J. ENVIRON. SYS., Vol. 4(1), Spring 1974

MODELING TOTAL VEHICLE EMISSIONS ON A REGIONAL LEVEL

HELMAN I. STERN
Division of Systems Engineering
Rensselaer Polytechnic Institute
Troy, New York

PATRICK A. PETRELLA, JR.
Stone and Webster Engineering Corporation
Boston, Massachusetts

ELMAR R. ALTWICKER
Bio-Environmental Engineering Division
Rensselaer Polytechnic Institute
Troy, New York

ABSTRACT

This paper presents a dynamic mathematical model for the projection of total annual emissions of hydrocarbons, carbon monoxide, and nitrogen oxides from mobile sources in urban regions. The model consists of three subsystems, 1) vehicle population, 2) vehicle activity, 3) vehicle emissions rates. The model is applied through the use of four separate vehicle emission compliance schedules to the Albany-Schenectady-Troy Standard Metropolitan Statistical Area (SMSA), based on 1964-1970 data. Emission projections for the period 1971-1990 are shown in graphical form.

Introduction

Much has been proposed and accomplished in the area of mobile source pollutant reduction in the past decade [1]. The Federal Government and some states have passed increasingly stricter laws regulating emissions from motor vehicles. This paper offers a dynamic mathematical model for projecting total annual hydrocarbon, carbon monoxide, and nitrogen oxide emissions for an

doi: 10.2190/MEY8-B9AF-E802-H5R8
http://baywood.com

urban region. Although concerned with gasoline-engine automobiles and light duty trucks, this method is applicable to any class of vehicle. The model is applied to the Albany-Schenectady-Troy SMSA, comprised of four counties in Eastern New York State, totaling approximately 2400 square miles of land area with a 1970 population of 722 thousand. Emission projections are given for the period 1971-1990 based on data from 1964-1970.

The basic model is comprised of three subsystems, 1) vehicle population, 2) vehicle activity, and 3) vehicle emission rates. Data from each of these subsystems are combined to allow computation of total annual pollutant emissions. The first subsystem updates the region's inventory of vehicles by predicting new vehicle sales and aging used vehicles. The second subsystem approximates future vehicle activity by determining annual vehicle mileage based on vehicle age. The third subsystem determines corrected vehicle emission rates for the three pollutants based on deterioration of the control devices used to reduce these emissions, and on results of field studies monitoring emission rates found in actual vehicle use. Figure 1 is a flowchart showing the major steps required to determine annual total emissions for a given type of vehicle and pollutant. One iteration of the process (one complete cycle through the flow chart) is required to determine the projected pollutants for a particular future calendar year.

The material to follow includes a discussion of the three basic subsystems, a mathematical representation of the total emissions model and an application of the model.

Vehicle Population

Many types of mobile pollutant sources may be found in an urbanized area. Besides gasoline automobiles and trucks there are diesel automobiles and trucks, farm equipment, construction equipment, motorcycles, and miscellaneous sources such as lawn mowers and snowmobiles. Estimates were made of the relative contribution of each vehicle type to total emissions. These estimates were based on 1) vehicle numbers, 2) vehicle usage in distance or time and 3) emission levels [2, 3]. As a result of this investigation only gasoline automobiles and light duty gasoline trucks were selected as significant mobile sources of the three pollutants under study.

Projections of these two vehicle types are based on new vehicle sales and vehicle amortization. Although used vehicle migration between urbanized areas is possible this factor was not considered as significant. However, for regions experiencing large net migration patterns relative to the base population this factor should be considered. Future new vehicle sales are estimated through regression analysis. Total regional population and average per capita income served as the independent variables; thus, two regression equations were generated—one for new car sales and the other for new truck sales. Estimates of

