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Impact of Air Quality Control Measures

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Contents

New York State Response to the Mandates of the Clean Air Act

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The Clean Air Act Amendments of 1977 require urban areas currently in nonattainment of national air quality standards to develop a control plan that will permit them to achieve the standards by 1982. The amendments also recommend consideration of 18 control strategies for those areas in violation of standards for transportation-related pollutants. This paper describes the approaches taken for seven upstate New York urban areas found to be in violation of air quality standards for transportation-related pollutants. It describes pollutant concentration monitoring, emissions modeling, and control strategy evaluation activities undertaken by the New York State departments of transportation and environmental conservation and the metropolitan planning organizations for these urban areas. Preliminary estimates of the effectiveness of the recommended mobile-source control strategies are given, as are discussions of the nonair quality impacts of the strategies.

The Clean Air Act Amendments of 1977 mandate that all states identify and notify the U.S. Environmental Protection Agency (EPA) of areas within their borders that are in violation of the national ambient air quality standards (NAAQS) (1). States that have such noncompliance areas must demonstrate that, through the incorporation of control strategies in their individual state implementation plans (SIPs) for achieving air quality, these NAAQS will be attained everywhere within their borders by 1982. If it is determined by a state that these standards will not be met by 1982 (even though all reasonably available emissions control measures will have been implemented through revised SIPs), that state may request from EPA an extension to 1987 of the deadline for achievement of the air quality standards.

Revised SIPs (or evidence that revised and effective SIPs are being developed) are to be submitted to EPA by the end of 1978 for approval. If a state fails to meet this requirement, the amendments provide for the imposition of a number of sanctions in the form of restricted or reduced federal funding for highways, loss of federal funding for state and local government air pollution control programs, and further restrictions of new sources and modifications to existing sources of air pollution in areas that are in violation of the standards. This paper summarizes the planning activities of the metropolitan areas of upstate New York to develop transportation elements of the SIP that will meet the requests of the act.

NEW YORK STATE'S APPROACH TO CONTROL STRATEGIES

The two major mobile-source pollutants are carbon monoxide (CO), and photochemical oxidants, generally referred to as ozone (O_3). For mobile-source (motor-vehicle-caused) pollutants, the Clean Air Act Amendments of 1977 require an investigation into the effects of 18 emission control strategies or reasonably available control technologies (RACTs). Broadly speaking, these RACTs may be classified as (a) those that involve vehicle and related modifications, (b) those that pertain to operational controls, and (c) those that relate to the encouragement of mode shifts (automobile to transit) and high-occupancy vehicles (HOVs) (see Table 1). Strategies that are shown to be effective in reducing mobile-source emissions and that are reasonably available for implementation are to be incorporated into control programs for the state's nonattainment areas.

The federal guidelines for the development of control programs (2) suggest that the metropolitan planning organization (MPO) in each urban area take the lead in evaluation of RACTs for mobile sources. The evaluation of control strategies by MPOs is to be considered a two-stage process: (a) the first stage is a preliminary examination of the RACTs by the MPOs by use of simplified assessment techniques (leading to local inputs to the SIP revision process in late 1978) and (b) the second stage is a closer look at those strategies that have the potential to reduce mobile-source air pollutants in an area (with the idea to further refine the SIP as necessary as new control information and techniques become known).

In order to gauge whether or not a control strategy could or should be implemented in an urban area, MPOs were required to assess the reduction effects of a strategy on air pollution. To assist MPOs in their appraisals, a task force of staff members from the New York State Department of Transportation developed preliminary methods to estimate the approximate air quality impacts of the various RACTs. These methods are detailed by Hartgen (3). Impacts other than those on air quality were also examined closely. These impacts include

1. Energy consumption effects,
2. Economic impacts,
3. Community effects,
4. Travel impacts,
5. Feasibility (social, economic, institutional, and political), and
6. Measures considered important in the individual urban areas.

In addition, MPOs determined how well strategies could work together in combination (i.e., packages) to effect pollutant reductions in their urban areas, and which of the RACTs are incompatible with each other and should not be relied on in certain combinations.

DETERMINING NONATTAINMENT AREAS

Subarea Monitoring

EPA determined in early 1978 that all of New York State (including the seven major upstate urban areas of Buffalo, Rochester, Syracuse, the Capital District, Utica-Rome, Binghamton, and Elmira) were in nonattainment of the federal O_3 standard, and that portions of Buffalo, Rochester, Syracuse, and the Capital District were also in violation of the CO standards.

A program of intensive air quality monitoring was initiated by the state department of transportation in early spring of 1978 to complement the CO data that are gathered at the long-term, continuous air monitoring station (CAMS) sites located across the state. The monitoring at these additional sites continued throughout the summer and fall of 1978 in an effort to better identify CO nonattainment areas and to define the degree of the state's mobile-source pollutant problem.

Monitoring air quality in the spring and summer rather than during the peak CO season (roughly October to February) is not ideal but is unavoidable. To compensate, a conservative factoring procedure was developed to arrive at estimates of the second highest 8-h CO concentration at the additional monitoring sites. The short-term measurements made at new sites were expanded by a factor made up of the ratio of the average

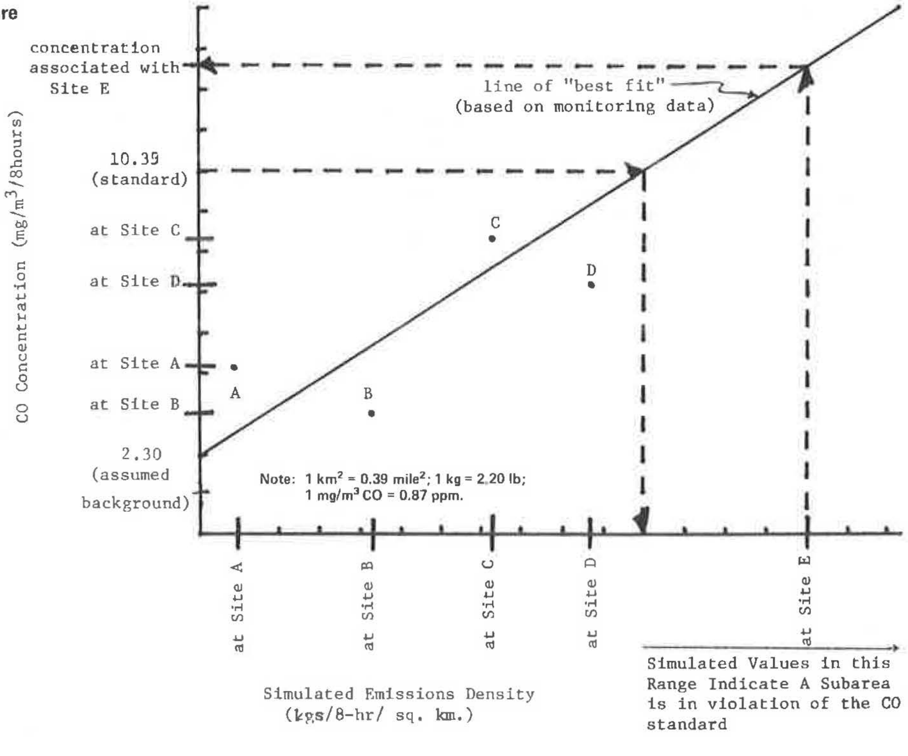
Table 1. Results of MPO strategy evaluations.

Control Strategy	Buffalo	Rochester	Syracuse	Capital District[a]	Utica-Rome	Binghamton	Elmira	Emission Reduction by 1982 due to Strategy (%)	
								CO	HC
Vehicle and related modifications									
0. Vehicle turnover	I	I	I	I	I	I	I	28-35	52.7-56
1. Vehicle inspection and maintenance program	I	I	I	I	I	I	I	9-13	2-4
16. Fleet fuel and power plant conversion	NA	P	NA	NA	NA	NA	NA	10-22	3-22
2. Control of fuel vapor emissions	X	X	X	X	X	X	X	X	X
17. Retrofit of uncontrolled vehicles	X	X	X	X	X	X	X	X	X
18. Control of extreme cold-start emissions	X	X	X	X	X	X	X	X	X
Operational controls									
15. Improvements in traffic flow	NA	I	IP	I	I	I	P	1.5-5.6	0.5-3.1
7. On-street parking controls	P	I	I	P	I	I	I	0-0.9	0-2.3
9. Establishment of pedestrian-only areas	I	I	I	NA	NA	NA	I	0-0.3	0-1
12. Staggered work hours	NA	I	P	P	NA	I	I	3.9-7.0	0.3-7.0
5. Road use restrictions	P	I	P	NA	I	NA	NA	0-6.0	0-0.3
14. Control of idling times	P	P	NA	NA	NA	NA	NA	1.5-4.9	0.6-2.1
Mode shifts and HOV encouragements									
8. Fringe and park-and-ride lots	I	I	I	I	NA	I	P	0.4-0.8	0-0.6
4. Exclusive lanes	I	I	NA	P	NA	NA	NA	0.1-5.0	0.1-0.2
4. Carpool programs		I	I	P	P	I	P	0-1.6	0.1-0.8
6. Long-range transit programs	I	NA	I	I	I	NA	P	X	X
11. Programs and facilities to encourage bicycling	NA	I	I	I	NA	I	P	0-1.3	0.5-1.2
10. Employer encouragement of pooling, transit and bicycle use, and walking	P	I	I	P	P	I	P	1.1-1.3	0.1-1.1
3. Improve public transit	IP	IP	IP					0.1-6.0	0.1-6.0
Increase service	NA			P	NA		NA		0-0.01
Decrease fare	NA			P	NA		P		0-0.04
13. Economic discouragement of single-occupancy automobile trips; congestion pricing	I	P	NA	NA	NA	NA	NA	0.3-2.6	0.15-0.4

Note: I = being implemented or studied, occurring naturally; P = potential shown, needs further study; NA = not available or inappropriate; X = insufficient data available to evaluate strategy at this time.

[a] Albany-Schenectady-Troy.

Figure 1. Procedure for determining highest CO concentration in an urban area.



short-term reading at an appropriate nearby CAMS site (made during the same short-term periods as those during which the new monitors were gathering data) and that CAMS site's second highest 8-h CO reading for the previous 12 months. That is

[estimated yearly 2nd maximum CO concentration (new site)]
÷ [measured average CO concentration over the short-term period (new site)]
= [measured yearly 2nd maximum CO concentration (CAMS site)]
÷ [measured average CO concentration over the same short-term period (CAMS site)] (1)

or

estimated yearly 2nd maximum CO concentration (new site)
= {[measured average CO concentration over short term (new site)]
× [measured yearly 2nd maximum CO concentration (CAMS site)]}
÷ [measured average CO concentration over same short term (CAMS site)] (2)

Estimating Maximum Concentration

To determine which subareas in each city have the highest emissions density, the New York State Department of Transportation air quality system uses the results of the traffic simulation process as input to calculate the amount of each primary pollutant emitted on a link-by-link basis by vehicle type and hour of the day (4). The estimates of CO emissions density, obtained for each CO nonattainment area through the assignment process, were related to appropriate CO concentrations measured at the subarea level. The establishment of these relationships permitted the calculation of the maximum CO concentration in each area. Figure 1 illustrates, in general form, the workings of this procedure. Figure 1 shows that an area's greatest CO concentration is associated with the greatest CO emissions density (site E); if this concentration estimate is above the 8-h standard of 10.35 mg/m^3 (9 ppm), the corresponding portion of the urban area would presumably be in violation (5).

Results obtained through application of this procedure, the known conservative nature of the estimates used to identify nonattainment areas, and the expected impact of natural vehicle turnover leads to the conclusion that all upstate urban areas will be in attainment of the CO standards on a subarea basis by 1982. Air quality monitoring and modeling data will continue to be updated to measure progress in achieving the CO standard.

Work is currently under way by the MPOs and the New York State departments of transportation and environmental conservation to identify and develop refined procedures to eliminate possible CO hot spots. Hot spots are tentatively identified as localized areas that, because of traffic volumes, roadway configuration, meteorological conditions, and public exposure, exhibit CO concentrations that may warrant alleviation.

Since O_3 is not produced directly by motor vehicles, vehicular emission of hydrocarbons (HC) is the pollutant that is modeled, forecast, and proposed for control.

RACT IMPACTS

Estimates of air quality impacts are based on the principle that changes in the emission rates of CO and HC are functions of both changes in speed and changes in vehicle kilometers of travel. The relationship between vehicle kilometers of travel and emissions of both HC and CO is assumed to be one to one (i.e., a 1 percent change in vehicle kilometers of travel would lead to a 1 percent change in emissions). The relationship between speed and emissions is not linear but may be assumed so over short intervals; it is generally less than one to one. Changes in concentrations of photochemical oxidants (produced from HC) are not necessarily linear with changes in vehicle kilometers of travel and, therefore, the analysis for HC should be conducted on an emissions basis rather than on a concentration basis (3).

The range of maximum CO and HC emission reductions that follow is based on optimistic projections that assume favorable implementation conditions. Table 1 presents, in comparative form, the various MPOs' views of the RACTs (6-12). RACTs and the identifying numbers they were assigned in the Clean Air Act Amendments of 1977 are given.

Vehicle and Related Modifications

Vehicle Fleet Turnover (RACT 0)

Newer automobiles generally have much more tightly controlled emissions than do older ones. Thus, as newer automobiles replace older ones in the fleet, this vehicle turnover (commonly referred to as RACT 0) will result in a significant reduction in air pollutants. Estimates of effectiveness of vehicle turnover were done by the department of transportation through the air quality and traffic assignment modeling process. The results show that vehicle turnover is the single most effective air pollution control strategy available and requires no special implementation action on the state or local level. CO reductions in the range of 30-35 percent and HC reductions of 50-55 percent may be expected by 1982. However, an economic downturn that causes changes in the normal pattern of new vehicle purchases could upset this expected pollutant decrease.

Vehicle Inspection and Maintenance Program (RACT 1)

A vehicle inspection and maintenance program could reduce CO by 9-13 percent and HC by 2-4 percent. Because of potential economic, political, and institutional problems with this strategy, implementation is only considered possible on a state, regional, or national level. An inspection and maintenance program may force the vehicle owner to incur the cost of a yearly (or more frequent) vehicle inspection and possibly major expensive repairs in the course of reregistering an automobile or truck. The inspection may be done at yet-to-be-established state inspections garages in an effort to minimize the chance of fraud. Regardless of whether private or public facilities are used, some sort of state administrative system would have to be set up to run an inspection and maintenance program. These problems may make this strategy very difficult to implement politically in today's economic situation, even though it is a potentially effective measure.

Conversion of Fleet Vehicles to Cleaner Engines or Fuels (RACT 16)

Estimation of the air quality effects of this control strategy involves estimation of an area's fleet (usually taxi and truck) size, use (i.e., vehicle kilometers of travel), and contribution to pollution. Then, by application of this to new engine and fuel emissions rates, the benefits attributable to the conversion strategy can be calculated. Pollutant reduction estimates were calculated in the range of 10-22 percent for CO and 3-

22 percent for HC and, thus, this appears to be a very effective strategy. There are, however, many serious problems associated with this RACT. An area that requires such controls may find that its businesses will leave the area rather than comply. Hence this technique must be imposed on a regional or national level. The degree of conversion needed may not be physically or technically possible by the 1982 target year. MPOs generally have little enthusiasm for this RACT.

Control of Fuel Vapor Emissions (RACT 2), Retrofit of Uncontrolled Vehicles (RACT 17), and Control of Extreme Cold-Start Emissions (RACT 18)

These strategies are being studied for effectiveness and feasibility by the New York State Department of Environmental Conservation. If they prove to have potential benefits, implementation will have to be on a state, region, or national basis so as not to unduly penalize or otherwise hinder the economic well-being of any one area.

Operational Controls

Improvements in Traffic Flow (RACT 15)

The potential effectiveness of improvements in traffic flow can be estimated by determining the overall (increased) capacity afforded by the improvement. If the relationship between the new capacity of a facility and the traffic demand is known, increases in traffic flow speeds due to improvement can be calculated by use of techniques contained in the Highway Capacity Manual (13). This increase in flow speeds can then be translated into estimates of reductions in pollutant emissions.

The effects of improvements in traffic flow are dependent on each individual project; no generalizations can be made. CO reductions in the area of 1.0-5.5 percent and HC decreases of 0.5-3.0 percent may be expected for larger improvements projects (e.g., a computerized traffic signal system).

Flow-improvement air quality benefits may be expected to be short lived—as congestion is relieved and traffic flow speeds are increased, new traffic will eventually be induced to use the highway facilities. Generally, flow improvements projects are relatively low in cost and are already being studied and implemented in the urban areas. The air quality impact is only one of the many impacts considered in the evaluation of a potential project.

On-Street Parking Controls (RACT 7)

Elimination of parking on a facility increases the capacity of that facility. In turn, this capacity increase results in improved flow speeds over the facility, which can be translated into anticipated emissions reductions. Depending on the extent of the elimination of on-street parking, a reduction of up to 0.9 percent for CO and 2.3 percent for HC may be expected. However, on-street parking control programs have already been implemented in many upstate areas and further elimination of on-street parking may have little beneficial flow or air quality impacts.

If on-street parking in a small area is eliminated [as in the case of a central business district (CBD) or shopping district], provision of alternative, off-street parking facilities should be considered. Otherwise, undesirable economic effects (i.e., shift of business from the CBD shopping district to outlying shopping centers where parking is available) and political pressure may be expected.

