences are highly important in determining air quality. In this paper, the meteorological aspect of the problem is emphasized, particularly the current state of our ability to model and predict the pollution emission to the air quality part of the process. Human health problems associated with air pollution will not be discussed.

Much of this paper is meant to have implications for and to be useful to the policy-making and planning processes in society. One of the benefits of making a diagram like Figure 1 is that it forces one to consider the problem from a broad perspective.

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From this point of view, it becomes clear that the processes that influence land use patterns are critically important in determining the net result of the entire human health and comfort system. The policy-making and planning processes are particularly important, for it is in this area that accurate information and estimates of the consequences of changes in specific portions of the system may have significant impact for the common good.

In this context, I would like to point out that the transportation industry has a unique role to play. In contrast to many protions of society, the advance planning component of transportation is strong and accustomed to making use of the best available engineering information in its operations. Consequently, the additional considerations that are necessary to protect and manage air quality come naturally to highway engineers and administrators. The transportation industry has an excellent opportunity to lead the way in rational planning to satisfy the immense demands that society makes for goods and services and also to protect environmental quality.

DISCUSSION OF THE PROBLEM

The problem of motor vehicle air pollution may be defined from a meteorological point of view as the transport and diffusion of material emitted from a line source near the surface of the earth. The problem is not really this simple, but the geometry strongly suggests this approach. One of the problems is that of scale. Like most complex systems, the factors that are important to small-scale processes in the atmosphere are very different from those that determine the larger scales. The phenomena that affect the transport and dispersion of highway pollution include, in meteorological terminology, the microscale and mesoscale. In this section, this distinction and its effect on highway air quality will be discussed.

Eschenroeder (7) has suggested the existence of a zone above highways in which the air is well mixed by the energy of the moving vehicles. This zone has the dimensions of twice the height of the average vehicle times the highway width and is called the mechanically mixed cell. This mixing zone or cell can be thought of as the cumulative effect of all the turbulent wakes that are formed behind each object moving along the highway. Within the mechanically mixed cell, pollution is supposed to be dispersed uniformly, to a first approximation, and this state is the effective initial distribution of air pollution that is acted on by micro- and meso-meteorological processes to affect air quality downwind of the highway.

It should be noted that, in this simple model, the quality of the air that drivers and passengers breathe directly above the highway is completely determined by the properties of the vehicles and their motors and is independent of meteorological processes. At sufficiently high winds, this certainly cannot be true. The extent to which the mechanically mixed cell is affected by external meteorological influences has not been studied in sufficient detail to allow any general statements at this time. This is an important point because it determines the pollution levels that highway travelers are subjected to and should be the object of an intensive experimental effort.

One operational conclusion that can be drawn from the mixing cell concept is that the effective height of emission of highway pollutants is the average height of the vehicles. For the remainder of this section, it shall be assumed that the actual highway emission pattern may be replaced by a line source concentrated at that height. This material, whether gaseous or particulate, is now subjected to the microscale wind transport and diffusion processes. Under most conditions, the wind near the ground varies logarithmically with height according to

$$U = \frac{U_*}{k} \ln \frac{z}{z_0} \tag{1}$$

where U is the wind speed at height z, k is the von Karman constant, U_* is a micrometeorological parameter called the friction velocity, and z_0 is the aerodynamic roughness and is directly related to the geometrical roughness of the surface. These last two parameters are important to the process by which atmospheric turbulence is generated near the ground. U_*, which is defined by

$$U_* = \sqrt{\frac{\tau}{\rho}} \tag{2}$$

where τ is drag force that the wind exerts on the surface and ρ is air density, can be thought of as representative of the turbulent velocity fluctuations that arise from the roughness of the surface and that do most of the work in diffusing material near the surface. The significance of the logarithmic wind law for highway air quality lies in the fact that, in all theoretical and empirical treatments of air pollution, air concentration is found to be inversely proportional to wind speed. Consequently, the air quality downwind of a freeway must be closely related to the effective height of emission, and an elevated highway configuration would be expected to result in significantly improved downwind air quality compared to at-grade highways. Again, this statement must be qualified by stating that highway measurements adequate to verify this prediction are only now being made.

An order-of-magnitude calculation has been made of the wind dilution effect on local air quality to be gained from elevating freeways. The effect of raising the highway to height z on the air concentration of pollution C at the same height at some arbitrary distance downwind was calculated (assuming a logarithmic wind profile and all other factors constant). The following relation was obtained:

$$\frac{100}{C}\frac{\partial C}{\partial z} = \frac{-100}{z \ln z/z_0} \tag{3}$$

If $z_0 = 0.1$ m, a value typical of suburban land use, this formula gives the following results:

Highway Height (m)	Percentage of Improvement per Meter Height	Highway Height (m)	Percentage of Improvement per Meter Height
1	43.5	6	4.1
2	16.7	7	3.4
3	9.8	8	2.9
4	6.8	9	2.5
5	5.1	10	2.2

As can be seen, large improvements in air quality immediately downwind would be expected for the first 1 or 2 m of elevation but with decreasing effect after that. It should be emphasized that this is only a rough order-of-magnitude estimate that neglects other effects, such as the mixing cell, which may be important or even dominate resultant air quality in some situations.

A second qualifying remark should be made at this point. The logarithmic wind law is strictly valid only for conditions in which the atmosphere is well mixed. Under other conditions, corrections must be made to this relation (21) that are, however, not large in magnitude and are well known; they provide a parameter called the Richardson number, which we will discuss in the following section.

At the same time that highway pollution is being transported by the wind, it is being diffused by atmospheric turbulence. It is useful to consider the energetics of turbulence at this point. The kinetic energy per unit mass e of the field of turbulence at a point may be defined as

$$e = \overline{\tfrac{1}{2}(u)^2} \tag{4}$$

where u is the turbulent component of the wind speed near the ground such that

$$U = \overline{U} + u \tag{5}$$

where $\overline{U}$ is the average wind speed. In both Eqs. 4 and 5, the bar signifies a spatial or a sufficiently long time average. Because turbulence is here considered as energy, it is instructive to look at the sources and sinks of turbulence energy near the ground. This problem was first treated by Richardson (28) who was particularly interested in the special case when turbulence vanishes in the atmosphere, a situation of critical significance to the air pollution problem.

The rate at which turbulence energy is generated mechanically by wind shear associated with surface roughness is given by (19)

$$U_*^2 \frac{\partial U}{\partial z} = K_m \left(\frac{\partial U}{\partial z}\right)^2 \tag{6}$$

where K_m is the turbulent diffusivity for momentum in the atmosphere and arises from the definition of U_*. The rate at which turbulence is suppressed by stable temperature gradients near the ground is given by

$$\frac{-g}{T}\,\frac{H}{\rho c_p} = \frac{g}{T} K_h \frac{\partial \theta}{\partial z} \simeq \frac{g}{T} K_h \frac{\partial T}{\partial z} \tag{7}$$

where g is the acceleration of gravity, T is air temperature in degrees Kelvin, c_p is the specific heat capacity per unit mass, H is the flux of sensible heat carried upward by turbulence (negative for stable conditions in which heat is diffused downward), K_h is the turbulent diffusivity for heat, and θ is the potential temperature, which in most practical cases may be replaced by temperature. It is apparent that the sign of this term changes if the sensible heat flux is upward, which corresponds to the normal condition during the day when heat is being transferred upward by convection from the warm ground. In this case, the temperature stratification is unstable, and turbulence is being generated by buoyant forces rather than being suppressed. For stable stratification, Richardson reasoned that turbulence would disappear when

$$\frac{g}{T} K_h \frac{\partial T}{\partial z} > K_m \left(\frac{\partial U}{\partial z}\right)^2$$

or

$$\frac{\frac{g}{T} K_h \frac{\partial T}{\partial z}}{K_m \left(\frac{\partial U}{\partial z}\right)^2} > 1 \tag{8}$$

that is, when the turbulence sink exceeds the source. The Richardson number Ri has come to be defined by

$$\mathrm{Ri} = \frac{\frac{g}{T}\frac{\partial T}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} \tag{9}$$

where potential temperature must be used in the numerator if large height increments are used in evaluating the temperature gradient. Experimentally, it has been found that turbulence vanishes at Richardson numbers around 0.3 (34). The fact that the critical Richardson number is not unity reflects experimental observations (21) that the ratio K_h/K_m is considerably less than one under stable conditions.

In the years since Richardson's pioneering work, the parameter that bears his name has assumed an overwhelming significance in micrometeorology. It has been shown experimentally (6) and theoretically (1) that the Richardson number is the most important single parameter in all micrometeorological processes. That is, Ri is more important than, say, wind speed or the temperature stratification considered alone. In particular, the Richardson number has been found to be enormously useful in organizing data into simple and understandable patterns. Figure 2 shows some typical micrometeorological data organized into useful functional relations by the use of the Richardson number. In this figure, the "phi functions" are essentially correction factors giving the effect of atmospheric stability, as measured by the Richardson number, on the simple logarithmic profile formulas such as Eq. 1. ϕ_h refers to the vertical diffusion of heat, ϕ_w to water vapor, and ϕ_m to momentum. Because pollution diffuses by the same physical mechanisms, similar phi functions would be expected to apply to air quality models although no current model has reached this level of sophistication.

The Richardson number has the disadvantage that its numerical value varies with height so that measurements of this parameter must be made at a standard height to be comparable. Another equivalent parameter, more useful in some ways, may be obtained by forming the ratio of the two energy source-sink terms as before but now by using the most fundamental definition on the left of Eqs. 6 and 7:

$$\frac{\frac{-g}{T}\frac{H}{\rho c_p}}{U_*^2\frac{\partial U}{\partial z}} = \frac{z}{\left(\frac{-\rho c_p T U_*^3}{kgH}\right)} \tag{10}$$

where the vertical derivative of the logarithmic wind law in this transformation is used. The quantity in parentheses, which has the dimension of length and is approximately constant with height, is called the Monin-Obukhov length L where

$$L = \frac{-\rho c_p T U_*^3}{kgH} \tag{11}$$

Under stable conditions (downward, negative heat flux H), the Monin-Obukhov length has the interpretation of being roughly the height at which turbulence is suppressed. Under stable conditions, then, pollution emitted near the ground would be expected to diffuse to height L. Under very stable conditions, L becomes small, and air pollution concentrations are high. Under unstable conditions, L is negative and has the physical interpretation as being the height at which convectively produced turbulence energy compares with mechanically produced energy. Above L, convection predominates and, under these conditions, turbulence levels are higher, atmospheric diffusion is more efficient, and air concentrations of pollution are smaller.

In qualitative terms, it is permissible to visualize atmospheric dispersion as a process similar to molecular diffusion in a solid or liquid body. The random motion of the molecules acts on superimposed gradients to transport properties, such as heat, "down the gradient" from regions of high concentration to low. In the analogy with turbulent motion in fluids, turbulence is thought of as essentially random motion that acts to mix or equalize distribution of fluid properties, and, thus, the net result is a transport process in which one region of the fluid gains at the expense of another. Formally, diffusivity K_s of a fluid property s expressed in units per unit mass of fluid can be defined by

$$F_{sx} = -\rho K_s \frac{\partial c}{\partial x} \tag{12}$$

where F_{sx} is the flux (transport per unit area and time) of s in the x-direction resulting from the diffusion process and c is the concentration per unit mass of air. The diffusivity so defined is formally equivalent to molecular diffusivity and, indeed, may be regarded as the sum of the molecular and turbulent processes. The size of the turbulent component of the diffusivity is, however, many orders of magnitude larger than the molecular term in natural fluid systems. The conclusion to be drawn is that turbulence is vastly more efficient at transporting fluid mass and associated properties, including pollution, than is molecular diffusion. That is the central significance of turbulence and also the fundamental reason for its existence.