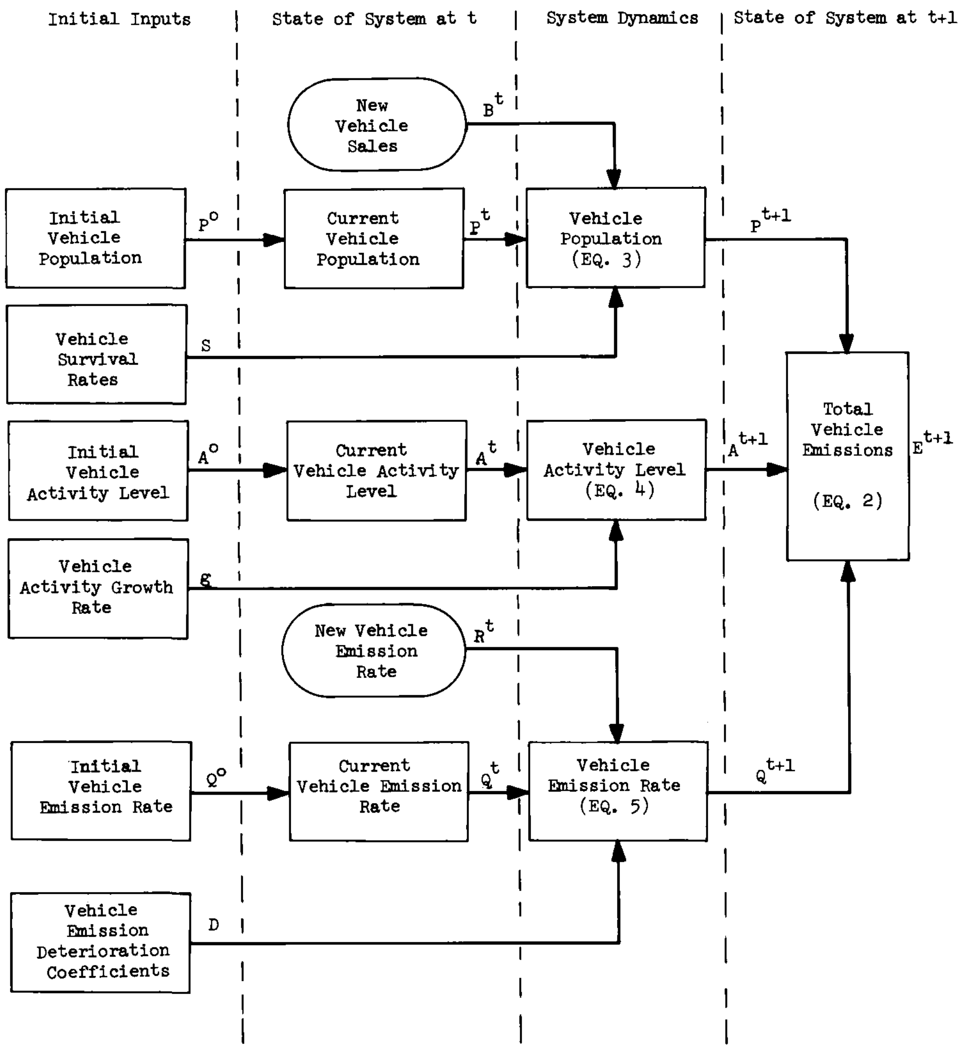

Figure 1. Flow chart of urban vehicle emissions model.

future per capita income and population were then used as an input to the regression equations in order to calculate future car and truck sales. This relationship should be altered if it is believed that future vehicle consumption patterns will change from past trends.

Six years of vehicle registration data over the period 1964-1970 were used to determine vehicle survival rates for the region. The registration data was given in terms of vehicle model year, with each year's data containing information on fourteen previous model years [2]. These data are shown for 1970 in Table 1. Knowing both the present calendar year and the model year, the vehicles' present age could be calculated. Vehicles are assigned age i if they are between i and i + 1 years of age. The vehicle amortization curves in Figure 2 are a result of regression fits to six years of data for the Albany-Schenectady-Troy SMSA. It is interesting to note that light duty trucks exhibited exponential decay life histories while automobiles reflected life patterns closely related to the normal distribution. Vehicle age specific mortality rates may be obtained by dividing the incremental difference of two successive years along the curves by the percentage of vehicles remaining at the start of the selected interval. The survival rates are obtained by subtracting the mortality rates from one. (Alternatively, one may compute the conditional survival rates by dividing the per cent of vehicles remaining at the end of one year by the per cent at the beginning of the year selected). These rates are analogous to the age specific survival rates used in demographic studies. The age specific survival rates for automobiles are shown in Table 2. As the light duty truck life history was represented by an exponential decay function its survival rate is necessarily a constant for all age groups and was computed at .8675.