Establishment of Pedestrian-Only Areas (RACT 9)

A literature search (prime source: Auto Restricted Zone by Alan Voorhees and Associates) (14) suggests that in typical automobile-free zones there would be a small diversion to transit (~1.5 percent of all work trips) and an increase in the number of total work trips (~5 percent) within five years. Calculations suggest a small reduction in area vehicle kilometers of travel and an increase in hot-spot vehicle kilometers of travel, but the major reason for building pedestrian malls is not to reduce air pollution. Air quality benefits of pedestrian-only areas range up to a 3 percent reduction in CO and up to a 1 percent reduction in HC.

There are serious political and financial obstacles to the introduction of automobile-free areas; thus implementation is somewhat difficult. Such areas are under consideration or have been implemented in a number of upstate areas: Buffalo, Rochester, Syracuse, and Elmira; however, it is unlikely that as-yet-unplanned pedestrian-only areas could be implemented by 1982. Because of negligible (or even negative) air quality effects, pedestrian-only, automobile-free areas should have as a foundation other community benefits in addition to air quality.

Staggered Work Hours and Four-Day Work Week (RACT 12)

The air quality benefit of staggered work hours results from an increase in vehicle speeds during the somewhat lengthened peak-hour periods. Once the speed changes are estimated, it is possible to determine the air quality impacts of this policy. The air quality benefits of a four-day workweek scheme are a function of the vehicle kilometers of travel saved through the elimination of one workday's worth of travel. Analysis of these strategies shows a maximum of 7 percent reduction in CO and HC emissions, assuming no additional travel on the extra day off or because of freer traffic flow during the peak hour brought about by staggered work hours. There is evidence that travel on the additional day off is reduced.

Results of work by Tannir (15) suggest that although there are user benefits, the effect of staggered work hours on the transportation system is not significant. Desimone (16) suggests that the four-day workweek would have a more significant impact on Los Angeles if it were widespread. A speed change of about 15 percent may be possible if the four-day workweek is widely used. Changes in the work schedule require the cooperation of employers and employees; employers should have about 500 or more employees and have an operation that permits shift splits. Air quality benefits tend to be of a localized nature. Transit service may be more efficient in that the peak load may be smoothed under a staggered-hours scheme; however, transit may lose some riders if employees under the new work hours find the bus schedule no longer convenient. Similar disbenefits may be seen in the area of carpooling: Existing carpools may disband as work schedules become varied within a firm or carpool-matching efforts made that much more difficult. Other carpools, however, may be formed.

Road Use Restrictions (Automobile Bans)(RACT 5)

The literature implies that there would be little or no diversion to transit if a street were closed but transit service were not improved. Estimates of the savings in travel distances and speed were made by running traffic assignments.

Maximum reductions are on the order of 6 percent for CO and 0.3 percent for HC under this strategy. Any air quality benefits would be very localized (i.e., on the street with the restriction) and areawide effects would be negligible. If provisions were not made to eliminate (through mode shift to transit) or adequately handle automobile traffic diverted around the restricted area, increases in vehicle kilometers of travel, congestion, fuel consumption, and air pollutant emissions would occur in the vicinity. This strategy may be politically and economically unfeasible because of the potentially adverse impacts on businesses and shops in the automobile-free areas. However, the potential also exists for taking advantage of the automobile-free nature of such a location—the result would be the creation of a very attractive, highly visible shopping area. Transit-only malls are being studied for Buffalo, Rochester, and Syracuse.

Control of Idling Times (RACT 14)

Truck fleet effects are more noticeable than those for taxi fleets. Besides possible air quality benefits, the control of fleet idling times may also result in fuel savings. The strategy may be difficult to enforce; convincing fleet operators of its necessity may also be difficult. It may induce cruising (especially by taxis) instead of stopping engines, and it may conflict with cold-start controls in wintertime.

Although this policy may be difficult to implement, estimates of its potential can be made. The approach is to determine the idling emissions rate (grams per minute) versus moving rate, then determine idling times for typical fleets. Finally, fleet sizes are computed and the maximum air quality impact is obtained by using the equation

$$\text{Grams CO or HC} = \text{fleet size} \times \text{idling hours per year}\ (\text{CO or HC idling rate}) \qquad (3)$$

Maximum potentials for this strategy are 1.5-4.9 percent reduction in CO and 0.6-2.1 percent reduction in HC.

Mode Shift and HOV Encouragements

Fringe and Park-and-Ride Lots (RACT 8)

Remote park-and-ride data were found for Rochester, Milwaukee, and Seattle; peripheral park-and-ride data were found for Albany and Atlanta. These data were used to determine average daily and peak-period ridership and bus trips per lot. Ridership figures were converted into the number of automobile trips saved by using diversion studies from the above areas. The number of automobile trips saved is then converted into vehicle kilometers of travel. The additional vehicle kilometers of travel used by the buses and the changes in the vehicle-capacity ratio for roads in the corridor are also taken into account.

The estimate of effectiveness for this strategy in the upstate areas is a reduction in CO emissions of 0.4-0.8 percent, and a reduction in HC emissions of up to 0.6 percent. Generally, few areawide air quality benefits can be expected from this strategy; any benefits would be seen mainly in the corridors served by the lots. The strategy is relatively easy and inexpensive to implement if use can be made of existing parking lots (e.g., at shopping centers). Depending on the size of an area's bus fleet, this strategy may require new equipment (and greater capital, and possibly operating resources) to serve the lots. Improvements in traffic flow may be seen as well as possible reductions in fuel consumption, travel time, and system vehicle kilometers of travel if automobiles left at home or in the lot are not used during the day.

Park-and-ride service may encourage undesirable sprawl or extended development patterns. Fringe lots around the CBD may increase automobile traffic (and the potential for worsensing air quality) in the area around these lots; however, these lots may also serve to concentrate activities and reinforce the attractiveness of the CBD.

Because of the lack of highway congestion or concentrated demand, this strategy may not be feasible in smaller areas; larger urban areas in upstate New York have already instituted this service and may find little potential for further implementation.

Exclusive Lanes and Carpool Programs (RACT 4)

Estimates of impact on travel distance and speed from the introduction of exclusive lanes are based on data contained in the literature. A 2.5 percent figure for potential reduction in peak-hour travel was used for several areas. The peak-hour traffic volumes were first obtained. The corridor vehicle kilometers of travel were obtained by multiplying the link volume by the link length. These vehicle kilometers of travel were reduced by the reduction factor. Speed changes were found to be very small. Maximum reductions were found to be in the range of 0.1-5.0 percent for CO and 0.1-0.2 percent for HC.

To estimate the potential associated with carpooling programs, carpool programs were reviewed for effectiveness and then changes in vehicle kilometers of travel and speed were estimated. An assumption of one-way-work-trips distance of 13.3 km (8.3 miles) and an initial vehicle occupancy of 1.2 persons/vehicle were used. The assumption was that carpooling could be increased by about 5 percent, a figure consistent with the experience in Knoxville, Tennessee. Potential maximum reductions estimated for this strategy are 1.6 percent for CO and 0.8 percent for HC.

Exclusive lanes have been operating or planned for specific needs in some of the upstate areas; however, evaluations show expansion of exclusive HOV lanes to be relatively unnecessary because of the lack of major congestion problems in the upstate urban areas. In some cases, the dedication of highway lanes to the exclusive use by HOV would create congestion problems; worsen the air quality situation; and increase fuel consumption, travel costs, and time. Improvements to facilities earmarked for HOV exclusive lanes would place an additional burden on local finances, further reducing the attractiveness and practicality of this strategy.

Carpools and buspools were found to offer potential air quality benefits as well as savings of fuel and finances, reductions in vehicle kilometers of travel, and easing of parking requirements. (These impacts are based on the assumption that the automobiles left at home are not used during the day.) Carpool programs should be directed toward areas outside of the transit service area so as not to effect a diversion of riders from transit use. Carpool programs and studies have already been instituted in some MPO areas. Because of differences in work shifts and locations of employment, this strategy may not be available to any great degree in some of the smaller urban areas.

Long-Range Transit Improvements (RACT 6)

The upstate areas are currently assessing the need for planning or implementing portions of long-range transit improvements programs. Programs may include new services to areas indentified through detailed corridor studies, extensive transportation system management improvements to the highway network in an effort to improve bus flows, transit malls, or new or innovative technologies. Air quality impacts will be a consideration in any decisions made regarding this strategy. However, any long-range transit planning will probably have little, if any, impact by 1982.

Encouragement of Bicycling (RACT 11)

Bicycles are a possible mode when vehicle trips are less than 6 min. Approximately 15 percent of all trips qualify and perhaps 5 of the 15 percent might actually be diverted to bicycles. Thus, the total vehicle kilometers of travel saved (in work trip travel) would be approximately the number of employees × 0.05 × 0.15 × 7 km, where 7 km is approximately the maximum length for a reasonable bicycle round trip. Maximum reductions in CO and HC emissions expected from this strategy are 1.3 and 1.2 percent, respectively.

In general, air quality benefits are expected to be seen in the corridors served by the bikeways. Bicycling as an alternative mode may not be possible for most of the year in the Northeast because of adverse climatic and weather conditions. The possibility of motor vehicle-bicycle accidents and the slowdown in traffic flow caused by motorists concerned about maneuvering in heavy bicycle traffic are potential disbenefits of this strategy.

Bicycle use may decrease fuel consumption in an area and may have general health benefits for riders. Bikeway networks have been implemented and are being studied or planned for in upstate New York areas.

Employer Encouragements of Pooling and Alternative Modes (RACT 10)

A literature review indicates that perhaps 2 percent of an area's work force might use vanpools and that a 10 percent increase in carpooling might be achieved. Estimates can quickly be obtained by making assumptions about the diversion and using known area figures for average trip length in order to obtain an estimate for total vehicle kilometers of travel saved. The upstate MPOs expect a maximum range of reductions of 1.1-1.3 percent for CO and 0.1-1.1 percent for HC to result from this strategy (assuming that automobiles left at home are not used during the day).

The potential to implement, maintain, expand, and benefit from such employer-involved programs is greatest in areas that have large companies; those areas that have smaller-scale employers, scattered work sites, or shift differences may show less promise. In general, no major problems with employer or employee cooperation in studies and matching programs are reported. Concern has been voiced about employers becoming involved in arranging and providing worker transportation to and from work. Extensive, successful employer encouragement efforts may require expansion of transit services that serve the work site and result in possible increased operating deficits or equipment needs.

Improved Public Transit (RACT 3)

Improved mass transit service has been proposed as a way to reduce emissions by encouraging diversion to bus. The approach was to use "backward" elasticities to estimate diversion to transit due to either a service increase or a fare decrease. Once the diversion was calculated, the average length of a bus trip was used to estimate the savings in vehicle kilometers of travel. Speed changes were estimated by using the Highway Capacity Manual (13). Additional bus vehicle kilometers of travel that result from increased service were added in to obtain a net effect.

Service increases and fare decreases of about 10 percent each show almost negligible air quality effects; reductions of only 0.01 percent for CO and 0.04 percent for HC were forecast. Additionally the upstate MPOs saw increases in costs (capital and operating) would be incurred locally if this strategy was implemented, which would make it potentially politically or economically infeasible.

Improvements to existing services and services to localized areas (identified through corridor studies) appear to be better than general increases in bus travel distances or fare decreases, given the desire to increase ridership, reduce emissions and fuel consumption, and minimize costs.

Single-Occupancy Discouragement and Congestion Pricing (RACT 13)

The parking price elasticity of travel demand is in the range of -0.2 to -0.6. The problem is that most elasticities in the literature have been obtained as forecasts rather than by use of actual data. When San Francisco instituted a 25 percent parking tax, the impact on retail business was minimal; of course, the transit system there was excellent. A reasonable assumption that could be used in upstate New York is that a $1.00 parking fee surcharge would result in a decrease in peak-hour work trips of at least 10 percent.

The upstate New York MPOs are concerned about the possible economic impact on the CBD of positive parking policies. If the CBD is to remain accessible, it may be necessary to greatly increase transit service. This may prove expensive and yet still not be able to restore potential lost business to the downtown area.

Entry restrictions or charges imposed on vehicles that try to drive into an area are also considered under the general strategy and also meet with the same potential obstacles to implementation as above. Further, the institutional problems (as well as negative air quality effects) involved in stopping vehicles and either turning them away or collecting tolls as they try to enter the controlled area may make this strategy infeasible.

A version of this strategy that attempts to minimize disbenefits is the one that imposes penalties (entry or parking) on automobile use during the (peak) hours of 7:00-10:00 a.m. This would maintain the attractiveness of the controlled area to the nonworker visitor (i.e., shoppers and other nonregular travelers) through improved parking availability and better flow. The workers (it is assumed) that have to travel to the controlled area every day would carpool or take transit to work rather than incur the penalties imposed on low-occupancy vehicles between 7:00 and 10:00 a.m.

OBSERVATIONS AND CONCLUSIONS

Our review of the upstate New York MPO RACT reports suggests the following:

1. The wide range of estimates of RACT effectiveness produced by the different MPO staffs is in most cases due to the differing characteristics of the seven upstate urban areas. In many cases, these strategies have been already implemented in some areas and thus incremental improvement is expected to be small.
2. Because areas are very different, spatially and demographically, RACT analysis must be done on an individual area basis in order to obtain approximate estimates.
3. Many strategies have negligible or even detrimental air quality effects. For example, increases in bus service may increase pollution if there is only a small increase in bus use. Similarly, exclusive bus lanes may increase congestion in the other lanes to a level that actually results in a decrease in air quality.
4. Most of the RACT proposals have potential merit not related to the improvement of air quality and have thus already been studied by MPOs because of these other potential advantages.
5. All upstate New York urban areas will be in attainment of air pollutant standards by 1982. Expected levels of vehicle turnover are enough to ensure attainment.
6. Strategies such as fleet conversion to alternate power sources and vehicle inspection and maintenance programs must be implemented on a regional or national level in order to reduce the possibility of severe local economic impact.

The RACT evaluation done by the MPOs does not commit or recommend any projects at this time based solely on the air quality potential that has been shown so far. The MPOs will use available EPA planning (section 175) funds to continue to investigate RACTs' potential.

ACKNOWLEDGMENT

We would particularly like to acknowledge the cooperation of the members of the MPO staffs and the people in the New York State Department of Transportation who were responsible for the analysis of the 18 RACTs in particular areas. The assistance of Ron Piracci of the Air Quality Section of the New York State Department of Transportation and Ted Davis of the New York State Department of Environmental Conservation was essential. The work of the New York State Department of Transportation task force on air quality and the testing unit provided preliminary estimates of RACTs' impacts. Special thanks are due to Diane E. Davis, who typed this paper under difficult time constraints.

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Simplified Method for Evaluation of Control Strategies for Revision of State Implementation Plans

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A method is presented for demonstrating the effect of transportation control strategies and the degree of control needed to attain national ambient air quality standards by 1982, as mandated by the Clean Air Act Amendments of 1977. The emphasis is on the use of emission-concentration relationships to predict the average, rather than the maximum, concentration expected at a particular location in a given year. The statistical relation between the average concentration and the maximum is used to predict the corresponding maximum. This relation is calibrated by using all of the monitored data in the region of interest. The limitations associated with simulation modeling are minimized and the method is applicable to transportation planning methods. Carbon monoxide data collected for 8 h in the Seattle-Puget Sound region of Washington is used for illustration. The method may be applicable to oxidant control strategies.

The Clean Air Act Amendments of 1977 mandated revisions to the state implementation plans (SIP) and placed the burden for preparation of these at the local level. Although desirable on political and operational grounds, it has placed a heavy burden on the municipal planners because air quality expertise is not readily available to them. Nowhere is this more apparent than in the area of conversion of estimated emissions to concentrations. This is usually done by simulation modeling. Assuming that the models consider enough variables to predict air pollution concentrations accurately and are understood well enough to use them properly, there is still the problem of knowing what assumptions should be made in using them. This problem is often circumvented by the use of what has been termed worst-case methodology. This essentially means maximization of the model—all variables in the numerator are maximized and those in the denominator are minimized. The result is a model that overpredicts; however, this is resolved by comparison of modeled values to the monitored data to determine a calibration factor. The worst-case approach to modeling is not suited for use in developing control strategies because it tends to portray conditions to be much worse than they really are; however, selecting the proper conditions that will provide the best estimates is a challenge.

Models that estimate emissions rather than concentrations avoid this problem; however, the results still have to be converted to concentrations. A method is presented that allows one to make this comparison with a high degree of accuracy. The predictions are area specific and amenable to use in the development of SIP strategies. This model can be used to supplement existing methodology or can be used exclusively. It is inexpensive to use and is well suited to planning methods. The use of the model is demonstrated by using carbon monoxide (CO) data collected in the Puget Sound region of Washington in 1977.

MODEL DESCRIPTION

The model uses statistics to determine the maximum concentration once an average concentration has been predicted. Statistically the maximum concentration that occurs during a sampling period is equal to the mean of the data plus some number of standard deviations from the mean. Larsen (1) suggested that a log-normal distribution fits air pollution data better than does a normal one and, assuming this, one can express this relation as follows:

$$C_{max} = Mg \times Sg^{n} \quad (1)$$

where

C_{max} = the log of the maximum,
Mg = the geometric mean,
Sg = the geometric standard deviation, and
n = the number of standard deviations from the mean associated with the probability of the maximum occurring.

