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CONTENTS

FOREWORD

The five papers presented in this RECORD are of significant interest to environmentalists and contribute broadly to the knowledge of air quality.

The first paper is an analysis of urban area automobile emissions according to trip type. The analysis uses travel data from the Pittsburgh transportation survey and emissions data developed by the Environmental Protection Agency, to estimate Allegheny County (Pittsburgh), Pennsylvania, automobile emissions according to trip purpose, length, origin, and destination. The results include estimates of daily evaporative emissions, cold-start and hot-soak emissions, and actual running emissions. The findings suggest that improved peak-period and radial transit may be effective in improving air quality through reducing automobile travel if such transit reaches peripheral areas of the county and does not rely on the automobile for residential collection and distribution.

In the second paper the authors examine means of reducing travel in the South Coast Air Basin of California by 20 percent. The authors state that the goal of reducing vehicle-miles of travel (VMT) by 20 percent cannot be achieved by only improving other travel modes and relying on voluntary shifts. Restricting the use or reducing the utility of the private car is necessary according to the authors. They further examine such methods as exclusive bus lanes, ramp metering, increase in public transportation service, car pooling and improved bicycle facilities. Some of the more stringent alternatives proposed by the authors are restriction of travel by gasoline rationing, assigned mileage quotas, and vehicle taxation.

The third paper clarifies some of the environmental issues associated with automobile-free zones and determines whether AFZs can reduce environmental problems. It gives planners an overview of the subject and suggests some procedures for future studies. The environmental effects of automobiles are explained briefly. Past experience with AFZs is presented to show the results of noise and air pollution studies taken in areas where autos have been prohibited. The paper summarizes the conditions under which AFZs can be expected to reduce transport-related environmental problems.

The fourth paper develops a simple model for estimating regional automobile emissions of carbon monoxide, hydrocarbons, and nitrogen oxides. The model is designed for situations where rough pollution estimates are desired at low cost. The model calculates the vehicle-miles of travel over different road types and effective vehicle speeds at which travel takes place for each specified subarea of the region. Then by use of emission functions that relate the output of pollutants to vehicle speeds, emission estimates are calculated for the given travel pattern. An application to the Watertown, New York, region is discussed.

The last paper develops the characteristics of a system of periodic motor-vehicle emission inspections and the type of inspection process required. The relationship of inspection to maintenance is described. A number of issues raised by the prospect of mandatory inspection and maintenance are discussed.

ANALYSIS OF URBAN AREA AUTOMOBILE EMISSIONS ACCORDING TO TRIP TYPE

Joel L. Horowitz, U.S. Environmental Protection Agency; and
Lloyd M. Pernela, University of Alaska

Travel data from the Pittsburgh transportation survey and emissions data developed by the Environmental Protection Agency have been used to estimate Allegheny County (Pittsburgh), Pennsylvania, automobile emissions according to trip purpose, length, origin, and destination. The results include estimates of diurnal evaporative emissions, cold-start and hot-soak emissions, and actual running emissions. Home-based work trips and trips to and from the central area of the county each produce one-third to one-half of Allegheny County automobile emissions and are the dominant causes of automobile emissions in the county. Cold starts and evaporations produce approximately half of the hydrocarbons and a quarter of the carbon monoxide. Trips shorter than 5 miles and trips longer than 5 miles produce roughly equal quantities of carbon monoxide and hydrocarbons. However, long trips produce greater quantities of nitrogen oxides. These findings suggest that improved peak-period and radial transit may be effective in improving air quality through reducing automobile travel if such transit reaches peripheral areas of the county. However, cold-start and evaporative emissions may significantly impair the effectiveness of transit approaches that rely on the automobile for residential collection and distribution.

•IN ACCORDANCE with the requirements of the Clean Air Amendments of 1970 (1), the administrator of the Environmental Protection Agency established ambient air quality standards for several common air pollutants including carbon monoxide, nitrogen dioxide, and photochemical oxidants. Achieving air quality consistent with these standards requires substantial reductions of emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) from automobiles. Significant reductions are expected from the federal emissions standards for new motor vehicles. In many cities, however, these reductions will not meet air quality standards and additional measures to reduce automobile emissions will be needed.

One approach in achieving additional reductions in automobile emissions is reducing automobile travel. Measures through which this might be accomplished include transit improvements, automobile use fees, and vehicular restraints. These measures can be expected to have significant effect on certain portions of urban area automobile travel and to have little or no effect on other portions of automobile travel. For example, park-and-ride transit service may reduce automobile vehicle-miles of travel (VMT) but is unlikely to reduce automobile trip frequency. Bus priority treatment and increased use of freeway bus systems are most likely to affect long trips, whereas demand-responsive service may be best suited to short trips. Transit improvements may be most effective in reducing work trips, and certain types of automobile fees and restraints may be most effective in reducing nonwork trips.

This paper presents estimates of automobile emissions for trips of various purposes, lengths, origins, and destinations in Allegheny County (Pittsburgh), Pennsylvania. The

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estimates are based on travel data obtained from the 1967 Pittsburgh transportation survey and on automobile emissions data developed by the Environmental Protection Agency. The estimates include diurnal evaporative hydrocarbon emissions, which are independent of travel behavior; cold-start and hot-soak evaporative emissions, which are dependent on trip volume but not trip length; and distributions of emissions according to trip purpose, length, origin, and destination.

METHODOLOGY

Data were obtained from the 1967 Pittsburgh transportation survey giving weekday automobile driver trips between traffic zones in Allegheny County for 8 trip purposes (home-based work, shop, school, personal business, social-recreational, and other; non-home-based; and total). Zone-to-zone travel times and roadway distances between zone pairs were also obtained. Average zone-to-zone speeds were determined by dividing trip lengths by travel times.

The data were used to develop projections of automobile emissions for Allegheny County internal trips in 1975 by assuming that travel patterns in 1975 would be the same as in 1967. The emissions estimates presented here may therefore be considered to apply to a hypothetical region whose 1975 travel patterns are the same as the Allegheny County internal trip patterns of 1967.

Emissions were computed for each trip in the Allegheny County data set and then summed over trip types to obtain emission estimates by trip type. Since the age of the vehicle used for a given trip is not included in the data, emissions for each trip were averaged over the age distribution of the Allegheny County automobile population. The following 4 equations describe the emissions model used:

$$E_p = E_p(1) + E_p(2) + E_p(3) \tag{1}$$

$$E_p(1) = L \sum_{i=n-16}^{n} \left[e_{ip} d_{ip}(n - i) m(n - i) s_{ip}(v) + k_{ip} m(n - i)\right] \tag{2}$$

$$E_p(2) = \alpha \sum_{i=n-16}^{n} c_{ip} d_{ip}(n - i) m(n - i) \tag{3}$$

$$E_p(3) = \sum_{i=n-16}^{n} h_{ip} m(n - i) \tag{4}$$

where

E_p = emissions of pollutant p, in kg;
$E_p(1)$ = running emissions of pollutant p, in kg;
$E_p(2)$ = cold-start emissions of pollutant p, in kg;
$E_p(3)$ = hot-soak evaporative emissions of pollutant p, in kg (nonzero for hydrocarbons only);
L = trip length, in miles;
n = calendar year 1975 (simulated);
e_{ip} = low-mileage running exhaust emissions of pollutant p by car of model year i, in kg/mile;
$d_{ip}(n - i)$ = deterioration factor for pollutant p by car of model year i when it is n - i years old;
$m(n - i)$ = fraction of Allegheny County VMT attributable to cars of model year i in calendar year n;
$s_{ip}(v)$ = speed adjustment factor for trip speed v;

k_{ip} = crankcase emissions of pollutant p by car of model year i, in kg/mile (nonzero only for hydrocarbons);
α = 1 if trip begins with a cold start, 0 otherwise;
c_{ip} = low-mileage cold-start emissions for car of model year i, in kg; and
h_{ip} = hot-soak evaporative emissions of pollutant p by car of model year i, in kg (nonzero for hydrocarbons only).

Emissions data were reported by Automotive Environmental Systems, Inc. (2) and by Thomas C. Austin of the Environmental Protection Agency in a private communication. Estimates of cold-start and running exhaust emissions were taken from these data by using methods suggested by Martinez et al. (3). Cold starts were associated with trips that originated at home or at work. Based on results obtained by General Motors (4), 50 percent of the evaporative emissions measured by the federal test procedure (5) were attributed to hot soaks. Average federal test procedure (FTP) evaporative emissions and crankcase emissions were obtained from Sigworth (6). Deterioration and speed adjustment factors are from Kircher (7). The mileage distribution was estimated as follows:

$$m(i) = \frac{a(i)M(i)}{\sum_{j=0}^{16} a(j)M(j)} \tag{5}$$

where

a(i) = fraction of Allegheny County cars that are i years old, and
M(i) = average annual miles driven by a car i years old [based on Department of Transportation information (8)].

In addition to the trip-related emissions of Eq. 1, each automobile registered in Allegheny County was considered to produce diurnal evaporative hydrocarbon emissions regardless of the use it received. These emissions were calculated as follows:

$$E_p(4) = \sum_{i=n-16}^{n} a(n - i)D_i \tag{6}$$

where

$E_p(4)$ = diurnal emissions averaged over the vehicle population, in kg/day, and
D_i = diurnal evaporative emissions for car of model year i, in kg/day.

Based on General Motors results (4), D_i is equal to 50 percent of evaporative emissions measured by the FTP.

RESULTS

Table 1 gives number of trips, VMT, and emissions according to trip purpose. Home-based work trips cause 33 to 39 percent of automobile emissions, depending on pollutant, and produce more emissions than any other type of trip. Non-home-based trips and home-based shopping trips follow in amount of emissions. Emissions of all pollutants are approximately proportional to VMT. Daily hydrocarbon evaporations, which are not related to travel behavior, are as follows:

HC	Amount	Percent
All trips	43.8	91
Daily	4.4	9
Total	48.2	100

Effects of cold starts and hot-soak evaporations on emissions attributable to trip purpose are given in Table 2. Cold starts, which are related to trip volumes but not to trip lengths or speeds, cause 24 percent of carbon monoxide emissions and 14 percent of trip-related hydrocarbon emissions. Hot soaks, which are also independent of trip lengths and speeds, contribute an additional 26 percent of trip-related hydrocarbons. Thus, 40 percent of trip-related hydrocarbon emissions are independent of trip lengths and speeds. Cold starts cause a small percentage of nitrogen oxides emissions (-3 percent) because high engine temperatures are required for nitrogen oxides formation. The lowest nitrogen oxides emissions result from home-based work trips because they are the only trips that have cold starts in both the home-to-destination and destination-to-home directions. Cold starts have a smaller than average effect on emissions from non-home-based trips, for only 25 percent of these trips begin with cold starts.

Table 3 gives the proportion of emissions attributable to the actual running portion of trips. Only 76 percent of carbon monoxide emissions and 55 percent of hydrocarbon emissions occur during actual running.

Table 4 gives the grams-per-mile emission rates of trips in Allegheny County and emission rates obtained from FTP emission factors adjusted for variations in trip speeds (7). The average Allegheny County carbon monoxide and hydrocarbon emission rates are respectively 14 and 29 percent higher than the FTP rates. There are several reasons for this. First, 57 percent of Allegheny County trips begin with cold starts, whereas the federal test assumes that cold starts are associated with only 43 percent of trips. In addition, the average trip length in Allegheny County is only 4.2 miles, whereas 7.5 miles is used in the federal test. Non-VMT-related emissions are therefore larger than running emissions in the Allegheny County sample but not in the federal test. This increases average Allegheny County grams per VMT when compared to federal test grams per VMT. If Allegheny County trips had been the same as the federal average of 7.5 miles with 43 percent cold starts per trip, average CO and HC emissions in the county would be 42 g/mile and 5.4 g/mile respectively, compared with 42 g/mile and 5.1 g/mile from the FTP results.

The remaining difference between the Allegheny County and federal test hydrocarbon emissions rates is because of differences between the federal test method of determining the contribution of diurnal evaporations to emissions per vehicle mile and the method used here. The federal test assumes that the average vehicle travels 26 miles per day, whereas the average Allegheny County vehicle travels 14 miles per day. Also, the federal test method weights each model year's contribution to diurnal emissions in proportion to that model year's VMT, whereas the weights used here are proportional to each model year's prevalence in the vehicle population (Eq. 6). Both of these differences increase Allegheny County's diurnal emissions relative to federal test emissions. When Allegheny County's diurnal emissions are determined by the federal test method, the previously obtained 5.4 g/mile hydrocarbon emissions factor is reduced to 5.1 g/mile, which equals the value obtained by the FTP.

Nitrogen oxides emissions have no evaporative sources and are relatively insensitive to cold starts and small variations in speeds, so Allegheny County and federal test nitrogen oxides emissions are approximately equal.

The relationship between emissions and trip lengths is shown in Figure 1. The proportion of carbon monoxide and hydrocarbon emissions attributable to short trips is far greater than their proportion of VMT. For example, trips of less than 5 miles are responsible for 53 percent of the carbon monoxide emissions and 49 percent of the hydrocarbon emissions, but only 33 percent of the VMT. The emissions per VMT for short trips are higher than those for long trips for two reasons. First, because cold-start and hot-soak evaporative emissions are independent of trip length, their contribution to average emissions per VMT increases as trip length decreases. Second, short trips in Allegheny County have lower average speeds than long trips (for example, 5 mph for a 1-mile trip compared to 23 mph for a 10-mile trip), which also increases short-trip emission rates. Nitrogen oxides emission rates, which are less sensitive to cold starts and variations in speeds, do not vary greatly with trip length, so only 31 percent of nitrogen oxides emissions are caused by trips that are less than 5 miles long.