Vehicle Activity

It has been shown that vehicles of different ages do not travel the same amount of distance annually. Vehicle usage (in annual miles driven) is a decreasing function of vehicle age. Table 3 shows the per cent of total annual vehicle miles, in a typical urban region, driven by each age group. It is expected that various urban activities such as commercial and industrial concerns utilize new vehicles heavily for a few years after which time they are replaced. Distributing the base year total vehicle mileage over these percentages results in a set of vehicle activity levels in annual miles per vehicle for each vehicle age group. In this study it is assumed that this distribution is invariant with time but grows in absolute value at a constant rate. This rate was determined for the study area by analyzing annual total miles driven per vehicle for both vehicle classes over the period 1965 to 1970. Since the vehicle distribution was relatively constant over this period any increase in total vehicle activity was assumed to be due to urban dispersal. This justified the assumption that the

Table 1. Calendar Year 1970 Used Vehicle Population

Model year	*Vehicle age*	*Automobiles*	*Trucks*
1969	1	35,846	4,232
1968	2	33,705	4,404
1967	3	28,233	3,134
1966	4	27,873	2,985
1965	5	29,346	2,914
1964	6	22,428	2,137
1963	7	19,592	1,870
1962	8	14,772	1,538
1961	9	8,551	1,240
1960	10	5,486	1,139
1959	11	2,101	833
1958	12	919	581
1957	13	1,083	717
1956	14	771	618
Totals		232,349	30,892

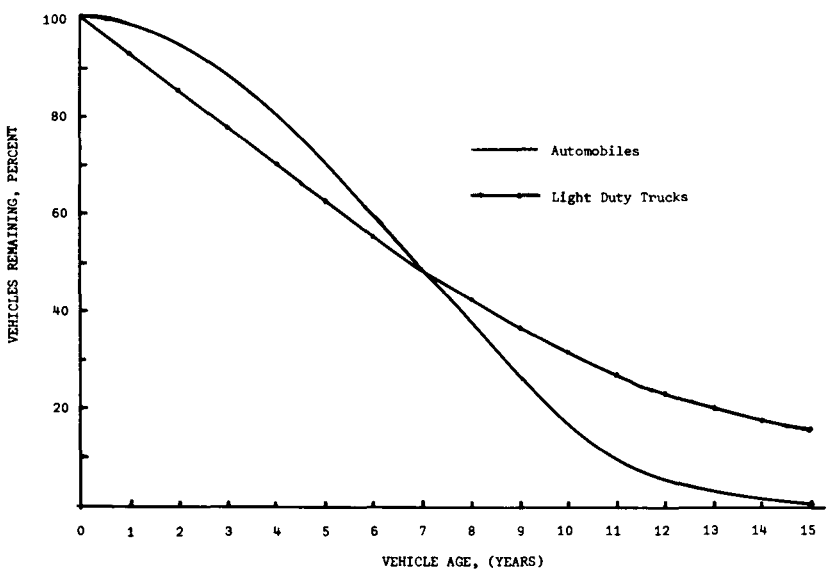

Figure 2. Normalized amortization of vehicles.

Table 2. Automobile Survival Percentages[a]

Transition Age	*Automobiles*
0-1	.9952
1-2	.9578
2-3	.9265
3-4	.9052
4-5	.8782
5-6	.8488
6-7	.8149
7-8	.7746
8-9	.7220
9-10	.6601
10-11	.5660
11-12	.6118
12-13	.6282
13-14	.6326
14-15	.6371

[a] Survival percentages are assumed independent of vehicle model year.

growth rate could be applied uniformly to the activity levels of each vehicle age group. If one wishes to introduce the effects of mass transit or reduced vehicle activity, due to energy constraints, it is necessary to modify the growth rate. In addition, if there is reason to believe that the relative usage behavior of owners of different aged vehicles will change over time one should define different growth rates for each vehicle age group.

Vehicle Emission Rates

Except for the State of California where the strictest emission standards are found, all states comply with the Federal specified levels of vehicle pollutant emissions. Table 4 gives these standards for each model year affected for both vehicle classes [4, 5, 6]. For certain model years, the table lists two values for the pollutant emissions. Each of these values corresponds to a particular test procedure as indicated in the table. For a manufacturer to have a vehicle model certified for production, it is not necessary for the test vehicle to pass both testing procedures. Rather, as the allowable emission levels were being developed, the test procedures to measure these levels were also being developed to more realistically represent on-the-road vehicle use. The same vehicle then, would show different emission levels depending on the test being employed. Therefore, it is important to specify the test procedure to be used when establishing emission levels because of the dependence of these levels on the test.