The molecular analogy is useful only in a very general sense. Unlike molecular properties, such as conductivity or viscosity that can be tabulated as physical constants for many systems, turbulent diffusivity is a complex function of the state of the flow. It is, for instance, a function of the Richardson number. The property of turbulence that makes it particularly difficult to deal with both practically and theoretically is that the diffusivity cannot, in principle, be treated as constant even in situations where the measured Richardson number is constant. The reason is that diffusivity is observed to be a function of the scale of fluid motion. If one follows a puff of smoke emitted from a source near the ground, it is easy to observe a rapid increase of size of the puff as it entrains (mixes with) fluid from the environment. This process is a function of the energy that is contained in scales of motion (or "eddies") that are smaller than the puff. It is a fundamental property of the atmosphere and all turbulent flow systems that, if measurements are made of the amount of kinetic energy available in the various scales of motion present in the turbulence, it is invariably found that more energy exists at large scales than at small scales. Consequently, as our smoke puff grows, it is subjected to more and more energetic diffusion by the scales of turbulent motion smaller than its current dimensions. The larger it gets, the faster it diffuses. Richardson (29) was the first to recognize this remarkable phenomenon, and he proposed that this variation could be well represented by

$$K_s \simeq \text{constant} \times 1^{4/3} \qquad (13)$$

where 1 is a representative size of the "eddy" of identifiable diffusing substance. Richardson's law has stood the test of time and now constitutes a primary objective of any new turbulence theory.

There are several consequences of these properties of turbulence that are of significance to the practical objective of modeling the dispersion of pollution in the atmosphere. If one chooses to model the dispersion of effluent by following individual puffs or identifiable portions of the polluted air, it is not possible to consider the diffusivity as constant. Richardson's law must be taken into account. If one considers the distribution of turbulence energy with height above the surface of the earth, it is reasonable to expect that, as one gains altitude, larger and larger scales of motion will exist because there is more "room." This has been found to be true observationally (23) along with the logical corollary that diffusivity increases strongly with height. Hence, if the Richardson number at a given height is constant in time, it is permissible to consider the diffusivity as constant at that height. However, if the process extends over a considerable range in height, as diffusion does, the diffusivity is not a constant but a function of height. Thus, the common assumption in air pollution meteorology that the diffusivity is a constant quantity is an approximation whose limitations should be explicitly recognized.

The dispersion of particulates, large enough to fall out near their source, has certain unique properties. Because particulates emitted from any source have a spectrum of sizes, the fallout is differential; big particles reach the ground first. This effect alone, in the absence of any turbulence or wind shear, is enough to produce a wide dispersion of the material that falls out and is deposited at the surface of the earth. The terminal velocity is given as follows for various sized particles and simple order-of-magnitude calculation of the distance downwind at which a particle of the indicated size would be deposited if the average wind speed was 2 m/sec and the release height was 2 m.

Particle Radius (μ)	Terminal Velocity (cm/sec)	Deposition Point Downwind (m)
5	0.3	1,333
10	1.3	308
50	32.0	12.5
100	136.0	2.94
400	340.0	1.18

As can be seen, the dispersion due to differential fallout is considerable. This is also a stability-dependent process because the shape of the wind profile (and hence the average value of the wind) and the turbulent diffusivity between the release height and the surface are a function of the Richardson number.

The magnitude of the differential fallout effect is heavily dependent on the shape of the particulate size spectrum. Insufficient measurements have been made of the size distribution of particulates emitted by motor vehicles to allow modeling of this process with any degree of confidence.

The horizontal dimensions of cities are such that many properties of the atmosphere above them belong to those of the meteorological mesoscale. The term "air pollution meteorology" usually refers to the phenomena of the mesoscale, and, indeed, most air pollution studies have been concerned with this scale. The reason for making this distinction is that many of the fundamental properties of this scale of motion are different from those of the microscale. Table 1 gives a summary of the contrasting properties of the two scales from which their differing significances to pollution derive. Mesoscale wind systems arise because of horizontal gradients in the temperature of the earth's surface. Sea and lake breezes are familiar examples of this phenomenon. These wind systems have the properties that the strongest wind speeds are usually near the surface of the earth, and wind direction often exactly reverses with height. Figures 3 and 4 show examples of pollution transport in the Los Angeles basin by the sea breeze, and Figure 5 shows the typical reversal of wind direction with height. Because mesoscale wind systems are strongly associated with the 24-hour period of the sun, the wind flow develops slowly enough that the component of the earth's rotation about the local vertical (Coriolis parameter), which is a function of latitude, becomes an influence. Measurements of the Richardson number are difficult to make in the free atmosphere. Consequently, atmospheric stability is usually specified by means of the lapse rate alone. Elevated inversion (temperature increase with height) layers are usually present in diurnal wind systems, and the height of the base of the inversion is an important parameter for mesoscale air pollution modeling. Within inversion layers, the Richardson number often becomes large enough that all turbulence ceases, and hence inversions are effective barriers to atmospheric dispersion. Figure 6 shows a typical temperature sounding in the Los Angeles basin and the famous inversion layer that is usually present over that area during the summer and fall months.

In qualitative summary, it may be said that the most important physical processes and parameters that determine the concentration of pollution in the air that we breathe are the rate at which pollution is emitted into the atmosphere ("source strength"), distance downwind from the source of pollution, wind speed, atmospheric stability near the ground (Richardson number), height of elevated inversion layers, and topography.

MATHEMATICAL MODELING OF AIR QUALITY

In this section, the application of mathematical and numerical techniques to the problem of estimating air quality is discussed. With reasonable generality, the governing equation for the concentration C of some pollutant is

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} + \frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)$$

$$+ R(t)C + S(x, y, z, t) \qquad (14)$$

where u and v are the horizontal and w the vertical components of the velocity of the air in the x-, y-, and z-directions; K_x, K_y, and K_z are turbulent diffusivities associated with turbulent transport in the three coordinate directions; R(t) is a chemical reaction function for the case in which the pollutant is chemically active; and S(x, y, z, t) is a completely arbitrary source function that expresses the rate at which pollutant is emitted into a unit volume. Many different approaches can be adopted in obtaining analytic or numerical solutions to this equation. The most common solutions and methods that are currently in operational use in estimating air quality will be emphasized.

Figure 1. The air pollution system.

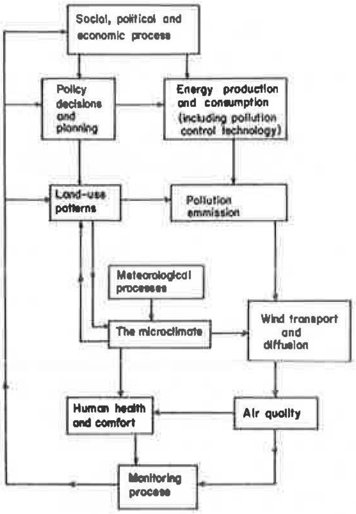


Figure 2. Micrometeorological measurements of the phi functions.

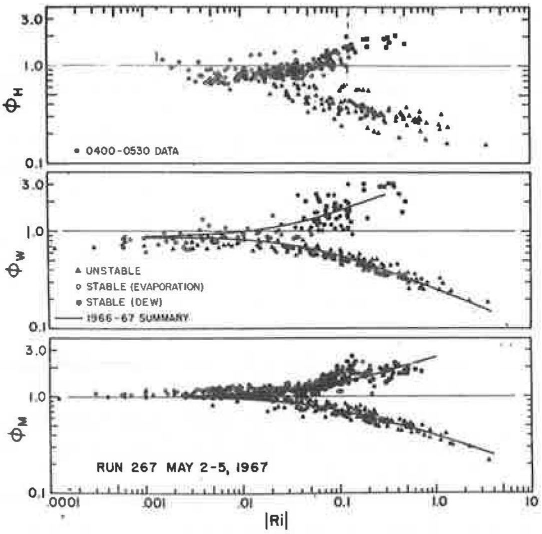


Table 1. Properties of microscale and mesoscale.

Phenomenon	Microscale	Mesoscale
Pollutant (primary gaseous and particulate pollutant)	—	Products of photochemical reactions
Space scale	1 to 100 m (highway corridor)	0.1 to 100 km (city, air basin)
Time scale	1 to 60 min	1 hour to 1 day
Primary transport processes (prevailing geostrophic wind)	Turbulence	Diurnal wind systems (sea breezes, etc.)
Source of transport energy	Surface roughness, wind shear, convection	Horizontal temperature contrasts, topography
Primary parameters (wind speed and surface roughness)	Richardson number	Latitude, stability (inversion height)
Typical model	Line-source Gaussian	Box

Figure 3. Los Angeles air flow pattern.

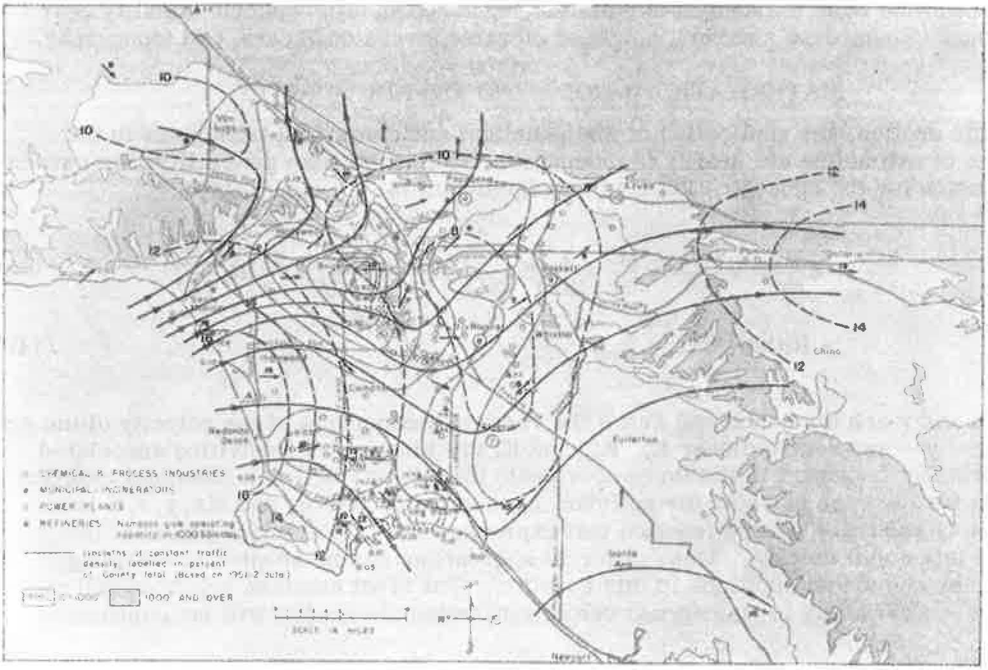


Figure 4. Los Angeles sea breeze.