Larsen suggested that 3.81 be used for n in Equation 1 by assuming the maximum to be the highest value out of 8760 (the number of hours in a year) or a probability of 1/8760. Equation 1 can be rewritten as

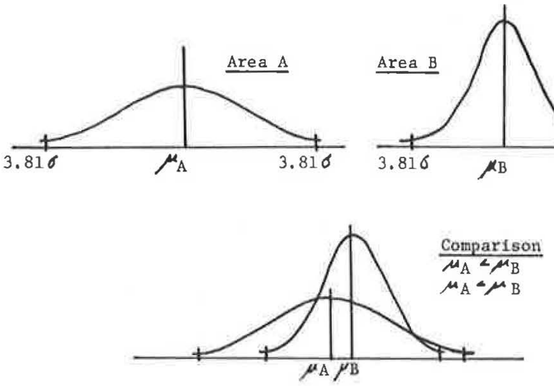
$$C_{max} = Mg \times Sg^{3.81} \quad (2)$$

As shown, the maximum concentration that occurs in an area is related to both the mean of the data and its standard deviation. The importance of considering Sg is due to the fact that it is a predictor of the probability that an extreme value will occur. This can be illustrated by comparing two hypothetical distributions, as shown in Figure 1. Area A has a flatter curve and, hence, a larger standard deviation, which indicates higher variability in the data and a greater chance of a larger extreme occurring. The two areas are superimposed, assuming area A to be less polluted than area B, as indicated by the bulk (and the mean) of the data being to the left of that in area B. A portion of area A can be seen that extends to the right of area B, which indicates that the probability is higher that area A will experience a larger maximum than will area B. An additional reason for considering the standard deviation is seen in Equation 1, where the mean is directly proportional to the maximum, whereas the effect of the standard deviation is nearly to the fourth power.

MODEL CALIBRATION

The statistical relationship depicted in Equation 1 is calibrated by using Mg and Sg of the data to calculate a C_{max}, which is then compared to the actual monitored maximum. One could use the second highest maximum, but here the extreme value is used for conservative reasons. This comparison is made for a large number of data sets, and the resultant data pairs (monitored and calculated maximums for each data set) can be compared by regression to produce the final empirically calibrated equation. In the study reported here, the data were collected for a six-week period in 12 separate metropolitan areas in the Puget Sound region. These 12 areas were chosen because they are potential hot spots, as indicated by high motor vehicle traffic density.

Figure 1. Comparison of CO distributions of two hypothetical areas.



A more complete description of the study is found elsewhere (2). The data are 8-h averages and the resultant equation will be used to calculate similar averaging time maximums.

Mg can be used directly or it can be calibrated. The best approach is dictated by which provides the best estimate in the final equation. Calibration has the advantage of accounting for the skewness of the data. To calibrate, the data are grouped and ranked in ascending order and the percentage of the time a data value group was exceeded is calculated. The data values and percentiles are made linear and a least-squares line is determined. The logarithm of the concentrations provides the necessary adjustment for these data. The percentile transformation is more involved but easily done. The position of the percentiles are symmetrical about the center of the scale and equal to their corresponding number of standard deviations from the mean. Any set of tables that gives the solution to the normal probability function can be used to provide this transformation. A final adjustment is made by converting everything to one linear scale rather than two that emanate from the center. This process can be illustrated by referring to the bell-shaped curves in Figure 1. The 3.81 standard deviations are 3.81 linear units from the center. An adjustment would produce a scale that is 7.62 linear units long and the mean or 50th percentile would be 3.81 linear units from the left origin. Similarly, the probability associated with the 3.81 units on the left would now be assigned the value of 0 and that associated with the 3.81 units on the right would be assigned the value of 7.62. This transformation is made for each percentile and the regression is done. Mg is the 50th percentile concentration and Sg is determined by using the concentration associated with the 15.87th percentile (16P) or 1.00 units to the left of the center (this is 2.81 units from the origin) and dividing it by Mg.

For each data set, a calculated and graphically determined Mg is found. A least-squares regression of these pairs provides the calibration of Mg. For the Seattle data, this was found to be

$$Mg = 0.15 + 1.01(50P) \tag{3}$$

Similarly, the calibration of Sg was accomplished and the resultant equation was found to be

$$Sg = -0.27 + 1.25(16P/50P) \tag{4}$$

The correlation coefficieints (r) for the two were 0.99 and 0.96, respectively. Substitution of these into Equation 1 provides the following equation:

$$C_{max} = [0.15 + 1.01(50P)]\ [-0.27 + 1.25(16P/50P)]^{n} \tag{5}$$

The best value of n is determined by arbitrarily assigning it a value and using Equation 5 to calculate a maximum for each data set, which is compared to the actual monitored maximum. Linear regression of the data pairs provides a correlation coefficient. The process is repeated with another value of n until the best fit is found. Figure 2 illustrates this process. For the Seattle data, the best value of n was 2.00.

Once the best n has been found, the corresponding regression slope and intercept become part of the final equation. For these data, the final equation was

$$C_{max} = 1.686 + 0.922\{[0.15 + 1.01(50P)] \ldots [-0.27 + 1.25(16P/50P)]^{2.00}\} \tag{6}$$

The correlation coefficient of this relationship was found to be 0.93 and the comparison between maximums predicted by this equation and those actually occurring is depicted in Figure 3. (These models were designed for U.S. customary units only; therefore, values in figures are not given in SI units.)

The large difference between the exponent of 2.00 and that proposed by Larsen may seem striking; however, there are two possible explanations of this. First, the data were collected for only six weeks (approximately 900 h) rather than a full year (8760 h). This probability would dictate an exponent of 3.0, which is midway between the two extremes. There is also a stronger reason for this discrepancy, which is in the area of the independence of the data values from each other in the same data set. This is especially true in regard to 8-h averages. If one assumes that 2.00 is correct, it would correspond to 44 samples/year. This compares favorably to the 50 samples/year indicated by Neustadter (3) and is certainly closer to the one-month study recommended by Meisel (4). A larger sample size would only increase the precision of the statistical parameters without appreciably changing their values.

MODEL UTILIZATION

Once the statistical relationship between major parameters of monitored data has been calibrated, it is used for CO by assuming

1. The average concentration that occurs for a pollutant in a given area is directly related to the average emissions of the pollutant in the same area, and
2. The standard deviation of the occurrence of a pollutant at a given location will not change from year to year.

Comparison of average rather than extreme values emphasizes the central tendency of the data, which is easily determined and is the strongest indicator of the data. Also, it is statistically more valid to compare the means of data sets rather than other parameters. Once a new mean has been determined, the statistical distribution of those data (such as Equation 6) is used to calculate the extreme value.

The second assumption is based on the hypothesis that the shape of the distribution of a population is due to factors independent of source strength (such as location of monitoring site with respect to pollutant sources, demographic and meteorological characteristics of the area, and the nature of the pollutant). A change in source strength should not affect the shape of the distribution but only shift it up or down scale. This

Figure 2. Comparison of regression equations and correlation coefficients for different exponents.

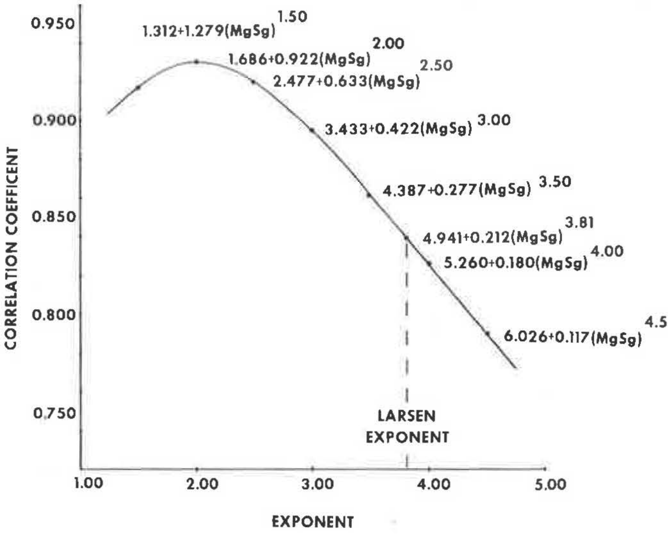


Figure 3. Comparison of calculated and monitored maximum CO 8-h averages.

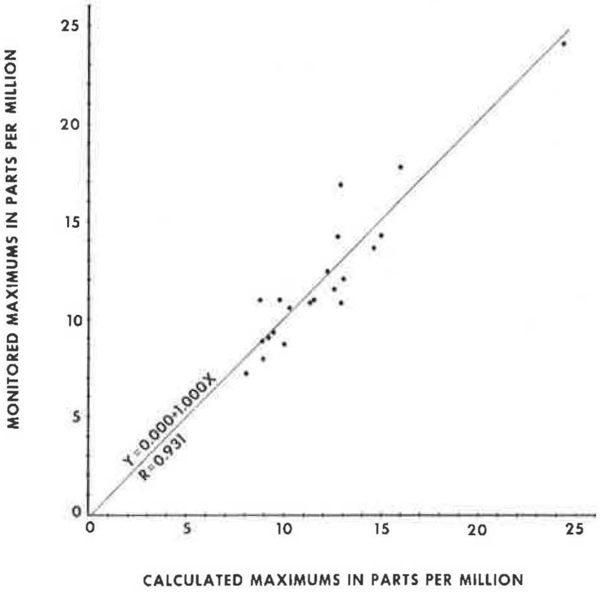
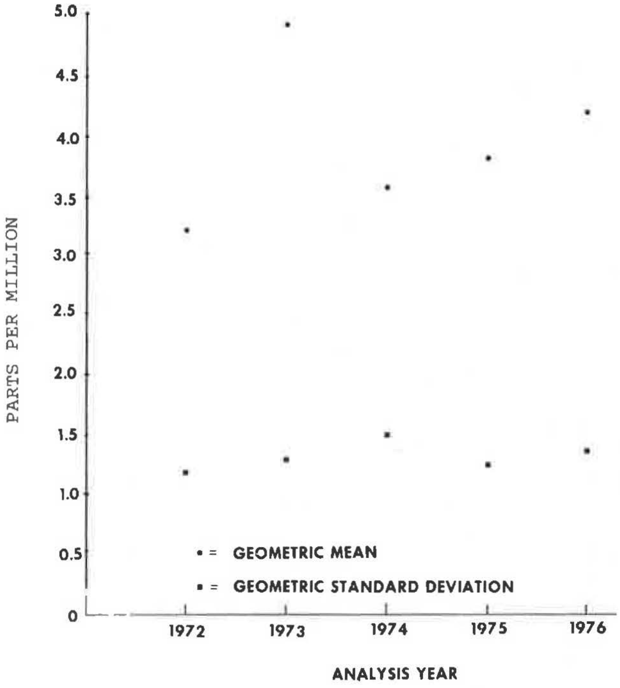


Figure 4. Trends in geometric mean and standard deviation for CO 8-h average concentrations.



hypothesis was tested for CO by analyzing data collected continuously for five years by the Washington State Department of Ecology at their James Street monitoring site in Seattle, Washington. Fifty data values were selected at random from each year of data and the mean and standard deviations were calculated and plotted (Figure 4) as a function of the year they represent. As can be seen, the standard deviation remains reasonably constant, but the means vary widely.

One should use monthly data to calibrate the model. All the data in the air shed should be used together for calibration. The only exception is that if different instrument methods of analysis are involved, it may be necessary to group the data accordingly; however, the data should at least be tested all together since the greater data size is more desirable even at the cost of some loss in precision. A month of data is used for each data set in order to consider seasonal variations and to allow more dynamic contingencies in the SIPs.

The calibrated relationship can be used to demonstrate the emission reduction needed to attain the standards and the influence of the strategies in the scenarios. A generalized form of Equation 6 will help in the discussion and is as follows:

$$C = ko + kl\ [Mg(Sg^{n})] \qquad (7)$$

Once the constants have been determined, the equation can be solved for Mg:

$$Mg = C - ko/[(kl)\ (Sg^{n})] \qquad (8)$$

By using the 8-h national ambient air quality standard (NAAQS) of 9 ppm and the standard deviation that was monitored in the location of interest, one can calculate a Mg that would correspond to attainment. Then by comparing this new mean to that monitored, one can determine the extent of the problem. In other words, rather

Table 1. Total CO.

District	1975 (kg/day)	1982 (kg/day)	Reduction from 1975 (%)	1990 (kg/day)	Reduction from 1975 (%)
Bellevue	23 406	13 956	40.4	5 346	77.2
Tacoma mall	15 382	9 114	40.8	3 695	76.0
Tacoma CBD	36 128	21 322	41.0	8 310	77.0
Everett	28 830	17 192	40.4	6 057	79.0
Renton	28 536	17 000	40.4	8 088	71.7
Tukwila	24 395	14 431	40.8	5 598	77.1
Duwamish	16 940	10 123	40.2	3 595	78.8
Montlake	6 995	4 165	40.5	1 411	79.8
University	26 760	15 990	40.3	6 060	77.4
Northgate	11 347	6 741	40.6	2 303	79.7
Seattle CBD	68 138	40 559	40.8	14 997	78.0
Bremerton CBD	24 210	-	-	4 853	80.0

Note: 1 kg = 2.2 lb.

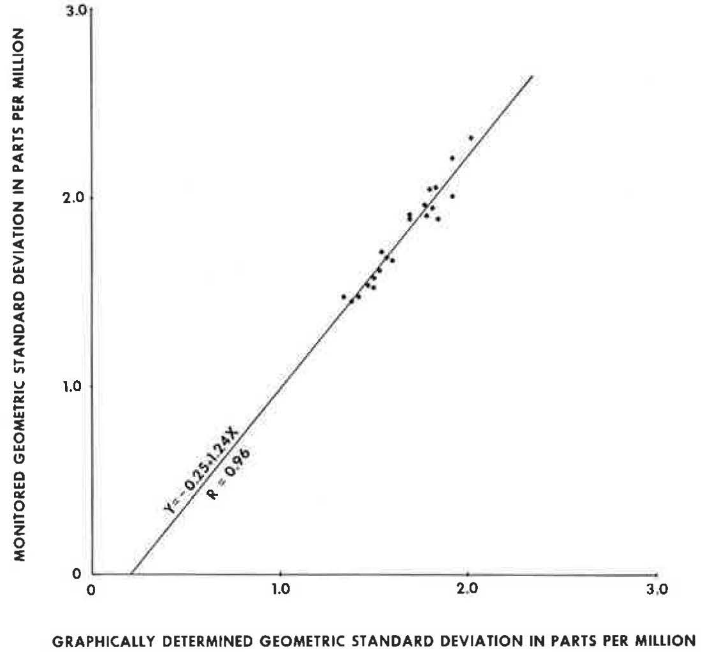


Figure 5. Comparison of graphically determined and monitored geometric standard deviation for CO 8-h averages.

than judging control strategies against the standards (maximum values), the criterion should be the mean, which is a much more behaved parameter and is statistically related to the maximum. Using the first assumption, the percentage decrease between the existing mean and that determined by Equation 8 is the percentage decrease needed in average emissions to attain the standards.

An analysis of the long-range element (LRE) transportation system for the base year and 1982 (by using the respective emission factors to determine the average emissions for each year) allows one to see the effect of the planned system without additional strategies. This was done for the Seattle data and is given in Table 1. The LRE projections for Bellevue, for example, show a decrease in average emissions of 40 percent between 1975 and 1982. (This would be the effect of no additional control strategies.) By using Equation 8 with the Bellevue data and the parameters in Equation 6, the decrease needed to attain the standards was determined to be 48 percent. This demonstrates that additional air pollution strategies are needed to reduce average emissions by 8 percent. Further, if a suggested strategy can be shown to reduce the average emissions by 4 percent, then one has demonstrated that more strategies are needed to achieve the remaining 4 percent reduction. One should remember that Sg from each data location can be used independently in Equation 8 to provide the corresponding Mg needed for that location. This allows one to establish strategies unique to each location. If analysis shows that a location cannot attain the standards by 1987, then this type of information would be a demonstration that the section 176 sanctions of the Clean Air Act Amendments of 1977 should be applied only to that part of the attainment area. Along these lines, the shrinking of the attainment area can be demonstrated on a yearly basis and, by using data that represent a month-long sampling period, the violation season can also be demonstrated to be shrinking. For example, in a given location, the violation season may be a six-month period. If attainment is expected in 1982, then, perhaps, by 1980 the violation season may be reduced to two months. If this can be demonstrated, then the more adverse strategies can be eased for the other four months. The advantages of this are readily apparent.

Another application of this method is in determination of the attainment date of the standards. Once a Mg has been determined by considering changes in average emissions, Equation 6 can be used to calculate the corresponding maximum. After this is done for several years, a plot can be made to depict the trend. This can be done for each location. Such a plot was prepared for the Seattle data and is shown in Figure 5.

Once strategies are considered, their effect on the attainment date can be illustrated by this method. This serves as a demonstration that the strategies will allow the standards to be attained.

OXIDANTS

This method may have an application in the area of photochemical oxidant control, where the average oxidant value is predicted by the usual methods. Once the statistical relation has been calibrated, then the predicted mean concentration is used to determine the maximum. There is a limitation in that the model allows a comparison between two variables rather than the large number needed to consider the complex interaction between pollutants and other conditions. A sophisticated method of grouping the data may resolve this problem.

