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AUTOMOBILE EXHAUST EMISSION MODAL ANALYSIS MODEL

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ABSTRACT

This report on modal analysis of automobile emissions was prepared for the United States Environmental Protection Agency's Division of Emission Control Technology, Ann Arbor, Michigan, under EPA Contract No. 68-03-0435. The work reported herein constitutes an application of a modal analysis emissions model to emissions data from the FY 73 and FY 74 Emissions Factors Programs.

The model was developed under EPA Contract No. 68-01-0435 and was extended and refined under the current contract. By means of the model, it is possible to calculate the amounts of emission products emitted by individual vehicles or groups of vehicles over an arbitrary driving sequence.

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1. INTRODUCTION

The modal emission model developed for the EPA under Contract No. 68-01-0435 and refined and extended under Contract 68-03-0435 makes possible the computation of vehicle emissions over an arbitrary driving sequence. The amounts of pollutants emitted over this sequence can be computed for individual vehicles or for groups of vehicles pooled to represent meaningful aggregations according to such constraints as model year or geographic location.

The model was initially applied to data from 1020 automobiles as obtained by Automotive Environment Systems, Inc. under EPA Contract No. 68-04-0042. These vehicles spanned model years 1957-1971 and represented the total population of such vehicles in use in early 1972. As new genre of vehicles enter the vehicle population and older vehicles are retired from the population, adjustments in the model must clearly be made if it is to be used for predictive purposes. Accordingly, it is important that the modal emissions data generated as part of the Emission Factors Testing Program be integrated into the modal emissions data base and that the modal emissions model be updated as required to accommodate the new data. The results reported herein represent efforts to integrate FY 74 emission factors data into the modal emissions model and to review the FY 71 and FY 73 results in the light of findings from the FY 74 program.

For many, if not most, purposes to which the modal emission model will be put, the prediction of emissions from an individual vehicle is not so much of interest as the prediction of emissions from an aggregate or collection of vehicles subject to some set of constraints such as geographic location, mix of model years, and time-history profile. For example, consider the impact of two alternative traffic management systems on ambient air quality. To determine relative desirability of the alternatives, it is more appropriate to consider the aggregate emissions from a representative sample of the vehicle population being controlled by the system than to consider emissions from individual vehicles in the population. The prediction of group emissions benefits from the fact that the law of large numbers operates to reduce the uncertainty in the predictions. If data from a large number of individual vehicles are pooled to estimate the group emission averages, those estimates are much more likely to reflect the actual difference in environmental impact than are comparisons made on individual vehicles.

In the FY 71 emission factors program, it was determined that model years and certain geographical considerations, such as altitude, provided a logical basis for stratification of vehicles into appropriate groups. Accordingly, eleven groups were established for application of the modal emission model to the FY 71 data. Similar considerations gave rise to six vehicle groups in the FY 73 program and two groups in the FY 74 program. The groups for FY 71, FY 73, and FY 74 are shown in the inset table. The rationale for geographic classification is based on the fact that, in the FY 71 and FY 73 programs, vehicles from Denver displayed, as a group, different emission characteristics than vehicles from low altitude cities. Los Angeles vehicles were distinguished as a separate group because of differences between emission standards for California and for other parts of the United States. In the FY 74 program, data from Denver were not available for analysis at the time this report was prepared.

In the ensuing sections of this report, the mathematical basis of the model will be reviewed as a prelude to its application to the emissions factors data for the various fiscal years. Included in this review will be a reiteration of the statistical basis employed to evaluate the accuracy and precision of the model in predicting emissions over the Surveillance Driving Sequence (SDS) and the Federal Test Procedure (FTP). Results will then be presented as tables of model coefficients for the several vehicle groups and tables of performance in terms of model bias and variance.

VEHICLE GROUP STRUCTURE
FOR EMISSION FACTOR PROGRAMS

FY 71 DATA

Group 1 - 1957-1967 Denver
2 - 1957-1967 low-altitude cities (non-California 1966, 1967)
3 - 1966 and 1967 California
4 - 1968 low-altitude cities
5 - 1969 low-altitude cities
6 - 1970 low-altitude cities
7 - 1971 low-altitude cities
8 - 1968 Denver
9 - 1969 Denver
10 - 1970 Denver
11 - 1971 Denver

FY 73 DATA

Group 1 - 1973 and 1974 Denver
2 - 1972 Denver
3 - 1973 and 1974 Los Angeles
4 - 1972 Los Angeles
5 - 1973 and 1974 low-altitude cities
6 - 1972 low-altitude cities

FY 74 DATA

Group 1 - 1975 low-altitude cities)
2 - 1975 Los Angeles)
) most vehicles equipped with catalytic converters

2. MODAL ANALYSIS EMISSION MODEL: THEORY, APPLICATION AND EVALUATION

The modal emissions model is a regression model which applies discrete data obtained from the Surveillance Driving Sequence (SDS) to predict the instantaneous emission rate $\dot{e}$ of a vehicle or group of vehicles as a function of speed v and acceleration a over any driving sequence. The primary feature of the model is a scheme whereby emissions from discrete time segments called modes can be expanded into a continuous function of time.