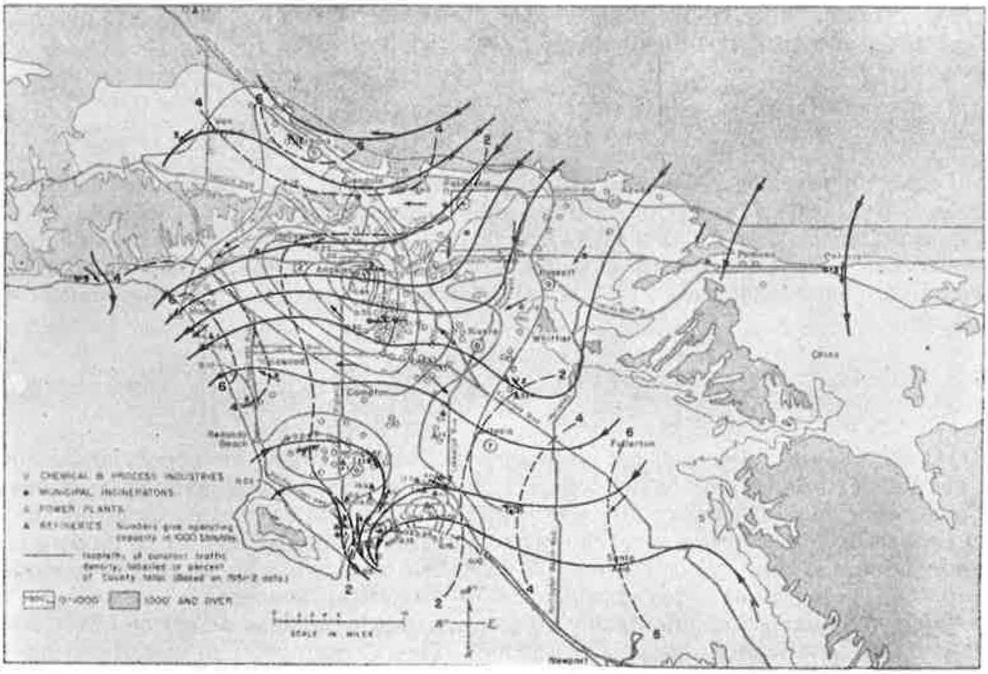
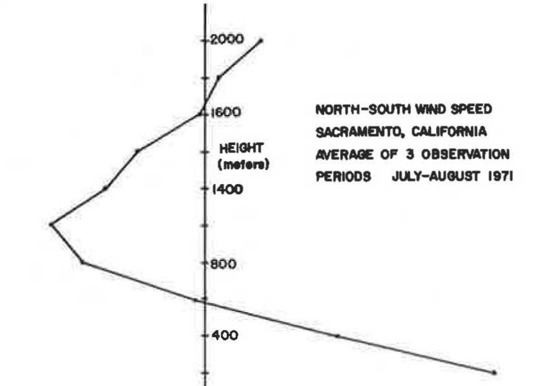


Figure 5. Mesoscale wind speed profile.



As it stands, Eq. 14 is formidable, and solutions are only possible if it is greatly simplified. For instance, if the mean wind is in the x-direction, vertical velocity is neglected, diffusion in the x-direction is neglected relative to wind transport, pollutant is nonreacting, and diffusivities are taken as constants, Eq. 10 reduces to

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} + K_y\frac{\partial^2 C}{\partial_y^2} + K_z\frac{\partial^2 C}{\partial_z^2} + S(x, y, z, t) \qquad (15)$$

For this case, application of boundary conditions appropriate for certain source configuration allows explicit analytic solutions to be found. Equation 15 is, in fact, essentially the molecular or Fickian diffusion equation, and numerous solutions are available in any text on heat conduction or molecular diffusion (4). For instance, one of the most commonly used solutions, which is valid for a point source of pollution emitted at height h, is

$$C = \frac{Q}{2\pi\sigma_y\sigma_z U}\exp\left[-\tfrac{1}{2}\left(\frac{y}{\sigma y}\right)^2\right]\left\{\exp\left[-\tfrac{1}{2}\left(\frac{z-h}{\sigma z}\right)^2\right]\exp\left[-\tfrac{1}{2}\left(\frac{z+h}{\sigma z}\right)^2\right]\right\} \qquad (16)$$

where Q is the rate of release of the pollutant, $\overline{U}$ is the average wind speed, and σ_y and σ_z are the standard deviations of the concentration from the "plume" axis as functions of distance downwind. This formula is formally analogous to normal or Gaussian bivariate probability distribution, and the term Gaussian is usually applied to models that use equations of this type. Turner (35) used this solution in an air pollution model for computing the sulfur dioxide concentration in Nashville, Tennessee.

The key to the success of this or any other Gaussian formula is selection of the appropriate σ's as functions of distance downwind. These terms are, in fact, functions of the diffusivity and hence functions of surface roughness and atmospheric stability, as measured by the Richardson number. Turner (36) has published a practical system for making air quality estimates based on procedures developed by Pasquill (26) and Gifford (8). In this scheme, stability is estimated from meteorological conditions, such as wind speed, cloud cover, and intensity of solar radiation, in terms of six stability classes, A (strongly unstable) to D (neutral) to F (strongly stable). The dispersion parameters σ_y and σ_z are then taken from graphs that specify downwind variation as a function of stability. Figure 7 shows the set of curves for σ_z.

Equation 16 includes the assumption that the surface acts like a perfect reflector; i.e., no deposition or absorption takes place. Clearly, this assumption is appropriate only for chemically inactive gases. The presence of elevated inversion layers can be handled by assuming that, when the plume dimensions have become comparable to the height of the base of the inversion H, this becomes a lid preventing further vertical growth, and thereafter mixing in the vertical is complete. If this distance downwind is assumed to be twice that at which one-tenth of the plume has penetrated the inversion, then the formula for air concentration becomes

$$C = \frac{Q}{\sqrt{2\pi}\,\sigma_y H \overline{U}}\exp\left[-\tfrac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (17)$$

where the concentration is now independent of the vertical direction, and this relation is supposed to be valid when $\sigma_z > 0.94$ H.

The Gaussian approach is easily extended to other source configurations. For a continuously emitting infinite line source, the solution at ground level is

$$C = \frac{2Q}{\sqrt{2\pi}\,\sigma_z U \sin\phi}\exp\left[-\tfrac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \qquad (18)$$

where ϕ is the angle between the wind direction at the line (zero at right angles).

Equations 16 and 18 are the working formulas for the great majority of practical schemes for estimating air concentration from air pollution source inventory informa-

Figure 6. Sounding of temperature and humidity over Los Angeles.

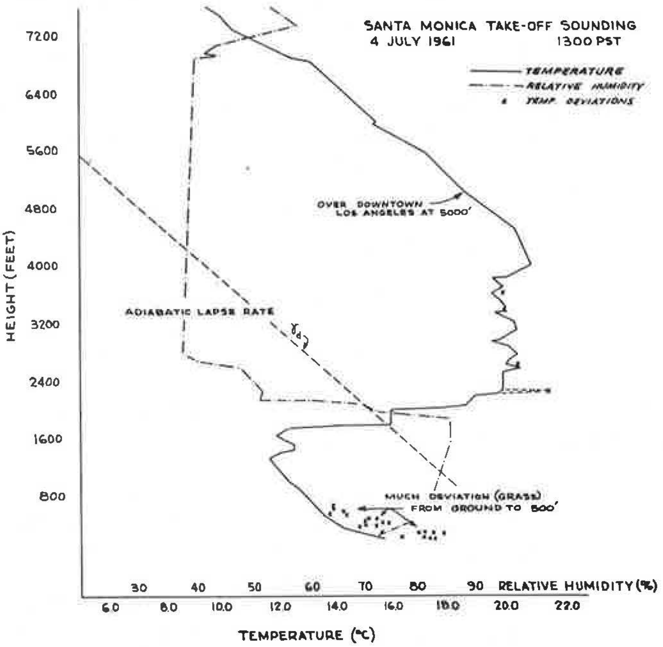
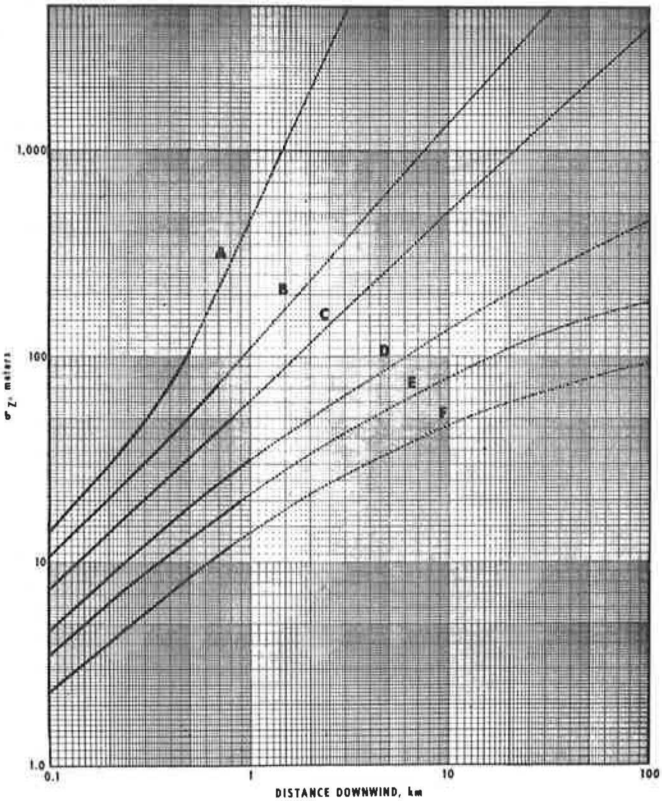


Figure 7. Vertical dispersion coefficient as a function of downwind distance from the source.



tion. Calculating the air concentration at a specific point in an urban area is done by dividing the city into a set of equal areas defined by a grid and assigning an appropriate source strength to each. For instance, in his Nashville study, Turner (35) obtained SO_2 source strengths for each square mile in a 17- by 16-mile rectangle. Downwind concentrations resulting from SO_2 emitted within a given square mile were calculated from the point source formula, assuming that the area emission was concentrated at a point. This calculation was repeated for each of 272 square-mile sources, and the results were counted to give the net result. Observed wind speeds and σ's estimated from observed meteorological conditions were used. Comparison between observed and computed 24-hour averages showed that 58 percent of all computed values were within ±1 pphm, a result that was taken as demonstrating the feasibility of the approach.

Several other investigators have made calculations similar to those of Turner. Koogler et al. (16) used Turner's equation with the addition of an exponential decay to account for SO_2 removal processes for Jacksonville, Florida. Koogler obtained 95 percent of his calculated SO_2 concentrations within ±1 pphm of observed values. Hilst (14) used essentially the same approach for the state of Connecticut, using an improved method of incorporating observed winds; 5,600 square area sources were used, each 5,000 ft on a side, and important individual sources, such as large power plants, were treated individually.

The most sophisticated air pollution model now in existence is the one being developed by Lamb (17) and Neiburger. This model includes improved solutions to the diffusion equation for point, finite line, and area sources, absorption of pollutants at the ground, simple chemical reactions whose rates may be given as arbitrary functions of time, and horizontally and time varying winds. In this model, the diffusion coefficients are constants, wind does not vary with height, and vertical motion is neglected. Preliminary calculations with this model, using observed winds and traffic data, were made for carbon monoxide. The results, although considered encouraging, revealed a major source of error associated with the neglect of vertical motion. Unrealistically large values of carbon monoxide concentration were calculated to occur in regions of horizontal convergence of the wind, indicating that removal of pollutant by vertical motion is an important process that cannot be neglected. This model is in an active state of development, and important and high-quality results are anticipated in the near future.