Table 3. Average Annual Mileage by Vehicle Age

Vehicle age	*Per cent of total annual vehicle miles driven*[a]
0	15.73
1	13.64
2	12.02
3	10.07
4	9.35
5	8.18
6	7.50
7	6.60
8	5.30
9	4.30
10	2.80
11	1.70
12	.80
13	.40
14	.40
15	.40
16	.40

[a] Data modified from reference 2 to conform to the vehicle age structure of this study.

The two values for a single model year are given only for comparison of the two test procedures.

Because of variance in manufacturing processes, poor or inadequate maintenance of vehicles, or total neglect of emission control systems, there is growing evidence that on the road vehicles emit pollutants at levels above the Federal standards [7]. Due to the relatively recent introduction of control devices, data on actual emissions is not abundant; indications are, however, that emission levels are greater than expected. New data is constantly added through surveys being conducted, for the most part, in California [8].

Due to these recent findings, the use of the Federal Standards in a study of a particular area is optimistic. Therefore, a table of modified emission levels was calculated based on a study by the National Academy of Sciences [1]. Listed in Table 5, these emission rates reflect an attempt to more closely model actual vehicle characteristics than if the established Federal levels were used. Table 5 gives not only the modified emission levels for the original Federal standards (termed Base Emission Rates), but also lists three alternative schedules. The second schedule now actually supercedes the original one in light of the most recent EPA decisions [5]. The third emission time-table differs from the second only in that the 1975 model year vehicles follow the 1972-1974 model year

Table 4. Federal Emission Standards

		Emissions in Gm/Mi.		
Model year	*Test*	*HC*	*CO*	NO_x
Pre-1968[a]	FTP[b]	10.0	77.0	4-6(NR)[e]
Pre-1968	CVS-C[c]	17.0	125.0	6.0(NR)
1968-69	FTP	3.4	35.0	(NR)
1970-71	FTP	2.2	23.0	(NR)
1970-71	CVS-C	4.1	34.0	(NR)
1972	CVS-C	3.4	34.0	(NR)
1973-74	CVS-C	3.4	34.0	3.0
1975	CVS-CH[d]	1.5*	15.0*	3.1**
1976	CVS-CH	0.41	3.4	0.4**

[a] Uncontrolled vehicle except for crankcase blowby control.
[b] FTP-Federal Test Procedure (California Seven Mode Cycle).
[c] CVS-C—Constant Volume Sampling, Cold Start.
[d] CVS-CH—Constant Volume Sampling, Cold/Hot Start.
[e] NR—No Requirement; average vehicle emission rate given.

* Interim Standards for 1975 Model Year Vehicles [5].
** Posponed Standards [5].

standards instead of the interim standards. The fourth alternative assumes no further emission reduction after the 1972 model year standards were reached. The impact of these four emission schedules on a specific urban region's total emissions profile over time will be compared in a later section of this paper. Since only unburned hydrocarbons have multiple sources (exhaust, engine blowby, and evaporation), the values for hydrocarbons reflect the total HC emitted from all three sources expressed in grams per mile.

Although the modified emission schedules in Table 5 were based on the Federal levels, they still do not accurately reflect actual driving conditions. While it is true that the Federal standards were derived from a driving sequence having cold and hot engine starts and operation, there is a growing indication that a very significant portion of vehicular emissions are generated during cold engine operation. Estimates of 1975 model year vehicles indicate that 85% of the hydrocarbons and carbon monoxides in a typical urban vehicle trip will be emitted while the engine is cold [9]. In addition, Martinez et al. [10] in their examination of Los Angeles data found cold start CO-emissions ranging from 48 to 130 per cent above hot running CO-emissions. This indicates the need to closely model a region's vehicle trip characteristics and their resultant effects on average emission rates in order to obtain a more accurate assessment of total pollutants emitted.