Despite their high carbon monoxide and hydrocarbon emissions per VMT, short trips

Table 1. Automobile emissions by trip purpose.

					Emissions[c]					
	Trips[a]		VMT[b]		CO		NO_x		HC	
Purpose	Number	Percent	Number	Percent	Amount	Percent	Amount	Percent	Amount	Percent
Home-based										
Work	487	28	2,860	39	137	39	10.8	39	16.0	33
Shop	247	14	730	10	40	11	2.7	10	5.2	11
School	22	1	123	2	5	2	0.5	2	0.7	1
Social-recreational	134	8	551	8	25	7	2.1	8	3.3	7
Personal business	181	10	667	9	33	9	2.5	9	4.2	9
Other	214	12	622	9	34	10	2.3	8	4.5	9
Non-home-based	441	26	1,730	24	75	21	6.7	24	10.0	21
All trips[d]	1,720	100	7,280	100	348	100	27.5	100	43.8	91

[a] Thousands per day.

[b] Thousands of miles per day.

[c] Thousands of kilograms per day.

[d] These are not exact totals because numbers have been rounded.

Table 2. Cold-start and hot-soak emissions by trip purpose.

	CO			NO_x			Cold-Start HC			Hot-Soak HC		
Purpose	Amount[a]	Percent Purpose	Percent Total	Amount[a]	Percent Purpose	Percent Total	Amount[a]	Percent Purpose	Percent Total	Amount[a]	Percent Purpose	Percent Total
Home-based												
Work	41.4	30	12	-0.438	-4	-2	2.97	19	6	3.26	20	7
Shop	10.5	26	3	-0.111	-4	0	0.75	14	2	1.65	32	3
School	0.9	18	0	-0.010	-2	0	0.07	10	0	0.15	23	0
Social-recreational	5.7	22	2	-0.060	-3	0	0.41	12	1	0.90	27	2
Personal business	7.8	24	2	-0.081	-3	0	0.55	13	1	1.21	29	3
Other	9.1	27	3	-0.096	-4	0	0.65	14	1	1.43	32	3
Non-home-based	9.4	13	3	-0.099	-1	0	0.67	7	1	2.96	29	6
All trips[b]	83.6	24	24	-0.885	-3	-3	6.00	14	12	11.6	26	24

[a] Thousands of kilograms per day.

[b] These are not exact totals because numbers have been rounded.

Table 3. Running emissions by trip purpose.

	CO		NO_x		HC	
Purpose	Amount[a]	Percent	Amount[a]	Percent	Amount[a]	Percent
Home-based						
Work	95.7	28	11.2	41	9.73	20
Shop	29.2	8	2.8	10	2.83	6
School	4.4	1	0.5	2	0.44	1
Social-recreational	19.7	6	2.2	8	1.97	4
Personal business	25.0	7	2.6	9	2.46	5
Other	25.1	7	2.4	9	2.43	5
Non-home-based	65.2	19	6.8	25	6.40	13
All trips[b]	264	76	28.4	103	26.3	55

[a] Thousands of kilograms per day. Included are hot-running exhaust and crankcase emissions.

[b] These are not exact totals because numbers have been rounded.

Table 4. Average grams-per-mile emissions by trip purpose.

	Emissions				
Purpose	CO	NO_x	HC	Avg Miles	Avg mph
Home-based					
Work	48	3.8	5.6	5.9	19
Shop	54	3.7	7.2	3.0	16
School	43	3.8	5.3	5.6	18
Social-recreational	46	3.8	5.9	4.1	18
Personal business	49	3.8	6.3	3.7	17
Other	55	3.7	7.2	2.9	15
Non-home-based	43	3.8	5.8	3.9	17
All trips	48	3.8	6.6[a]	4.2	18
Federal test	42	3.9	5.1[a]	7.5	18

[a] Includes daily evaporations.

Table 5. Geographical characteristics of emissions (all purposes).

					Emissions[c]							
	Trips[a]		VMT[b]		CO		NO_x		HC			
District	Number	Percent	Miles	Percent	Amount	Percent	Amount	Percent	Amount	Percent	Avg Miles	Avg mph
1[d]	362	21	900	12	67	19	3.2	11	8.1	17	2.5	11
1	710	41	3,650	50	170	49	13.8	50	20.6	43	5.1	17
2	456	26	2,160	30	94	27	8.3	30	11.9	25	4.7	19
3	498	29	2,330	32	105	30	8.8	32	13.9	29	4.7	19
4	292	17	1,720	24	66	19	6.8	25	8.4	17	5.9	22
5	269	16	1,510	21	61	17	5.9	21	7.8	16	5.6	21

[a] Thousands per day.

[b] Thousands of miles per day.

[c] Thousands of kilograms per day.

[d] Internal trips only.

emit less per trip than do long trips. Trips whose length is less than 5 miles, which produce 31 to 53 percent of automobile emissions, account for 70 percent of all trips.

The relationship of emissions to trip origins and destinations was investigated by dividing Allegheny County into 5 districts as shown in Figure 2. District 1 is the city of Pittsburgh. Table 5 gives the emissions for all types of trips that originate or terminate in each district and for District 1 internal trips. Table 6 gives the same information for home-based work trips. In both cases, trips to or from District 1 are the dominant source of emissions. District 1 trips for all purposes produce 43 to 50 percent of total automobile emissions. Work trips to District 1 produce about 20 percent of total emissions, or roughly 57 percent of all work-trip emissions, but trips internal to District 1 generate a small proportion of emissions, 11 to 19 percent of the total. In addition, trips internal to District 1 account for only half of total District 1 trips, which suggests that trips originating or terminating outside of District 1 may be responsible for a substantial fraction of the pollutants emitted inside District 1. District 1 internal trips are both shorter and slower than the average Allegheny County trip. These trips therefore generate a larger proportion of regional carbon monoxide and hydrocarbon emissions than of VMT. Other trips, which are longer and, in most cases, faster than average, tend to have carbon monoxide and hydrocarbon emissions that are slightly less than proportional to VMT.

CONCLUSIONS

The results presented here suggest several conclusions concerning the effectiveness of measures designed to improve air quality by reducing automobile use.

Allegheny County automobile emissions of carbon monoxide and hydrocarbons appear to be respectively 14 and 29 percent higher than estimates based on the FTP emission factors would suggest, even after the federal test factors are adjusted for variations in trip speeds. Thus, differences between regional trip characteristics and trip characteristics assumed in the FTP may significantly affect automobile emissions. In the case of Allegheny County, these differences tend to increase the air quality improvements that would result from automobile emissions reductions.

Home-based work trips and trips to or from the central area of the county respectively produce 33 to 39 percent and 43 to 50 percent of Allegheny County automobile emissions and are the main causes of automobile emissions in the area. Thus, measures designed to reduce automobile use within these trip categories, such as improved peak-period and radial transit service, increased long-term parking fees, and restrictions on central area automobile use may be especially useful in improving air quality. To be effective, however, these measures will have to affect trips to and from the central area as well as District 1 internal trips.

Trips shorter than 5 miles and trips longer than 5 miles produce roughly equal quantities of carbon monoxide and hydrocarbons. Thus, measures affecting long trips, such as freeway bus service and bus priority treatment, and measures affecting short trips, such as demand-responsive transit, may have similar effects on carbon monoxide and hydrocarbon emissions. Greater quantities of nitrogen oxides, however, are produced by long trips than by short trips.

Approximately 50 percent of the hydrocarbon emissions and 25 percent of the carbon monoxide emissions are produced by cold starts and evaporations. These emissions, which are not affected by trip lengths or speeds, can significantly impair the emission-reduction effectiveness of transit improvements such as park-and-ride that rely on the automobile for residential collection and distribution. The impairment is particularly severe in the case of hydrocarbons. For example, park-and-ride transit that serves trips whose average length is 10 miles and requires a 1-mile home-to-transit automobile trip would achieve only about 65 percent of the reduction in automobile hydrocarbon emissions that would result from the use of a transit approach that had equal ridership but did not require automobile access.

ACKNOWLEDGMENTS

The authors thank George Furguson and Wade Fox, of the Southwestern Pennsylvania Regional Planning Commission, for their assistance in obtaining the travel data used in

Table 6. Geographical characteristics of emissions (work trips).

					Emissions[c]							
	Trips[a]		VMT[b]		CO		NO_x		HC			
District	Number	Percent	Miles	Percent	Amount	Percent	Amount	Percent	Amount	Percent	Avg Miles	Avg mph
1[d]	99	6	335	5	25.0	7	1.16	4	2.81	6	3.4	12
1	250	14	1,640	23	77.9	22	6.14	22	8.92	19	6.6	19
2	126	7	837	11	36.0	10	3.26	12	4.25	9	6.6	22
3	144	8	935	13	42.7	12	3.51	13	4.97	10	6.5	20
4	94	5	712	10	28.8	8	2.77	10	3.40	7	7.6	23
5	79	5	598	8	24.8	7	2.30	8	2.90	6	7.5	22

[a] Thousands per day. [b] Thousands of miles per day. [c] Thousands of kilograms per day. [d] Internal trips only.

Figure 1. Cumulative distribution of emissions by trip length.

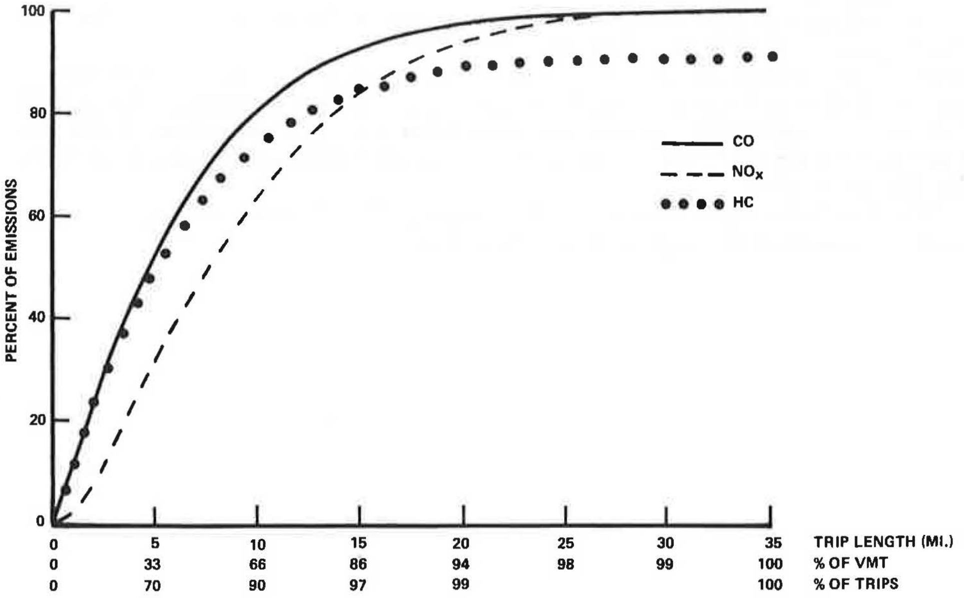
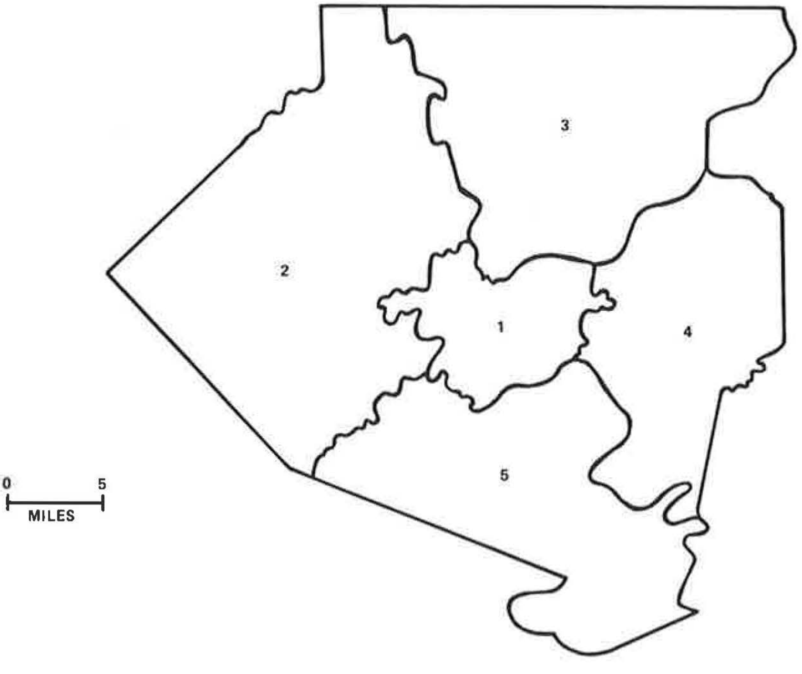


Figure 2. District boundaries for the city of Pittsburgh and Allegheny County.



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CAN VEHICLE TRAVEL BE REDUCED 20 PERCENT IN THE SOUTH COAST AIR BASIN?

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This report covers a study to evaluate the possibility of reducing vehicle travel in California's South Coast Air Basin. Air pollution programs, analysis of travel, travel constraints, and reduction strategies are reviewed. The study concludes that a 20 percent reduction in VMT for the basin cannot be achieved in the short run because the automobile is more of a necessity here than in many other urban areas. This stems from the general form of the basin and its low population density. However, a 20 percent reduction is possible in the long run if area growth is controlled and land use is restricted.

•IN THE not too distant past, every city had a thriving public transportation system. But once Henry Ford had perfected his assembly line, it was only a matter of time until the automobile replaced the public conveyance in urban travel. The train, streetcar, and bus could not compete with the personal automobile. People bought cars and wanted roads. Public policy in this country was directed at providing highway facilities for the automobile.

Although these policies served the people well for over four decades, they are now being questioned. One of the public concerns is air quality, particularly in metropolitan areas.