In addition to the Gaussian models and Neiburger and Lamb's improved version of this technique, there are four other major approaches to the problem of calculating air quality from measurable parameters. One is based on the statistical theory of turbulence, originally introduced by Taylor (33). In this approach, emphasis is placed on the statistical properties of velocity fluctuations of ensembles of passively floating particles or marked fluid. The statistical theory deals directly with the spread of a group of particles with respect to a frame of reference moving with the fluid (Lagrangian frame), which is the most fundamental manner in which to treat turbulent diffusion. Because measurements are almost always made with respect to a fixed (Eulerian) frame of reference, a central problem in applying the statistical theory to practical dispersion problems is to establish the correspondence between Lagrangian and Eulerian turbulence parameters. The statistical theory may be the most fundamental approach but is probably the most remote from immediate practical application at this time.

Another major approach that is only now being developed and hopefully represents a useful compromise between the unashamed empiricism of the Gaussian models and more satisfying basic theory is the hydrodynamics approach. In this technique, the fundamental equations of meteorological dynamics and thermodynamics are numerically solved on a three-dimensional grid using approximate topography as a boundary condition to provide the mesoscale flow and stability. Smaller scale flow features, or "turbulence," are handled by means of diffusivity parameters. A less satisfying variant of this approach would be to use observed three-dimensional winds to specify the mesoscale flow. This alternative appears less satisfying because of the extraordinary measurement problem.

Three-dimensional numerical integrations are so demanding of computer storage and computational speed that only relatively crude models can be solved at this time.

It remains to be seen whether computer capabilities develop fast enough for this approach to be of practical utility in the near future.

The next of the major approaches to the problem is the similarity theory, introduced by Monin (20) and developed further by Batchelor (3), Gifford (9), and Pasquill (27). In this technique, a semi-empirical framework based on dimensional analysis is adopted to organize pollutant data in terms compatible with micrometeorological practice. The similarity theory is the newest of major approaches to the problem of turbulent diffusion of pollution emitted near the surface of the earth. It is the only theory that now permits direct application of standard micrometeorological procedures and parameters such as the Richardson number. At this time, however, the similarity theory has not been worked out for a sufficient variety of source configurations to allow immediate incorporation into practical air pollution models.

The last approach to be discussed here is the so-called box model, which is very simple but nevertheless useful for mesoscale applications. In situations where a well-defined inversion acts as an effective lid on vertical dispersion and when pollution is emitted more or less uniformly over a large urban area, it may often be acceptable to calculate concentration from

$$C = \frac{kQ}{\overline{U}H} \tag{19}$$

where $\overline{U}$ is the average wind speed between the surface and the height of the base of the inversion, k is a constant, and Q is an emission rate per unit area. Hanna (11) has shown that simple formulas like Eq. 19 are often as accurate as much more sophisticated approaches.

The modeling approaches that have been discussed are meant to be used in a practical engineering sense. They must ultimately be judged in this spirit. Before attempting an overall evaluation of the state of the art of highway air quality modeling, it is instructive to look at an operational attempt to use some of the techniques presented.

During the past 2 years, the California Division of Highways has been conducting an extensive environmental impact program to evaluate the effect on air quality of current highways in the state and to make projections of the effect of future planning decisions regarding highway construction. At present, this program is limited to an evaluation of the probable air quality impact of the decision to build or not to build highways whose routes and configurations were planned well before the overriding significance of environmental impact became clear. There were four major objectives of the program. One was to generate reliable data on the current state of air quality near highways. The second objective was to develop and verify practical highway air quality models. The third was to develop models for assessing highway impact on the air quality of entire mesoscale air basins. The fourth was to use verified models to estimate air quality in 20 years' time for the built and not-built cases for particular highway plans. At present, several contracts have been awarded to research and development groups in the private sector to perform these impact studies. Following is a brief outline of the results of the first of the studies to be completed, which was an air quality analysis and impact study of proposed Cal-92 and -238 near Hayward, California.

The Hayward area lies on the coastal plain to the east of the southern portion of the San Francisco Bay. The immediate topography is uncomplicated; on a larger scale, Hayward lies in the basin that encloses the bay. The firm that was awarded the contract collected all available air quality and meteorological data for the area, established additional meteorological and air pollution monitoring stations, developed a Gaussian transport and diffusion model, verified the model with data taken during a special concentrated observation period, and performed calculations with the model to estimate air quality in the region for 1990 with and without the proposed freeways. On the whole, there is no doubt that this was a highly professional piece of applied science and is well representative of the current state of measurement techniques and modeling capability. For these reasons, whatever criticism is made, the techniques employed or results obtained in this study are to be taken as applying to the field as a whole.

Figure 8 shows an example of the basic data that were collected in the Hayward area by the contractor. The pollutant is carbon monoxide averaged over 24 hours. The numbers attached to the data points refer to the various sites used in the study. The extreme day-to-day variability is typical of pollution data. The horizontal dashed line is the ambient air quality standard for carbon monoxide (12 hours at 10 ppm). Figure 9 shows a cumulative frequency diagram derived from the 1,063 hourly measurements of carbon monoxide made during the 2½ months of this study. The figure shows, for instance, that hourly average carbon monoxide concentrations of 10 ppm were equaled or exceeded 18 percent of the time during this study. Figure 10 shows the noncumulative frequency distribution for the same data but now broken down by site. The variability from site to site and the apparent bimodal character of these curves are striking. In addition, it could be said that these curves do not have the usual smooth appearance of well-defined and stable statistics. The question must be asked as to whether the conditions of this study allowed time for sufficient data to be gathered to allow reliable statistical generalizations to be made. Figure 11 shows a similar analysis of weekday versus weekend data for all sites.

The investigators state that, although the analysis is not presented in sufficient detail to allow evaluation, a significant correlation was found between carbon monoxide and the product $\overline{U}H$, where these parameters have the same meaning as in the box-model approach discussed previously, so that the result amounts to partial validation of that approach.

Figure 12 shows a summary of a concentrated microscale study in the immediate vicinity of an existing freeway section that ran approximately north-south. All data are shown from a variety of meteorological and traffic situations, and it is difficult to see a clear pattern such as simple models (e.g., the line-source Gaussian) would lead you to expect. Figure 13 shows a typical individual case for downwind data and Figure 14 for upwind data. Although these displays appear to be more reasonable than the previous scatter diagram, serious methodological questions arise from consideration of these data. The measurements were made by moving a van containing air pollution sensing apparatus from point to point. Thus, the data are not simultaneous and contain large variations of meteorological parameters from point to point. Such a procedure would not be acceptable in any professional micrometeorological study. Measurements must be simultaneous to be comparable. The contractor did the best job possible with the time and resources available; however, a better job needs to be done.

A validation analysis was made of the highway diffusion model. The objective was to estimate the contribution to carbon monoxide concentration at specific locations from an existing freeway alone. The background concentrations were larger than the calculated freeway contributions. It is difficult to have confidence in the modeling approach on the basis of this analysis alone.

An additional criticism can be made concerning the lack of analysis of the properties of the model itself. At a minimum, a sensitivity analysis of the operational model should be made to determine the relative importance of the various input data and the degree of precision needed. For instance, how sensitive are the validation calculations to uncertainties in, say, the wind speed or freeway emission rate? Without such information, it is difficult to interpret a validation analysis.

To fulfill the final portion of the study, the contractor used the developed models to make air quality projections for 1990. On the mesoscale, a number of calculations were made for various wind directions and stabilities for the cases in which the proposed Cal-92 and -238 were built and not built. In general, the mesoscale calculations showed little difference between these two cases.

On the microscale, within 1,000 ft of the highway corridor, relatively large differences were found between the built and not-built cases. Figure 15 shows typical results that indicate lower upwind concentrations of carbon monoxide and considerably higher downwind concentrations of carbon monoxide for the built case in comparison with the not-built one. In view of the uncertainties in the validation program discussed previously, it becomes doubly uncertain as to how to interpret or use these microscale projections. An important point to note is that these calculations are presented, as is appropriate, in the form of air concentrations at various distances from the freeway. The

Figure 8. Time variation of carbon monoxide concentration.

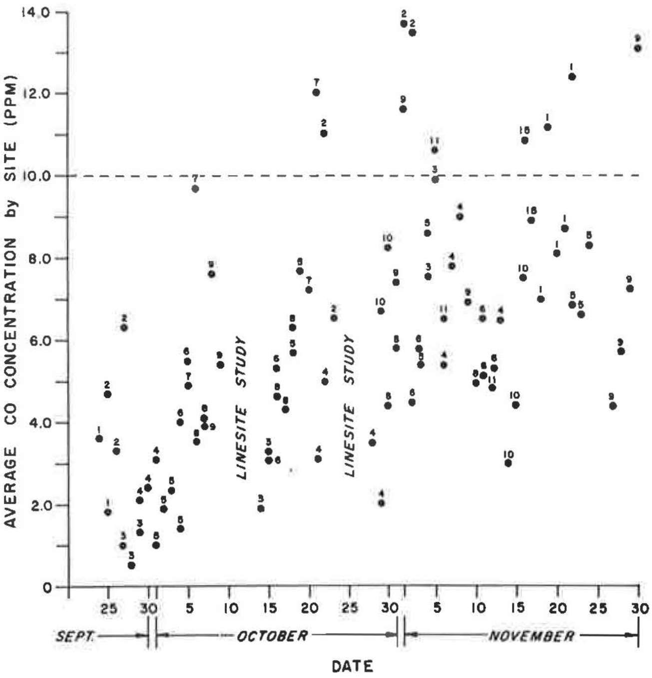


Figure 9. Cumulative probability distribution for carbon monoxide concentration.

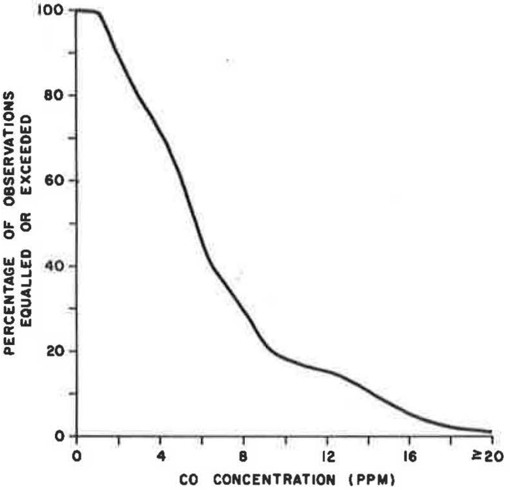


Figure 10. Carbon monoxide frequency distribution.

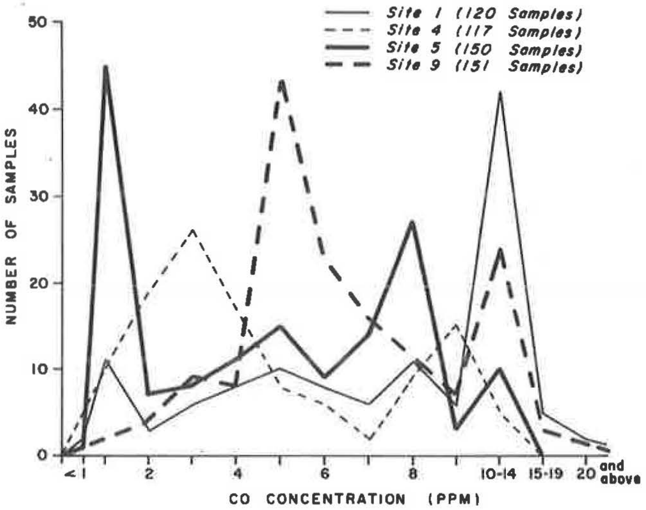


Figure 11. Frequency distribution of carbon monoxide concentration.