Table 5. Emission Rate Schedules Used to Calculate Total Pollutants (Gm/Mile)

Vehicle model year	*HC*	*CO*	*NO_x*
I. Base Emission Rates:			
Pre-1963	26.71	135.63	6.0
1963-1967	23.06	135.63	6.0
1968-1969	10.94	77.04	6.0
1970-1971	8.25	51.00	6.0
1972-1974	3.85	42.32	3.0
1975-1990	0.66	5.10	0.4
II. One Year Delay with Interim Standards (for 1975 model yr.):			
Pre-1963	26.71	135.63	6.0
1963-1967	23.06	135.63	6.0
1968-1969	10.94	77.04	6.0
1970-1971	8.25	51.00	6.0
1972-1974	3.85	42.32	3.0
1975	2.25	23.71	1.7[a]
1976-1990	0.66	5.10	0.4[a]
III. One Year Delay (No Interim Standards):			
Pre-1963	26.71	135.63	6.0
1963-1967	23.06	135.63	6.0
1968-1969	10.94	77.04	6.0
1970-1971	8.25	51.00	6.0
1972-1975	3.85	42.32	3.0
1976-1990	0.66	5.10	0.4
IV Present (1972) Model Year Rates:			
Pre-1963	26.71	135.63	6.0
1963-1967	23.06	135.63	6.0
1968-1969	10.94	77.04	6.0
1970-1971	8.25	51.00	6.0
1972-1990	3.85	42.32	3.0

[a] Most recent decision by EPA postpones these NO_x standards for one year. Postponements not included in final calculations.

As vehicles age, their control devices deteriorate to some degree. This loss of effectiveness was allowed for by using deterioration factors based on vehicle age. These deterioration factors are given for hydrocarbons and carbon monoxide for model year vehicles from 1968 to 1974 inclusive, and are listed in Table 6 [1]. At the present time, there is insufficient data to determine deterioration factors

Table 6. Average Vehicle Emission Deterioration Factors

	Deterioration Factor	
Vehicle age (years)	*HC*	*CO*
0	1.000	1.000
1[a]	1.063	1.055
2	1.165	1.123
3	1.205	1.161
4	1.232	1.183
5[a]	1.252	1.195
6	1.267	1.198
7	1.279	1.198
8	1.287	1.199
9	1.293	1.200
10[a]	1.296	1.201
11	1.299	1.201
12	1.300	1.202
13	1.301	1.202
14	1.3015	1.203
15[a]	1.302	1.203

[a] Based on California Air Resources Board Field Surveillance data taken prior to 1972. These deterioration factors are subject to revision once more recent and comprehensive data have been analyzed. Deterioration above the standards in 1975 and later model years not allowed for. All other values graphically interpolated by the authors.

for devices controlling nitrogen oxide emissions. Thus the results on nitrogen oxide emissions presented in the application are underestimated.

The Emissions Model

Total emissions for a given year may be obtained as the product of three factors; 1) vehicle stock, p, (number of vehicles) 2) vehicle activity, a, (annual miles per vehicle) and 3) the vehicle emission rate, q, (grams per vehicle mile traveled). For a given vehicle type and pollutant the emissions for period (t, t + 1) of all vehicles age i may be determined by the equation,

$$e_i^t = q_i^t a_i^t p_i^t \quad i = 1, \ldots n \qquad (1)$$

The state of the system at time t may be described in terms of three (n X 1) column vectors where n represents the number of vehicle age groups considered.

P^t = a (n X 1) vehicle population age vector with common element, p_i^t, representing the number of vehicles of age i at time t.

A^t = a (n X 1) vehicle activity level vector with common element, a_i^t, representing the average annual number of miles driven by a vehicle of age i during time period (t, t + 1).

Q^t = a (n X 1) vehicle emission rate vector with common element, q_i^t, representing the number of grams emitted per mile driven by a vehicle of age i during time period (t, t + 1).

Thus, a (n X 1) vector, E^t, representing the distribution of annual emissions by vehicle age groups may be determined by the following matrix equation,

$$E^t = \hat{Q}^t \hat{A}^t \tag{2}$$

The matrices $\hat{Q}^t$ and $\hat{A}^t$ are of size (n X n) with q_i^t and a_i^t in the i^{th} diagonal position and zeroes elsewhere.

To determine the total emission vector for the next period it is necessary to "age" the present vehicle stock and record the number of new vehicles purchased along with their emission characteristics. The aging process involves updating vehicle activity levels by a growth factor, vehicle amortization and deterioration of emission control devices. These effects may be represented by a linear dynamic equation for each subsystem considered (see Figure 1).