The conflict between air quality and the automobile was first recognized in 1951 when Professor A. J. Haagen-Smit of the California Institute of Technology identified the photochemical process of smog formation. He deduced that automobile exhaust was the primary source of atmospheric pollutants in the Los Angeles area. The first efforts to reduce air pollution, taken by local government, were aimed at preserving both the right to breathe clean air and the privilege to drive. It is now recognized that travel must be curtailed to reduce air pollution.

CALIFORNIA'S AIR POLLUTION CONTROL PROGRAM

Los Angeles County formed an air pollution control district in 1947 that placed various controls on industry and later on individual households. Within the South Coast Air Basin, other control districts were formed and local regulations have become progressively more restrictive.

In 1962, the state formed the Motor Vehicle Emissions Control Board, which required various controls for new and used cars. The state broadened its control in 1967 by forming the State Air Resources Board (ARB).

ARB continued technical efforts to reduce emissions and in 1970 established ambient air quality standards for several pollutants.

One important point in the state's 1970 air quality standards (1) was the recognition that these standards could not be achieved by controlling exhaust pipes and smoke stacks alone. Restrictions in the use of the personal automobile would also be required.

Publication of this paper sponsored by Committee on Passenger and Freight Transportation Characteristics.

FEDERAL AIR POLLUTION PROGRAM

The 1970 California plan was to be carried out over a period of 15 to 20 years. Before the public had a chance to evaluate ARB's action, the federal government intervened with the Clean Air Amendments of 1970. As a result, the U.S. Environmental Protection Agency (EPA) established national ambient air quality standards that were more restrictive than those proposed by ARB. The major difference between the two plans was the time allowed for implementation. Instead of a transition period of 15 to 20 years, the federal program was to be implemented on what might be considered a crash basis—by 1975 or 1977 at the latest, as shown in Figure 1 (1). As required by the federal law, California developed an implementation plan for achieving the national ambient air quality standard for the state. It is in this plan that a 20 percent reduction in vehicle-miles of travel (VMT) in 1977 is proposed.

ANALYSIS OF TRAVEL IN THE BASIN

The number of registered motor vehicles in Los Angeles, Orange, Riverside, San Bernardino, and Ventura counties in 1972 was 6,182,482. Although the South Coast Air Basin does not include some of these counties in their entirety, the major portion of their population, vehicle registration, and travel is within its boundaries.

The Los Angeles Regional Transportation Study (LARTS) shows that 20,300,000 vehicle trips are made on an average weekday compiling 134,000,000 vehicle-miles (215 000 000 vehicle-kilometres) of travel. On the average Saturday or Sunday, 14,700,000 vehicle trips are made compiling 105,900,000 vehicle-miles (170 000 000 vehicle-kilometres) of travel.

Based on these figures, average Saturday or Sunday travel is 70 percent of average weekday travel and average Saturday or Sunday trip-making is 73 percent of average weekday trip-making. Other trip characteristics are given in Table 1.

LARTS data show that 628,400 trips are made daily to the central business district (CBD). This represents only 3.1 percent of the LARTS trips. Another survey was conducted on a significant length of a major freeway providing direct access to central Los Angeles. Approximately 6,260 postcards were handed out during this survey to drivers during the morning commuting period between 6:15 and 8:00 a.m. Nearly 2,560 of these were returned. Responses indicated that 300, or 12 percent, of the drivers were destined for the downtown area, 15 miles (24 km) away. This analysis shows that downtown commuting, even on freeways, is not the major reason for travel.

Transit service in the basin is provided by 13 public transit companies. In 1972 these companies operated 2,005 buses that traveled 78,700,000 miles (120 000 000 km) and carried 208,000,000 passengers. There is now no fixed-rail transit in the basin. The last fixed-rail transit facilities were abandoned in the early 1960s.

In 14.9 percent of the households in the LARTS area, no vehicle was available (1967 data). In 85.1 percent of the households, at least one vehicle was available; and in 44.1 percent, two or more vehicles were available.

Work-related trips had the lowest vehicle occupancy of all trip types. Average vehicle occupancy for each trip type is given in Table 2.

INCREASING THE USE OF OTHER TRAVEL MODES

An essential part of any program to reduce auto vehicle-miles traveled is the improvement of other travel modes. The following is an analysis of various proposals for improving these modes. (One suggestion for improving public transit, the development of rail rapid transit, has not been considered because it cannot be implemented by 1977.)

Improving Public Transit

Public transit currently accounts for slightly over 2 percent of the total person trips in the basin. It accounts for over 20 percent of all commuter trips to the Los Angeles CBD but only 5 percent of all commuter trips. In eastern cities the data indicate that 27 percent of all commuter trips are carried by public transit. Much of the reason for the small percentage in the Los Angeles area is the well-developed highway system.

There are, however, various steps that can be taken to make public transit more attractive and increase its use.

Preferential Treatment for Buses on Freeways—The time relationship between the highway system and the bus system, based on LARTS data, is shown in Figure 2. Plans are being made to provide preferential bus and car pool treatment, like the San Bernardino Busway, on other freeways to substantially change this time relationship.

The San Bernardino Busway runs parallel to the San Bernardino Freeway from El Monte to the east of downtown Los Angeles. The eastern seven miles is complete and ready for use. When the full 11 miles is in operation in 1974, the time savings for each passenger, compared to a bus trip without the exclusive lane, is expected to be 15 to 18 minutes. It is anticipated that when the lanes are open full length, bus volumes will reach 100 per hour.

The U.S. Department of Transportation also has a freeway operations improvement program in the Los Angeles area. One aspect of the program is to keep the freeways free-flowing by ramp metering. Traffic signals are placed at on-ramps to interrupt access to the freeway. In theory, the freeways remain uncongested and, once the motorist gets through the meter, he or she is compensated for the wait because the freeway is free-flowing. During the most congested period, delays due to traffic backup at the meter reach about 8 min. Buses are allowed to bypass the meter, thus saving passengers these 8 min.

Increased Public Transportation Service—Many people in the basin have no access to public transportation and are completely dependent on the auto. But even if it were possible to double the basin's transit fleet by 1977, only 4 percent of the total trips now being made could be handled. Table 3 (2, 3) gives a comparison of the availability of transit in the Los Angeles area to that of other large metropolitan areas in the east.

Encouraging Commuter Car Pooling

Based on the occupancy rate of 1.1 (Table 2) for private vehicle use for commuting in the basin, there are 11 people in each 10 cars driven to work. Obviously, if the vehicle occupancy were increased and the trip demand remained constant, there would be a decrease in total VMT.

During World War II when there was extreme rationing and a limited number of vehicles, the average occupancy during the peak period was 1.7 persons per vehicle. It is difficult to expect a higher vehicle occupancy now even with rationing. In California, a 1.7 vehicle occupancy during the peak period would result in a 30 percent reduction in home-work travel and a 7 percent reduction in overall travel. But a 7 percent reduction through voluntary measures is optimistic. A more reasonable figure might be 2 to 3 percent.

Improving Other Facilities

As restrictions are placed on the use of the automobile, both bicycle and pedestrian travel can be expected to increase and improvements in their facilities will be needed.

Bicycle Facilities—Most bicycle riding is for recreation, but bikes are a regular means of transportation for the young and some adults. Bicycle use in Europe (though decreasing at this time) indicates that this form of transportation could replace the automobile for some short trips. According to LARTS data shown in Figure 3, 10 percent of total VMT is for trips of less than 3 miles in length. Bicycling could become more popular in this range.

Bicycle sales are currently at an all-time high nationally, exceeding new car sales. One reason for this is the acceptance of the 10-speed bicycle, which makes it easier to pedal longer distances. Some small cities such as Davis, California, having experienced a marked increase in bicycle use, found it advantageous to build bike trails, designate special traffic lanes, and provide special bicycle parking facilities. More cities are following this example.

With increased bicycle use comes increased safety problems. In 1971 in California there were 8,573 bicycle injuries or deaths, an increase of 35 percent over the previous year. Better bicycle facilities could improve this safety record, but there is no ap-

Figure 1. Expected South Coast Air Basin oxidant levels.

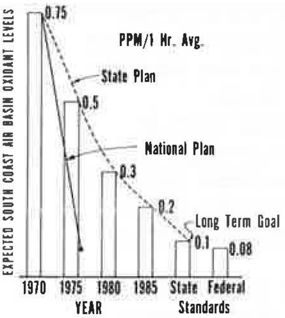

Table 1. Trip characteristics and relationships.

Trip Type	Average Length of Weekday Trips (miles)	Daily VMT (percent)	
		Five Day	Seven Day
Home-work	9.0	32	25
Work-other	7.2	11	75
Home-shop	3.0	7	
Home-other	5.7	27	
Other-other	4.7	23	
All trips	5.9	100	100

Note: 1 mile = 1.6 km.

Table 2. Vehicle occupancy rates.

Trip Type	Average Weekday	Average Saturday Sunday
Home-other	1.7	2.0
Other-other	1.3	1.6
Work-other	1.1	1.1
Home-work	1.1	1.1
Home-shop	1.4	1.5
All trips	1.4	1.8

Figure 2. Automobile bus 30-minute isochrone from downtown Los Angeles.

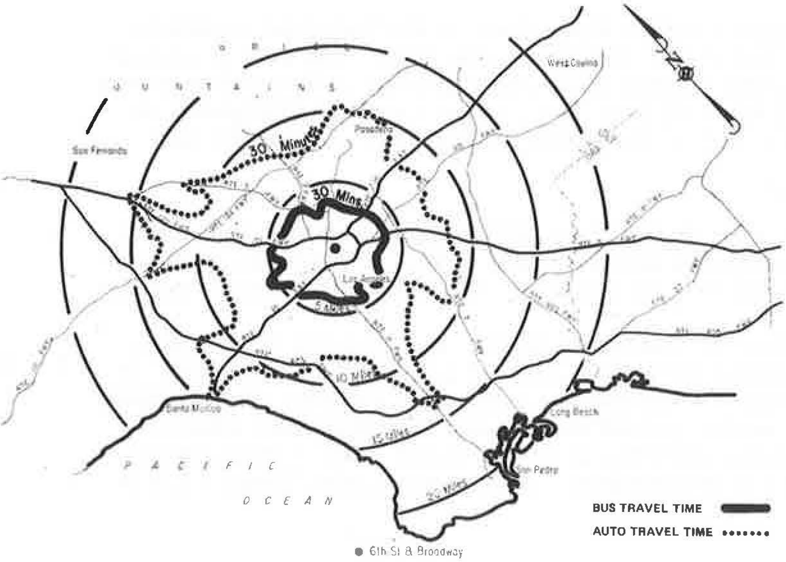

Figure 3. Distribution of miles driven by trip length for all trip types.

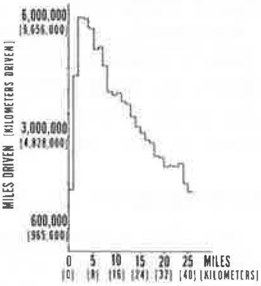

Table 3. Availability of transit.

Area	Commuter Trips by Transit (percent)	Available Daily Seat-Miles per Person
Los Angeles	4.8	1.00
New York	39.0	4.88
Boston	20.1	2.65
Chicago	24.4	2.89
Baltimore	16.9	1.94

Note: 1 mile = 1.6 km.

Table 4. Reduction strategies.

Strategy Description	VMT Reduction (approximate percent)
Improved public transit	3
Improved public transit and tax on auto use	4
Auto-free zones	0.6
Increased parking cost	Negligible
Four-day workweek	0.6
Exclusive bus and car pool lanes	2.5
Exclusive bus and car pool lanes[a]	3.2
Increased commuter car pools[b]	4.4

Note: The percentage figures cannot be totaled because some of the strategies are competitive.

[a] With 3 cents per mile tax.

[b] Average freeway automobile occupancy of 1.5.

Figure 4. World and U.S. vehicle registratio of cars, buses, and tru

parent economically satisfactory way to provide for the bicycle on crowded city streets or along many busy highways or freeways.

Pedestrian Facilities—The public does not generally view walking as a substitute for auto travel. Nationally, about 5 percent of the work force walks to work (4). This, of course, includes workers in all of the small communities. The percentage for the basin would be expected to be less.

There are currently many needs for improving pedestrian facilities and, no doubt, these improvements would attract additional walkers, but improved pedestrian facilities cannot be expected to result in any measurable reduction in total vehicle travel.

Reduction Strategies

Others have come to the conclusion that it is difficult to attract people into using other modes of travel. Preliminary analyses indicate that some reduction in VMT could be achieved by using various strategies (5). The strategies and the percentage of reduction estimated are given in Table 4.

Data given in Table 4 are based on the optimistic assumption that there will be no increase in travel demand. Considering the low demand for public transit as a substitute for the private car, it is most unlikely that any of the estimated reductions will be reached.

PROPOSALS FOR RESTRICTING THE USE OF THE AUTOMOBILE

The data presented in the preceding section lead one to conclude that the goal of reducing VMT by 20 percent cannot be achieved by merely improving other travel modes and relying on voluntary shift. The next step in planning to meet the goal is to analyze methods of restricting the use or reducing the utility of the private car.

Rationing

Rationing by one method or another is most often suggested for reducing travel. The arguments for rationing are (a) it has the potential of providing equally for all people, (b) it does not require large initial expenditures on the part of individual motorists, (c) we have prior experience with rationing, (d) results are immediate, and (e) the program can be terminated at any time. There are, of course, many administrative and enforcement problems.

Some proposals suggest that rationing be applied only during the smoggy season (summer and autumn). But, people must have an alternate mode to meet their travel needs. It is not economically practical to provide for this by having a large standby bus fleet for use only during this rationing period.