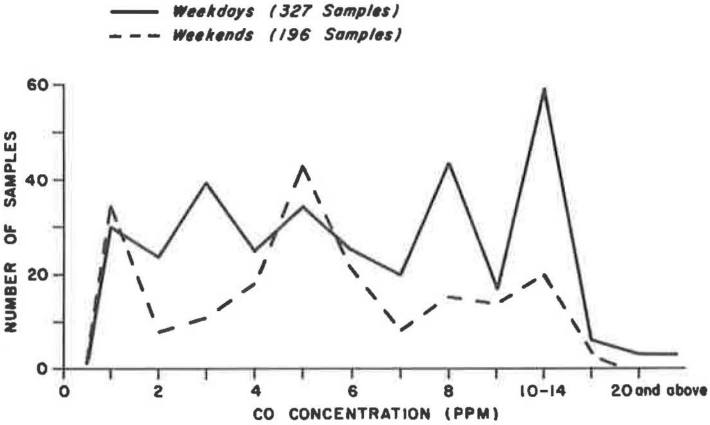


Figure 12. Carbon monoxide concentration near Nimitz Freeway.

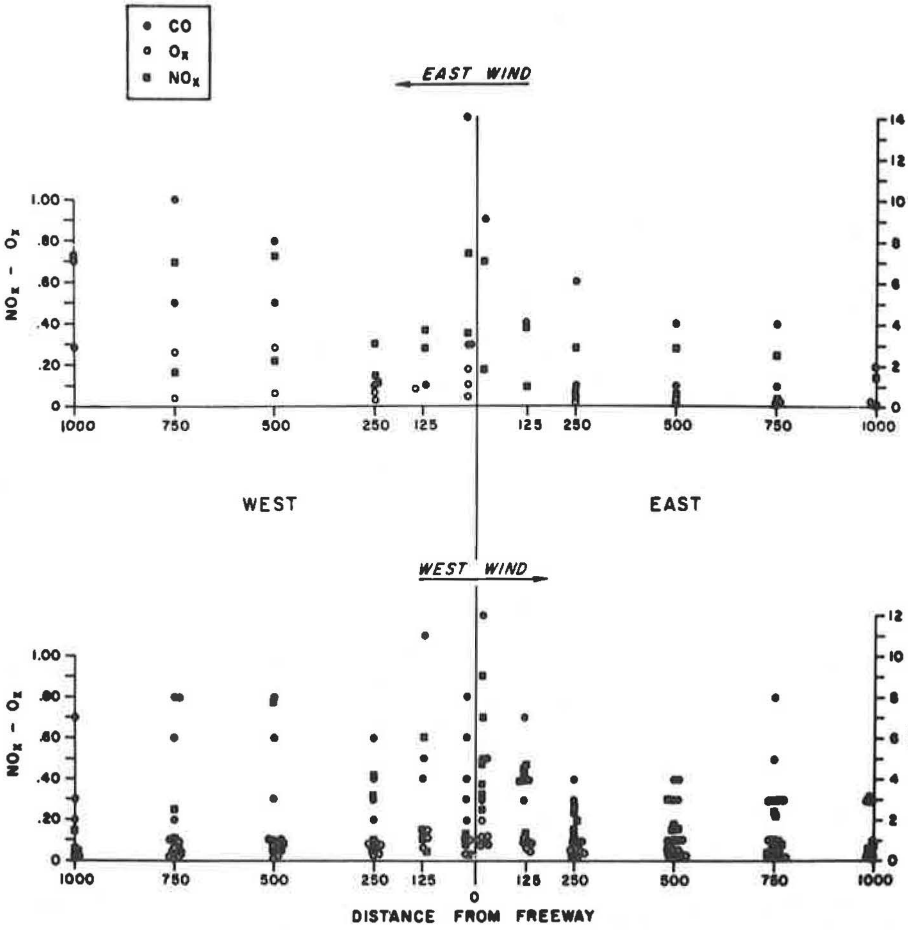


Figure 13. Pollution measurements made upwind of Nimitz Freeway.

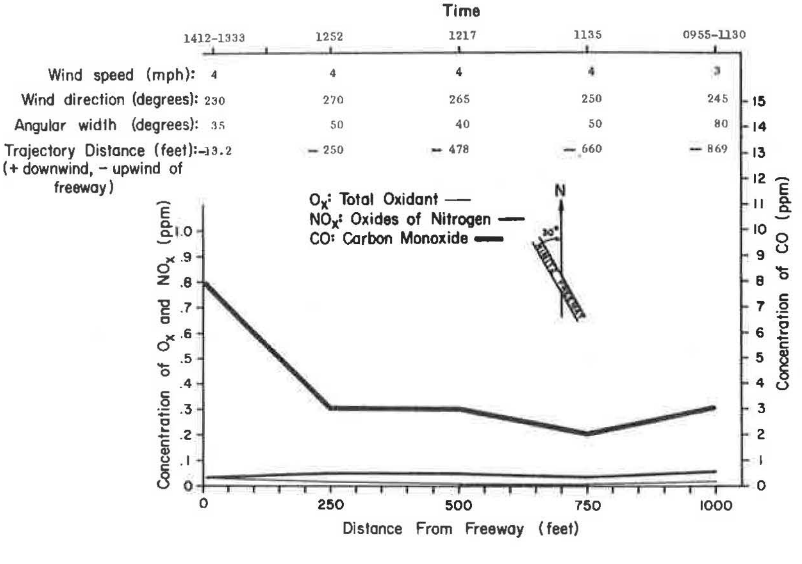


Figure 14. Pollution measurements made downwind of Nimitz Freeway.

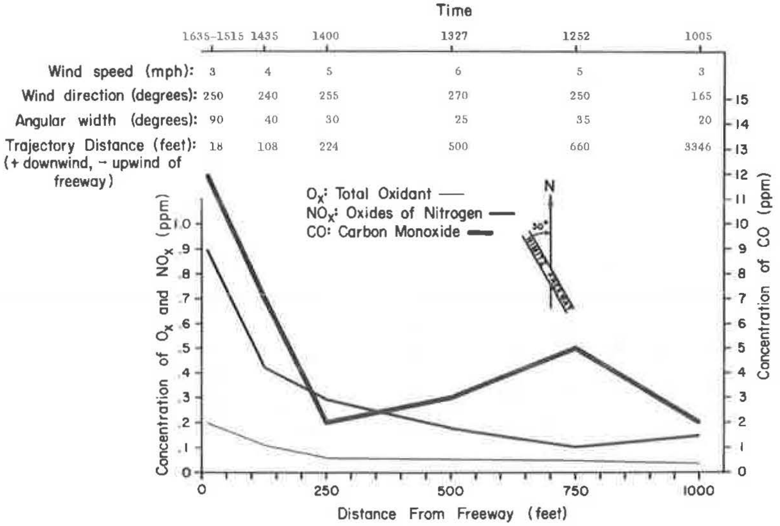
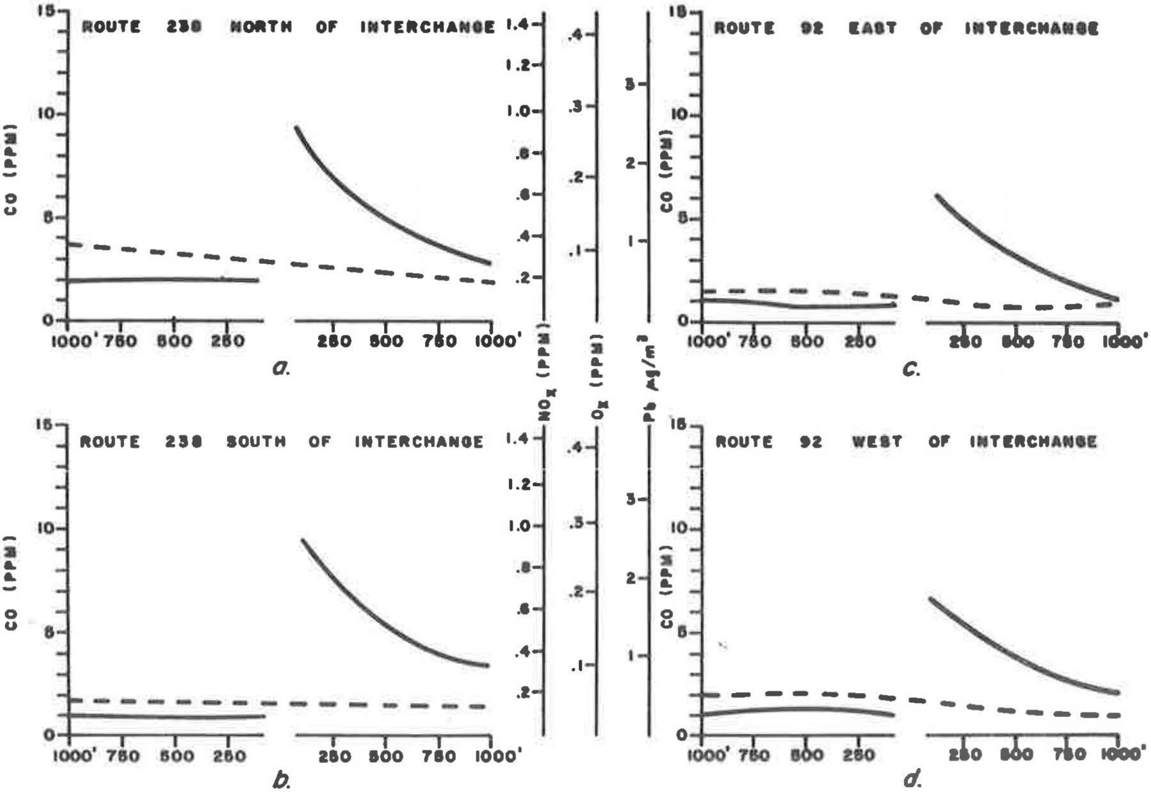


Figure 15. Projections to 1990 for air quality with and without a freeway.



validation measurements, however, were made only at one point, and we have no way of knowing the ability of the model to predict spatial variation.

It is difficult to assess the overall state of the field of air pollution modeling. The field is moving very fast, and many complex problems are involved and must be considered. In particular, the measurement phase is critically important and must be discussed in connection with the modeling effort.

First of all, it is clear that the physical rigor of all operational and research models is not high. The treatment of diffusion parameters, for instance, is usually highly arbitrary and unconnected with what we know of the physics and energetics of turbulence. In particular, diffusion coefficients are almost never given as functions of the Richardson number and surface roughness, despite extensive mircometeorological experience that this is so. Nevertheless, I think that this is of far less importance than the measurement and methodological questions to be discussed next.

Typical measurement programs in air pollution meteorology are grossly inadequate. The example discussed previously was a good state-of-the-art effort that attempted to apply, with great energy and professional competence, known techniques and standard methods to the problem. Nevertheless, it is clear that the information and results obtained are not adequate for the purpose of making future projections. Thus, a general and serious constraint must be faced. Performance must improve if reliable projections of the air quality impact of highway development are to be made.