2.1 MATHEMATICAL BASIS OF THE MODEL

The emission-rate function can be visualized as a surface in a three-dimensional space in which the dimensions are speed v, acceleration a, and instantaneous emission rate $\dot{e}$. The surface is represented mathematically in the form

$$\dot{e} = f(v, a)$$

where $\dot{e}$, v and a are all assumed to be continuous functions of time.

In general, the multiple regression equation for emission rate $\dot{e}$ as a function of velocity and acceleration is written in the form

$$\begin{aligned} \dot{e}(v,a) &= c_1 u_1(v,a) + c_2 u_2(v,a) + \dots . c_k u_k(v,a) \\ &= \sum_{i=1}^{k} c_i u_i(v,a) \qquad (1) \end{aligned}$$

where the u_i are called "basis functions" and are selected in such a way as to best span the variation of instantaneous emission rate $\dot{e}$ in response to instantaneous speed and acceleration. The basis functions u_i need not be orthogonal but are linearly independent.

For a particular vehicle the emission rate surface $\dot{e}(v,a)$ is completely specified by the model-generated coefficients (c_i) for any driving sequence within the domain spanned by the basis functions. Since the regression model is a linear model, coefficients for groups of vehicles can be computed by averaging the coefficients of all vehicles within the group.

Although Equation (1) represents an emission rate function $\dot{e}(v,a)$ applicable over the entire (v,a)-plane, greater flexibility is afforded if the equation is decomposed into two functions, one applicable when $a = 0$, the other when $a \neq 0$. The first, denoted $\dot{e}(v,0)$, applies to constant-speed operation and, since it is a function of v only, can be abbreviated $\dot{e}_s(v)$. The second function, denoted $\dot{e}_A(v,a)$, characterizes vehicle emission rates during periods of acceleration or deceleration. For purposes of spanning the entire (v,a)-plane, the functions $\dot{e}_A(v,a)$ and $\dot{e}_S(v)$ can be combined as the composite function

$$\dot{e}(v,a) = h\,\dot{e}_S(v) + (1-h)\,\dot{e}_A(v,a) \tag{2}$$

where h is a weighting function dependent on acceleration a and bounded in the interval $0 \leq h(a) \leq 1$.

In the original version of the model the form of $\dot{e}_S$ and $\dot{e}_A$ were:

$$\begin{aligned} \dot{e}_S &= b_1 + b_2 v + b_3 v^2 \\ \dot{e}_A &= d_1 + d_2 v + d_3 a + d_4 av + d_5 v^2 + d_6 a^2 \\ &\quad + d_7 va^2 + d_8 v^2 a + d_9 v^2 a^2 \end{aligned} \tag{3}$$

In matrix vector notation, (3) can be written

$$\begin{aligned} \dot{e}_S &= \underline{B}\,\underline{F}' \\ \dot{e}_A &= \underline{D}\,\underline{G}' \end{aligned} \tag{4}$$

where $\underline{B} = (b_1\ b_2\ b_3)$

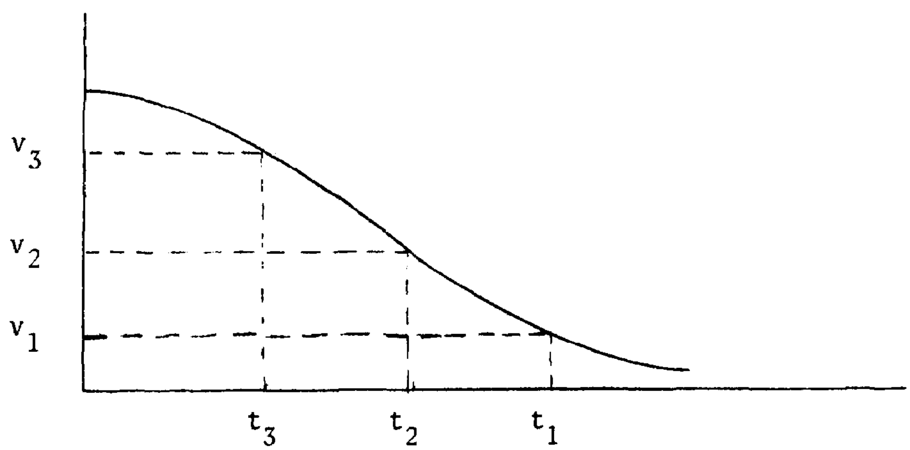
$\underline{F} = (\ 1\ v\ \ v^2)$

$\underline{D} = (d_1\ d_2\ d_3\ d_4\ d_5\ d_6\ d_7\ d_8\ d_9)$

$\underline{G} = (1\ v\ a\ av\ v^2\ a^2\ va^2\ v^2a\ v^2a^2)$

and $\underline{F}'$ and $\underline{G}'$ denote, respectively, the transposes of the vectors $\underline{F}$ and $\underline{G}$.

Let us consider a typical time segment or mode of the SDS of duration T. The sequence is specified in terms of the speed at each of n discrete, equally spaced points in time as shown in Figure 1. Note that time increases to the left.