If the amount of fuel allowed each individual were based on individual needs, then gas rationing could provide some degree of equity for all people. People could compete equally for the limited supply of fuel. This is the ideal case. In reality, however, many individuals would find "special deals," and we could expect black-marketing problems similar to those which occurred during World War II. One suggestion for overcoming enforcement problems is to have an open market for ration stamps. This is the system currently being considered by the federal government. Regardless of the specific method used, the ration area would have to be extended beyond the basin limits by approximately 100 miles (160 km) to prevent frequent trips across the border to obtain unrationed fuel.

Reducing the supply of fuel to individuals by 20 percent would not result in an equal drop in vehicle travel. Rationing would accelerate the swing to small cars and motorcycles. The switch to smaller vehicles would offset actual emission reductions, since exhaust pollutants are a function of miles driven and are not directly related to the fuel consumed (6).

Mileage Quotas

Another way to reduce travel is to assign mileage quotas for each automobile. If the automobile is driven more than the quota allows or if inspections indicate that the odometer seal has been broken, the owner could be fined or the vehicle impounded for a period of time. This procedure could have many variations. Individual cases could be examined in an attempt to provide greater fairness or the system could be used to place even more stringent restrictions on older high-emission vehicles than on newer low-emission vehicles.

Odometers would be checked at annual inspections, roadside checks, and at change of ownership. Border checks would have to be set up in order to adjust quotas for mileage driven outside the basin.

Taxation

Many proposals for restricting automobile use are directed at increasing the price of operating a vehicle to the point where people will reduce vehicle travel. This is an application of the traditional market mechanism for allocating goods.

There has been little effort to increase vehicle taxation to cover the cost of air pollution. For example, California's annual agricultural losses due to air pollution have been estimated at $44,000,000. If 80 percent of this loss is associated with vehicle emissions, it would cost about $5 per vehicle to compensate for these losses. The figure would be higher if all vehicle-related air pollution losses were incorporated in the cost of operating the automobile.

The perceived marginal cost for any given short automobile trip is near zero (7). In planning a program to reduce vehicle travel, it may be more important to increase the perceived cost than the actual cost. Unfortunately, most of the methods suggested for increasing the perceived cost include frequent but inefficient methods of collecting the tax. These "frequent reminder" taxing methods, such as toll collection, though they could be set high enough to discourage vehicle use, involve high collection cost and thus reduce available revenue that could be used to improve alternate modes of transportation.

There is little empirical data for using high taxes to limit fuel sales. All evidence indicates that the price-demand elasticity for gasoline is very small. In some European countries where fuel costs are the equivalent of $0.80 to $1.00 a gallon ($0.21 to $0.26 a litre), the use of the automobile is increasing at 10 to 20 percent per year (8). Figure 4 (10) shows the worldwide increase in vehicle ownership. Large increases in vehicle use are occurring in areas where income levels are much lower than in the basin and where effective public transit systems are available.

If the people of the basin should select a high gas tax as a method of reducing travel, additional research would be required to develop a recommended taxing level. Demand forecasts developed by others indicate an order of magnitude of the price elasticity of demand for motor fuel of 0.16 to 0.07. If 0.10 is used as an arc elasticity over the range in question, then the price of gasoline (including tax) would have to be increased by 200 percent to achieve a 20 percent reduction in the fuel sales. This means that fuel now costing $0.38 per gallon ($0.10 a litre) would have to be priced at $1.10 per gallon ($0.29 a litre) to reduce consumption by 20 percent.

Another approach to increasing the cost of motor fuel is to limit the total amount of gasoline sold in the basin by rationing fuel at the wholesale level and then letting the retail price respond to demand. The supply and demand would probably equalize when prices reach the range reported above.

REDUCING THE CONVENIENCE OF THE AUTOMOBILE

A major reason that the automobile enjoys overwhelming popularity is that it is the most effective system yet devised for fulfilling many personal desires. Flexibility and convenience are two of these desires but there are others. Henry Ford II was quoted as saying, "When you put a fellow behind the wheel, he gets a different feeling about himself. It is a feeling of independence that he is not likely to get on a bus or a train" (9).

One approach that could be used to reduce vehicle travel is to limit its flexibility and convenience and, therefore, its ability to satisfy the users' desires by restricting automobiles from certain areas, increasing trip time by lowering speed limits, and limiting the days that certain vehicles can be driven.

The following are some often-suggested methods for reducing travel and conclusions as to their usefulness.

Restricting Through Traffic

The traffic passing through the basin is less than 1 percent of the total travel. Because of the geographical size of the basin and the difficulties in bypassing it, there is no justification for restricting through traffic.

Changing the Workweek

There are several ways that a reduced workweek can be set up, but in this analysis we assume that a four-day plan is spread over six working days, Monday through Saturday, and that 80 percent of the labor force is on the four-day workweek. A 15 percent reduction in work travel could then be expected.

Because commuter driving represents about 31 percent of workday travel, we should expect 6 percent weekday travel reduction. However, many additional miles would be driven on the extra day off. As reported in the section on travel analyses, normal Saturday or Sunday travel in the basin is only about 20 percent below weekday travel. Personal travel on the extra day off might be somewhat less than on Saturday or Sunday because children would be in school and spouses would be working. At best, the four-day workweek might achieve a 4 percent reduction in VMT.

Limiting Growth and Development

Limitations on population growth and urban expansion in the basin have a great potential for limiting travel in the long run. But within a five-year period, reversing current population trends or modifying land-use patterns would be difficult. Even if all residential and commercial building were curtailed, greater use of existing facilities would allow continual population increase and dispersion in the basin in the short run.

SUMMARY AND CONCLUSIONS

A 20 percent reduction in vehicle travel cannot be achieved in the short term by attracting people to other travel modes. The reluctance to give up the personal automobile has been attributed to many factors, including its superiority in meeting personal requirements such as the desire for privacy, flexibility, and convenience.

There are other factors that make the automobile more of a necessity in the basin than in many of the other urban areas. This stems from the general urban form and the low population density. The population density for Los Angeles is about one-half that of San Francisco, Washington, D.C., and Chicago and one-fourth that of New York City. These high-density cities all have considerably more use of public transit than does the Los Angeles metropolitan area.

The suburban types of developments that are characteristic of this area are directly associated with the low population density and high vehicle use. To compound the problem, primary access to many employment opportunities and new shopping facilities is by private motor vehicle. If this characteristic life-style expands, the difficulty of providing adequate public transportation will increase.

A substantial reduction in VMT by 1977 cannot be achieved through voluntary measures. Neither can it be achieved by improving public transportation nor by incentives for using other travel modes. It will have to be accomplished by the use of constraints. If constraints are placed on the use of the automobile, it is clear that car pools will be formed, transit service expanded, walking and bicycle use increased, and many trips shelved. Some of the vehicle travel constraints that are discussed in this report could be combined into an acceptable package aimed at meeting the goal of reduced VMT. Some proposals such as increasing the availability of public transportation in the basin and providing preferential freeway access for buses and car pools to maintain free-flow conditions would appear to be valuable portions of any plan. However, the major effort to control VMT growth in the long term must be in land-use restrictions and areawide planning.

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ENVIRONMENTAL IMPLICATIONS OF AUTOMOBILE-FREE ZONES

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The purpose of this paper is to clarify some of the environmental issues associated with automobile-free zones and to determine whether automobile-free zones can reduce environmental problems. It is designed to give planners an overview of the subject and to suggest some procedures for future studies. Past experience with automobile-free zones has indicated that noise and air pollution are significantly reduced on streets where automobiles are banned. As to the wider, external effect of automobile-free zones, few or no data exist, but an analytical procedure is suggested to assess this effect: compare trips to a target area, with and without the automobile-free zone, and convert this trip information into pollution-emission data. Although the relationship between automobile-free zones and nonautomobile modes is not certain, it appears that these modes conserve more energy than do automobiles and that they emit lower levels of certain pollutants. To reduce area-wide environmental problems, it is suggested that automobile-free zones be centrally located in relation to market areas and transit systems, that provisions be made to handle rerouted traffic, and that use of nonautomobile modes to automobile-free zones be encouraged.

•THE PRACTICE of reserving areas free of road traffic can be traced back to ancient times but current interest in this concept stems from the problems generated by automobiles in modern cities. The term automobile-free zone (AFZ) might apply to any area in which traffic is banned, but in this paper it will refer to districts of high activity in urban areas where the use of private automobiles has been severely curtailed or prohibited. A common example is a central shopping district closed to automobile traffic on a full- or part-time basis. AFZs can also be found in residential, institutional, and recreational areas.

It has been maintained that the creation of AFZs will help reduce the environmental damage caused by automobiles. This paper will investigate this claim in greater depth. For the purposes of this paper, "environment" will be used in a somewhat restricted manner to refer only to air quality, noise level, and natural resource consumption. Analytical procedures for further research will be suggested throughout the text.

ENVIRONMENTAL EFFECTS OF AUTOMOBILES

With regard to AFZs, the major environmental effects of automobile use have been air and noise pollution. The following is an overview of these two phenomena as a background for studying AFZs.

Air Pollution

The most lethal environmental effect of automobiles is the pollution caused by engine exhausts. Based on Environmental Protection Agency data for 1971, motor vehicles

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account for as much as 62 percent of all nationwide carbon monoxide emissions (Table 1). This percentage is even higher when only urbanized areas are considered as in Table 2 (10). Air pollution is usually measured in terms of the concentration of pollutant over time [such as parts per million (mg/m^3) of air per hour] or in terms of pollution to vehicle usage in grams per vehicle-mile.

The primary pollutants in automobile exhaust are carbon monoxide (CO); hydrocarbons (HC); nitrogen oxides (NO_x), mostly nitrogen dioxide; lead (Pb); and particulate matter. Larger automotive engines also emit considerable amounts of sulfur oxides (SO_x), mostly sulfur dioxide. Lead is generally excluded from emission tables because of the current uncertainty regarding its effect and criticality; sulfur oxides are included in emission tables because of their significance as emissions from stationary sources and from nonautomobile modes of transportation. The effects of these pollutants on humans, in the amounts common in urban areas, range from the irritation of mucus membranes to the shortening of the lives of many individuals (1).

Air pollution can vary from place to place, depending on such factors as local climatic conditions and the physical structure of the environment. Even local design considerations play a role. For example, pollution is generally magnified on streets fronted by solid rows of tall buildings, which interfere with normal wind patterns; these conditions can create heated channels in which inversion layers are formed and photochemical processes are made easy.

The emission rates of automobiles vary considerably; high engine displacement, cold starts, poor engine maintenance, leaded fuel, and stop-and-go driving conditions all contribute to higher pollution. Average emission rates, in grams per vehicle-mile (1 vehicle-mile = 1.6 vehicle-kilometre), for automobiles in 1973 were as follows:

Pollutant	1973	1974
CO	62	56
HC	8.5	7.5
NO_x	5.4	5.2
SO_x	0.2	0.2
Particulates	0.6	0.6
All	76.7	69.5

Standards have been formulated by the U.S. Environmental Protection Agency for the emissions of various engine types and for the air quality of entire geographic regions.

Noise

Less dangerous than air pollution, but perhaps more annoying, is the problem of vehicular noise. This has several sources, but recent studies have identified the chief cause in automobiles as tire-roadway interaction and in trucks as exhaust noises (3).

Noise levels are measured in decibels (dB) on a logarithmic, rather than an arithmetic, scale. For example, a decrease of only 10 dB appears to an observer as a halving of the original noise. A soft whisper at 5 ft (1.5 m) will register about 34 dB; the interior of a quiet office will average around 55 dB; and the sound level at the side of an expressway may be as high as 90 dB (4). Since the human ear does not respond in the same manner to all frequencies, a special "A-weighted" scale is generally used for measurements with sound-level meters. This scale gives readings in dBA, a measure that more accurately represents the apparent noise levels of vehicles. Because noise is a function of varying sound levels occurring over time, a tenth percentile (L_{10}) measurement is often used. This indicates a specified median noise level exceeded during only 10 percent of the period in question. Decibels indicate only sound level or intensity, and thus, high-pitched and intermittent sounds, which are more objectionable than low-pitched and steady sounds, are not distinguished by simple dBA measurements.

The effect of traffic noise on humans seems to be more a matter of psychology than physiology. A number of studies have pointed to "annoyance" as being the most widespread effect (5, 6). It is doubtful that highway noises alone cause hearing damage, but the effects of noise annoyance on behavior and mental health cannot be disregarded. One report found that high noise levels are often accepted by the public because noise is "no worse here than elsewhere" or "busy areas are expected to be noisy" (7).

Sound levels measured 50 ft (15.2 m) from vehicles traveling at 30 to 39 mph (13.5 to 17.5 m/s) average from 60 to 70 dBA for autos, 63 to 82 dBA for motorcycles, and 72 to 86 dBA for trucks. A single automobile will register about 65 dBA while traveling along a roadway, and a stream of automobiles may average as high as 78 dBA. A number of studies have reported that heavy trucks in the traffic stream constitute the primary source of highway noise complaints. These can be responsible for sound levels in excess of 95 dBA (8). It appears that sound-level complaints are associated more with individual vehicular noise than with volume flow (7). Complaints of traffic noise generally occur when levels rise above 68 or 70 dBA (3).

Various agencies have attempted to set maximum noise levels. These commonly range from a low of 45 or 50 dBA for quiet areas at night to a high of 75 dBA for busy areas during the day (3). Ambient noise in cities is already at a level of about 60 dBA during the day and 50 dBA at night (3).

EFFECTS WITHIN THE AFZ

It would seem logical that, if automobiles are banned from a particular area, the environmental nuisance they create in that area will be reduced. To test this, a number of experiments have been conducted before and after the restriction of automobiles in certain districts, and a selection of these is summarized on the following pages and in Tables 3 and 4 (8, 9, 10). The only air pollutant measured by the studies quoted here is CO. This is because CO is more inert and more localized than the other pollutants and it is generally easier to associate changes in the CO levels along roadways with changes in automotive use.