Specifically, present measurement programs have the following faults. Air concentration of pollutants, diffusion, and standard meteorological parameters are measured, but the Richardson number is not. This deficiency ensures lack of repeatability in the results and makes an unacceptably large scatter in the data inevitable. The Richardson number has been shown to be the single most important parameter governing all micrometeorological processes. It should be a standard part of any air quality measurement program. Secondly, measurements are not adequately extensive in either time or space. Two and a half months is not a sufficiently long time to develop reliable meteorological or air quality statistics. Likewise, measurements of air quality at various distances from a highway must be simultaneous or, again, the data will not be interpretable.

It may be argued that the measures that are implied in the criticism, i.e., more sophisticated and extensive measurements, would be too expensive to fund. The counter argument is that present practices are not producing the results needed. It would be better to run far fewer measurements on a higher plane; the results would be far more useful.

Until adequate measurements are available, the question of model validation remains academic. However, considerably more effort could and should be spent in analysis of the properties of the models themselves. Intensive sensitivity studies reveal acceptable and unacceptable properties of models. In addition, such sensitivity information helps put the instrumental and observational effort in better perspective. For instance, it does not make sense to make an expensive effort to measure an input parameter that has little effect on the final model output.

SUMMARY AND CONCLUSIONS

This report has attempted to tie together the physical processes by which the microclimate is related to diffusion and transport of pollution on the microscale and mesoscale. There are four general areas in which conclusions from this review are appropriate:

1. The microclimate emerges from this discussion as a concept of considerable importance to the problem of measuring and predicting air quality. Large horizontal variations of important physical processes exist within cities. These "neighborhood contrasts" are strongly coupled to land use patterns and hence directly related to the planning processes in urban and regional governments. In particular, the evaporation rate, as indicated by relative abundance of green, freely transpiring plants, is the single most important parameter that determines the microclimatic response of a specific locality to a given radiation load and other large-scale meteorologic factors. Because

air pollution emission from motor vehicles is also closely related to land use patterns, the air pollution system as a whole is thus strongly coupled to land use. The numerical relation between land use categories and emission of vehicular air pollution will be discussed fully in another report.

2. The processes through which pollution diffuses from highways are also largely determined by the microclimate. In particular, surface roughness and atmospheric stability, as measured by the Richardson number or its equivalent, the Monin-Obukhov length, are the most important parameters controlling microscale transport and diffusion. In view of its central importance to micrometeorological and diffusion processes, an important conclusion to be drawn from this review is that measurement of the Richardson number should be a standard part of highway air quality programs. Extensive micrometeorological experience indicates that this is necessary to allow measurements made at different locations or at different times to be compared.

3. Consideration of the multitude of air pollution models that are available to estimate air quality leads to the conclusion that the models generate far more information at greater precision than is available from field measurements. In fact, the need for better and more comprehensive measurements is the most important conclusion to be drawn from this review. The measurement problem is severe because large local variability in the underlying microclimate leads to local contrasts in all processes governed by the microclimate. Hence, any measurement program must be carefully designed to ensure that the measurements are, in fact, representative of the area in question. In particular, pollution and meteorological parameters must be measured simultaneously within the study region over an adequate averaging time.

4. The state of the art of air quality modeling has been briefly reviewed in this report. The prevailing standard in the field, the Gaussian family of models, is deficient in the sense that the diffusion parameters that are used in these models are not derived directly from the physical processes that are known to dominate turbulent diffusion on the microscale, i.e., the microclimate, surface roughness, Richardson number parameter complex. More generally, it appears that far more attention needs to be paid to the properties of the models themselves. Comprehensive sensitivity analyses should be made in conjunction with model verification programs. Such information will allow better information as to the predictability of air quality and of the requirements of measurement and verification programs.

REFERENCES

1. Batchelor, G. K. The Conditions for Dynamic Similarity of Motions of a Frictionless Perfect-Gas Atmosphere. Quarterly Jour. of Royal Meteorological Society, Vol. 79, 1953, pp. 224-235.
2. Compilation of Air Pollutant Emission Factors. Office of Air Programs, U.S. Environmental Protection Agency, 1972.
3. Batchelor, G. K. Diffusion From Sources in a Turbulent Boundary Layer. Archiwum Mechaniki Stosowanej, Vol. 3, 1964, pp. 661-670.
4. Crank, J. The Mathematics of Diffusion. Oxford Univ. Press, England, 1956, 347 pp.
5. Davenport, A. G. The Relationship of Wind Structure to Wind Loading. National Physical Laboratory Symposium, No. 16, London, 1965, pp. 54-102.
6. Deacon, E. L. Vertical Diffusion in the Lowest Layers of the Atmosphere. Quarterly Jour. of Royal Meteorological Society, Vol. 75, 1949, pp. 89-103.
7. Eschenroeder, A. O. Kinetics and Transport in a Polluted Urban Atmosphere. Presented at 69th National Meeting of the American Institute of Chemical Engineers, Cincinnati, May 16-19, 1971.
8. Gifford, F. A. Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion. Nuclear Safety, Vol. 2, 1961, pp. 47-51.
9. Gifford, F. A. Diffusion in the Diabatic Surface Layer. Jour. of Geophysical Research, Vol. 67, 1962, pp. 3207-3212.
10. Goddard, W. B. Heat, Mass and Momentum Transfer Processes in the Biosphere. Univ. of California, Davis, PhD dissertation, 1971, 68 pp.

11. Hanna, S. R. Simple Methods of Calculating Dispersion From Urban Area Sources. Presented at National Conf. on Air Pollution Meteorology, Raleigh, N.C., April 5-9, 1971.
12. Halstead, M. H., Richman, R. L., Covey, W., and Merryman, J. D. A Preliminary Report on the Design of a Computer for Micrometeorology. Jour. of Meteorology, Vol. 14, 1957, pp. 308-325.
13. Hilst, G. R., and Bowne, N. E. A Study of the Diffusion of Aerosols Released From Aerial Line Sources Upwind of an Urban Complex. Traveler's Research Center, 1966.
14. Hilst, G. R. An Air Pollution Model of Connecticut. Presented at IBM Scientific Computing Symposium, 1967.
15. Knox, J. B. The Power Crisis: How Should It Be Met? Lawrence Livermore Laboratories, Univ. of California, Livermore, 1972.
16. Koogler, J. B., et al. A Multivariate Model for Atmospheric Dispersion Prediction. Jour. of Air Pollution Control Assn., Vol. 17, 1967, pp. 211-214.
17. Lamb, R. G. An Air Pollution Model of Los Angeles. Univ. of California, Los Angeles, MS thesis, 1968, 104 pp.
18. Lettau, H. Note on Aerodynamic Roughness-Parameter Estimation on the Basis of Roughness-Element Description. Jour. of Applied Meteorology, Vol. 8, 1969, pp. 828-832.
19. Lumley, J. L., and Panofsky, H. A. The Structure of Atmospheric Turbulence. Interscience Publishers, New York, 1964, 239 pp.
20. Monin, A. S. Smoke Propagation in the Surface Layer of the Atmosphere. Advanced Geophysics, Vol. 6, 1959, pp. 331-344.
21. Morgan, D. L., Pruitt, W. O., and Lourence, F. J. Analyses of Energy, Momentum and Mass Transfers Above Vegetative Surfaces. Dept. of Water Science and Engineering, Univ. of California, Davis, 1971, 120 pp.
22. Munn, R. E. Descriptive Micrometeorology. Academic Press, New York, 1966, 243 pp.
23. Myrup, L. O. Temperature and Vertical Velocity Fluctuations in Strong Convection. Quarterly Jour. of Royal Meteorological Society, Vol. 93, 1967, pp. 350-360.
24. Myrup, L. O. A Numerical Model of the Urban Heat Island. Jour. of Applied Meteorology, Vol. 8, 1969, pp. 908-918.
25. Outcalt, S. I. The Development and Application of a Simple Digital Surface-Climate Simulator. Jour. of Applied Meteorology, Vol. 11, 1972, pp. 629-636.
26. Pasquill, F. The Estimation of the Dispersion of Windborne Material. Meteorological Magazine, Vol. 90, 1961, pp. 33-49.
27. Pasquill, F. Atmospheric Dispersion of Pollution. Quarterly Jour. of Royal Meteorological Society, Vol. 97, 1966, pp. 369-395.
28. Richardson, L. F. The Supply of Energy From and to Atmospheric Eddies. Proc. Royal Society, London, Series A, Vol. 97, 1920, pp. 354-373.
29. Richardson, L. F. Atmospheric Diffusion Shown on a Distance-Neighbour Graph. Proc. Royal Society, London, Series A, Vol. 110, 1926, pp. 709-727.
30. Roberts, O. F. T. The Theoretical Scattering of Smoke in a Turbulent Atmosphere. Proc. Royal Society, London, Series A, 1923, pp. 640-660.
31. Sellers, W. D. Physical Climatology. Univ. of Chicago Press, 1965, 272 pp.
32. Sutton, O. G. Micrometeorology. McGraw-Hill, New York, 1953, 333 pp.
33. Taylor, G. I. Diffusion by Continuous Movement. Proc. London Mathematical Society, Vol. A20, No. 196, 1921.
34. Townsend, A. A. The Structure of Turbulent Sheer Flow. Cambridge Univ. Press, England, 1956.
35. Turner, D. B. Relationships Between 24-Hour Mean Air Quality Measurements and Meteorological Factors in Nashville, Tennessee. Jour. of Air Pollution Control Assn., Vol. 11, 1961, pp. 483-489.
36. Turner, D. B. Workbook of Atmospheric Dispersion Estimates. National Air Pollution Control Administration, Cincinnati, 1969.

PREDICTING MOTOR VEHICLE AIR POLLUTION CONCENTRATIONS FROM HIGHWAY NETWORK ANALYSIS

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An urban diffusion model has been developed that uses urban transportation planning variables, such as speeds, volumes, and distances on network links, together with readily available meteorological data to forecast concentrations of carbon monoxide in an urban area. The model includes a submodel that computes carbon monoxide concentrations in urban street canyons, taking account of carbon monoxide produced within the canyon as well as background carbon monoxide. The model is particularly well suited to evaluation of the relative air pollution potential of alternative urban highway networks. It can also be used to evaluate alternative strategies for meeting air quality standards and to indicate sites for air quality monitoring stations. The model has been validated in a 2-year program that has included comparison of historical data from continuous air-monitoring stations and instrumented sites in St. Louis and San Jose. The model will be expanded to take account of other pollutants such as oxides of nitrogen.

•THE growing severity of review of new highway construction at the corridor and route location levels requires analysis of environmental factors at the time alternative networks are studied. This is particularly important for urban network study, where the choice of paths through the network may be greatly influenced by traffic and construction requirements that make certain paths more attractive than others. No matter how attractive the proposed network changes may be to the traffic engineer or city planner, they cannot be implemented if there are environmental effects that are unacceptable to the local community.

Methods for evaluating the effect of network changes on community values have been proposed (1) including the effects of air pollution. The study of air pollution effects at the network level will help to avoid future problems. Also, air pollution effects occur on a scale similar to that of the network, and they should be analyzed throughout the network, not just in the vicinity of the new construction.

A model, designated APRAC-1A, for analyzing air pollution concentrations that result from urban highway networks has been developed at the Stanford Research Institute. This model is programmed for a large-scale electronic computer to accept highway network descriptions and meteorological parameters that are commonly available and will produce concentration values at designated coordinates in the area. Further, the model is sensitive to changes in network configuration and traffic volumes.