Vehicle Population Dynamics

Given the number of vehicles at time t of age i − 1, those surviving to age i at time t + 1 are easily estimated through the use of the survival rates shown in Table 2. Since it is assumed that no used vehicles enter or leave the region only the addition of new vehicle sales are required to complete a determination of the vehicle stock at time t + 1. These operations may be written compactly by the following matrix equation

$$P^{t+1} = S\,P^t + B^t \tag{3}$$

where

S = a (n X n) vehicle survival matrix with the survival rates on the subdiagonal and zeroes elsewhere.

B^t = a (n X 1) net vehicle migration vector with the number of new vehicle sales in period (t, t + 1) in the first position and zeroes elsewhere.

Vehicle Activity Dynamics

A vehicle activity level growth rate, g, is used to increase the vehicle activity levels uniformly over all age groups. Thus, simple scalar multiplication of the vehicle activity level vector by g is sufficient to determine the new activity levels for the year t + 1.

$$A^{t+t} = gA^{t} \tag{4}$$

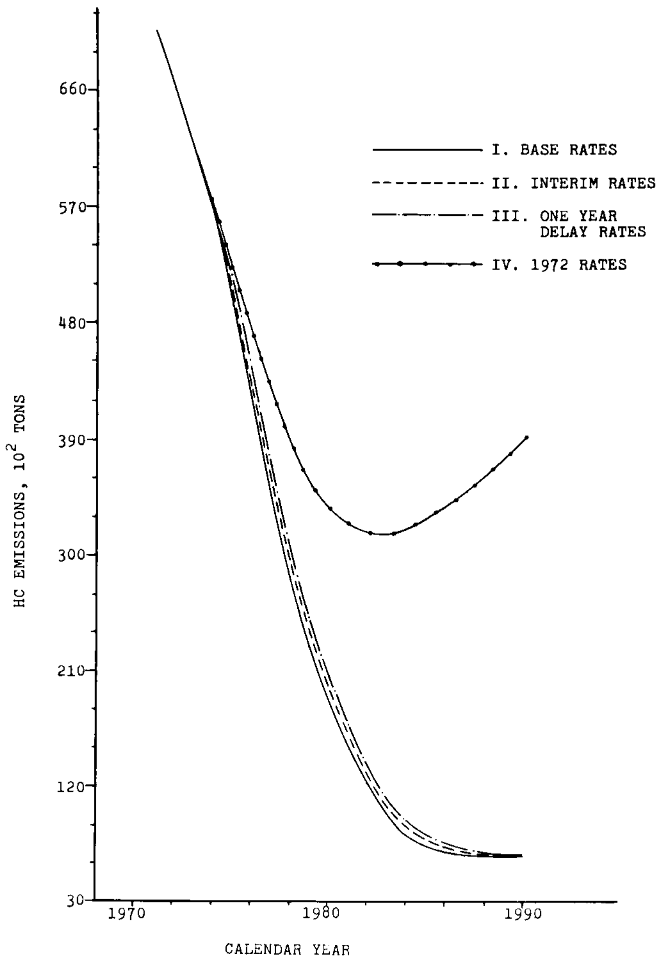

Figure 3. Total hydrocarbon emissions.