All "before and after" studies should be carefully examined with regard to methodology and basic assumptions. Only a series of observations taken over a period of time can be considered valid. Because data collection procedures vary widely in different studies and direct comparisons of results are of doubtful value, the information presented here is perhaps more useful for indicating what ranges can be expected in reducing noise and air pollution, than for comparing and predicting precise levels. Although the studies presented here may not be directly comparable, they do confirm that local levels of noise and air pollution have been lowered significantly where auto traffic has been restricted.

Gothenburg, Sweden

Since 1970, the center of Gothenburg has been divided into quadrants, and through traffic between these quadrants is prevented by physical barriers. Only transit vehicles and local automobiles enter the core area. These measures reduced CO concentrations by 25 ppm (28.75 mg/m^3) from 30 to 5 ppm (34.50 to 5.75 mg/m^3). Noise tests indicated a drop of 3 dBA in the average level from 75 to 72 dBA (8).

Marseilles, France

A series of experiments at limiting traffic was carried out in the central area of Marseilles in October 1971. For 10 days, private automobiles were banned and only taxis and buses were allowed into the core. Surveys taken before the ban indicated CO concentrations averaging 18.8 ppm (21.62 mg/m^3), while the levels during the ban averaged only 3.6 ppm (4.14 mg/m^3). A second experiment was carried out in which traffic was again allowed into the core, but all parking was prohibited. The results of this test were less dramatic, but the CO level was still reduced by as much as 44 percent to an average of 10.4 to 12.9 ppm (11.96 to 14.835 mg/m^3) (8).

New York City

In April 1971, New York City's Department of Air Resources conducted tests to determine the reduction of noise and air pollution that resulted from prohibiting all traffic

Table 1. Estimated nationwide emissions of five major pollutants, 1971.

Source of Emission	CO	HC	NO_x	SO_x	Particulates
Gasoline motor vehicles[a]	62.2	11.4	6.8	0.2	0.7
Other vehicles	15.3	3.3	4.4	0.8	0.3
All modes	77.5	14.7	11.2	1.0	1.0
Stationary facilities	1.0	0.3	10.2	26.3	6.5
Industrial processes	11.4	5.6	0.2	5.1	13.5
Solid waste disposal	3.8	1.0	0.2	0.1	0.7
Other	6.5	5.0	0.2	0.1	5.2
All sources	100.2	26.6	22.0	32.6	26.9

Note: Amounts are in millions of tons, where 1 ton = 907.18 kg.

[a] Gasoline motor vehicles account for 62 percent of CO emissions, 43 percent of HC emissions, 37 percent of NO_x emissions, 0.9 percent of SO_x emissions, and 3 percent of particulate emissions.

Table 2. Contribution of motor vehicles to total atmospheric emissions in twelve metropolitan areas.

City	CO	HC	NO_x
Stockholm	99	93	53
Tokyo	99	95	33
Osaka	99	95	25
Los Angeles	98	66	72
Toronto	98	69	19
New York City	97	63	31
Washington, D.C.	96	86	44
Madrid	95	90	35
Chicago	94	81	35
Pittsburgh	80	70	29
Ankara	75	57	52
Philadelphia	70	47	27

Note: Amounts are in percentages of total emissions.

Table 3. Reductions in carbon monoxide levels before and after the restriction of automobiles.

			Reduction	
Area	Before	After	Amount	Percent
Gothenburg, central area	30.0	5.0	-25.0	83.3
Marseilles				
Auto ban	18.8	3.6	-15.2	80.8
Parking ban	18.8	11.6	-7.2	38.2
New York, Madison Avenue	14.0	6.9	-7.1	50.7
Tokyo				
Asakusa	2.5	2.1	-0.4	16.0
Ginza	8.3	2.6	-5.7	68.6
Ikebukuro	7.3	3.5	-3.8	52.0
Shinjuku	7.7	2.0	-5.7	74.0
Vienna, central area	7.4	4.1	-3.3	44.6

Note: Amounts are in parts per million, where 1 ppm = 1.15 mg/m^3.

Table 4. Reductions in noise levels before and after the restriction of automobiles.

			Reduction	
Area	Before	After	Amount	Percent
Gothenburg, central area	75.0	72.0	-3.0	4.0
Tokyo, Ginza	75.0	70.0	-5.0	6.4
New York, Madison Avenue	73.2	66.4	-7.2	9.8
Vienna, central area	—[a]	—[a]	-3 to -6	

Note: Amounts are in dBA.

[a] Not available.

(except buses) on a major street. The tests were made on Madison Avenue, which was closed from noon to 2:00 p.m. on weekdays for 2 weeks. The department reported that a 40 to 75 percent reduction of the usual morning concentrations of CO occurred during the periods of the traffic ban. Their data indicated that the periods ordinarily exhibiting levels as high as 22 or 23 ppm (25.30 or 26.45 mg/m^3) never rose above 9 ppm (10.35 mg/m^3) and sometimes went as low as 3.5 ppm (4.025 mg/m^3). After the street closing experiment ended, pollution levels went up to their previous levels or higher (9).

Noise measurements taken during the traffic ban averaged 65 to 68 dBA, in contrast to the usual 70 to 78 dBA. Intermittent peak values also decreased to 72 to 82 dBA during the ban, from 79 to 106 dBA. General background noises under both ban and nonban conditions were in the 60 to 68 dBA range (9).

Tokyo

Since 1970, autos have been banned from the Ginza, Shinjuku, Ikebukuro, and Asakusa shopping districts of Tokyo. The ban is in effect on Sunday, the busiest shopping day in Japan. Counts of carbon monoxide concentration indicated reductions of up to 80 percent; AFZ counts averaged around 2.5 ppm (2.875 mg/m^3). Although median noise levels reportedly were reduced by 5 to 7 dBA (8) these results may have been based on an inadequate sample size.

Vienna, Austria

An AFZ has been in effect in Vienna since 1971; only buses and service vehicles are allowed to enter the central area between 10:30 a.m. and 7:00 p.m. Measurements indicated CO reductions of 45 to 65 percent, to about 9.1 ppm (10.465 mg/m^3). Noise has decreased by 3 to 6 dBA although a slight increase in noise has been reported on adjacent streets during delivery hours (10). Vienna now plans to enlarge the AFZ.

EXTERNAL EFFECTS OF THE AFZ

The many air and noise quality studies of AFZs have concentrated mainly on the immediate effects on the streets in which autos have been banned. Very little information is available on the environmental effects outside the AFZ.

For example, the establishment of an AFZ might simply divert large volumes of traffic from the closed-off streets to adjacent roadways, causing noise and pollution levels to rise in those areas. An AFZ might attract so much new traffic that pollution levels for the surrounding area would rise. Also, the elimination of direct paths of travel might cause increases in total vehicle-miles of travel (VMT) and thus compound the pollution problem. Or, an AFZ might induce many travelers to change to low polluting nonautomobile modes. The magnitude and nature of these problems remain conjectural, until further empirical data are collected. It seems obvious, though, that to determine the total environmental effects of an AFZ will require an analysis of the external effects as well as the internal ones. The following hypothetical situation shows how an analysis might proceed.

An AFZ is being considered for the central business district (CBD) of a small city. Changes in travel behavior are likely to result from this depending on the size of the AFZ in relation to the size of its affected area. Certain people may be attracted to the AFZ from peripheral shopping areas because of improved transit access or other such amenities, or others who formerly shopped in the CBD may be diverted to competing areas because of the AFZ's less convenient automobile access. There will also be a large group of trip-makers, such as workers in the area, who will continue to travel to the CBD whether or not an AFZ is established. If planners wish to estimate the overall effects on air pollution that these changes in travel behavior will generate, they might use the following procedure.

1. Establish the size of the area to be affected.
2. Calculate the trips generated in the affected area for present conditions, some future year with an AFZ, and the same future year with no AFZ. The estimation of

travel in the affected area can be based on existing models of trip generation and assignment. But because changes in travel behavior may be accompanied by shifts in the mode of transport used, modal split should be carefully calculated.

3. Translate trip information into noise and pollution emission data. The emissions for the three alternatives can then be compared to show the net increase or decrease in noise and air pollution in the affected area resulting from the establishment of the AFZ. The conversion of trip information into pollution emission data is fortunately not as formidable as might be expected. Computer simulation packages are available for predicting air pollution effects for alternative development plans. These require such data inputs as the traffic volume on each link of the roadway network, the characteristics of each link in terms of speed and congestion at various times of the day, and a set of emission factors. The outputs can be in kilograms of each pollutant emitted in the study area. When these models are combined with background emission and diffusion models, the actual concentrations of pollutants in particular subareas can be estimated (although at the present time this is only possible for carbon monoxide).

Similar models are available for predicting noise levels. They require the same types of data and produce a listing of links where the L_{10} noise level exceeds a specified dBA.

4. Summarize the information and calculate the net changes in pollution attributable to the AFZ according to quantity and types of pollutants and their distribution by area and time period.

AUTOMOBILE-FREE ZONES AND NONAUTOMOBILE TRANSPORTATION

The preceding section assumed that AFZs are more accessible to nonautomobile modes of travel than are conventional areas; that they encourage the use of nonautomobile modes; and that nonautomobile modes cause less environmental damage than do automobiles. This section will examine these assumptions in greater detail and will focus on mass transit.

Accessibility to Nonautomobile Modes

A flat statement cannot be made about the accessibility of AFZs to nonautomobile modes of transportation unless the circumstances relating to market area and site location are known. For example, an AFZ located at a junction point of transit lines that serve its market area is obviously much more accessible than if it were in a peripheral location. If the AFZ has a city- or region-wide market area, its accessibility is increased in or near the central core, because transit networks of American cities generally radiate from this point. Thus, only if an AFZ is properly located in relation to the spatial structure and transport network of its market area is its accessibility to nonautomobile modes of transit high.

Stimulation of Use of Nonautomobile Modes

If an AFZ is highly accessible by nonautomobile modes, do people use these modes instead of their cars? No simple answer can be given because of the lack of empirical data. Cases in which an AFZ has stimulated transit patronage have usually been complicated by realignments in transit service and shifts of riders from some routes to others.

In predictions of the overall effects on transit in the future, the following variables might be used as indirect indicators of the influence of an AFZ:

1. The type of transit system serving the AFZ, its level of service (both directly to the AFZ and throughout the affected area), and its marketing efforts;
2. Travel times to the AFZ by transit versus travel times by automobile;
3. Walking distances to destinations in the AFZ from transit stops versus walking distances from automobile parking and drop-off areas; and
4. Transit fares versus automobile parking rates and fines near the AFZ.

Another factor that may be important in stimulating the use of nonautomobile modes is the policy that dictates which modes will be excluded from the AFZ and which modes will be allowed to operate within the AFZ.

Environmental Effects of Nonautomobile Modes

If AFZs are shown to stimulate use of nonautomobile modes of transport, are these modes any better for the environment than automobiles? The answer to this question revolves around transit's effect on air pollution, noise, and resource consumption versus the automobile's effect.

Air Pollution—In a 1972 study by Scheel (11), emission data were collected under a variety of operating conditions for automobiles, buses, commuter trains, and rapid transit trains. These data indicated that the absolute levels of pollution were lower for vehicles with small power plants than for those with large ones (Table 5). Thus, total emissions were lower per vehicle-mile for automobiles than for public transportation modes. However, because public transportation is characterized by higher vehicle occupancy, the emissions of each mode were compared by passenger-miles and weighted by the relative effect of the pollutant being considered, where

$$\text{Relative effect} = \frac{\text{(g/vehicle-mile)(relative effect of air quality stds concentration)}}{\text{person/vehicle}}$$

These comparisons revealed that public transportation modes had lower CO and HC emission rates than automobiles, but higher SO_x and particulate emission rates (Table 6).

Noise—There is a lack of comparative data on noise levels because of the variety of data collection techniques and units of measure used in different studies. A survey taken in London indicated that local streets carrying bus traffic had average noise levels 0.5 to 4 dBA higher than those on local streets without bus traffic (12). Although levels even on the bus streets were well below the 70-dBA level likely to cause complaints, buses have noise characteristics similar to trucks and could be responsible for occasional annoying peaks throughout the day. The sound levels of rapid transit trains typically range from 81 to 110 dBA (4), but trains are generally confined to segregated corridors and would presumably not add significant noise to the street environment. The effect of elevated railways or personal rapid transit (PRT) systems could be more serious, however, depending on the type of system and its location. In any event, ambient noise caused by street traffic is high; if more use of public transit causes a decrease in traffic volume, a decrease could be expected in the level of ambient noise.

Natural Resources—Air and noise quality are not the only environmental factors of importance; energy requirements and resource consumption should be considered in future modal comparisons. Because of the current scarcity of energy sources, interest has focused on the efficiency of each transport mode in terms of fuel consumption. Figure 1 shows that, even with low average occupancy levels, public transport modes are considerably more efficient than automobiles in terms of passenger-miles per gallon (14). Policies that encourage increases of vehicle occupancy can significantly increase the efficiency of all modes but public modes are still likely to be more efficient because of their higher capacities.

Although energy consumption is an important issue, future studies of urban areas and their transportation problems need to examine other relationships of transportation to natural resources. One study that attempted to be more comprehensive concluded that "mass ownership of private automobiles is incompatible with any resource-conserving future, because autos and the industries they create are the predominant energy consumers in Western and Japanese society" (13). With this in mind, we can perhaps make more rational decisions regarding the structure of cities (including the applicability of AFZs) and the priorities to be placed on particular modes of transport. It appears that AFZs can be accessible to nonautomobile transit if they are properly located, but their effect on stimulating the use of nonautomobile modes is presently unknown. As for the nonautomobile modes themselves, they are generally more energy-conserving than autos; they emit less CO and HC per passenger-mile; and their use can

Table 5. Emission rates for various vehicle engines and operations.