Figure 1 shows one output of the model—concentration isopleths for the St. Louis area based on the historical network file of the IBM 360 urban planning program battery. The concentrations shown in Figure 1 are those that would result for a specified set of meteorological conditions if the traffic grew at the rate forecast and if no improvements were made in vehicular emissions. Figure 2 shows how the concentrations would change with improved emission control devices on the vehicles.

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The APRAC-1A diffusion model can be used to derive a number of different kinds of indexes for various uses. For example, the community-values analysis has suggested that "population dose" might be a meaningful community-effects parameter. Population dose can be computed from 8-hour average concentration values at the traffic zone centroids, multiplied by the zone population. Other pollution-related indexes could also be developed.

MODEL FORMULATION

The APRAC-1A model has several components: an emissions model that converts the traffic input data into spatially distributed emissions, a diffusion model that describes the mixing and transport of the pollutant as it moves downwind, submodels that convert conventional meteorological data to atmospheric mixing parameters, and a submodel that describes phenomena in downtown street canyons (streets lined by tall buildings). The model is discussed in detail elsewhere (2, 3, 4); however, the following brief description is included to illustrate its capabilities.

Emissions Submodel

The emissions submodel is organized to accept highway data that describe each link in the network. The link data required are node coordinates, distance along link between nodes, average daily traffic volume, and average speed. These parameters are commonly available from historical record files in traffic planning programs or can be derived from other commonly available materials such as maps.

Emissions from each link are computed according to a composite route model that was developed (5) by measuring emissions from a large number of vehicles over a composite urban route and then fitting the following exponential relation between the resultant average emissions, E (grams/vehicle-mile) and average route speed, S (mph):

$$E = \alpha S^{\beta} \tag{1}$$

The original values of the constants α and β were derived from tests performed on vehicles that were not equipped with exhaust emission control devices. Parameters for vehicles with various degrees of emission control have been estimated (1). These estimated values of α and β for various model years are as follows:

Model Year	α	β
1972 to 1974	160	0.48
1975 to 1979	16	0.48
After 1980	8	0.48

The emission model somewhat underestimates emissions for congested streets and overestimates them for freely flowing traffic streams because idling and low-speed emissions have been averaged over a composite route that includes both types of travel. The validation program indicated that this effect is noticeable, but not serious, in larger scale studies with numerous links because the emissions from a variety of streets tend to be grouped and treated together. An alternative emissions model has been developed (6) for use in detailed investigations of small areas. This alternative model, however, requires knowledge of fine details such as number of signals per mile and ratio of volume to capacity.

Because hourly values are usually desired from the model, the average daily traffic must be allocated to the individual hours. The model contains provision for describing diurnal traffic patterns (Fig. 3). These patterns are usually available from local traffic departments or from a regional transportation study.

For purposes of calculating the concentration at a point receptor, the total emissions within logarithmically spaced annular segments are determined. These segments are aligned with the mean transport wind as shown in Figure 4. The innermost sector extends 125 m from the receptor—roughly comparable to the size of a city block. The outer sectors are 22.5 deg wide, which corresponds to the plume width predicted by Gifford (7) for slightly unstable conditions; the broader 45-deg sectors near the receptor allow for large initial dispersion. Emissions are assumed to be uniformly distributed within each sector. The smaller sectors near the receptor provide the higher resolution required for nearby sources. Emissions in each segment are calculated as the sum of the emissions on all the links and parts of links that lie within the segment.

Diffusion Model

The "Gaussian plume" diffusion formulation used by this model assumes that the vertical concentration profile from a crosswind line source (such as a road) is Gaussian in shape (Fig. 5). The spread of this vertical concentration distribution is characterized by its parameter, σ_z, which has been found experimentally to be reasonably well approximated by an equation of the form

$$\sigma_z = ax^b \qquad (2)$$

The parameters a and b depend on the atmospheric stability; x is the downwind travel distance.

A simple box model is applied for distant segments when there is a limiting mixing depth, h, determined by the vertical temperature stratification. Under these conditions, pollutants tend to be distributed uniformly in the vertical after sufficient travel has taken place, and the concentration, C_i, from the ith segment is proportional to the source strength, Q_i, in that segment and the distance subtended by it $(x_{i+1} - x_i)$. the concentration is inversely proportional to wind speed, u, and mixing depth, h:

$$C_i = \frac{x_{i+1} - x_i}{uh} Q_i \qquad (3)$$

A change from the Gaussian model to the box model is made at the distance where the two would give equal values of concentration if applied to a line source.

Mixing Height Submodel

Mixing height is determined from the morning lapse rate at the nearest National Weather Service Radiosonde station using the physical characteristic that a mixed layer of the atmosphere has an adiabatic lapse rate. The observed lapse rate and the surface temperature at a given hour during the day determine the height at which a parcel of air lifted adiabatically would reach the temperature observed at that height by the radiosonde. This is the mixing height. During daylight hours, observed airport surface temperatures are used to determine mixing height. During predawn hours, airport temperatures are augmented to account for urban heat island effects. Interpolated values are used during post-sunset hours.

Stability Submodel

Atmospheric stability is categorized to determine the proper function to use for σ_z. The stability submodel has employed a method that makes use of observed wind speed and cloud cover and the intensity of isolation. The last factor is not measured but can be estimated by using available cloud cover measurements. In general, daytime stability increases with wind speed and decreases with increased solar heating. At night, the stability increases with the increased surface cooling. Increased wind reduces the stability. The model reflects these effects.

Street Submodel

In evaluating the performance of the model after the first-stage development, extensive comparisons (including regression analyses) were made of calculated concentrations with those observed at the Community Air Monitoring Program stations in Chicago, St. Louis, Denver, Cincinnati, and Washington, D.C. The agreement was generally

Figure 1. Calculated concentration patterns based on forecast of 1990 traffic without emission controls.

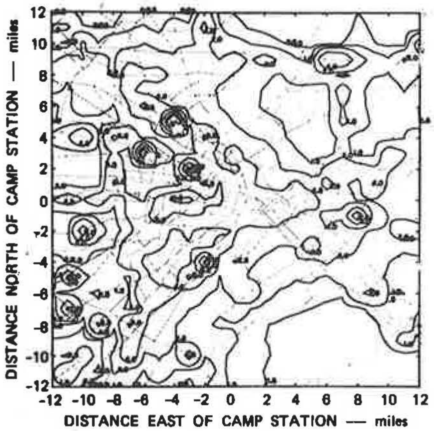


Figure 2. Calculated concentration patterns based on forecast of 1990 traffic with emission controls.

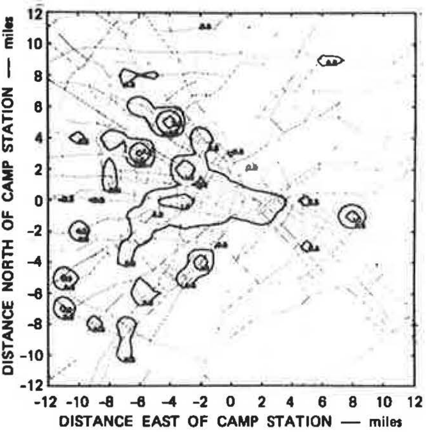


Figure 3. Hourly distribution of traffic.

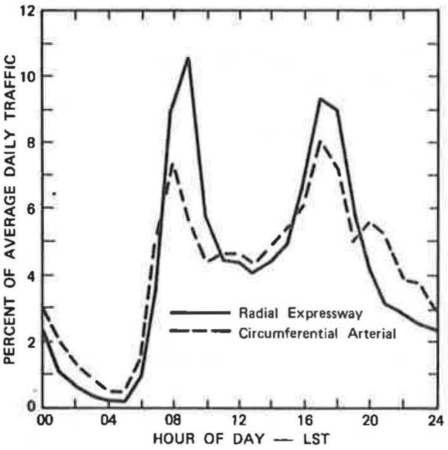


Figure 4. Segments used for spatial partitioning of emissions.

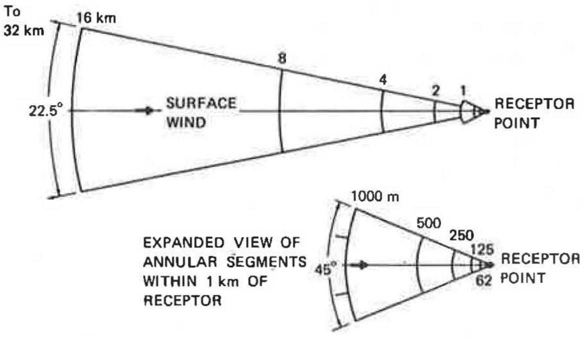
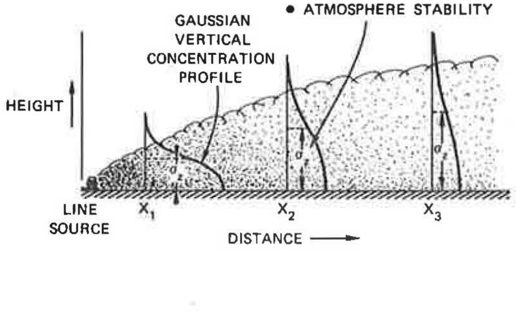


Figure 5. Vertical diffusion according to Gaussian formulation.



fair to good, at least in terms of trends, although there were some instances of poor agreement. Field experiments conducted since the model was initially formulated have revealed several reasons for the observed disagreements. Foremost is the fact that local effects in street canyons and around buildings can sometimes cause carbon monoxide (CO) concentrations to vary by as much as a factor of 3, or 10 ppm from one side of the street to the other. It is obvious that any model that did not account for these effects could be expected to have large errors. A submodel has been developed to take account of these street canyon effects.

Observed distributions of CO imply a helical air circulation in street canyons like that shown in Figure 6. Locations on the leeward side of the building (Fig. 6) are exposed to substantially higher concentrations than on the windward (left) side because of the reverse-flow component across the street near the surface. Thus, the concentration, C, at a point is the sum of two contributions. One is the concentration, C_b, of the air entering the street canyon from above. It is assumed that the concentration computed by the basic diffusion model represents C_b. The second component, ΔC, arises from the CO emissions generated within the street canyon.

Equations for calculating the ΔC components on both the leeward and the windward sides were empirically derived by Johnson et al. (3) and modified by Ludwig and Dabberdt (4). These equations predict that the additive concentrations from the local street traffic are proportional to the local street emissions, Q_L (in grams/meter-second), and inversely proportional to the roof-level wind speed, u (in meters/second), as augmented by a small amount (0.5 m/sec has been found to work well) to account for the air movement induced by traffic. In front of the downwind buildings the air begins its downward flow at roof-level concentration. Pollutants are gradually entrained as the air sinks toward street level, so that CO concentrations on this side of the street increase slightly in the downward direction. The concentrations of the added CO should be inversely proportional to the width of the street, W, which governs the volume of air available for dilution of the emissions from the vehicles in the street. Entrainment has been assumed to vary linearly with height, z, through the depth, H, of the street canyon. Thus, the added CO concentration is given by the following equation for the side of the street on which the buildings face the wind:

$$\Delta C = K \frac{Q_L}{w(u + 0.5)} \frac{H - z}{H} \tag{4}$$

For the other side of the stree, box-model reasoning is used. The volume into which the emissions are mixed is limited by the air circulation toward the buildings and upward. As the air moves from the street-level source, the volume into which the pollutants are mixed increases; the concentration is taken to be inversely proportional to the slant direction, r, between the receptor and the nearest traffic lane. For concentrations in front of the upwind buildings, the equation is

$$\Delta C = K \frac{Q_L}{r(u + 0.5)} \tag{5}$$

The constant, K, is the same for both equations. When the wind blows nearly parallel (within ±30 deg) to the street, the additive concentration, ΔC, is described by the average of the values from Eqs. 4 and 5 and is the same on both sides of the street.