This would not be a problem at all; one may be able to show a reasonable correlation between the change in average traffic emissions and the change in average oxidant concentrations to produce a new average oxidant concentration for 1982. Then one would proceed as above to determine the associated maximum. Certainly, this method could be used when simple one-to-one relationships have been found or a simple approach is being considered. For example, the well-known relationship betwen the 6:00-9:00 a.m. nonmethane hydrocarbon (NMHC) concentrations and the afternoon oxidant maximum may be even stronger if one correlates the average 6:00-9:00 a.m. NMHC value that occurs during a month with the average oxidant value from that same month. The correlation results from a large number of data sets, where each set represents one month of data. This relationship is used to determine the average oxidant expected due to a reduction in NMHC emissions.

CONCLUSION

This method requires a regional approach to analysis. This is due to the need for numerous data sets for calibration; however, this is not undesirable due to the nature of the transportation planning process, the nature of the air pollution problem, and the need for comprehensive strategies. Specifically, the transportation system is regionwide in approach and considers regional growth and development because air pollution characteristics of one area are not completely independent of those in another area in the same city or air shed. It is recommended that one use all of the data in the region for the calibration of the statistical relationship. By analyzing for each area, one can differentiate between them. For example, resources can be properly allocated, strategies can be formulated that do not inhibit adjacent areas, and existing problem-area boundaries can be redefined where and as needed to ensure the attainment of NAAQS without undue restriction on neighboring community growth and development.

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Analysis of Air Quality Sensitivity to Development Pattern Changes and Growth Levels

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To determine the impact of population and employment distribution changes as well as additional population and employment growth on air quality, regional vehicle kilometers of travel and emissions were obtained for four land-development-pattern scenarios for the year 2000. The scenarios include two activity-center scenarios, a dispersion scenario, and a centralization scenario. A fifth scenario was developed on the basis of additional growth beyond the forecast level. The distribution pattern of population and employment had little or no effect on ambient air quality; the alternative patterns showed little variation. The predicted differences in ambient air quality were less than the potential margin of modeling error. Carbon monoxide levels varied by only 6 percent. The centralization scenario produced the highest concentration, but one that is still 43 percent below the federal standard. Ozone predictions showed even less variation; the range was only 2 percent. Given a regional total, the distribution pattern appears to have little effect on regional air quality. A second result is that, although the absolute level of population has an effect on air pollution levels, these two variables are not directly proportional. A 27 percent increase in population resulted in a 16 percent increase in carbon monoxide emissions but only in an 8 percent increase in predicted maximum ambient concentrations. Large changes in population and employment produced smaller changes in ambient air quality.

Improved air quality is a goal in most metropolitan areas of the country. The Federal Highway Administration (FHWA) and Urban Mass Transportation Administration (UMTA) joint regulations and, more recently, the Clean Air Act Amendments of 1977 have increased the emphasis on transportation efforts to achieve this goal. Unfortunately, most analyses of the application of transportation control strategies have indicated that the amounts that vehicle kilometers of travel and vehicular pollutant emissions can be reduced through the application of such strategies are generally low. Given that the level of impact of the transportation management and control strategies is low, some planners have suggested that massive changes in the urban form and structure will be required to achieve desired reductions in vehicle kilometers of travel and air pollutants. The adopted transportation plan for the Denver region is being reevaluated and revised to meet a number of criteria, one of which is reduction of air pollution. As part of this effort, a sensitivity analysis is being performed. A number of possible urban forms are being used to determine the degree to which vehicle kilometers of travel and, therefore, air pollution can be reduced by changes in land use.

PAST STUDY FINDINGS

Past studies referred to here tend to confirm the assumption that a denser development pattern tends to produce less travel, but they also show that the change in travel patterns is likely to be small. In a case study of the transportation and air shed simulation (TASSIM) air quality model in the Boston metropolitan area (1), increases in the density of urban activities over a base or benchmark condition were found to lead to a reduction in average daily round trips and vehicle kilometers of travel; conversely, decentralization led to increases in both of these indicators of travel. However, shifts in urban development activity of a very large magnitude (up to 20 percent) were found to result in small changes in travel patterns (up to 6 percent). The TASSIM study then concluded that, although centralization reduces aggregate travel activity as measured by statistics such as vehicle kilometers of travel, central travel activity is not reduced enough to improve air quality.

Alan M. Voorhees and Associates came to a similar conclusion in a study conducted in the Baltimore-Washington area (2) in which little significant change in travel patterns was found between alternative development patterns. Another analysis conducted in the Boston area involved 22 alternative development patterns. Large-scale changes in land use were found in existing large urban areas, but they had insignificant impacts on aggregate travel characteristics (3). Average trips, average trip lengths, and the total distance traveled were virtually unchanged in most of the alternatives. Only in a few high-density scenarios did the distance traveled decline somewhat because of increased transit ridership.

As part of the areawide environmental impact statement for Denver waste water facilities (4), the U.S. Environmental Protection Agency (EPA) examined the effects of large-scale changes in emissions distribution (17-25 percent). The analysis indicated that regionwide control of pollutant levels is not achieved by substantial redistribution of emissions. This study found almost no detectable change in ozone (O_3) concentration or distribution.

Zahavi (5) used travel-time budget theory to question the belief that people in compact cities need less motorized travel than do those in dispersed cities because more destinations are within walking distance. He found instead that daily travel distance per automobile is remarkably similar in all cities.

The Cost of Sprawl (6) postulated that vehicle trips could vary by as much as 60 percent between a planned, mixed high-density-development scenario and a sprawl, low-density single-family dwelling scenario (6). This study also postulated that some change in average trip length might occur for nonwork purposes.

SCENARIOS

The objective of the land use and air quality sensitivity analysis was to provide a general indication of the levels of reduction of vehicle kilometers of travel and air pollution emissions that might be expected from some rather extreme changes in land use within the region and from changes in travel patterns and conditions. Thus, a number of development scenarios were selected for testing (7); their composition reflected these extreme conditions and was not intended to suggest actual expected future conditions. The general approach used was to maintain a common transportation system and to maintain an overall population and employment control total. Within this framework, population and employment concentrations were varied to reflect four different growth patterns:

1. An activity-center scenario in which population and employment growth are distributed outside of the urban core area among a number of high-density activity centers,
2. A second activity-center scenario in which employment is concentrated in the activity center but population is distributed in a more dispersed pattern,
3. A dispersion scenario in which population and employment growth are distributed in a uniform dispersed pattern throughout the metropolitan area, and
4. A centralization scenario in which population and employment growth are predominantly concentrated in the urban core area.

In addition to the four growth pattern tests, an accelerated-growth scenario was also tested. This test assumed that the Denver region would grow to a population level 27 percent greater than was assumed in the population level of the year 2000 plan.

Benchmark Condition

The benchmark condition to which the results of the sensitivity analysis were compared consists of the adopted year 2000 regional growth and development plan and the year 2000 restated transportation plan. All of the development scenarios tested use a control total activity level of 2.35 million population and 1.13 million employment. The activity levels represent the current regional policy forecasts for population and employment. The distribution of population and employment for the benchmark condition is in accordance with the distribution pattern approved for use in the plan restatement process. These distributions involve the combination of concentrated activity in the region's central core area, growth concentrations in 11 activity centers and three high-density corridors, and semidispersed low-density growth elsewhere in the metropolitan area.

We decided to use a single, common transportation system (the restated transportation plan) for the sensitivity analysis. We reasoned that a constant transportation system configuration would focus the sensitivity analysis on changes in land use. Further, given the focus of the restated transportation plan as largely that of improvement of the current system, not on extensions nor, for that matter, major deletions of this system, we reasoned that the system would be in place throughout the region despite any major land use configuration changes that might occur through policy decisions over the next 20-50 years.

Land Use Scenarios

Scenarios tested represent abstract extremes of land use patterns, which range from centralization of activity within the central business district (CBD) of the Denver region to a dispersed activity pattern. They are summarized in Table 1.

1. Activity-center scenario 1—The bulk of 1975-2000 population and employment growth (60 percent and 90 percent, respectively) is in 11 activity centers. Only 5 percent and 10 percent of population and employment growth is in the central core (125 000 population and 205 300 employment). Each activity center has the same population and employment in the year 2000 (48 000 and 42 000, respectively).
2. Activity-center scenario 2—Employment is concentrated in 11 activity centers; population is distributed in a dispersed pattern. Ninety percent of 1975-2000 employment growth is in the activity center and 10 percent is in the CBD. Population distribution is same as in the benchmark pattern.
3. Dispersion—Population and employment growth between 1975-2000 will occur in a dispersed pattern; activity centers and the CBD will remain static. All population growth and 95 percent of employment growth will be distributed across the region outside activity centers and the CBD.
4. Centralization scenario—The major share of population growth from 1975-2000 and the majority of employment growth will occur in the CBD; elsewhere densities will be low to moderate. Twenty-five percent of the population growth between 1975-2000 and 60 percent of the employment growth will be allocated to the Denver CBD. This results in extremely high densities [36 250 persons/km^2 (14 000 persons/mile^2) and 41 500 employees/km^2 (16 100 employees/mile^2)]. Current Denver densities are 20 000 persons/km^2 (7700 persons/mile^2) and 20 500 employees/km^2 (7900 employees/mile^2).
5. Growth scenario—An activity level 27 percent higher than was forecast in the benchmark is assumed for 2000. It will be distributed proportionally across the region and follow the benchmark distribution.

PROCEDURES FOR PROCESSING GROWTH AND DEVELOPMENT SCENARIOS

The transportation model used operates on 654 zones and external stations. Trip generation is performed by use of cross-classification techniques for four groups of household income. Trip distribution and modal split are based on logit formulations for single-occupancy automobile trips, shared ride, and transit passengers. Automobile vehicle loading procedures involve the production of three trip tables, one for the morning 2-h peak, a second for the afternoon 2-h peak, and a third for the off-peak hours. The loading procedures reflect capacity restraint in the peak periods and an unconstrained situation in the off-peak.

The air pollution dispersion model was developed by Systems Applications, Inc. (SAI). The air pollution model translates the morning peak, the afternoon peak, and the off-peak roadway volumes and speeds into automobile emissions. The air pollution dispersion model then predicts carbon monoxide (CO) and O_3 air quality levels by time of day by 2.59-km^2 (1-mile^2) grid. The area modeled is approximately 50 × 50 km (30 × 30 miles).

Data processing costs precluded complete model runs for all alternatives. The full modeling process was used to produce the benchmark scenario only. The results of alternative growth pattern and additional growth scenarios were synthesized. First, zonal population and employment data sets were developed, based on the scenario descriptions discussed earlier. These data sets were then used to estimate the total number of trips produced and attracted for each zone. These trips were then compared to the trips generated by use of a similar methodology under the benchmark scenario. The resulting growth factors were then applied to the benchmark scenario trip table. By doing this, special generators (such as parks, military bases, and shopping centers) were automatically included and updated. Trips to and from each zone grew or declined in proportion to population and employment changes. Similarly, trip interchanges were affected as surrounding zones grew or declined, which lengthened or decreased trip lengths. Changes in transit modal share and automobile occupancy rates brought about by population and employment location relative to transportation facilities were also accounted for. For example, as trips to the CBD increased, so did automobile occupancy rates and the transit modal share.

In order to prepare zonal population and employment data sets for the alternative-growth scenarios, a set of operations were defined and applied to current 1975 population, employment, and land use data sets and also to the baseline plan-2000 zonal data set. The algorithms produced year 2000 total population and employment allocations by zone for each scenario. An assumption was made that the alternative scenarios would all have similar household sizes and income distributions. A second assumption was made that retail employment in each zone would vary directly with total employment. The location of regional shopping centers was held constant.

Based on the above information, the numbers of trip ends for each zone were produced. In order to do this, an equation was developed that combines all trip ends, both production and attractions, for all trip purposes. Growth factors used in a FRATAR calculation of trip interchanges were developed by dividing the predicted

Table 1. Distribution of population and employment.

Area	1975		2000 Benchmark and Growth		2000 Activity Center 1		2000 Activity Center 2		2000 Dispersion		2000 Centralization	
	Population (%)	Employment (%)	Population (%)	Employment (%)	Population (%)	Employment (%)	Population (%)	Employment (%)	Population (%)	Employment (%)	Population (%)	Employment (%)
Central core area	6	22	5	17	5	18	5	18	4	16	17	42
11 activity centers	8	12	9	16	22	39	9	39	-	-	-	-
Remainder of study area	72	56	72	56	59	33	72	33	-	-	69	47
Total metropolitan study area	87	90	86	89	87	90	86	90	86	90	86	90
Denver region total	100	100	100	100	100	100	100	100	100	100	100	100

trip ends in each zone by the predicted trip ends found in the baseline year 2000 case. (A FRATAR distribution is a zonal growth distribution model based on the assumption that the change in trips in an interchange is directly proportional to the change in trips in the origin and destination zones contributing to the interchange.)

The growth factors were then applied in FRATAR to the afternoon peak automobile vehicles trip table. The resulting afternoon peak trip table was then loaded onto the plan network by use of capacity restraint. Morning peak and off-peak trip network loads were then synthesized. This was accomplished by holding the relation between the afternoon peak and the morning and off-peak constant between the base case and each of the alternative scenarios. All-day volumes by link were then summarized for input into the air quality dispersion model. Speeds were summarized by roadway functional classification and area type.

The Colorado Department of Highways used the link and speed information to produce a projection of emissions by link for each hour of the day. This emissions file assumed that the automobile emission controls called for in the Clean Air Act Amendments of 1977 would be achieved by the manufacturers. It also assumed that the inspection and maintenance program passed by the Colorado State Legislature would still be in place in the year 2000.

Controls on tailpipe emissions have led to the situation where approximately 50 percent of hydrocarbon (HC) emissions and 25 percent of CO emissions are currently produced merely by turning an automobile on and off (9). These percentages are expected to grow in the future. This cold start-hot soak phenomenon dramatically limits the effectiveness of reduced trip lengths through changes in land use form. The air pollution model used is not truly sensitive to the cold start-hot soak phenomenon. Although the overall emissions rates do include a cold start-hot soak assumption, emissions are calculated based on vehicle kilometers of travel at defined speeds. They do not vary in the SAI model with trip lengths.

IMPACT ON VEHICLE KILOMETERS OF TRAVEL AND SPEEDS

Changes in the vehicle kilometers of travel that resulted from the land development pattern changes are described in Table 2. As shown under the vehicle-kilometers-of-travel change factor column, the growth scenario represents an approximate 21 percent increase in vehicle kilometers of travel, whereas the other scenarios result in 2-3 percent decreases in vehicle kilometers of travel, except for the dispersion scenario, which represents a 4 percent decrease in vehicle kilometers of travel. The lower vehicle kilometers of travel from the dispersion scenario represents an unrealistic situation in which employment is uniformly distributed across a set of zones.

The second factor that affects air pollution emissions is vehicle speed. As given in Table 2, all of the scenarios produce an average speed (weighted by vehicle kilometers of travel) of approximately 45-50 km/h (28-31 mph), except for the high-growth scenario, which results in an average speed of only 39.3 km/h (24.4 mph). As speeds decrease, emissions of CO and HC increase.

Note that the high-growth scenario produces both the highest vehicle kilometers of travel and the lowest speeds, or what we would intuitively expect to be the worst air pollution emission case. The benchmark scenario produces the next highest vehicle kilometers of travel but also produces a relatively high speed. The other scenarios produce indeterminate results that vary little from the benchmark in average speed and vehicle kilometers of travel.

Table 2. Vehicle kilometers of travel and speed summary.

Scenario	Vehicle Kilometers of Travel	Change Factor	Speed (km/h)
Baseline	46 139 000	-	49.1
Activity center 1	44 607 000	0.97	46.7
Activity center 2	45 590 000	0.99	46.7
Dispersion	44 219 000	0.96	50.0
Centralization	45 189 000	0.98	46.8
Growth	55 696 000	0.21	39.3

Note: 1 km = 0.62 mile.

EFFECT OF GROWTH AND DEVELOPMENT ON AMBIENT AIR QUALITY

Table 3 summarizes the predicted ambient air quality for the various growth and development alternatives. The most significant result displayed in this table is the lack of variation in predicted levels of CO and O_3 among the scenarios.

The variation in CO predictions is from 53 percent of the 10.35 mg/m^3 (9 ppm) 8-h standard under the benchmark scenario to 57 percent of the standard under the high-growth scenario. For O_3 the variation is even smaller—from 88 percent of the 234 μg/m^3 (0.12 ppm) standard for the benchmark scenario and upward to 89 percent of the standard under the first activity-center scenario.

The distribution pattern of population and employment appears to have little or no effect on ambient air quality. The predicted differences in ambient air quality are less than the potential margin of modeling error. Thus, the absolute order of growth and employment distribution alternatives is of questionable value. What is important is the extremely small effect of alternative development patterns on air quality. A second result is that, although the absolute level of population has an effect on air pollution levels, the two are not directly proportional. Large changes in population and employment appear to produce propor-

Table 3. Ambient air quality predicted for growth and development alternatives.

	CO		O_3	
Scenario	Predicted 8-h Concentration	Percentage of 10.35 mg/m^3 Standard	Predicted 1-h Concentration	Percentage of 234 μg/m^3 Standard
Baseline	4.8	53	0.105	88
Activity center 1	4.9	54	0.107	89
Activity center 2	4.9	54	0.106	88
Dispersion	4.9	54	0.106	88
Centralization	5.1	57	0.106	88
Growth	5.2	57	0.106	88

Note: 1 mg/m^3 CO = 0.87 ppm; 1 μg/m^3 O_3 = 0.51 x 10^{-3} ppm.

Table 4. Emissions inventory and projections.

