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

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

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:

$$E_p = E_p(1) + E_p(2) + E_p(3) \qquad (1)$$

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

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

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

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.

Purpose	Trips[a]		VMT[b]		Emissions[c] CO		NO_x		HC	
	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.

Purpose	CO Amount[a]	CO Percent Purpose	CO Percent Total	NO_x Amount[a]	NO_x Percent Purpose	NO_x Percent Total	Cold-Start HC Amount[a]	Cold-Start HC Percent Purpose	Cold-Start HC Percent Total	Hot-Soak HC Amount[a]	Hot-Soak HC Percent Purpose	Hot-Soak HC 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.

Purpose	CO Amount[a]	CO Percent	NO_x Amount[a]	NO_x Percent	HC Amount[a]	HC 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.

Purpose	Emissions 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).

District	Trips[a] Number	Trips Percent	VMT[b] Miles	VMT Percent	Emissions[c] CO Amount	CO Percent	NO_x Amount	NO_x Percent	HC Amount	HC 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).

	Trips[a]		VMT[b]		Emissions[c]							
					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.

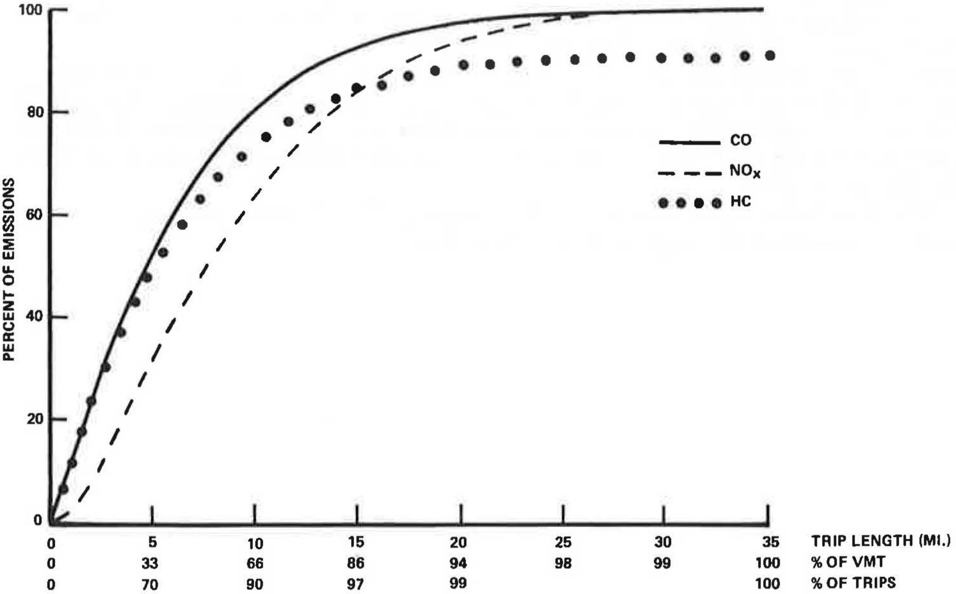
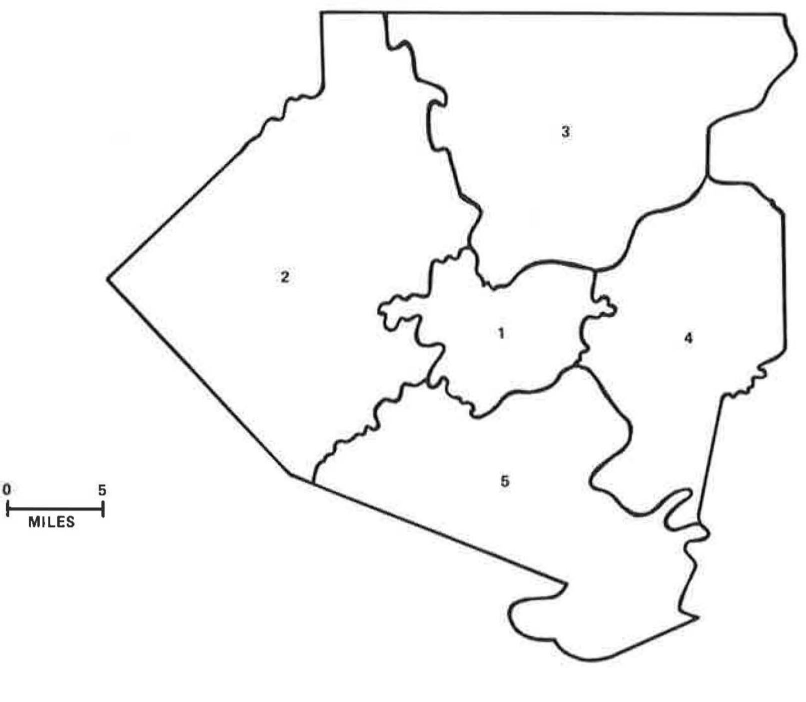


Figure 2. District boundaries for the city of Pittsburgh and Allegheny County.



this study and David Syskowski, of the Environmental Protection Agency, for computer programming assistance. The views expressed in this article are those of the authors and are not necessarily supported by the Environmental Protection Agency.

REFERENCES

1. Clean Air Amendments of 1970. 42 U.S.C. sec. 1857, PL 91-604, Dec. 31, 1970.
2. A Study of Emissions From Light Duty Vehicles in Six Cities. Automotive Environmental Systems, Inc., Publication APTD-1497, March 1973.
3. Martinez, J. R., Nordsieck, R. A., and Eschenroeder, A. Q. Morning Vehicle-Start Effects on Photochemical Smog. Environmental Science and Technology, Vol. 7, No. 10, Oct. 1973, pp. 917-923.
4. GM Low Volatility Gasoline Program. General Motors Corporation, June 1968.
5. Federal Register. 40 C.F.R. 2.100, Jan. 1, 1972.
6. Sigworth, H. W. Estimates of Motor Vehicle Emission Rates. Office of Mobile Sources Air Pollution Control, U.S. Environmental Protection Agency, March 1971.
7. Kircher, D. S. Light Duty Gasoline Powered Vehicles. In Compilation of Air Pollutant Emission Factors, 2nd ed., U. S. Environmental Protection Agency, Publication AP-42, April 1972.
8. Annual Miles of Automobile Travel. U.S. Department of Transportation, Nationwide Personal Transportation Study Rept. 2, April 1972.