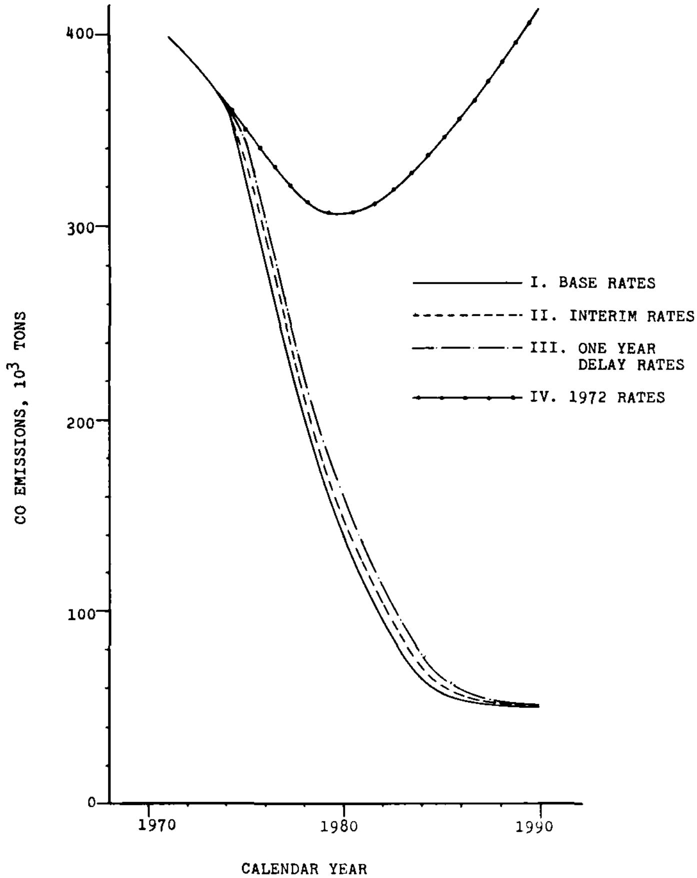

Figure 4. Total carbon monoxide emissions.

Emission Rate Dynamics

The emission rate dynamics equation takes the form

$$Q^{t+1} = DQ^t + R^t \tag{5}$$

The initial emission rate vector Q^0 is determined by applying the appropriate deterioration factors found in Table 6 to the values found in Table 5 for the appropriate emission rate schedule. For example, to determine the HC emission rate in 1970 for vehicles of age five, one multiplies 23.06 by 1.252. To estimate the emission rate in 1971 of vehicles six years of age let d_5 be the ratio

1.267/1.252 and perform the multiplication $d_5q_5^{1970}$ to obtain q_6^{1971}. By arranging the d_i's on the subdiagonal of a matrix D the current emission rates may be deteriorated one year as reflected in the first term of equation 5.

It is now necessary to determine the emission rate of new vehicles from the appropriate schedule in Table 5 and place it in the first cell of the vector R^t. The vector R^t plays the same role in equation 5 as B^t does for equation 3. Having updated the state of the system one year one may repeat the computation in equation 2 to obtain the new emission vector. Summing the elements of the emission vector yield the total emissions for the entire vehicle stock. This procedure is repeated until the horizon projection year is reached. These operations are shown in flow chart form in Figure 1 for one period.

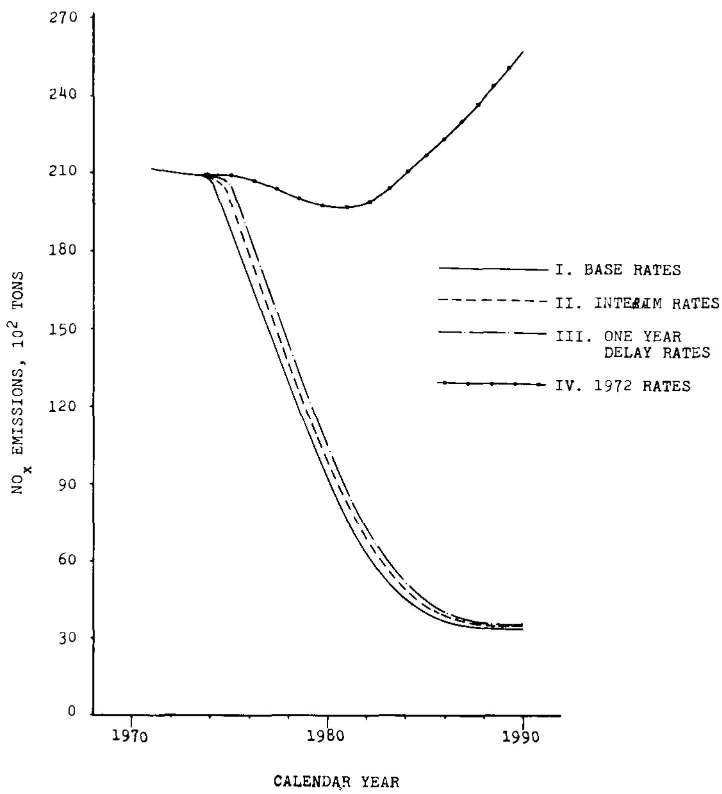

Figure 5. Total nitrogen oxide emissions.