		CO Emissions (Mg/day)			HC Emissions (Mg/day)		
Year	Scenario	Vehicle	Total	Total Compared to Benchmark	Vehicle	Total	Total Compared to Benchmark
1976-1978	Existing	2200	2384	4.48	190	224	3.43
2000	Benchmark	295	532	1.00	33	65	1.00
2000	Activity center (population and employment)	293	531	1.00	33	66	1.01
2000	Activity center (employment)	296	533	1.00	33	66	1.01
2000	Dispersal	277	514	0.97	31	63	0.97
2000	Centralization	292	530	0.99	33	66	1.01
2000	Growth	381	627	1.18	44	80	1.22

Note: 1 Mg = 1.1 tons.

tionally smaller changes in ambient air quality.

COMPARISON WITH FEDERAL STANDARDS

The Denver region currently experiences frequent violations of the national ambient air quality standards for CO, O_3, nitrogen dioxide (NO_2), and suspended particulate matter; however, the severity of the violations appears to be steadily decreasing. The federal Clean Air Act of 1960 established ambient air quality standards that allow for an adequate margin of safety for protection of public health. The air quality impacts of the growth and development scenarios were compared against these federal standards for the two pollutants that were examined—CO and O_3. The federal standards below are for the second worst case that occurs annually.

CO

Emissions of air pollutants are generated by a variety of sources. In order to analyze the cause of air pollution in the Denver region and to forecast future ambient air quality levels, we needed to develop an up-to-date inventory of the emission sources for each pollutant. The inventory of current emissions in the Denver region indicates that about 2359 Mg (2600 tons) of CO are released into the air on a typical winter day. Winter, because it is the worst season for CO pollution, is modeled in future year projections.

As given in Table 4, by 2000 regionwide CO emissions are projected to decline by 74-84 percent from current CO emission levels. Note that vehicular sources are calculated to account for 93 percent of current CO emissions; however, this percentage will fall to 55 percent by the year 2000 under the benchmark scenario.

The variation in total emissions is reduced by holding projected nonvehicle emissions constant for the various development scenarios. The assumption is made that the location of population will not affect the number of airplane trips, space heating requirements, or industrial emissions. The variation in total CO emissions is then from 97-116 percent of the benchmark emissions; the dispersion scenario is the lowest and the high-growth scenario is the highest.

The emissions listed in Table 4 were input into the air pollution dispersion model by time of day and geographic area. The result is a decrease in the predicted second maximum CO levels from violation of 22.77 mg/m^3 (19.8 ppm) in 1977 to a prediction of 5.52 mg/m^3 (4.8 ppm) under the benchmark scenario. The two activity-center scenarios as well as the dispersion scenario result in predicted 8-h concentrations of CO of 5.64 mg/m^3 (4.9 ppm) or, effectively, the same as under the benchmark scenario. The centralization and the high-growth scenarios result in slightly higher predicted CO concentrations of 5.87 mg/m^3 (5.1 ppm) and 5.98 mg/m^3 (5.2 ppm), respectively. The range of predicted 8-h CO concentrations is quite small for all scenarios, ranging from 53-57 percent of the 10.35 mg/m^3 (9 ppm) standard.

O_3

The federal standard for O_3 is a 1-h average of 234 $\mu g/m^3$ (0.12 ppm). In 1977 the second highest recorded 1-h average concentration in the Denver region was 304 $\mu g/m^3$ (0.156 ppm), 30 percent higher than the standard.

The inventory of current emissions in the Denver region indicates that for HC (a primary precursor of O_3) nearly 227 Mg (250 tons) are currently emitted on a typical summer day—summer is the time when O_3 levels are at their peak. Vehicular sources currently account for 85 percent of HC emissions. This is predicted to decline to 50 percent by the year 2000 under the benchmark scenario. Over this period of time, total HC emissions (as delineated in Table 4) decline from an existing level of 227 Mg/day to a projected benchmark of 65 Mg/day (72 tons/day) in the year 2000, a decline of approximately 72 percent. The variation in HC emissions over the year 2000 scenarios is 97-122 percent of those generated under the year 2000 base case. The lowest HC emissions are found in the dispersion scenario; the highest are under the high-growth scenario.

Predictions of ambient air quality levels show a decline in projected levels of O_3 over the 22-year time period to the year 2000. O_3 levels will decline from the second worst maximum of 304 $\mu g/m^3$ (0.156 ppm) in 1977 to 205 $\mu g/m^3$ (0.105 ppm) under the benchmark scenario in the year 2000. The various growth and development alternatives show only minor variation from the benchmark scenario. The first activity-center scenario results in the highest predicted O_3 concentrations. Note that the geographic area where 195 $\mu g/m^3$ (0.1 ppm) is exceeded was effectively identical for all of the scenarios and the benchmark.

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Travel and Emissions Impacts of Transportation Control Measures

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The Clean Air Act Amendments of 1977 and the Transportation-Air Quality Planning Guidelines jointly developed by the U.S. Environmental Protection Agency and the U.S. Department of Transportation require the states and metropolitan planning organizations to prepare revised state implementation plans and conduct air quality alternatives analyses to meet national ambient air quality standards. This paper summarizes basic information developed from a synthesis of literature to assist metropolitan planning organizations and other agencies in meeting the requirements of the planning guidelines. Specifically, the paper (a) identifies transportation control measures for reducing emissions, (b) summarizes the effects on travel and emissions of individual measures and packages of measures, and (c) suggests approaches and issues to be addressed in air quality planning.

This paper summarizes basic information developed from a synthesis of the literature to assist metropolitan planning organizations (MPOs) and other agencies in meeting the requirements of the transportation-air quality guidelines jointly developed by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation (DOT).

The objectives of this paper are

1. To identify transportation control measures for reducing air pollution emissions and meeting national ambient air quality standards (NAAQS),
2. To identify the travel and emissions impacts of individual control measures and packages of measures, and
3. To suggest approaches for selecting, analyzing, and evaluating impacts of transportation system management (TSM) and longer-range control measures.

Virtually all urban areas of the nation of more than 200 000 population currently do not meet NAAQS for photochemical oxidants (O_x). Many of these areas also exceed NAAQS for carbon monoxide (CO). Vehicular travel within these urban areas is a major source of both pollutants.

Transportation-related air quality problems are of two general types: localized and regional (1). Localized transportation-related air quality problems generally cause CO concentrations that exceed either the 1-h or, more likely, the 8-h CO air quality standard. Factors that contribute to this problem include the high vehicular traffic volumes that occur under traffic conditions frequently found in densely developed portions of urban areas.

Regional transportation-related air quality problems are typically caused by vehicular and stationary source hydrocarbon (HC) and nitrogen oxide (NO_x) emissions, which react chemically in the atmosphere to produce O_x pollutants. The chemical reactions that produce oxidants are complex and depend on many factors, such as prevailing meteorological conditions and the topographic, land-use, and industrial characteristics of an urban area (2).

The distinction between CO and O_x pollutants is important in that different control measures are required to effectively address localized, as opposed to regional, air quality problems.

TRANSPORTATION CONTROL MEASURES

Reasonable Available Control Measures

The Transportation-Air Quality Planning Guidelines (3) stipulate that state implementation plan (SIP) revisions "must provide for expeditious implementation of reasonably available control measures". The transportation control measures considered by EPA to be reasonably available include (at a minimum) those listed below (3):

1. Inspection and maintenance programs;
2. Vapor recovery;
3. Improved public transit;
4. Exclusive bus and carpool lanes;
5. Areawide carpool programs;
6. Private automobile restrictions;
7. Long-range transit improvements;
8. On-street parking controls;
9. Park-and-ride and fringe parking lots;
10. Pedestrian malls;
11. Employer programs to encourage carpooling and vanpooling, mass transit, bicycling, and walking;
12. Bicycle lanes and storage facilities;
13. Staggered work hours (flexitime);
14. Road pricing to discourage single-occupancy automobile trips;
15. Controls on extended vehicle idling;
16. Traffic flow improvements;
17. Alternative fuels or engines and other fleet vehicle controls;
18. Other than light-duty vehicle retrofit; and
19. Extreme cold-start emission reduction programs.

The control measures listed are very similar to the tactics covered by the Federal Highway Administration (FHWA) and Urban Mass Transportation Administration (UMTA) TSM regulations (with the exception of inspection and maintenance programs, vehicle retrofits, vapor recovery, and fleet vehicle control programs).

Characteristics of Individual TSM Tactics

Figure 1 presents a slightly different and more detailed classification of TSM strategies and corresponding individual tactics that traffic engineers and urban transportation planners may consider in the preparation of SIP revisions and air quality alternatives analyses. The following important characteristics of commonly implemented TSM tactics are identified in Figure 1:

1. Size of urban area for which the tactic is applicable,
2. Typical geographic areas of application,
3. Geographical scale (i.e., localized or regional) of the tactic's air quality impacts, and
4. Implementation costs.

The likely geographic scale of air quality impacts varies by tactic. The strategies that primarily impact localized (CO) air quality include:

1. Traffic operations,
2. Traffic signalization,
3. Pedestrian and bicycle activity,
4. Commercial vehicle activities, and
5. Roadway assignment strategies.

In contrast, pricing, paratransit, and transit management strategies are more likely to impact regional (O_x) air quality (4). Strategies that may impact both localized and regional air quality include route diversion, parking management, transit operations, intermodal coordination and work-schedule strategies.

TRAVEL AND EMISSIONS IMPACTS OF CONTROL MEASURES

This section presents estimated travel, emissions, and related (e.g., energy consumption and cost) impacts of individual transportation control measures and packages of control measures. The sources of the estimates include both locally and federally funded air quality and energy conservation planning studies conducted over the last five years. The lack of well-documented, consistent information on observed (i.e., before and after) travel, emissions, and related impacts of implemented transportation control measures effectively precludes the presentation of such information for most control measures.

The following points should be considered in interpreting and applying the estimates in this subsection:

1. Readers should carefully check the time (e.g., peak period 8-h or daily) and geographic area (e.g., spot location, corridor, or areawide) stratification of the impact estimates. Such stratifications may vary by control measure and source.
2. The impact estimates by control measure have been simplified and the descriptions of the packages of control strategies have been summarized. For details on the specific assumptions made in the analysis of each control measure, the readers should consult the original references cited.
3. The travel and emission impact estimates were developed by using manual and computer modeling procedures developed for many different urban areas. This may partially contribute to the reported differences in impacts across control measures and urban areas.
4. Air pollution emission and concentration estimates and travel estimates were not available in some of the sources.

Individual Control Measures

The effects on vehicle kilometers of travel and emissions of selected individual transportation control measures are presented in Table 1. The sources of and the urban areas for which the estimates were prepared are also indicated in Table 1.

Most of the individual control measures identified in Table 2 are estimated to reduce weekday, areawide vehicle kilometers of travel and CO and HC emissions by 1 percent or less. The control measures likely to reduce weekday, areawide vehicle kilometers of travel and emissions by more than 1-1.5 percent include

1. Inspection and maintenance programs,
2. Vehicle retrofits,
3. Major employer-based carpool and vanpool programs,
4. 1-day-a-week driving ban,
5. Areawide parking cost increases,
6. Flexible working hours,
7. Major increases in gasoline prices, and
8. Idling controls.

However, most of the above individual control measures are likely to reduce vehicle kilometers of travel and emissions by less than 5 percent.

Figure 1. Characteristics of commonly implemented TSM tactics.

STRATEGY	TACTIC	APPLICABLE CITY SIZE, POPULATION				AREA OF APPLICATION						AIR QUALITY IMPACTS		IMPLEMENTATION COST THOUSAND $					
		<50,000	<250,000	<1,000,000	>1,000,000	Spot	Rdwy. Fac.	Corridor	Local Area	Major Area	Region	Local	Regional	<10	<50	<100	<500	<1,000	>1,000
Traffic Operations	Intersection & Roadway Widening	x	x	x	x	x	x					x			x	x	x	x	x
	One-Way Streets	x	x	x	x				x			x			x	x			
	Turn Lane Installation	x	x	x	x	x						x		x	x				
	Turning Movement & Lane Use Restrictions	x	x	x	x	x						x		x					
	New Freeway Lane Using Shoulders		x	x	x		x					x	x			x	x		
Traffic Signalization	Local Intersection Signal Improvement	x	x	x	x	x						x		x	x				
	Arterial Signal System	x	x	x	x		x					x				x	x		
	Area Signal System	x	x	x	x				x	x		x	x				x	x	x
	Freeway Diversion & Advisory Signing			x	x			x				x					x		
	Freeway Surveillance & Control			x	x		x	x				x	x				x	x	x
Pedestrian and Bicycle	Widen Sidewalks	x	x	x	x	x	x					x			x				
	Pedestrian Grace Separation	x	x	x	x	x						x					x	x	
	Bikeways	x	x	x	x				x			x			x	x			
	Bike Storage		x	x	x	x			x	x		x		x	x				
	Pedestrian Control Barriers			x	x	x						x		x					
Roadway Assignment	Exclusive Bus Lane-Arterial											x							
	•Take-a-Lane		x	x	x		x					x		x	x				
	•Add-a-Lane		x	x	x		x					x					x	x	x
	Bus-Only Street			x	x		x					x			x				
	Contra-Flow Bus Lane		x	x	x		x					x			x	x			
	Reversible Lane Systems		x	x	x		x					x			x	x			
	Freeway HOV Bypass			x	x		x					x			x				
	Exclusive HOV Lane-Freeway																		
	•Take-a-Lane			x	x		x					x	x		x	x			
	•Add-a-Lane			x	x		x					x	x				x	x	x
Route Diversion	Area Licensing			x	x					x		x	x		x	x	x		
	Auto Restricted Zones				x					x		x	x		x	x	x		
	Pedestrian Malls		x	x	x				x			x				x	x		
	Residential Traffic Control	x	x	x	x				x			x		x					
Parking Management	Curb Parking Restrictions	x	x	x	x	x	x					x	x	x					
	Residential Parking Control		x	x	x				x			x		x	x				
	Off-Street Parking Restrictions			x	x				x	x		x	x	x					
	HOV Preferential Parking			x	x			x	x				x	x					
	Parking Rate Changes		x	x	x				x	x	x	x	x	x					
Transit Operations	Bus Route & Schedule Modifications	x	x	x	x		x	x	x	x		x	x		x	x			
	Express Bus Service		x	x	x		x	x				x	x		x	x			
	Bus Traffic Signal Preemption			x	x		x					x	x		x	x	x		
	Bus Terminals	x	x	x	x				x			x			x	x	x	x	x
	Simplified Fare Collection	x	x	x	x						x		x		x	x			
Transit Management	Marketing Program	x	x	x	x						x		x		x	x	x		
	Maintenance Improvements	x	x	x	x						x		x			x	x		
	Vehicle Fleet Improvement	x	x	x	x						x		x			x	x	x	
	Operations Monitoring Program		x	x	x						x		x		x	x	x	x	x
Intermodal Coordination	Park-Ride Facilities		x	x	x			x				x	x	x	x	x	x		
	Transfer Improvements	x	x	x	x			x			x		x	x	x				
Commercial Vehicles	On-Street Loading Zones		x	x	x	x			x			x		x					
	Off-Street Loading Areas		x	x	x				x	x		x			x	x	x		
	Peak Hour On-Street Loading Prohibition		x	x	x	x			x			x		x					
	Truck Route System	x	x	x	x			x				x	x	x	x				
Work Schedule	Staggered Work Hours & Flex Time			x	x					x	x	x	x	x	x				
	4-Day Week			x	x					x	x	x	x	x	x				
Pricing	Peak-Hour Tolls				x		x		x			x	x	x	x	x			
	Low-Occupancy Vehicle Tolls				x		x		x			x	x		x	x			
	Gasoline Tax	x	x	x	x						x		x		x	x			
	Peak/Off-Peak Transit Fares		x	x	x						x		x		x	x	x		
	Elderly and Handicapped Fares	x	x	x	x						x		x		x	x			
	Reduce Transit Fares	x	x	x	x						x		x	x	x				
Paratransit	Carpool Matching Programs		x	x	x				x	x	x		x	x	x	x			
	Vanpool Programs	x	x	x	x				x				x		x	x			
	Taxi/Group Riding Programs			x	x					x	x		x	x	x				
	Dial-a-Ride	x	x	x	x				x	x			x			x	x		
	Jitney Service		x	x	x		x	x					x		x				
	Elderly and Handicapped Service	x	x	x	x					x	x		x	x	x	x	x		

Table 1. Impacts of selected individual transportation control measures on vehicle kilometers of travel and emissions.