Engine and Operations	CO	HC	NO_x	SO_x	Total
Automobile					
1970 standard	47	4.6	6.0	0.27	57.87
1975 standard	3.4	0.41	3.0	0.27	7.08
Bus, diesel					
Arterial street	28.3	1.65	36.3	5.2	78.53
Downtown	50.6	2.76	54.4	5.2	112.96
Bus, gas turbine					
Arterial street	4.0	0.20	10.5	5.2	19.90
Downtown	6.8	1.15	12.2	5.2	25.35
Commuter train					
Roots blown	1,040	80	234	48	1,402
Turbocharged	240	80	235	48	603
Rail transit					
Typical cycle	6.75	2.7	271	1,030	1,310

Note: Amounts are in grams/vehicle-mile, where 1 mile = 1.6 km.

Figure 1. Fuel efficiency of six urban transport modes.

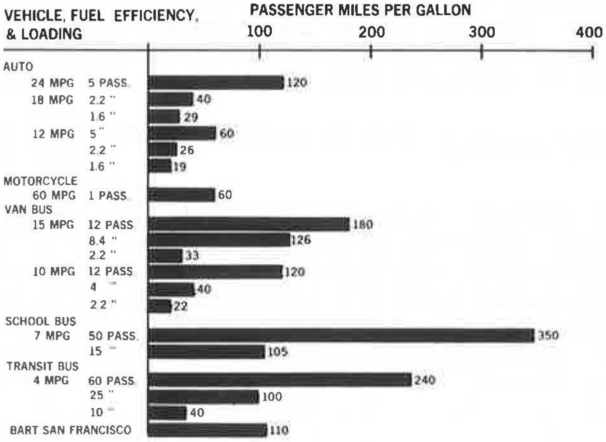

Table 6. Relative effects of emissions from 4 vehicle engines.

Engine and Operations	Gases						
	CO	HC	NO_x	SO_x	Total	Particulates	Total
Automobile							
1970 standard	0.24	1.56	3.27	0.18	5.25	0.25	5.50
1975 standard	0.02	0.14	1.63	0.18	1.97	0.25	2.22
Bus, diesel							
Arterial street	0.02	0.10	3.50	0.52	4.14	2.08	6.22
Bus, gas turbine							
Arterial street	0.003	0.012	0.97	0.52	1.50	2.08	3.58
Commuter train							
Turbocharged	0.004	0.08	0.58	0.10	0.76	0.33	1.09
Rail transit							
Typical cycle	0.00	0.002	0.72	3.40	4.12	1.54[a]	5.66

Note: Amounts are in grams/person-mile, where 1 mile = 1.6 km.

[a] Based on 7,250 g/ton (g/907 kg) of coal, 10 percent fly ash, and 80 percent collection efficiency on control equipment (by person-miles).

lead to lower ambient noise levels. Conversely, public transport modes generate greater emissions of SO_x and particulates and may be responsible for intermittent noise peaks. If it is found that the use of public transportation is stimulated by AFZs or by other resource-conserving strategies, then their ill effects should be made explicit from the start. Then true costs and benefits can be assessed, and appropriate measures applied.

CONCLUSIONS

The creation of an AFZ must be part of a comprehensive plan so that the overall environmental implications and the social and economic benefits can be properly assessed.

There is evidence to demonstrate that definite and often dramatic improvements in noise and air quality can be expected on streets where automobiles are banned. But, an AFZ can improve areawide environmental conditions only if specific conditions are achieved.

First, for regionwide markets, AFZs should be located in a central area because (a) travel distances to other points in the area will be short, resulting in less transport-related noise, air pollution, and resource consumption and (b) access by radially oriented transit systems will be high, encouraging some travelers to use public transit instead of automobiles. Automobile-free zones for neighborhood or district-scale markets should be near the junction of transit lines. This will ensure more transit access than a location along the midpoint of a single transit line would.

Second, the altered traffic patterns in areas adjacent to the AFZ should be anticipated so that traffic flows smoothly. Signal timing, street directions, and intersection geometrics should be adjusted where necessary. Parking should be strictly limited to certain off-street facilities to eliminate "cruising" by drivers looking for curb spaces. Streets used for rerouting traffic should be carefully chosen with respect to land use and existing pollution and noise levels. Increasing the parking supply by creating peripheral parking garages may enhance the economic feasibility of an AFZ but is likely to be counterproductive in terms of air quality and energy consumption.

Third, nonautomobile modes should be allowed to operate within the AFZ to encourage access by these modes. Bicycle lanes, especially, should be considered for access to the AFZ. If it is not feasible to allow public transit within the AFZ, transit stops should not be further away than automobile drop-off and parking areas. Undesirable effects of nonautomobile modes should be calculated in advance, and appropriate remedies applied if warranted.

The overall environmental effect of an AFZ depends entirely on its size and importance in relation to the rest of the region. Because transportation is a major source of noise and air pollution, a large AFZ, which meets the criteria outlined above, may have a significant effect on reducing regionwide environmental hazards. A small AFZ, which meets the same criteria, might have no regional effect at all but may have a significant local effect. Environmental considerations, which have in the past played a small role in urban decision-making, must be included in the planning process.

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A SIMPLE MODEL FOR ESTIMATING REGIONAL AUTOMOTIVE EMISSIONS

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A simple model for estimating regional automotive emissions of carbon monoxide, hydrocarbons, and nitrogen oxides is developed. The model is designed for use when rough, low-cost pollution estimates are desired. Traffic volumes are assumed to be available. Given the characteristics of the regional highway network, the model calculates the vehicle-miles of travel over different road types in each specified subarea of the region and the vehicle speeds at which travel takes place. Then by use of emission functions that relate the output of pollutants to vehicle speeds, emission estimates are calculated for the given travel pattern. An application to the Watertown, New York, region is discussed.

•OFTEN urban and regional transportation planners want to estimate emissions of pollutants from automotive sources under different sets of assumptions (1). Several elaborate methods for producing these estimates are available (2, 3, 5, 11). But, use of these methods requires investments in time, money, and labor that can easily outweigh the value of the results that are obtained. For policy exploration, rough, low-cost emission estimates are usually all that are required so the model developed in this paper is designed for those situations where highly accurate results are not necessary. The model is for use with travel forecasts that are already available and with a dispersion model capable of translating emission quantities into air quality.

OVERVIEW OF THE MODEL

When actual or projected traffic volumes for each link in a regional highway network for a specified time period are used as input, the model will provide estimates of emissions for each subarea of the region. The model is shown schematically in Figure 1. It is assumed that the region has been subdivided into separate and adjacent subareas for which emission estimates are to be provided and that the user has a detailed map of highway links and intersections for the region to be studied.

Each element of a model run can be classified as being a fixed component, an input component, or an output component. A model run is the calculation of emission levels for a given level of traffic over a set time period. In this context, a fixed model component does not change from run to run, but input and output components do change. Inputs are provided by the user and outputs are calculations produced by the model using the input and fixed components.

The model components can be described as follows (the letter designations correspond to those in Figure 1):

Type	Designation	Description
Fixed	A	A primary link/subarea map that specifies miles of primary highway links in each subarea in the form of a primary link/subarea matrix of road mileages. (From

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		these data, it is possible to calculate total link lengths in miles and the total road mileage in each subarea.)
	B	An equivalence network/subarea map that specifies miles of secondary highway links in each subarea.
	C	A set of functions relating emissions of selected pollutants, in pounds per vehicle-mile, to vehicle speed in miles per hour with adjustments for the different emission rates of different car model years.
	D	A delay subroutine breaking down road time into idle, speed changing, and cruise time from which an average vehicle speed is calculated.
Input	E	Estimates of traffic volume on each link of the primary road network for number of vehicles using the link during a designated time period and the average freeflow speed in miles per hour per car. (It is assumed that all cars travel at the average speed and that a relationship among speed, link capacity, and traffic density has been established.)
	F	Estimates of traffic volumes and the average free-flow speed over each link in the secondary highway network for total number of vehicles using the network during a designated time period.
Output	G	Estimates of emissions of each pollutant in pounds per time period for each link of the primary highway network.
	H	Estimates of emissions of each pollutant in pounds per time period for the secondary highway network.
	I	Estimates of total emissions in pounds per time period for each subarea and for the whole region.

So highway networks are fixed components; traffic forecasts are input components; and emission estimates are output components. But, fixed components may change; for example, they may change to accommodate a new road that may need to be included in the networks. The terminology, then, derives its meaning from the context of the model run.

MATHEMATICAL DETAILS

The following representation is a link/subarea incidence matrix for road type r in the primary network.

$$A^r = \begin{array}{cc} & \text{Subareas} \\ \text{Links} & \begin{bmatrix} a^r_{11} & a^r_{12} & \cdots & a^r_{1J} \\ a^r_{21} & a^r_{22} & \cdots & a^r_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ a^r_{I1} & a_{I2} & \cdots & a^r_{IJ} \end{bmatrix} \end{array} \qquad (1)$$

where

A^r = an $(I \times J)$ link/subarea incidence matrix for road type $r (r = 1, 2, \ldots, R)$;
I = total number of links;
J = total number of subareas;
R = total number of road types in the primary network;
j = subarea;
i = link; and
a^r_{ij} = number of miles of road type by link in a subarea.

We partition A^r into J column vectors by writing

$$A^r = (A^{r1}, A^{r2}, \ldots, A^{rJ}) \tag{2}$$

where A^{rJ} denotes the link vector for road type r in a particular subarea j (i.e., column j of A^r). Thus,

$$A^{rJ} = (a^r_{1J}, a^r_{2J}, \ldots, a^r_{IJ})' \tag{3}$$

for subarea j and road type r, where prime indicates transpose.

The following are matrices of $(I \times 1)$ vectors. $T^r = (T^{r1}, T^{r2}, \ldots, T^{rJ})$ gives subareal link trips for road type r, and $V^r = (V^{r1}, V^{r2}, \ldots, V^{rJ})$ gives subareal average link speeds for road type r. The partitions are constructed to correspond to Eqs. 2 and 3 for link mileages.

$$T^{rJ} = (t^r_{1J}, t^r_{2J}, \ldots, t^r_{IJ})' \tag{4}$$

and

$$V^{rJ} = (v^r_{1J}, v^r_{2J}, \ldots, v^r_{IJ})' \tag{5}$$

where

t^r_{ij} = traffic volume, in vehicles per day, on link i of road type r in subarea j, and
v^r_{ij} = average speed on link i of road type r in subarea j.

Assume that there are K pollutants of interest. We establish a set of pollution functions in the form

$$p(k) = f(v) \tag{6}$$

where

$p(k)$ = pounds of pollutant k emitted per vehicle-mile;
$f(v)$ = function of vehicle speed, in miles per hour; and
K = total number of pollutants.

We can construct a partitioned emissions matrix for each pollutant for each road type by using Eq. 6:

$$P^r(k) = \left[P^{r1}(k), P^{r2}(k), \ldots, P^{rJ}(k)\right] \tag{7}$$

where each partition (column) of the matrix $P^r(k)$ represents the pounds of pollutant k emitted per vehicle-mile at the corresponding average speed and highway links of road type r.

To calculate $m^r_{ij}(k)$—pollutant k emissions on a per mile basis for each link i of road type r in subarea j—we multiply corresponding elements of vectors T^r and $P^r(k)$:

$$m^r_{ij}(k) = (t^r_{ij}) \left[P^r_{ij}(k)\right] \tag{8}$$

for $i = 1, 2, \ldots, I$; $j = 1, 2, \ldots, J$; $k = 1, 2, \ldots, K$; and $r = 1, 2, \ldots, R$. The partitioned matrix $M^r(k)$, $[M^{r1}(k), M^{r2}(k), \ldots, M^{rJ}(k)]$ represents pollutant k per mile of each link of road type r for the traffic volumes in each subarea.

Total emissions of pollutant k for each road type r in each subarea j are then given by

$$E^{rJ}(k) = \left[M^{rJ}(k)\right]' A^{rJ} \tag{9}$$

for j = 1, 2, . . ., J; k = 1, 2, . . ., K; and r = 1, 2, . . ., R.

Finally, total emissions of pollutant k on primary networks are given by

$$E^J(k) = \sum_{r=1}^{R} E^{rJ}(k) \tag{10}$$

for k = 1, 2, . . ., K; and j = 1, 2, . . ., J.

This procedure estimates emissions over the R road types in the primary highway network. Slightly different calculations are carried out for the network of secondary roads. Because all secondary roads are considered collectively we have a link/subarea matrix

$$A^S = \left(a^s_{11}, a^s_{12}, \ldots, a^s_{1J}\right) \tag{11}$$

where S = total number of secondary roads. The (1 × J) vector $T^s_1 = (t^s_{11}, t^s_{12}, \ldots, t^s_{1J})$ gives subarea secondary traffic volumes, where t^s_{1J} represents the number of vehicle trips made per time period over secondary roads in subarea j. The corresponding (1 × J) vector giving average speeds is $V^S = (v^s_{11}, v^s_{12}, \ldots, v^s_{1J})$. The pollution functions given by Eq. 6 are the same for secondary networks.