EVALUATION OF MODEL PERFORMANCE

Extensive measurement programs have been conducted in San Jose (3) and St. Louis (4) to test the performance of the various submodels and of the composite model itself. The program and its results as they apply to each of the submodels and the overall performance are described briefly.

Emissions Submodel

San Jose has an extensive computer-based traffic monitoring system that provides detailed information on the traffic in the central business district. This detailed traffic information allowed the emissions submodel to be applied in this area with good confidence. The traffic flow is known from the monitoring network; the average speed was determined from the movements of a project van around the downtown perimeter.

Emissions calculated from the submodel were compared to independent estimates made from a CO mass budget analysis that was based on upper-level wind measurements and CO concentrations measured around the central business district with helicopter- and van-borne instruments. Similar studies were undertaken in St. Louis, where the traffic information was not quite so detailed. The difficulties with the method include uncertainties in the wind field and possible significant changes of CO emission rate during the measurement periods, but the results were sufficiently reliable that serious inaccuracies in the emissions submodel would have been noted if they had been present. The averages of the cases studied show that the two types of CO emission estimates agree within a factor of about 1.5. There seems to be no justification for changing the submodel for most urban applications at this time. Better measurements and recent studies of vehicular accelerations and decelerations on freeways would allow refinements for future applications to these roadways.

Mixing Height Submodel Evaluation

Vertical profile measurements of temperature up to 1,000 m were obtained from helicopter flights and from balloon soundings. These were used to determine mixing depths, which were compared with submodel calculations. Decreases in lapse rate usually marked the top of mixing layer. On several days, the mixing depth was also estimated from measurements made with a laser radar (lidar) that can detect a sharp reduction in aerosol concentration at the top of the mixing layer. The submodel mixing depth was within 50 percent of the mixing depth obtained from temperature soundings and lidar observations in about two-thirds of the cases studied. The submodel used to determine the mixing depth is adequate if representative low-level morning temperature soundings are available.

Stability Submodel Evaluation

The algorithm used to determine stability category was checked against measurements of wind direction variability, and it was found that the two were very consistent. The dependence of σ_z on downwind distance and stability has been revised to reflect the vertical diffusion reported by others for urban fluorescent particle tracer tests in St. Louis, Minneapolis, and Winnipeg.

Street Canyon Submodel Evaluation

Streets in downtown San Jose and St. Louis were instrumented to obtain the data necessary to describe and model the street effects. CO concentrations were measured in detail in the street canyon; winds (in three dimensions) were also measured at numerous locations. Data were automatically collected and recorded on magnetic tape and subsequently used to determine the air circulations and the distributions of CO in the street. Use of this submodel has substantially improved the performance of the model in highly urbanized downtown areas.

Overall Performance of the Model

Performance of the total model, including all its subunits, has been checked against the data obtained at the CO-measuring sites in downtown St. Louis street canyons. Figure 7 shows comparisons of measured and calculated CO concentrations in these two street canyons. The measurements were made at a height of about 4 m, 3 m from the buildings. The street canyon labeled Broadway had a height-to-width ratio of about 1.5 and the other (Locust) had a ratio of about 2. Observations in San Jose indicated good model performance in canyons wider than they were high.

About 650 hours of data were used to test the model performance. The calculated and observed values of CO concentration had root-mean-square differences of 3 to 4 ppm in the street canyon and about 2.5 ppm at roof level. This agreement was achieved by

Figure 6. Cross-street circulation between buildings.

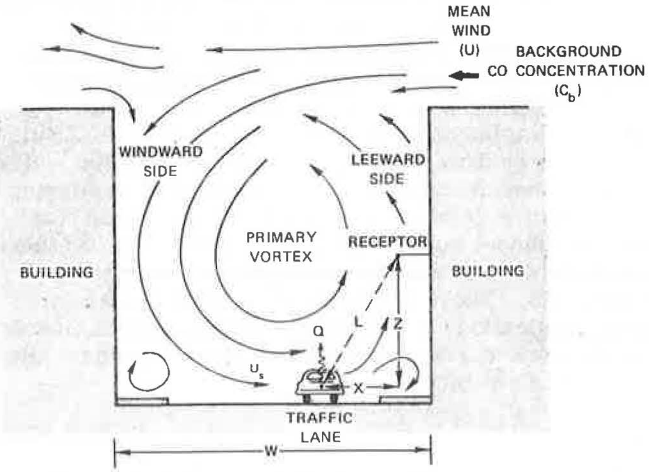
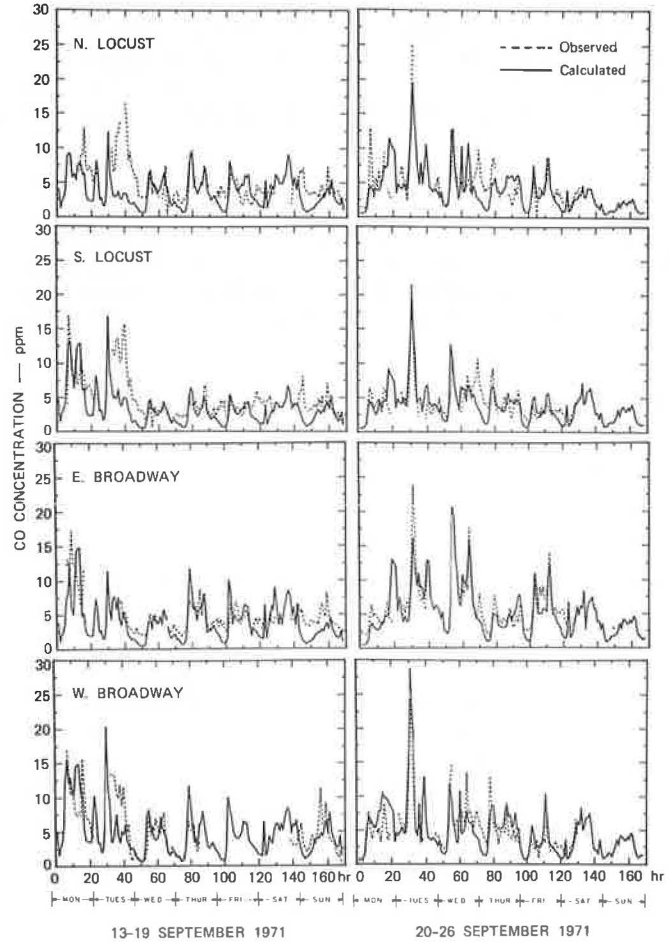


Figure 7. Comparisons of observed and calculated CO concentrations.



using readily available meteorological and traffic data and without any special calibrations. The model was able to predict median and 98th-percentile concentrations for the period within about 2.5 ppm.

APPLICATIONS

Ultimately, it is hoped that urban planners will incorporate diffusion models and their capabilities for forecasting air pollution into the planning process. In addition to its use for comparing the air pollution from alternative network configurations, the model could be used to study the effects of various land use practices and to provide a rational approach to identifying which mixes and configurations of industrial, commercial, and residential areas will reduce air pollutant concentrations. The effects of transporting a part of the commuting population in other than private vehicles are also amenable to investigation with diffusion models.

Various air pollution control strategies can be evaluated by using diffusion models. In the broad sense, the topics discussed in the preceding paragraph—land use practices, alternative transportation systems, and highway network configurations—all represent control strategies. The simplest control strategy appears to be emission reduction, which is readily treated by the APRAC-1A diffusion model (Figs. 1 and 2). On a relatively small scale, improving traffic flow in highly congested areas will reduce air pollution. For the study of these effects, more detailed traffic and emissions models are required to provide better input to the diffusion model and its street canyon submodel. Recently, the feasibility of this type of application has been demonstrated (8). It should be quite feasible to evaluate the effects of actions such as better signal progression, one-way street patterns, and left-turn lanes.

In addition to its use as a tool for evaluating air pollution control strategies, the APRAC-1A diffusion model will provide guidance for locating monitoring stations and estimating the conditions that prevail between existing, widely spaced monitoring sites. For example, in Figure 1, pollution concentrations show peaks in certain areas for the meteorological conditions indicated. Monitoring in such areas will indicate the peak levels to be expected in the area, and the fact that these are the maximum points can be verified by a small number of measurements in adjacent areas. Further, once the levels forecast by the model are verified by measurement, running the model with current traffic and meteorological conditions will provide a continuing picture of what is going on between the stations.

At the present time, the APRAC-1A model provides a way of forecasting CO concentrations that have been verified by an extensive field test program. It is clear that the model formulation will be applicable to other nonreactive gaseous pollutants, and perhaps lead aerosols, if appropriate emissions models are developed. In addition, the model may provide useful information on some reactive pollutants.

By demonstrating the ability to trace a nonreactive gas like CO, the model also shows that it can describe the concentration of the sum of the products of some reactive pollutants produced by vehicles. For example, some data obtained during the model verification indicate that it will be possible to forecast NO_x concentrations resulting from vehicular emissions. Such a forecast would not distinguish between NO and NO_2, and no emission model is available that describes NO_x emissions adequately. We hope to be able to address these problems in the near future because the usefulness of the model in certain areas will be greatly enhanced by the addition of that capability.

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REFERENCES

1. Klein, G. E., et al., Methods of Evaluation of the Effects of Transportation Systems on Community Values. Final rept., Stanford Research Institute, Menlo Park, Calif., 1971, 290 pp.
2. Ludwig, F. L., Johnson, W. B., Moon, A. E., and Mancuso, R. L. A Practical Multi-Purpose Urban Diffusion Model for Carbon Monoxide. Final rept., Stanford Research Institute, Menlo Park, Calif., 1970, 184 pp.
3. Johnson, W. B., Dabberdt, W. F., Ludwig, F. L., and Allen, R. J. Field Study for Initial Evaluation of an Urban Diffusion Model for Carbon Monoxide. Final rept., Stanford Research Institute, Menlo Park, Calif., 1971, 240 pp.
4. Ludwig, F. L., and Dabberdt, W. F. Evaluation of the APRAC-1A Urban Diffusion Model for Carbon Monoxide. Final rept., Stanford Research Institute, Menlo Park, Calif., 1972, 167 pp.
5. Rose, A. H., Jr., et al. Comparison of Auto Exhaust Emissions in Two Major Cities. Jour. of Air Pollution Control Assn., Vol. 15, No. 8, Aug. 1967.
6. Curry, D. A., and Andersen, D. G. Procedures for Estimating Highway User Costs and Air and Noise Pollution Effects. Final rept., Stanford Research Institute, Menlo Park, Calif., 1971.
7. Gifford, F. A., Jr. Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion. Nuclear Safety, Vol. 2, No. 48, 1961.
8. Ludwig, F. L., Sandys, R. C., and Moon, A. E. Preliminary Studies of the Modeling of Air Pollution Effects From Traffic-Engineering Alternatives. Submitted to Jour. of Air Pollution Control Assn., 1972.