	Percentage Reduction			
Control Measure	Vehicle Kilometers of Travel[a]	Emissions	Area	Reference
Inspection and maintenance		8.1—HC[b]	Washington	5
		4.7—HC[b]	Baltimore	6
		6.4—8-h CO		
		6—CO	Urban area in New York	7
		1—HC		
Improved transit service				
10 percent increase in bus service	0.02		Albany	7
10 percent ($0.05) decrease in fares	0.22		Albany	7
$0.10 decrease in fares	0.70[b]	0.3—HC[b]	Baltimore	5
Increased frequency of service to CBD	0.1		Washington	8
Express bus service to CBD combined with increased frequency	0.3		Washington	8
Increased frequency of service and extended coverage	1.1-2.2		San Diego	9
HOV preferential lanes	2.5[c]		Albany	7
HOV lane on freeway	0.2[b]	0.1—HC[b]	Baltimore	6
	0.6		Washington	8
Carpool or vanpool				
Major employer-based carpool or vanpool program	1.5	1.3—HC 1.3—CO	>500 000 population	4
Carpool matching and promotion	0.4		Washington	8
Carpool cost subsidy				
$0.016/passenger kilometer	0.3		Washington	8
$0.031/passenger kilometer	0.7			
Vanpooling	1.2		Washington	8
Carpool locator	0.4[b]	0.2—HC[b]	Baltimore	6
Major employer matching	1.0		Chicago	10
Meet and ride program	1.0		Chicago	11
Major employer matching	1.2		Numerous areas	11, 12
Areawide programs	0.12		Numerous areas	11, 12
Automobile-restricted zones				
Automobile-restricted zone	0.4		Washington	8
One-day-a-week driving ban	8.8		Washington	8
Parking management				
$1.00 parking surcharge	0.8[b]	0.3—8-h CO 0.3—HC[b]	Baltimore	6
$2.00 parking surcharge	1.5[b]	0.7—8-h CO 0.8—HC[b]	Baltimore	6
Outlying parking cost	4.8[b]	1.5—8-h CO 2.7—HC[b]	Baltimore	6
Preferential parking for carpools	0.6		Washington	8
Areawide parking cost increase				
$1.00	0.8		Washington	8
$2.00	1.7		Washington	8
$3.00	2.5		Washington	8
CBD parking cost increase				
$1.00	0.3		Washington	8
$2.00	0.6		Washington	8
$3.00	0.9		Washington	8
Reduced parking supply in CBD	0.5		Washington	8
Increased parking costs in seven high-density areas				
Commercial rates	14—subareas		Washington	13
Commercial rates + $1.00	29—subareas		Washington	13
Commercial rates + $2.00	30—subareas		Washington	13
Park-and-ride lots and fringe parking				
Six park-and-ride lots	0.8[c]		Syracuse	7
Six peripheral park-and-ride lots	0.5[c]		Syracuse	7
Pedestrian malls	0.3—region[c]		Syracuse	7
	+1.9—CBD[c]		Syracuse	7
Staggered work hours				
Flexible working hours	3.7[b]	2.0—HC[b]	Baltimore	6
	4.0[b]		Washington	5
Pricing strategies				
Increase gasoline prices $0.05/L	1.5[b]		Baltimore	6
Double gasoline prices	5.1		Washington	8
Triple gasoline prices	9.7			
Quadruple gasoline prices	13.8			
Tolls for single-occupancy automobiles to CBD				
$0.50	0.2		Washington	8
$1.00	0.4			
Vehicle ownership tax				
$100/vehicle	0.1		Washington	8
$200/vehicle	0.2			
$400/vehicle	0.4			
Carpool tax rebates				
$250/year	0.05		Washington	8
$500/year	0.1			
Idling controls		3.4—CO 1.5—HC	Upstate New York	7
Traffic flow improvements				
Preferential traffic control	0.1	1—HC[b]	Washington	8
Progressive signalization to increase speeds by 1 percent		1—8-h CO	Washington	5
Retrofits				
Light-duty vehicle		9.3—8-h CO 3.2—HC[b]	Baltimore	6
Light-duty trucks		0.3—8-h CO 0.2—8-h HC		
Heavy-duty gasoline-powered trucks		6.3—8-h CO 1.6—HC[b]		

Notes: 1 km = 0.62 mile; 1 L = 0.26 gal.

[a] Percentages apply to weekday areawide vehicle kilometers of travel, except where noted. [b] Peak period. [c] Peak hour.

Selected control measures such as preferential lanes for high-occupancy vehicles (HOVs), automobile-restricted zones, and parking cost increases for the central business district (CBD) also may reduce localized CO emission by several percent. The impact estimates presented in Table 2 strongly suggest that urban areas that must reduce daily, areawide emissions by more than 2-3 percent may have to rely on packages of control measures or strong regulatory measures, such as gasoline price increases, increased parking costs, or staggered working hours.

Packages of Control Measures

The estimated vehicle kilometers of travel and emissions impacts of selected packages of control measures are described in Tables 2-6. Because of the widely different packages of transportation control measures analyzed in the various planning studies applicable to this discussion, a separate exhibit was developed for each planning study.

Tables 2 and 3 are excerpted from a recently published EPA report (1). Table 2 describes 10 prototype control packages selected for analysis of localized CO

Table 2. Summary of estimated impacts of the localized prototype scenarios.

	Impact on Morning Peak-Hour Corridor Vehicle Volume[a]		Impact on Morning Peak-Hour CO Concentration at Reference Receptor, from Affected Facility Emissions (μg/m³)[b]				Program Costs[c] ($000s)	
			Typical, Good Dispersion[d]		Typical, Poor Dispersion[d]			
Prototype Scenario	Base Peak-Hour Volume	Change (%)	Base Value	Change (%)	Base Value	Change (%)	Capital (One-Time Implementation)[e]	Operating per Year[f]
1. Expanded express bus service in mixed freeway traffic; favorable impacts	19 667	-1.47	5756	-2.4	8210	-2.5	3168-4788	1447
2. Freeway lane reserved for buses and carpools; favorable impacts	19 667	-6.30	5756	-11.4	8210	-9.3	3720-5350	1839
3. Ramp metering and bus bypass lanes; favorable impacts	19 667	-3.06	5756	-6.7	8210	-6.5	5224-6844	1703
4. Reserved bus and pool lane, ramp metering, and bus bypass lanes; modest impacts	19 667	-3.97[c]	5756	-[g]	8210	-[g]	4862-6482	1751
5. Reserved bus and pool lane, ramp metering, and bus bypass lanes; favorable impacts	19 667	-6.98	5756	-8.7	8210	-10.1	6248-7868	2266
6. Contraflow freeway lane reserved for buses; favorable impacts	14 750	-1.69	4798	+4.7	6759	+3.4	962	541
7. Contraflow bus lane, expanded express bus service, and park-and-ride lots; favorable impacts	14 750	-3.72	4798	+2.3	6759	+1.5	3668-5288	1818
8. Contraflow bus lane, expanded express bus service, and lots; assuming 70%-30% directional split; favorable impacts	13 500	-4.07	4066		5748	-2.7	3668-5288	1818
9. Reserved arterial median lane for express buses; favorable impacts	3 750	-15.47	4964	-15.7	6485	-15.3	3594-4134	1130
10. Contraflow curb lane for local buses on pair of one-way arterials; favorable impacts	5 000	-4.40	3992[h] 3349[i]	-13.3[h] +10.9[i]	4992[h] 4793[i]	-13.7[h] +9.9[i]	468	123

Note: 1 μg/m³ CO = 870 ppm.

[a] Volume is for freeway or arterial segments approximately 0.6 km (1 mile) out from the CBD (adjacent to the CBD in the case of scenario 10).
[b] CO concentration 15 m (50 ft) from downwind edge of primary corridor facility, based on vehicular emissions from affected facilities only; uninterrupted traffic flow conditions are also assumed.
[c] Costs are in 1976 dollars.
[d] This value includes the vehicles originally using the corridor freeway, but estimated as being unable to pass through during peak hour because of flow breakdown caused by congestion.
[e] The two capital cost entries represent the range in costs depending on whether existing parking facilities (e.g., shopping center) or newly constructed facilities are required for park-and-ride lots.
[f] Represents incremental operating costs.
[g] CO concentration impacts for scenario 4 could not be reliably estimated.
[h] Inbound arterial.
[i] Outbound arterial.

Table 3. Summary of estimated impacts for the regional prototype scenarios.

	Change in Regional Weekday Vehicle Kilometers of Travel		Change in Regional Weekday Highway Emissions		Change in Annual Highway Fuel Consumption (L000 000s)	Program Costs[b] ($000 000s)	
Prototype Scenario[a]	Percentage of Total	Percentage of Work Trip	HC (%)	CO (%)		Capital (One-Time Implementation)	Incremental Operating per Year
11. Carpool or vanpool program, medium-sized city; favorable impacts	-1.5	-5.0	-1.2	-1.3	-9.8	-	76
12. Carpool or vanpool program, large-sized city; favorable impacts	-1.5	-5.0	-1.4	-1.3	-43.9	-	404
13. Reserved bus or pool lanes, ramp metering, and bus bypass lanes on all appropriate freeways; modest impacts	-0.25	-0.8	-0.1	+0.1	+5.7	14 586-19 446	5253
14. Reserved bus or pool lanes, ramp metering, and bus bypass lanes on all appropriate freeways; favorable impacts	-0.44	-1.5	-0.4	-0.4	-10.2	18 744-23 604	6798
15. Reserved median lane for express buses on appropriate radial arterials; modest impacts	-0.23	-0.8	+0.4	+0.8	-6.1	18 868-21 704	5984
16. Reserved median lane for express buses on appropriate radial arterials; favorable impacts	-0.38	-1.3	-0.1	+0.2	-11.0	18 868-21 704	5984
17. Carpool or vanpool program and freeway reserved lanes; modest impacts	-1.0	-3.3	-0.4	-0.6	-27.3	9 804-14 664	5408
18. Carpool or vanpool program and freeway reserved lanes; favorable impacts	-1.9	-6.3	-1.8	-1.7	-53.4	11 190-16 050	5921
19. Carpool or vanpool program, reserved lanes, ramp metering, and bus bypass lanes; modest impacts	-1.0	-3.3	-0.8	-0.6	-27.6	14 586-19 446	5957
20. Carpool or vanpool program, reserved lanes, ramp metering, and bus bypass lanes; favorable impacts	-1.9	-6.5	-0.8	-1.8	-53.8	18 744-23 604	7202

Note: 1 L = 0.26 gal.

[a] All scenarios except 11 are for a large-sized city 1 000 000 + standard metropolitan statistical area (SMSA) population. Scenario 11 is set in a medium-sized city (500 000-1 000 000 SMSA population).
[b] Costs are in 1976 dollars.

Table 4. Impacts of selected transportation control packages on vehicle kilometers of travel for San Diego.

Package	Reduction in Weekday Vehicle Kilometers of Travel (%)
1. $2.50 parking surcharge for all-day parkers, 57 percent transit service increase (i.e., 200 buses)	9.0
2. 57 percent (i.e., 200 buses) transit service increase	1.1
3. 150 percent (i.e., 525 buses) transit service increase	2.2
4. $1.00 parking surcharge for all-day parkers, 57 percent transit service increase	1.9
5. $1.00 parking surcharge for all-day parkers, 150 percent transit service increase	3.3

Table 5. Impacts of selected transportation control packages on vehicle kilometers of travel for Washington, D.C.

Package	Reductions in Weekday Vehicle Kilometers of Travel (%)
1. Comprehensive employee incentives—carpool matching for employers of more than 100 employees, preferential carpool parking, and vanpooling for large employers and long-distance commuters	1.7
2. Package 1 plus preferential HOV lanes on major facilities	1.9
3. Package 2 plus expanded transit coverage and decreased headways	2.8
4. Pricing disincentives—double fuel costs, base parking charge of $1.00 areawide + $2.00 in CBD, and reduced parking supply in CBD	6.0
5. Areawide traffic incentive and restraints—preferential HOV lanes on major facilities and ARZ in CBD	0.9
6. Package 5 plus expanded transit coverage and decreased headways	2.0
7. Packages 2, 4, and 5	8.3
8. Packages 2, 4, and 6	9.4

Table 6. Impacts of selected transportation control packages on vehicle kilometers of travel and emissions for Washington, D.C.

Package	Percentage Reduction in Vehicle Kilometers of Travel			Reduction in Emissions (1977 base)	
	Peak 3-h	Peak 8-h	24-h	CO—8-h (%)	HC—Peak Period (%)
1. Flexible work hours, commercial parking rates at government facilities, progressive signalization, implementation and maintenance programs, heavy-duty retrofit, ban nonresidential parking in selected areas, and other measures	3	1	1	12.1	13.2
2. Package 1 plus exclusive bus lanes, increased bus frequencies, encourage carpooling and vanpooling, restrict peak-hour truck deliveries in D.C., $2.00 parking surcharge in selected areas, $1.00 surcharge in selected areas, and other measures	1.6	5	5	16.8	23.3
3. Exclusive bus lanes, flexible work hours, encourage carpooling and vanpooling, commercial parking rates at government facilities, progressive signalization, implementation and maintenance programs, ban nonresidential parking in selected areas, charge hourly parking rates throughout day, heavy-duty retrofit, 2 lanes for low-occupancy automobiles, and facility inside beltway	19	7	7	16.8	26.5
4. Package 3 plus downtown ART and 25 percent reduction of transit fares	21	8	8	18.1	29.8

concentration impacts. The first eight localized scenarios deal with the priority treatment of HOVs on freeways, and the last two deal with priority treatment of buses on arterials. The programs implemented in a scenario typically consist of several complementary actions, such as reserving a freeway lane, expanding express bus service, and providing park-and-ride lots in the corridor. The freeway-based scenarios (scenarios 1-8) are likely to achieve reductions in overall peak-hour corridor traffic volumes that range between 1.5 and 7 percent

The arterial scenarios analyzed (scenarios 9 and 10) can promote 4-15 percent reductions in peak-hour vehicular volumes. As is true for the freeway scenarios, the attainment of such reductions is highly dependent on the specific setting in which such strategies may be implemented. However, the percentage reductions in vehicular volumes for arterials are based on smaller base volumes and are not fully comparable to the corridor volumes in the freeway scenarios.

In scenarios 6 and 7, CO concentrations are estimated to increase relative to the base conditions. The increase in CO concentrations in several contraflow reserved-freeway-lane scenarios reflects the travel and meteorological conditions assumed in those scenarios. The results do not indicate that contraflow lanes, per se, have undesirable air quality effects, but rather illustrate the importance of a careful analysis of the potential air quality effects of implementing a contraflow lane on freeways that carry heavy traffic volumes in the off-peak direction.

Both the capital and annual operating and maintenance costs of the localized scenarios are sizable. The costs of purchasing and operating new buses for express bus service represent a substantial part of the total cost of the scenarios.

Table 3 describes the 10 scenarios selected for analysis of regional HC and CO emission impacts. The first two regional scenarios (11 and 12) deal with areawide carpool and vanpool programs and focus on major employers in medium- and large-sized regions, respectively. Scenarios 13 and 14 deal with the application of a combination freeway-corridor strategy (e.g., reserved lanes, express bus, park-and-ride lots) for several corridors throughout the region. Scenarios 15 and 16 do the same for a combination of both areawide carpool and vanpool and freeway-corridor strategy components.

The effects of the 10 regional scenarios on vehicle kilometers of travel, emissions, and costs are summarized in Table 3. Reductions in total regional vehicle kilometers of travel in the range of 1.0-1.9 percent are attributable to scenarios 11, 12, and 17-20, which involve carpool and vanpool programs and focus on large employers. These reductions correspond to reductions of 3-6.5 percent in weekday work-trip travel distances. This represents a substantial shift of low-occupancy automobile trips to transit, carpools, and vanpools during peak travel periods, which will reduce congestion and conserve energy. These same scenarios are also estimated to yield the largest reductions in regional HC and CO emissions.

Scenarios 13-17, which involve the implementation of reserved lanes on multiple-radial freeways or arterials in a region, generally result in total regional and work-trip vehicle-kilometers-of-travel reductions of less than 0.5 and 1.5 percent, respectively. The small reductions in travel distances are in large part related to the limited size of the peak-period radially oriented CBD travel market in most large urban areas.

Table 4 (14) summarizes the estimated percentage of reduction in vehicle kilometers of travel associated with control packages that incorporate various parking surcharges and regional travel service improvements. A maximum percentage reduction in travel distance was estimated to occur if a \$2.50 parking surcharge were imposed on all-day parkers in high-density employment areas and transit service were expanded by almost 60 percent.

Vehicle-kilometers-of-travel reductions of 1-3 percent were projected for the remaining control packages despite major increases in transit service and the selected applications of \$1.00 parking surcharge on all-day parkers.

Tables 5 and 6 present the estimated vehicle-kilometers-of-travel and emissions reductions for 12 transportation control packages analyzed for the Washington, D.C., metropolitan area. Table 5 (8) illustrates that weekday, areawide travel distances can be reduced by 8-9 percent by implemention of comprehensive packages of carpool and vanpool programs, HOV preferential lanes, pricing disincentives, parking supply restrictions, and various combinations of automobile-restricted zones (ARZs) and expanded regional transit service. Pricing disincentives (package 4) are estimated to reduce weekday, areawide vehicle kilometers of travel by 6 percent. The packages that involve the implementation of carpool and vanpool programs, HOV preferential lanes, and expanded transit service (1, 2, and 3) were estimated to cause 1.7-2.8 percent reductions in travel distances. The combination of an ARZ in the CBD and HOV preferential lanes on major radial facilities was estimated to yield approximately a 1 percent reduction in vehicle kilometers of travel.

In Table 6 (5), packages 2, 3, and 4, which involve the application of a wide range of control measures, were estimated to yield 5-8 percent reductions in weekday vehicle kilometers of travel. However, the estimated reductions in peak 3-h travel distances were substantially higher, ranging between 16 and 21 percent.

The estimated CO and HC emissions reductions are significantly larger than the corresponding reductions in vehicle kilometers of travel for each package in Table 1. The effects of the inspection and maintenance program and the heavy-duty vehicle retrofit program included in these packages appear to be important factors that contribute to these estimates.