We calculate pollutant k emissions on a per mile basis for the secondary network by the following equation:

$$m^s_{1J}(k) = (t^s_{1J})\left[p^s_{1J}(k)\right] \tag{12}$$

where $m^s_{1J}(k)$ represents the pounds of emission per vehicle-mile of pollutant k in subarea j over secondary links. The emissions vector for pollutant k is $M^S(k) = [m^s_{11}(k), m^s_{12}(k), \ldots, m^s_{1J}(k)]$. Total emissions of pollutant type k in each subarea of secondary links are then given by

$$E^{SJ} = M^S(k)(A^S)' \tag{13}$$

Total emissions, in pounds per time period, of each pollutant in each subarea are obtained by adding contributions from primary and secondary network sources (i.e., Eqs. 10 and 13).

APPLICATION

The emissions model was applied to the Watertown region (Jefferson County) in upstate New York. The region was subdivided into six subareas, each made up of one or more townships (Table 1). The goal was to estimate emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) in a subarea from automotive sources for one day in 1970.

Four road types were used (Table 2). Limited-access expressways, main arterials, and subordinate arterials formed the primary highway network, and township roads formed the secondary network.

To summarize the calculation procedure, subarea estimates are made of total vehicle-miles of travel in an average day for each road type. Travel on each road type is assumed to be at the speed limit (i.e., free-flow speed) adjusted downward for congestion, traffic signals, and other delays. Emissions per vehicle-mile of CO, NO_x, and HC are estimated by referring to emission functions that relate emission rates to

Figure 1. Schematic model.

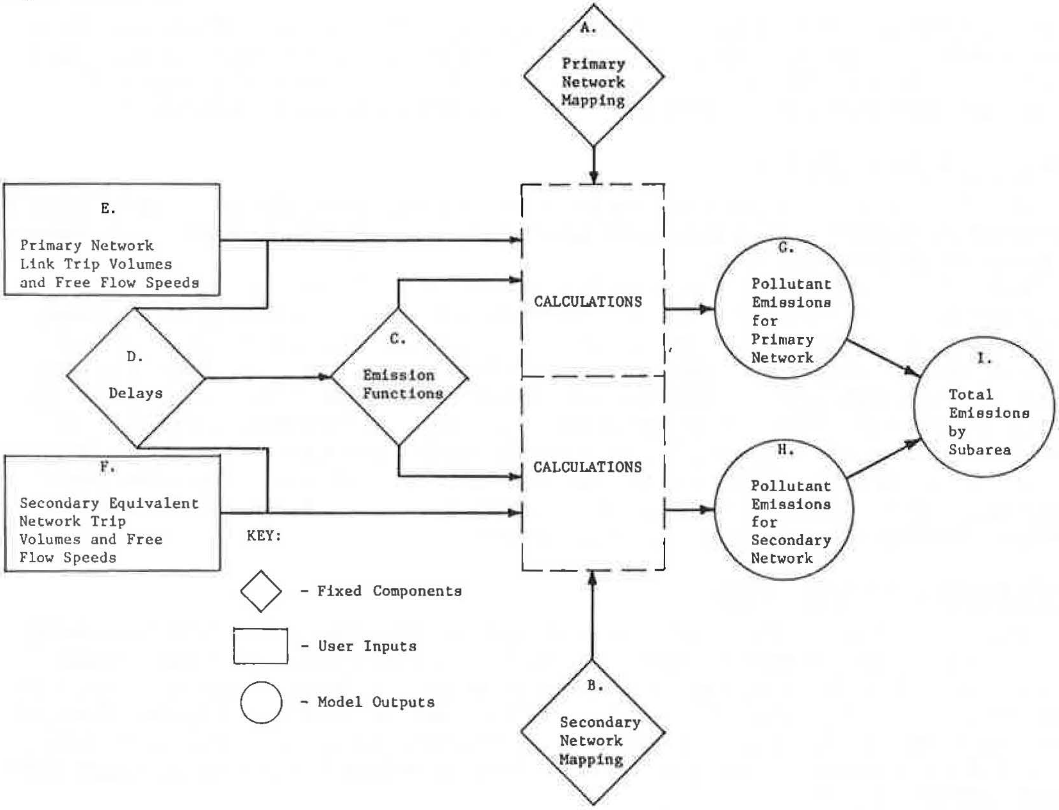

Table 1. Subarea composition.

Subarea	Townships	Subarea	Townships
1	Alexandria Cape Vincent Clayton Lyme Orleans	3	Pamelia Watertown
		4	Brownville Hounsfield
2	Antwerp Champion LeRay Philadelphia Rutland Theresa Wilna	5	Adams Ellisburg Henderson Lorraine Rodman Worth
		6	Watertown City

Table 2. Road types.

Road Type	Description	Watertown Region Example
1	Limited-access expressway	Interstate 81
2	Main arterials	State routes
3	Subordinate arterials	County routes
4	Tertiary roads	Township roads

Table 3. Dimensions of Watertown region highway networks.

	I-81		State Routes		County Routes		Township Roads		Total	
Subarea	Links	Miles	Links	Miles	Links	Miles	Links	Miles	Links	Miles
1	6	16	46	103	96	156	195	246	343	521
2	2	3	62	143	87	139	237	241	388	526
3	7	19	29	63	17	32	48	56	101	170
4	1	1	25	54	25	43	83	98	134	196
5	8	17	46	105	91	139	213	224	358	485
6	0	0	13	13	15	13	30	35	53	51
Total	24	56	221	481	331	522	806	900	1,377	1,949

Note: 1 mile = 1.6 km.

speed for the vehicle year under consideration. Then the emissions of each pollutant per vehicle-mile are multiplied by total vehicle-miles to give total emissions in each subarea for primary and secondary networks. The main elements of this procedure with particular reference to the Watertown region are described as follows.

Traffic Volume Estimates

The dimensions of the primary and secondary highway networks are given in Table 3. Information identifying each link in the highway system by location, length, and capacity were compiled in matrix form.

In developing estimates of average daily 1970 traffic volumes for each link of the primary road network and for all secondary network roads collectively, we were provided the following data by the Region 7 Office of the New York State Department of Transportation: statewide traffic volume reports for state routes, 1964-1971; traffic counts on Jefferson County roads and selected township roads, 1959-1967; TOPICS data for Watertown city, 1971; origin-destination study data for Watertown city, 1961; and special traffic counts performed on an irregular basis. Because these sources pertain to activity in different regions at different times; the estimates for regionwide travel activity in 1970 were put together from the information available for 1970 and other years. Traffic volume data are given in Table 4.

Calculation of Emission Factors

The emission rate for any pollutant is a function of vehicle speed. While traveling over any particular stretch of road, a driver may change vehicle speed many times—the vehicle may start, idle, alternately accelerate and decelerate, come to a partial or full stop for a traffic light, start again, accelerate and decelerate, and so on. Because emissions vary nonlinearly as the vehicle changes from one driving state to another, the emission estimation technique must take this variability into account to obtain realistic emission factors.

For this model, travel is divided into two categories: travel at free-flow speed and travel delay. The average delay on any road link is a function of the road type and the volume-to-capacity ratio. Once an estimate of average delay is obtained for each road link in the highway network, it is proportioned into two subcategories—speed-changing delays and standing delays. Emission rates are, in the end, calculated for cruising at free-flow speeds, speed changing, and standing.

Figure 2, developed from information in the Highway Capacity Manual (4), shows average delay for each road type; capacity is defined as that traffic volume at which traffic is at a standstill because of congestion. This underestimates true delay because it is assumed that no vehicle starts its trip on the road link in question (e.g., there is a zero average delay at low volume-to-capacity ratios) and it is also assumed that no travel takes place above free-flow speed when in reality high-speed travel does take place.

Table 5 gives the proportions used to separate delay time into standing and speed-changing components for each road type. These proportions are an extension of factors developed by the New York State Department of Transportation in connection with the development of a pollution emission model and described in unpublished material as "[developed from] theoretical considerations of the probable number of stops, stop durations, acceleration rates, deceleration rates and speed limits."

Emission functions that relate emissions, in pounds per vehicle-mile, to vehicle speed were developed from data collected from six sources (6, 7, 8, 9, 10). Figure 3 shows the function for carbon monoxide; Figure 4, for hydrocarbons; and Figure 5, for nitrogen oxides. These functions apply to 1970 and any years when emissions were uncontrolled. Adjustments of these functions for the effects of emission-control devices can be made by applying uniform percentage reductions of emissions on the vertical axis at the corresponding point for speed on the horizontal axis. The U.S. Environmental Protection Agency has published data to calculate these adjustments (10, Table 3.1.1-1).

Table 4. Estimated average daily vehicle-miles of travel, 1970.

Subarea	I-81	State Routes	County Routes	Township Roads	Total
1	20,000	215,000	38,000	16,000	289,000
2	8,000	459,000	45,000	21,000	533,000
3	54,000	202,000	15,000	8,000	279,000
4	10,000	178,000	13,000	13,000	214,000
5	64,000	91,000	27,000	19,000	201,000
6		130,000	70,000	35,000	235,000
Total	156,000	1,275,000	208,000	112,000	1,751,000

Note: 1 mile = 1.6 km.

Figure 2. Average delay function.

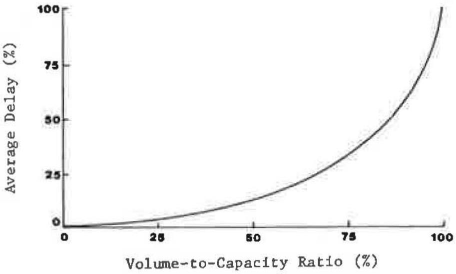

Table 5. Percentage of traffic standing still at various volume-to-capacity ratios.

Volume-to-Capacity Ratio	I-81	State Routes	County Routes	Township Roads
0.1	0	0	0	1
0.2	0	4	5	7
0.3	5	12	14	17
0.4	8	19	25	30
0.5	15	30	36	42
0.6	26	45	50	60
0.7	50	61	65	80
0.8	85	87	88	93
0.9	98	98	98	99
1.0	100	100	100	100

Figure 3. Emission function for CO.

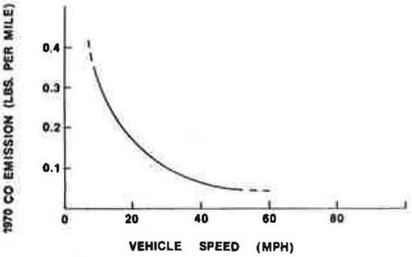

Figure 4. Emission function for HC.

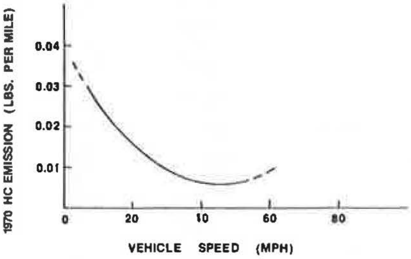

Figure 5. Emission function for NO_x.

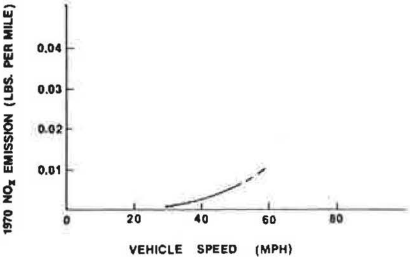

Table 6. Emission factors.

Driving Condition	CO (lb/vehicle-hour)	HC (lb/vehicle-hour)	NO_x (lb/vehicle-hour)
Standing	0.2	0.10	0.00
Speed-changing	4.3	0.53	0.25
Cruising			
20 mph	3.9	0.34	0.00
30 mph	3.4	0.32	0.00
40 mph	3.3	0.33	0.10
50 mph	3.8	0.38	0.10
60 mph	4.6	0.52	0.26
70 mph	5.9	0.69	0.35

Note: 1 lb = 0.4536 kg.

Table 7. Estimated subarea transportation emissions.

Road Type	Subarea	CO (lb/day)	HC (lb/day)	NO_x (lb/day)
I-81	1	1,600	500	500
	2	640	200	200
	3	4,320	1,350	1,350
	4	800	250	250
	5	5,120	1,600	1,600
	6	0	0	0
	Subtotal	12,480	3,900	3,900
State routes	1	19,305	3,861	2,574
	2	41,310	8,262	5,508
	3	18,135	3,627	2,418
	4	16,065	3,213	2,142
	5	16,830	3,366	2,244
	6	17,940	2,080	0
	Subtotal	129,585	24,409	14,886
County routes	1	3,915	783	522
	2	5,508	1,102	734
	3	1,576	315	210
	4	1,170	234	156
	5	2,649	530	353
	6	9,660	1,120	0
	Subtotal	24,478	4,084	1,976
Township roads	1	1,670	334	223
	2	2,570	514	343
	3	864	173	115
	4	1,125	225	150
	5	1,913	383	255
	6	2,760	320	0
	Subtotal	10,903	1,949	1,086
	Total	177,446	34,342	21,848

Note: 1 lb = 0.4536 kg.

Using this information, it is possible to develop emission factors for the three travel categories. Table 6 gives the factors that are stored in the computer as functions.

The estimates the model produced of subarea and regional emissions of CO, HC, and NO_x from transportation sources for an average 1970 day are given in Table 7.

One of the problems with judging the usefulness of the model presented in this paper is the lack of a suitable procedure for testing its accuracy or validity. For example, it would be desirable to compare the pollution estimates obtained from this model with the quantities of pollutants that are actually emitted in a region. But for many reasons this kind of testing is impractical, so when using this model one must keep in mind the restrictions that accompany the use of any untested procedure.

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THE ROLE OF PERIODIC MOTOR VEHICLE INSPECTION IN AIR POLLUTION ABATEMENT

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In many areas of the United States, exhaust emissions from motor vehicles are a major contributor to air pollution. Consequently, governments at all levels are adopting measures designed to reduce emissions from both existing and new vehicles. Most of these measures attempt to reduce emissions per mile rather than the number of vehicles or the number of miles of operation. For these measures to be effective, the vehicles must meet appropriate emission standards throughout their useful life, which requires an effective program of continuing maintenance for each vehicle. This can be ensured by a system of periodic motor vehicle emission inspection. This paper develops the characteristics of such a system and the type of inspection process required. The relationship of inspection to maintenance is described. Issues raised by the prospect of mandatory inspection and maintenance are discussed and resolutions suggested.