Projected Emissions for the Albany-Schenectady-Troy SMSA

The emissions model [11] is applied to the Albany-Schenectady-Troy SMSA to project total emissions to the year 1990. The base year (1970) used vehicle population vectors for automobiles and trucks are shown in Table 1 [2]. For each of the pollutants considered a comparison of the effects of introducing the four emission schedules on the total emissions produced by all automobiles and trucks in the region is made. Figures 3 through 5 show the projected levels for each of the three pollutants according to each emission schedule listed in Table 5. All schedules except schedule IV resulted in a marked drop in pollutant levels for the next twenty years, even when the increased number of vehicles in the area is accounted for. If emission levels were to remain at their present 1972 model year rates (Schedule IV), however, total pollutants emitted would eventually rise due to this vehicle population increase. The impact of the interim

Table 7. Tonnage and Per Cent Increase (of schedule I over schedule II, cf. Table 5)

	HC Increase		*CO Increase*		*NO_x Increase*	
Year	10^2 tons	%	10^3 tons	%	10^2 tons	%
1971	0.0	0.00	0.0	0.0	0.0	0.00
1972	0.0	0.00	0.0	0.0	0.0	0.00
1973	0.0	0.00	0.0	0.0	0.0	0.00
1974	0.0	0.00	0.0	0.0	0.0	0.00
1975	12.0	2.43	13.0	4.04	10.0	5.29
1976	11.0	2.61	13.0	4.66	9.0	5.33
1977	12.0	3.46	13.0	5.49	8.0	5.37
1978	10.0	3.53	12.0	6.03	7.0	5.43
1979	11.0	4.82	11.0	6.63	7.0	6.42
1980	10.0	5.35	11.0	7.91	6.2	6.78
1981	9.0	5.88	10.0	8.62	5.9	7.89
1982	8.0	6.56	9.4	9.94	5.4	8.77
1983	6.8	7.00	7.8	10.06	4.5	8.69
1984	6.0	7.17	6.6	10.15	3.8	8.54
1985	4.1	5.45	4.4	7.76	2.6	6.47
1986	2.5	3.60	2.8	5.33	1.7	4.64
1987	1.3	1.97	1.3	2.54	0.8	2.31
1988	0.7	1.04	0.7	1.35	0.4	1.14
1989	1.3	1.94	1.5	2.96	0.9	2.59
1990	1.4	2.10	1.5	3.03	0.8	2.33

emission rates (Schedule II) for 1975 model year vehicles over the original base emission rates (Schedule I) is small. The predicted increase in pollutant emissions between these two schedules reaches a maximum of approximately 7, 10, and 9 per cent for HC, CO, and NO_x, respectively. These maximum increases occur in the mid-1980's as shown in Table 7. To choose a control strategy of allowing a pure one year delay with no interim standards also yields a small increase for the Albany region. This may be seen by comparing the appropriate curves in Figures 3, 4 and 5 [11].

Conclusion

The model developed here represents a general approach to regional emissions. Refinements will have to come primarily from a more detailed analysis of the trip characteristics of a particular region, new data on deterioration factors for control devices, and actual compliance information of specific groups of cars.

REFERENCES

1. Semi-annual Report by the Committee on Motor Vehicle Emissions of the National Academy of Sciences to the Environmental Protection Agency, Washington, D.C., January 1, 1972.
2. New York State Department of Motor Vehicles, Research Library.
3. C. T. Hare and K. J. Springer, Small engine emissions and their impact, *Automotive Engineering*, S.A.E., 80, No. 7, July 1972.
4. Environmental News, Environmental Protection Agency, Washington, D.C., Released Wednesday, June 30, 1971.
5. E. W. Kentworthy, Auto makers win a delay of year on exhaust curbs, *New York Times Newspaper*, Vol. CXXII, No. 42,082, Thursday, April 12, 1973.
6. *Federal Register*, Vol. 35, No. 219, Part II, Tuesday, November 10, 1970.
7. M. L. Brubacher and J. C. Raymond, California Air Resources Board, A status report: California vehicle exhaust control, *J. Air Pollut. Control Assoc.*, 19, 224, 1969.
8. J. M. Gall and D. A. Olds, Vehicle maintenance for low emissions–A customer education problem, *S.A.E. Paper*, #710070, January 1971.
9. K. E. Wendell, J. E. Norco, and K. G. Croke, Emission prediction and control strategy: Evaluation of pollution from transportation systems, *J. Air Pollut. Contr. Assoc.*, 23, 91, 1973.
10. J. R. Martinez, R. A. Nordsieck, and A. Q. Eschenroeder, *Env. Sci. & Techn.*, 7, 917, 1973.
11. Details on the computer models may be found in a project report submitted by P.A.P. to the graduate faculty of Rensselaer Polytechnic Institute in partial fullfillment of the Master of Engineering degree requirements, July 1973.