In summary, Tables 2-6 illustrate that weekday, areawide reductions in vehicle kilometers of travel of nearly 10 percent may be attained by using transportation control packages that involve pricing disincentives, carpool and vanpool programs, HOV preferential lanes, and expanded transit service. The combination of such control measures with inspection and maintenance programs offers the potential for even larger reductions in CO and HC emissions. However, the capital and annual operations and maintenance costs of such packages can be significant.

SELECTION OF CONTROL MEASURE PACKAGES

The purpose of this subsection is to identify several basic points that pertain to the development of successful transportation control packages for meeting NAAQS.

Definition of Air Pollution Problem

A clear, quantitative description of the air pollution problems of each urban area is a basic requirement for transportation-air quality planning. This includes determination of the required percentage reductions in emissions and concentrations by type of pollutant and the geographic areas (i.e., hot-spot locations) for which such reductions are required.

The information is essential if effective localized and regional transportation control packages are to be proposed, analyzed, and implemented. Such information also will help to minimize institutional and political conflicts about whether or not NAAQS are being achieved.

Inspection and Maintenance Programs

Automobile emissions inspection and maintenance programs are potentially important measures for reducing mobile-source emissions. A recently published study by EPA (15) notes that 33 air quality control regions had been considered by EPA to need such programs in order to meet NAAQS. More recent data suggest that many additional regions also may eventually need such measures.

Inspection and maintenance programs have several potentially important benefits. First, total emissions from a given fleet of vehicles can be reduced through a properly designed and operated inspection and maintenance program. Emission reductions can be achieved through vehicle operating changes rather than by promoting changes in travel behavior that are difficult to forecast and achieve. The travel reductions needed to meet NAAQS may be less because of inspection and maintenance programs. Second, such programs provide an incentive to maintain a vehicle in good operating condition, which can result in improved performance, fuel efficiency, and longer vehicle life.

Selection of Transportation Control Packages

The estimates of vehicle kilometers of travel and emissions strongly indicate that many urban areas that have serious air quality problems must develop comprehensive packages of transportation control measure to meet NAAQS by mid-1982. Travel distance and emissions are not likely to be reduced by more than 2-3 percent by use of only control measures such as carpool and vanpool programs, transit service improvements, and HOV preferential lanes, alone or in combination. A balanced package of incentive and disincentive control measures (e.g., pricing or parking management) may be necessary to achieve targeted reductions in mobile source emissions. Implementation of significant disincentives measures will be controversial and consequently their impacts must be fully explored in order to assist decision makers in evaluating such approaches.

Impact Identification and Estimation

The air quality alternatives analyses called for in the joint EPA-DOT guidelines require that a comprehensive assessment of the impacts of alternative transportation control measures be conducted. The types of impacts that should be considered at least qualitatively, but also quantitatively where data and methodologies are available, in an alternatives analysis include (a) air quality, (b) energy consumption, (c) community, (d) financial, (e) economic, (f) travel, and (g) related impacts.

The magnitude as well as the incidence of these impacts should be estimated carefully. The incidence of impacts rather than the magnitude of the impacts is frequently the source of controversy in many transportation planning analyses. The potential implementation of travel disincentives will require thorough analyses to ensure that the benefits and negative impacts of a transportation control package are distributed equitably and that the air quality impacts are not achieved by the creation of serious hardships for selected population subgroups.

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Exhaust Emissions, Fuel Consumption and Traffic: Relations Derived from Urban Driving Schedule Data

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Traffic variables were calculated from the defined speed-time history of the LA-4 driving schedule for each of the 18 stop-to-stop cycles that constitute this schedule, in a manner similar to that previously applied to field data. The ability of these traffic variables to explain emissions and fuel consumption was examined by using data from 12 automobiles run on federal test procedure dynamometer tests. It was found that hydrocarbon emissions can be expressed as a linear function of average trip time per unit distance for urban driving at low speeds. Relations of variables that are more difficult to measure for actual traffic are required for carbon monoxide and oxides of nitrogen. Data collected from a single test can yield a relation from which a vehicle's fuel consumption at any urban speed can be estimated.

When a vehicle is driven in urban traffic it undergoes frequent changes in speed as a result of interactions with other vehicles and the complex traffic control system. Despite the complexities of urban speed-time histories, a simple relation has been found between fuel consumption and average traffic speed (1-3). On the basis of experiments conducted in street traffic, it was concluded that the fuel consumed per unit of distance (ϕ) can be expressed as a linear function of the trip time per unit of distance ($\bar{t}$) for average traffic speeds less than about 60 km/h. That is,

$$\phi = k_1 + k_2\bar{t} = k_1 + k_2/\bar{v} \qquad \bar{v} < \sim 60 \text{ km/h} \qquad (1)$$

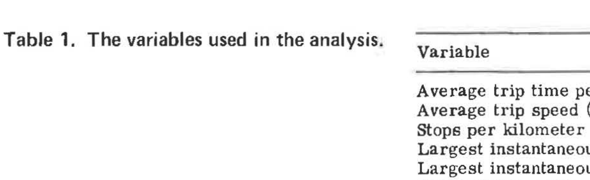
where $\bar{v}$ is the average trip speed, and k_1 and k_2 are vehicle-dependent parameters (1-3).

Equation 1 has previously been used successfully to explain fuel consumption measured in the field (1-5), measured by using different fixed-urban-driving schedules (5), and calculated by others by use of computer simulation (6, 7). One reason why a simple relation can explain fuel consumption so well in such a complex process as urban driving is that other variables important to the determination of fuel consumption were shown (1, 2) to be correlated with $\bar{t}$ in actual urban traffic. Therefore, their effects are implicitly imbedded in Equation 1.

It was found (2) that when a long speed-time record of a vehicle was analyzed, the relation (Equation 1) applied with essentially the same parameters irrespective of which of four different sampling methods was chosen. One of these sampling methods used "microtrips", which are defined as portions of travel between consecutive stops of the vehicle (2).

The LA-4 fixed-urban-driving schedule, which is the basis of the federal test procedure (FTP) used by the U.S. Environmental Protection Agency (EPA) to estimate official emissions and city fuel economy, consists of 18 stop- (in one case a near stop) to-stop cycles (see Figure 1). Each execution of the LA-4 driving schedule provides 18 microtrip data. The nine traffic variables shown in Table 1 were computed for the 18 cycles from the speed-time definition of the LA-4 driving schedule (8) in a similar manner to the approach used previously (1). The cycle, or microtrip, is defined from the beginning of the stop to the moment that the vehicle again comes to a stop; that is, stopped portions occur at the beginning of the cycles. One of the variables considered is stops per kilometer (S), defined as follows: Each cycle involves one stop and has an associated distance of travel (D). If the cycle is repeated N times, N stops are generated in ND kilometers. Hence, we may consider the individual cycle to be characteristic of a speed-time profile with D^{-1} stops per kilometer. The other variables in Table 1 are defined in the same way as those introduced in other reports (1, 2).

Figure 1. Speed-time history of the LA-4 driving schedule and three phases of the 1975 FTP.



The intercorrelations among the traffic variables defined in Table 1 for the LA-4 driving schedule were examined in the same way as was previously done for data collected in the Detroit metropolitan area. The results are discussed in a more detailed version of this paper (9).

We will use the speed-time definition of the LA-4 driving schedule and data collected from automobiles driven on this schedule on a chassis dynamometer (a) to explore whether emissions for a fully warmed vehicle can be explained in terms of simple traffic variables, as was previously done for fuel, and (b) to investigate whether one test on the LA-4 driving schedule can provide enough information to derive Equation 1 for a particular automobile.

RESULTS

In the 1975 FTP, which is used to measure official EPA emissions and city fuel economy, vehicles execute the LA-4 fixed-urban-driving schedule on a chassis dynamometer. A 12-h soak at normal room temperature precedes the test. The first five cycles, from time 0 to 505 s, are referred to as the cold-start phase. Cycles 6-18 (505-1372 s) are called the stabilized phase. At the end of cycle 18 the engine is switched off for 10 min. The first five cycles are then repeated (cycles 19-23); this third phase is called the hot start. To obtain the official FTP emissions and fuel economy values, the data from the cold-start and hot-start phases are weighted by factors of 0.43 and 0.57, respectively, to reflect estimated proportions of cold and hot starts.

By use of an approach similar to that we previously used (1), we apply multivariate analysis to emissions in the hope of identifying those independent (i.e., traffic) variables that best explain the various emissions. In an attempt to obtain data for vehicles after they have reached stable operating conditions, we exclude the cold phase (i.e., cycles 1-5) from the analysis. However, because the test includes a hot-start repeat of cycles 1-5, noncold data are available for each of the 18 cycles.

Exhaust emissions data are analyzed for 12 arbitrarily chosen 1975 and 1976 automobiles, which were run on the FTP by General Motors. Each automobile was equipped with a catalytic converter, so emissions both before (engine-out) and after (tail pipe) the catalytic converter are studied.

Hydrocarbons

Results of regression analyses of both engine-out and tail-pipe hydrocarbon (HC) emissions for the 12 automobiles are shown in Table 2. For tail-pipe HC, the best single variable is $\bar{t}$ for 5 automobiles, f_s^T for 3, and W for 1; however, no traffic variable has significant correlations for 3 automobiles.

The engine-out results show more consistency from

Table 1. The variables used in the analysis.

Variable	Symbol	Unit
Average trip time per unit distance	$\bar{t}$	s/km
Average trip speed ($=\bar{t}^{-1}$)	$\bar{v}$	km/h
Stops per kilometer or D^{-1}, where D is distance traveled in cycle	S	km^{-1}
Largest instantaneous deceleration, or braking, during cycle	b_{max}	m/s^2
Largest instantaneous acceleration during cycle	a_{max}	m/s^2
Acceleration noise, defined as $[(\int a^2\, dt)/T]^{1/2}$, where a is instantaneous acceleration and T is cycle duration	σ_a	m/s^2
Work performed per unit distance to accelerate the vehicle $= \int av\,dt/D$, where v is the instantaneous speed and integration occurs only for $a > 0$	W	m/s^2
Fraction of time spent stopped	f_s^T	
Fraction of distance traveled coasting or braking, defined as $a < -0.15\ m/s^2$	f_c^D	

Table 2. Multiple correlation coefficient between HC(g/km) and the first two traffic variables to enter a linear piecewise regression, and the simple correlation coefficient with $\bar{t}$.

	Engine-Out			Tail Pipe		
Automobile	Best Single Variable and Second Variable Entering	Multiple Correlation Coefficient	Correlation with $\bar{t}$ Alone	Best Single Variable and Second Variable Entering	Multiple Correlation Coefficient	Correlation with $\bar{t}$ Alone
1	$\bar{t}$, W	0.984	0.951	f_s^T, a_{max}	0.890	0.819
2	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]
3	$\bar{t}$, b_{max}	0.890	0.873	$\bar{t}$, a_{max}	0.737	0.626
4	$\bar{t}$, W	0.955	0.929	$\bar{t}$, -	0.537	0.537
5	$\bar{t}$, b_{max}	0.771	0.744	-[a]	-[a]	-[a]
6	W, σ_a	0.924	0.837	W, $\bar{v}$	0.852	0.526
7	$\bar{t}$, b_{max}	0.764	0.736	-[a]	-[a]	-[a]
8	$\bar{t}$, W	0.926	0.899	$\bar{t}$, W	0.954	0.944
9	$\bar{t}$, W	0.928	0.897	$\bar{t}$, $\bar{v}$	0.681	0.628
10	W, f_s^D	0.892	0.766	f_s^T, b_{max}	0.670	0.574
11	$\bar{t}$, f_s^T	0.888	0.861	$\bar{t}$, $\bar{v}$	0.849	0.782
12	$\bar{t}$, W	0.934	0.870	f_s^T, $\bar{v}$	0.721	-[a]

Note: Second variable explains insignificantly more variance.

[a] Regression not significant at $p = 0.05$.

Table 3. Engine-out HC emissions at arbitrary urban speed expressed in terms of those at average trip speed of LA-4 driving schedule.

Automobile	r	a[a] (g/km)	b[a] (g/s)	α[b] (km/s)
1	0.951	0.15	0.0135	0.0080
2	(0.038)	-[c]	-[c]	-[c]
3	0.873	0.37	0.0063	0.0058
4	0.929	0.55	0.0076	0.0054
5	0.744	0.23	0.0030	0.0053
6	0.837	0.78	0.0094	0.0051
7	0.736	0.72	0.0045	0.0037
8	0.899	0.20	0.0097	0.0074
9	0.897	0.12	0.0066	0.0076
10	0.766	1.15	0.0062	0.0033
11	0.861	0.62	0.0084	0.0053
12	0.870	0.10	0.0225	0.0084
Average	0.851	0.45	0.0089	0.0059

[a] Parameters in regression $y(\bar{t}) = a + b\bar{t}$ where $y(\bar{t})$ is HC(g/km) at average trip speed $\bar{t}$ (s/km).

[b] The slope α is defined by $[y(\bar{t})]/[y(\bar{t}_0)] - 1 = \alpha(\bar{t} - \bar{t}_0)$ where $\bar{t}_0 = 114.4$ s/km is the average trip speed for the LA-4 driving schedule, and $\alpha = b/(a + b\bar{t}_0)$.

[c] Regression not significant at $p = 0.05$.

automobile to automobile. The best single variable is $\bar{t}$ for 9 of the automobiles and W for 2, but no traffic variable has any significant correlation with HC for 1 automobile. The single variable $\bar{t}$ explains more than half of the variance in HC for 11 of the 12 automobiles studied. The average variance explained by $\bar{t}$ is more than 70 percent for these 11 automobiles. Because of their higher correlations with traffic variables, we will first discuss engine-out HC for individual automobiles. Later we will show that similar results apply to tail-pipe values averaged over all of the automobiles.

For low-speed urban traffic we obtain a relation between engine-out HC and average trip time per unit distance similar to that found for fuel, namely

$$y(\bar{t}) = a + b\bar{t} \tag{2}$$

where $y(\bar{t})$ is HC emissions in grams per kilometers at average trip time per unit distance, $\bar{t}$. Specific values of a and b are given in Table 3.

Information was available that enabled us to compute the engine-out time rate of HC emissions at idle for three automobiles. The values are compared below to the parameter b in Equation 2 (see Table 3).

Automobile	b (mg/s)	HC Emission Rate at Idle (mg/s)
10	6.2	6.4
11	8.4	8.3
12	22.5	16.8

We see that, as in the case of fuel consumption (3), the coefficient of $\bar{t}$ can be associated with the time rate at idle.

A plot of $y(\bar{t})$ versus $\bar{t}$ is shown in Figure 2 for automobile 11, the automobile that has the just below median rank correlation coefficient (i.e., rank 7 out of 12, see Table 2). The broken line that extends beyond the data is to indicate the intercept (a) in Equation 2. This relation is not valid for high speeds ($\bar{t} < \sim 60$ km/h), where HCs, in fact, increase with speed. The correlation coefficients for $y(\bar{t})$ versus $\bar{t}$ are increased for all automobiles if cycle 19 (the first cycle after the 10-min soak) is deleted; further improvements result if cycle 20 is also deleted.

A relation of the form of Equation 2 enables us to express the fractional change (f) in emissions that corresponds to a change in trip time from $\bar{t}_0$ to $\bar{t}$ as a simple multiple of the change in trip time. The dependence of f on $\bar{t}$ can be expressed in terms of a single quantity (α) as follows:

$$f = [y(\bar{t}) - y(\bar{t}_0)]/y(\bar{t}_0) = \alpha(\bar{t} - \bar{t}_0) \tag{3}$$

where α is given explicitly by

$$\alpha = b/(a + b\bar{t}_0) \tag{4}$$

Values of α are given in Table 3 for the 11 automobiles that had significant correlations between $y(\bar{t})$ and $\bar{t}$.

If R is the ratio of emissions at the two trip times $\bar{t}$ and $\bar{t}_0$ [i.e., $y(\bar{t})/y(\bar{t}_0)$], then

$$R = 1 + f = 1 + \alpha(\bar{t} - \bar{t}_0) \tag{5}$$

We take $\bar{t}_0 = 114.4$ s/km, the average value for the LA-4 driving schedule, and also the average value for an FTP test because the sum of the weighted factors in phases 1 and 3 is unity. One of the shaded areas in Figure 3 includes the relation (Equation 5) for our automobiles; i.e., the boundaries of the shaded area correspond to the largest and smallest of the 11 values of α.

Relations of the form

$$R = \exp(A + B\bar{v} + C\bar{v}^2) \tag{6}$$

are given in an EPA document (10) for the speed range 24-72 km/h for tail-pipe emissions for 11 different cases (high and low altitudes) together with separately determined values at the particular average speeds of 16 and 8 km/h. When each of these 11 relations (Equation 6) for HC is plotted over its stated range of validity as a function of $\bar{t}$, none shows other than small departures from linearity. All 11 curves are contained within the indicated area in Figure 3, which also shows the maximum and minimum of the specific values given for 16 and 8 km/h.

Figure 2. Engine-out HC emissions in g/km [= $y(\bar{t})$ versus $\bar{t}$ for automobile 11.