•UNDER the impetus of the Clean Air Amendments of 1970, air pollution abatement programs are being developed. Such programs, particularly when applied to vehicles, are generally based on a strategy of reducing the emissions from each source rather than reducing the number of sources or the amount each source is used. Measures to reduce emissions have included retrofitting existing vehicles with emission-control devices, encouraging the use of gaseous fuels, and imposing emission standards on new vehicles. Experience has shown that where the devices used are essentially passive, as in positive crankcase ventilation devices, they are effective and remain effective. Unfortunately, that is not always the case for emission-control devices that have to do with the operation of the engine. When such a device is not effective, it is usually because the vehicle is malfunctioning. Any vehicle will emit more if it is malfunctioning or misadjusted than if it is operating properly. For present vehicles, malfunctions may cause increases in emissions from a few percent to several hundred percent. For the very low-emission vehicles to be produced in the latter part of this decade, rather common types of malfunctions are expected to produce increases of several thousand percent. The problem is to make emission-reduction measures effective by returning malfunctioning vehicles to proper operation.

NATURE OF INSPECTION NEEDED

Periodic motor vehicle inspection is to be the first step in a process of returning malfunctioning or misadjusted vehicles to proper operating condition. (The second step is the performance of the necessary maintenance or repair to return such vehicles to proper operating condition.) The chief characteristics of a satisfactory inspection process are a capability to determine whether a vehicle is operating properly and to indicate the nature of the malfunction or misadjustment if it is not operating properly. In addition, the process should be simple, cheap, and rapid.

A vehicle engine and emission-control devices operate differently at different speeds and loads; they may operate properly under some conditions but not others. To ensure low emissions and correct operation requires that the vehicle be checked at a sufficient number of speeds and loads. Because correct operation is defined in terms of emis-

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sions, the emissions are the proper measure of correct operation. Fortunately, it has been shown that for light-duty vehicles [under 6,000 lb (2700 kg) gross weight], measurements taken under at most 4 different conditions of speed and load are adequate to determine whether a vehicle is operating properly. The Clayton Manufacturing Company, which has done much of the work in this area, terms these modes of operation KEY MODES (1). In developing its simple KEY MODE test cycle, which applies to light-duty vehicles, the company found that the measurement of carbon monoxide (CO) and hydrocarbons (HC) at idle and at 2 different speeds when the vehicle is operating under load on a dynamometer is adequate to determine whether the vehicle is operating properly. Although future vehicles may require measurements under more modes of operation and will also require the measurement of oxides of nitrogen (NO_x), the KEY MODE cycle is indicative of what will be required.

That the inspection process should indicate the nature of any malfunctions or misadjustments is not immediately obvious. It might seem that if a vehicle is not operating properly it should merely be necessary to take it to a mechanic to be fixed. However, the mechanic needs to know what to fix—a diagnosis. In theory at least, the mechanic should be able to diagnose malfunctions, but most garages do not have dynamometers for testing under load. Moreover, most vehicles continue to drive quite well despite even major malfunctions, particularly in the ignition and fuel metering systems. This makes diagnosing by road testing uncertain, even for experienced persons. Thus, if the inspection process also gives diagnostic information, maintenance and repair are greatly facilitated. In fact, because the inspection process under discussion requires operating the vehicle at enough different speeds and loads to check for proper operation, and because any increase in the level of 1 or more of the emissions above the proper level at a given speed and load indicates a certain kind of malfunction or misadjustment, the inspection process provides diagnostic information. The Clayton Manufacturing Company has systematized the presentation of the test data so that, by noting which levels of emissions are excessive and in which mode of operation, the mechanic may use a simple chart to tell where the trouble is likely to be. Then, if the indicated trouble spot or spots are repaired or adjusted by using standard procedures, the vehicle is very likely to operate properly. Of course the mechanic would use the standard tools and instruments normally available in any properly equipped garage.

The need for the inspection process to be simple, cheap, and rapid is obvious when one considers the number of motor vehicles in the United States. The kind of inspection being discussed here requires that the inspecting technician drive the car onto the dynamometer, insert a sampling probe into the tail pipe, and record (this may be done automatically) the emission levels from the instruments at idle (zero speed) and at 2 or 3 constant speeds. The sampling probe is then removed and the car driven off the dynamometer. The technician notes whether the emission levels indicate proper operation. If not, the card with the emission levels is given to the vehicle operator. The levels constitute the diagnostic information needed to effect repairs. The capital costs for the inspection facility, assuming yearly inspection, are about $2.00 per inspected vehicle, and the operating cost is about $1.05 per inspection. The time required to perform an inspection is less than 5 minutes (2). The procedure, cost, and time figures are for 1972 and earlier light-duty vehicles.

As the emission control system on new vehicles becomes more complex to meet increasingly stringent emission standards, the inspection process for these vehicles will also become more complex. It will probably be necessary to provide a port for sampling the exhaust upstream of any catalytic or thermal reactor as well as at the tail pipe. It will also be necessary to add an instrument to read the level of NO_x emitted. Finally, it might be necessary to add a third speed at which measurements would be taken. Assuming that more instruments were added so that measurements would be made simultaneously at the sampling port ahead of any reactor and at the tail pipe, the additional capital cost per inspection lane would be less than twice as much. An additional speed, if required, would increase the time per test and the operating cost by no more than 25 percent. The increase in time would also reduce somewhat the number of cars per year that could be handled by an inspection lane and further increase the capital costs. However, not all inspection lanes would have to be so equipped or operated.

In summary then, the inspection would be done periodically to ascertain whether the vehicle is operating properly from an emissions standpoint. It would measure emissions directly under enough different loads and speeds to test the vehicle adequately. In cases where the vehicle overemits it would provide diagnostic information to aid a mechanic in making necessary repairs. It would be simple, cheap, and rapid.

INTEGRATION OF INSPECTION AND MAINTENANCE

Of course merely inspecting an overemitting vehicle will not reduce its emissions. That can only be accomplished by appropriate repair or adjustment. It seems likely that it will be necessary to provide some compulsion to ensure that the maintenance is done. An easy to implement and effective form of compulsion is to require that the inspection be passed as a condition to continue operating the vehicle. Under this scheme, the owner of the vehicle would take it to be inspected any time during, say, a 2-week period before the registration date. If the vehicle passed, it could be registered. If not, it would have to be repaired and reinspected. It could not be registered without first passing the inspection.

ISSUES RAISED BY MANDATORY INSPECTION AND MAINTENANCE

Who would do the inspection?

The 2 common choices are for the state to set up inspection stations and operate them with state employees or for the state to license private organizations (probably garages) to perform the inspections. Proponents of state-run inspection stations cite the undesirability of having a garage with an interest in performing repairs make the inspection. Proponents of a system of licensed private inspectors point out that state inspection would require a huge public investment and a large addition to an already large staff of state employees. Both points of view are valid, but public confidence in an inspection scheme dealing with emissions seems to be the overriding factor. On balance, it seems necessary that the state should do the inspecting.

But a third possibility lies between the 2 opposing points of view. Inspecting could be assigned to a nonprofit organization. This approach has been used often in the past, notably by the federal government, to resolve just such conflicts as have arisen here. When used properly it permits tight governmental control without the need for a large bureaucracy. It may be a feasible alternative to state operation of the inspection system.

How and where will the system get started?

An inspection system should have as large an effect on air pollution as possible, as soon as possible, so it should be started first in air quality control regions that have the worst air pollution problem.

An obvious way to proceed is to start with pilot programs in selected areas. Each program could start with as few as 5 to 10 inspection lanes and involve as few as 1 to 2 hundred thousand vehicles. These numbers are small enough to require not a large initial investment or number of people, but large enough to provide realistic experience.

The major problem in starting such pilot programs concerns the proper way to involve the automotive service industry. The standards set for passing the inspection are the key to its involvement. Initially the standards must not be too strict or the service industry will not be able to respond. Both the number of vehicles to be maintained and the nature of the malfunctions and misadjustments to be corrected are of concern. One way to handle the transition period would be to set initial standards at, say, 3 times the average emission level. That is, if an emission level for any kind of emission measured under any mode of operation exceeded 3 times the average level for the same measurement for similar vehicles, the vehicle would fail the test. Any such level is associated with a gross malfunction or misadjustment. Test programs indicate that about 10 percent of the vehicles would be affected. These are the worst emitters and would show the most improvement from maintenance and repair. Moreover, they would be the ones with the most obvious problems and would be the easiest for the service industry to repair. As the worst emitters are found and corrected the standards would tighten somewhat. As the service industry gains experience, the standards could be further tightened to cause the rejection of all vehicles that were overemitting. An approach such as this is needed both to make maximum initial impact and to allow the service industry the time and experience to prepare itself to maintain vehicles for low emissions. Once the pilot program shows that the inspection system is working, the system could be expanded in an orderly way to cover the entire control region.

Does a new-vehicle low-emission warranty obviate the need for inspection?

Even though a vehicle may be covered by a warranty for a certain mileage, it may require maintenance for malfunction or misadjustment. Such parts as the ignition system and the carburetor typically require repair and periodic maintenance well before 50,000 miles (80 000 km). The emission-control system is designed to reduce emissions from a properly operating engine. Usually it is not able to cope with the increased emissions from an improperly operating engine. The intent of the warranty is that, if the engine is operating correctly and if the emission-control system is properly maintained, the emissions will remain low for the stated mileage. This guards against designs that will not tolerate normal engine wear. The decision by the Environmental Protection Agency to permit 1 replacement of the catalytic reactor during the first 50,000 miles (80 000 km) for 1975-76 vehicles emphasizes the need for maintenance.

Are there other effective inspection procedures that do not require a dynamometer?

The key point in this issue is effectiveness. There are many measures of effectiveness including cost, cost per unit of emission reduction, and total emission reduction. All of these and others have been proposed, but to some extent miss the point of the reason for periodic motor vehicle inspection. Because the purpose of inspection and maintenance programs is to ensure that vehicles are operating properly, the criteria for inspection effectiveness should be how well it distinguishes proper from improper operation and how much diagnostic information it supplies. By these criteria, it is evident that an idle test or similar test is ineffective because some parts of the engine, such as the high-speed part of the carburetor, are not tested.

There is still the question of the effectiveness of inspection. Basically, such an inspection consists of the thorough examination of the various parts of an engine using diagnostic instruments. If the inspection is properly done, the vehicle that passes is operating correctly and has low emissions. The disadvantages are that it costs more, takes more time, and does not directly measure emissions (except possibly CO). And, it requires more skilled personnel because it is more specific to the particular make and model of vehicle. So, it is less suitable than the kind of inspection proposed.

Is a program of mandatory periodic maintenance as effective as a system of inspection and maintenance?

The idea here is that periodically all vehicles would have to undergo a mandatory "tune up." An approved procedure would be used, the work would be done by a licensed garage, and a certificate would be issued to show that the work had been done. The certificate would be required to register the vehicle. There are 2 problems with this scheme. The first is that the procedure would necessarily have to be a compromise between completeness and cost. It would be very expensive to do a complete maintenance on every vehicle. Anything much beyond a check of the ignition system, a replacement of points, condenser, and spark plugs, and an adjustment of the carburetor would result in much unneeded work. Yet this sort of limited procedure would not repair many vehicles that were seriously overemitting. The compromise would become even more unsatisfactory as the newer vehicles with more complex emission-control systems appeared.

The second problem is the difficulty in ensuring that the work is done properly. There would be an enormous possibility for fraud, perhaps with the collusion of vehicle owners. Any system that requires the public to periodically have work done, the results of which are difficult to perceive, would be extremely difficult to make effective. Compared to an inspection system with built-in checks and balances, the mandatory maintenance scheme is ineffective and undesirable.

Does this approach place the burden of emission reduction on poor people who drive older cars?

The assumptions that only old cars emit and that they are driven mostly by poor people are invalid. The truly poor tend to be the old, the sick, the handicapped, and young children and their mothers. Such people are not the ones that do the bulk of the driving. But, there are no real alternatives to reducing emissions in the most effective way. And, the number of vehicles is so large that even then emissions will not be reduced sufficiently to meet the requirements of the clean air amendments. As for the truly poor, it is probable that they will continue to be subsidized, and, when necessary, the subsidy will cover the costs of a vehicle, including inspection and maintenance.

Should safety inspection be combined with emission inspection?

There is evidence that safety inspections are worthwhile and that the 2 kinds of inspection would reinforce each other (2, 3). A major obstacle to any inspection system is the inconvenience to the owner in periodically bringing a vehicle in for inspection. If there is to be both a safety inspection and an emission inspection, they should be done at the same time and the same place.

SUMMARY

A system of mandatory motor vehicle inspection and maintenance should have the following characteristics:

1. The state (or a state-supervised nonprofit organization) should perform the inspection, but maintenance should be done by whomever the owner of the vehicle chooses.
2. Inspection should be tied to registration so that a vehicle would have to pass inspection to be driven.
3. The procedure should test the vehicles under a sufficient number of modes of operation (speed and load) to ensure that vehicles that pass are operating correctly. The procedure should provide diagnostic information to aid in the repair of vehicles that do not pass. The test procedure should be simple, cheap, and rapid.
4. The inspection system should start with pilot programs in selected areas with severe air pollution and be expanded as necessary.
5. If there is a system of safety inspections, it should be combined with the system of emission inspections to minimize inconvenience to vehicle owners.

A mandatory system of inspection and maintenance having these characteristics would complement and render more effective the program of automotive emission reduction that we now have. Without such a system the present program will probably not be fully effective.

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