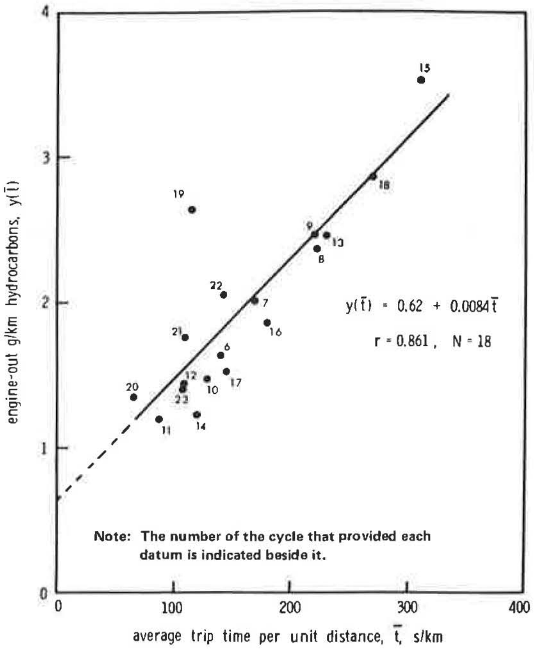


Figure 3. HC emissions versus $\bar{t}$, expressed as a multiple (R) of their value at the average trip time per unit distance of the LA-4 fixed driving schedule.

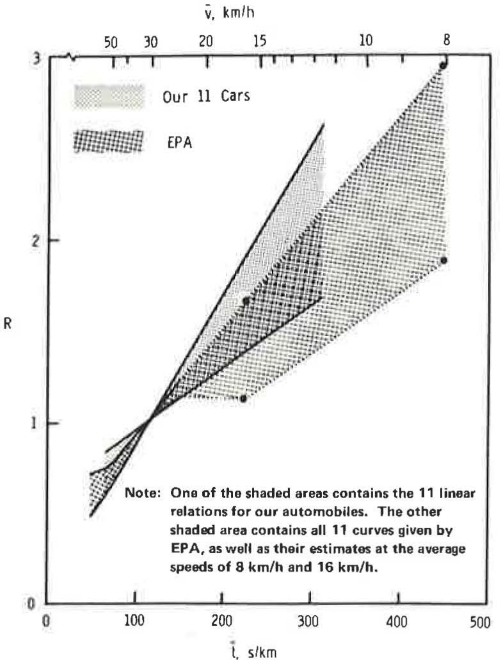


Figure 4 shows Equation 5 plotted with $\alpha = 0.0059$ km/s, the average value for the 11 of our automobiles that had significant correlations. A curve that represents the average values for the EPA data is also shown and is in reasonable agreement with our result. If $y(\bar{t})$ were directly proportional to $\bar{t}$ (i.e., a = 0 in Equation 2), then α would have the value 1/(114.4 s/km) = 0.0087 km/s, which may be compared to the observed values given in Table 3.

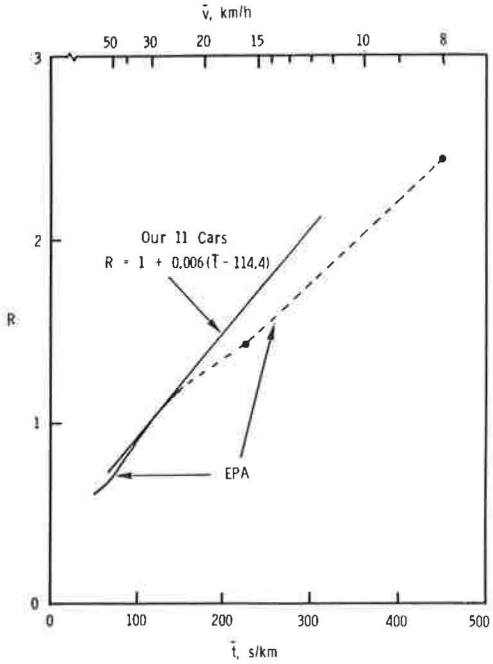
In the above analysis, for our automobiles only engine-out HC emissions were used because the larger variability of the tail-pipe emissions reduced correlations with traffic variables for individual automobiles (see Table 2). We averaged all of the automobiles in an attempt to reduce the effect of this variability. For each automobile, the ratio (p) of grams per kilometer HC for each cycle to the average value for that automobile for all cycles except 19 and 20 was determined. These two cycles, which occur just after the 10-min soak, sometimes have much higher HC emissions than do the other cycles. The average value of the ratio p over the 12 automobiles is shown plotted versus $\bar{t}$ for all 18 cycles in Figure 5. The least-squares fit to the data for 16 cycles (excluding 19 and 20) shown in Figure 5 leads, through Equation 4, to a value of $\alpha = 0.0067$ km/s for Equation 3. This may be compared to the average of the 11 engine-out values, namely, $\alpha = 0.0059$ km/s. Thus, the overall tail-pipe HC emissions exhibit a dependence on trip speed essentially similar to that found in the engine-out case.

The following statement summarizes all the data discussed above and shown in Figures 2-5: In low-speed urban driving, for each 1-s increase in trip time per kilometer, the HC emissions for a given vehicle increase by about 0.6 percent of their value at the average trip speed of the LA-4 driving schedule.

In general, the fractional difference between the HC emissions $\epsilon(\bar{t}_1)$ and $\epsilon(\bar{t}_2)$ at two different average trip times per unit distance $\bar{t}_1$ and $\bar{t}_2$ s/km, respectively, is expressed as

$$[\epsilon(\bar{t}_2) - \epsilon(\bar{t}_1)]/\epsilon(\bar{t}_1) = [0.006\,(\bar{t}_2 - \bar{t}_1)]/[1 + 0.006(\bar{t}_1 - 114)] \qquad (7)$$

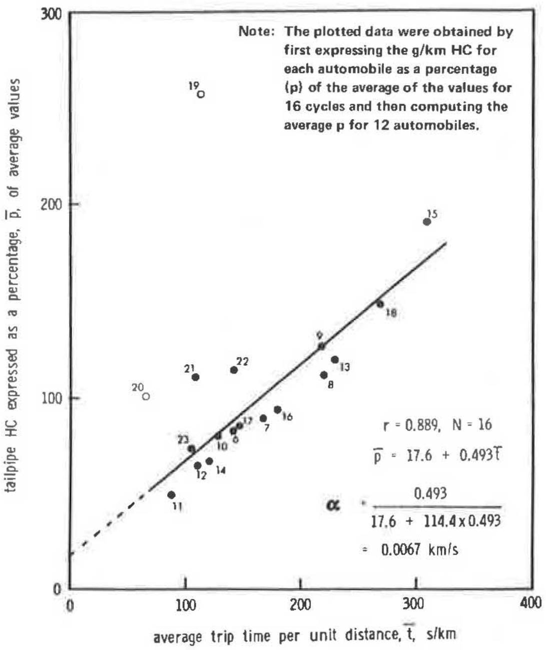
Figure 4. Average values of the Figure 3 representations.



Application to Published Computer Simulation Results

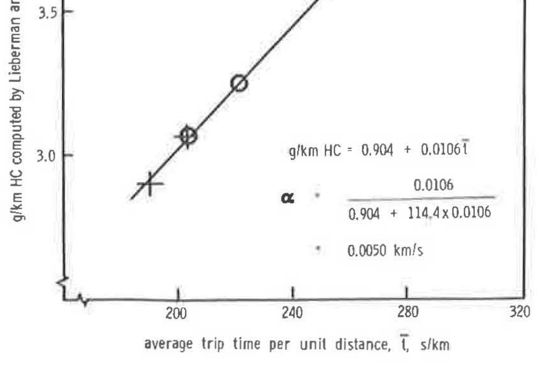
Lieberman and Cohen (11) calculated the effect on fuel economy and emissions of permitting right turns on red at signalized intersections. They applied a detailed computer simulation model to a network of streets in Washington, D.C. Emissions and fuel consumption were obtained by summing contributions from each individual vehicle maneuver.

Figure 5. Dependence of tailpipe HCs on average trip speed.



Note: The plotted data were obtained by first expressing the g/km HC for each automobile as a percentage (p) of the average of the values for 16 cycles and then computing the average p for 12 automobiles.

Figure 6. HC emissions estimated by using detailed computer simulation versus the corresponding average trip times per unit distance from the same simulation.



Three levels of flow were simulated (11), each with and without a right-turn-on-red policy, and the average speeds for these six cases were calculated. It was shown (6) that the six values of average speed alone may be used with the aid of Equation 1 to estimate effects on fuel consumption without performing the detailed summation of the computed fuel used for each detailed maneuver. Equation 1 has also been applied to right-turn-on-red field data (4). Further similar computer simulation data (12) were also shown (7) to fit the linear fuel consumption relation (Equation 1).

We now apply a similar approach to the HC emissions determined in the simulation (11). The six values of HC emissions given in Table 1 of Lieberman and Cohen (11) for a composite vehicle are shown in Figure 6 as a function of the value of $\bar{t}$ determined in their simulation. A linear relation between grams per kilometer and $\bar{t}$ fits the data very well. This relation may be written in the form of Equation 3 with $\alpha = 0.050$ km/s, which may be compared to the value, $\alpha = 0.0059$ km/s, obtained for our 11 automobiles.

As in the case of fuel consumption (4, 6, 7), the effect of traffic changes on HC emissions may be explained in terms of a simple linear function of $\bar{t}$, irrespective of whether the changes are due to different traffic volumes or different operating policies.

Applications to HC Measured on Dynamometer Replications of Street Driving

Data are given for HC emissions for trips at the four urban speeds of 19, 29, 31, and 50 km/h in Figure 3 of Herman and others (13). A linear least squares fit to the four $[\bar{t}, y(\bar{t})]$ pairs derived from these data yields

$$y(\bar{t}) = 0.075 + 0.001\,84\,\bar{t} \qquad r = 0.918 \tag{8}$$

Substitution of the parameters of this regression into Equation 4 yields $\alpha = 0.0065$ km/s, which may be compared to the value, $\alpha = 0.0059$ km/s, derived for our 11 automobiles.

It would seem that the data currently available are not sufficient to support substantially more elaborate expressions of the speed dependence of HC emissions in urban traffic than the one proposed above. The degree of complexity of EPA's Equation 6 would appear to be difficult to support.

The simplicity of Equation 5 would allow us to make simple analytical estimates of the effect of increasing circulation speeds in congested central business district (CBD) networks on overall traffic system HC emissions, as we have previously done for fuel (14).

Carbon Monoxide

No consistent automobile-to-automobile interpretation of tail-pipe carbon monoxide (CO) emissions has emerged from this study. This may be due, in part, to the large effects that can result in tail-pipe CO due to small, essentially erratic, excursions into mixture enrichment. Note that, as before, cold-start data are excluded. For 7 of the 12 automobiles in the engine-out case, W (see Table 1) explained more variance in CO than did any other single variable. The variable W and grams per kilometer CO were significantly correlated ($p < 0.05$) for 11 of the 12 automobiles. The variable $\bar{t}$ had a correlation significant at this level for 8 automobiles.

Analysis of tail-pipe CO in a similar way to that represented in Figure 5 yields a weak correlation with $\bar{t}$ and a value of $\alpha \approx 0.01$ km/s. A treatment of the CO simulation data of Lieberman and Cohen (11) yields a

Table 4. Fuel consumption per unit distance (ϕ) as a function of $\bar{t}$ for 17 cycles of the LA-4 fixed driving schedule (cycle 15 has been excluded).

Automobile	$\phi = k_1 + k_2\bar{t}$			Idle Fuel Flow Rate (mL/s)	Inertia Weight Class (kg)	Multiple Correlation Between ϕ and $\bar{t}$, W
	r	k_1 (mL/km)	k_2 (mL/s)			
1	0.901	71.6	0.959	-	2500	0.964
2	0.943	61.9	0.689	-	2000	0.984
3	0.918	84.2	0.761	-	2300	0.983
4	0.929	74.5	0.558	-	1800	0.979
5	0.903	56.3	0.960	-	1400	0.976
6	0.885	75.8	0.578	-	2000	0.977
7	0.941	77.7	1.052	-	2500	0.990
8	0.921	68.8	0.773	-	2300	0.982
9	0.915	77.0	0.700	-	2000	0.986
10	0.883	74.1	0.516	0.392	2000	0.967
11	0.938	65.3	0.656	0.535	1800	0.984
12	0.890	74.8	0.540	0.431	2000	0.979

linear relation between grams per kilometer CO and $\bar{t}$ that has a similar absence of scatter to that found for HC (Figure 6). However, this near perfect fit to a linear relation [which also occurs for nitrogen oxides (NO_x) but with a very small slope] appears to result from the smooth analytic dependence of emissions on acceleration and speed that is built into the simulation model. The regression obtained from the results of the simulation for CO implies a value of α of 0.007 km/s.

Watson and Milkins (15) and Watson, Milkins, and Bulach (16) used computer simulation to obtain relations that have little scatter between CO and average speed and between HC and average speed. They concluded (16) that, for these emissions, models that accounted for variations in traffic speed alone were as reliable as more complex models. The present analysis of actual emissions data yields this same conclusion for HC but a less definitive result for CO. The analytic relation between CO and speed given (15) gives a value of α of 0.0085 km/s.

An analysis of the measured CO emissions that correspond to trips at the four urban speeds given in Figure 5 of Herman and others (13) gave no significant relation between grams per kilometer CO and $\bar{t}$, in contrast to the result discussed above for HC.

The coefficient of $\bar{t}$ in a regression of $\bar{t}$ on grams per kilometer CO is unlikely to be interpretable in terms of the time rate of CO emissions at idle, because this idle rate is so small. We find that, typically, the time rate of engine-out CO emissions at idle is about 0.15 times the average rate over the 18 warm LA-4 cycles.

NO_x

Although the catalyst has a much smaller effect on NO_x than on HC and CO, the correlations with traffic variables were nonetheless slightly higher for the engine-out emissions. The catalyst is an oxidizing device, so nominally, there should be no effect on NO_x.

One variable, W, had the highest correlation with engine-out grams per kilometer NO_x for 11 of the 12 automobiles. For all 12 automobiles the correlations between grams per kilometer NO_x and W ranged from 0.81 to 0.96; the average was 0.90 For the tail-pipe case the correlations between grams per kilometer NO_x and W ranged from 0.69 to 0.96; the average was 0.88.

An analysis of the type represented in Figure 5 provided no useful relationship between grams per kilometer NO_x and $\bar{t}$. The constant terms in the 12 linear regressions of W on grams per kilometer NO_x are relatively small and unsystematic in sign. This suggests a relationship of the form

$$\text{g/km } NO_x = aW \tag{9}$$

for low-speed urban driving.

Fuel Consumption

The fuel consumed in each of the 18 cycles was calculated from the tail-pipe gaseous emissions by use of the carbon balance technique. The fuel consumed per unit distance (ϕ) has large correlations with both S (see Table 1) and $\bar{t}$ for all 12 automobiles. In no case was the simple correlation coefficient less than 0.9, in good agreement with earlier findings (2, 3, 5).

For a more detailed examination of the relations between ϕ and traffic variables, we excluded cycle 15, which has a distance of only 0.11 km. This corresponds to our previous treatment of field fuel consumption data, in which only data that represent more than 0.2 km of travel were analyzed (3).

For the remaining 17 cycles, the best single variable to explain ϕ was $\bar{t}$ for 10 of the automobiles and S for 2, although in no case were the correlation coefficients for these two variables substantially different. When $\bar{t}$ was forced to be the first variable, the second variable to enter a piecewise linear regression was W for all 12 automobiles. This result is in agreement with that obtained in urban street traffic (1, 2).

The parameters k_1 and k_2 of Equation 1 as determined from the 17 cycles are shown in Table 4. The average fuel flow rate (I) during periods when the vehicle was idling was calculated for three automobiles for which we had appropriate data available. For these k_2 is approximately proportional to I (see Table 4), in agreement with the result from urban street traffic (3). As was found for field data, the parameter k_1 is approximately proportional to the vehicle weight.

SUMMARY AND DISCUSSION

The results presented show that HC emissions (g/km) can be expressed approximately as a linear function of the average trip time per unit distance ($\bar{t}$). This result implies that the speed dependence of grams per kilometer HC may be characterized by a single parameter. The results are in reasonable quantitative agreement with information given by EPA. Both our results and those of EPA can be approximately summarized as follows: For each 1-s increase in $\bar{t}$, the grams per kilometer HC emissions increase by about 0.6 percent of their value at the average trip speed of the LA-4 driving schedule.

This simple result can be used to derive the speed dependence of results obtained by detailed computer simulation and by replicating an actual urban speed-time history on a chassis dynamometer.

The dynamic variable that best explains the emissions of NO_x and CO on an individual LA-4 test is W, the work performed per unit distance to accelerate the vehicle. This result is in accord with the usual association between NO_x and acceleration characteristics. It is difficult to characterize overall traffic characteristics of an urban system in terms of W. However, this finding does not preclude the possibility that speed characteristics alone, through their correlations with acceleration characteristics, might provide an adequate description of CO and NO_x emissions for a more extensive data set.

The fuel consumptions in individual cycles of one FTP were shown to fit a linear relation in $\bar{t}$, a result comparable to that obtained in urban street traffic. The parameters in this relation are interpretable in the same way as those for the field data. The FTP fuel economy is the fuel economy appropriate for a particular urban speed, namely, the average speed of the LA-4 driving schedule (5). The linear relation derived from the individual cycles of one FTP test permits fuel economy to be calculated at any urban speed.

We have organized the detailed information contained in one FTP test in a form different from that customarily used. The relations obtained show reasonable stability from automobile to automobile. This approach would appear to offer a fruitful method for investigation of system parameter changes. Information such as that in Figures 2 and 6 and Table 4 could be more instructive in before-and-after comparisons than the simple FTP overall values, especially since the overall values can be much affected by anomalous behavior in only one small part of a test.

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