The total emission e(T) produced during time duration T of the mode is

$$e(T) = \int_0^T \dot{e}(v,a)dt \tag{5}$$

and in discrete space can be approximated by

$$e(T) = \sum_{i=1}^{n-1} e(v_i, a_i) \Delta t \tag{6}$$

where

$$v_i = \frac{v(T_i) + v(T_{i+1})}{2}$$

$$a_i = \frac{v(T_{i+1}) - v(T_i)}{\Delta T} \tag{7}$$

and $\qquad n \Delta T = T.$

In terms of (6), therefore, the average emission rate over time T is

$$\langle \dot{e} \rangle_T = \frac{1}{T} \sum_{i=1}^{n-1} \dot{e}(v_i, a_i) \Delta T \tag{8}$$

Note, however, that this average emission rate can be computed from the total emissions measured during the time duration of the mode. The total emissions, called the "bag values" for the mode, are an estimate of and can be identified with $e(T)$. Therefore

$$\langle \dot{e} \rangle_T = e(T)/_T \tag{9}$$

and from (2), (4), (8), and (9) one can write

$$\langle \dot{e} \rangle_T = \frac{1}{T} \sum_{i=1}^{n-1} \left[h_i \, \underline{B} \, \underline{F}_i' + (1 - h_i) \, D\underline{G}_i' \right] \Delta$$

$$= \underline{B} \left[\frac{1}{T} \sum_{i=1}^{n-1} h_i \, \underline{F}_i' \Delta T \right] + \underline{D} \left[\frac{1}{T} \sum_{i=1}^{n-1} (1-h) \, \underline{G}_i' \Delta t \right] \tag{10}$$

Note the quantities in brackets are the weighted time averages of the basis function vectors $\underline{F}$ and $\underline{G}$ respectively over the time duration of the mode.

Therefore, one can write:

$$e(T)/T = \underline{B}\,\underline{\bar{F}}' + \underline{D}\,\underline{\bar{G}}' \tag{11}$$

where $\underline{\bar{F}}$ and $\underline{\bar{G}}$ are the weighted time averages of the basis functions vectors $\underline{F}$ and $\underline{G}$ for the mode under consideration. Since the total emissions for each mode are known, as well as the corresponding times in mode, the weighted time averages $\underline{\bar{F}}$ and $\underline{\bar{G}}$ can be computed using the speed-acceleration profiles of the SDS for each mode. The coefficient vectors $\underline{B}$ and $\underline{D}$ can be computed through least squares regression analysis.

The emission rate regression equation is intentionally expressed as a sum of two terms in (11) to stress the fact that emission rate is a composite function consisting of a function of speed only and a function of both speed and acceleration. Because of the linearity of the model, however, (11) could just as well be expressed as

$$\frac{e(T)}{T} = \underline{B}\,\underline{\bar{F}}' + \underline{D}\,\underline{\bar{G}}' = \underline{A}\,\underline{\bar{X}}' \tag{12}$$

where $\underline{A}$ is a 12-element row matrix of coefficients, consisting of the 3 coefficients from $\underline{B}$ and the 9 coefficients from $\underline{D}$. Similarly, $\underline{\bar{X}}'$ is a 12-element column matrix, the elements of which are weighted time averages (3 from $\underline{\bar{F}}$ and 9 from $\underline{\bar{G}}'$). The vector $\underline{A}$ can represent a set of coefficients for either a single vehicle or a group of vehicles.

2.2 APPLICATION OF THE MODEL TO DRIVING SEQUENCES

The calculation of total emissions over a prescribed time history of speed and acceleration is performed by appropriate integration of the emission-response function. Though this integration can be performed for an endless variety of time histories, those for which instrumentally measured emissions are known are of particular interest. Total emissions are, therefore, calculated for the Surveillance Driving Sequence (SDS) and for the first 505 seconds of the Federal Test Procedure (FTP). Comparison of measured (bag) values for these two sequences with corresponding values computed by the model provide measures of model performance. In this connection, it is convenient to regard the SDS as a "training sequence" and the FTP as a "test sequence." The input modal data used in computing the regression coefficients for each vehicle are obtained from the SDS. When these coefficients are employed to compute the SDS bag value, therefore, there is present an element of "reciting" what was learned in the training phase. When the same coefficients are employed to compute total emissions for the FTP sequence, however, no such reciting is involved because the FTP constitutes an independent test. The same vehicles were evaluated by the emissions model over both the SDS and FTP driving sequences.

2.3 PERFORMANCE EVALUATION OF THE MODEL: ERROR STATISTICS

Evaluation of the performance of the model is achieved by comparison of measured emissions and emissions computed from the model. For this purpose it is convenient to define "bag value error" as

$$R = C - O$$

where O denotes the measured or observed bag value and C denotes the bag value computed from the model. Note that R changes from one vehicle to another and even from one test to another on the same vehicle. These variations can be due to errors of measurement, whether of the modal input data or the bag value, or they can be due to the fact that the model does not faithfully integrate the time-varying emission contributions in the same way as they are accumulated in the bag-value measurement. If one computes the error R for a number of vehicles, however, one can assess probabilistically whether a bias exists in the computation. Statistical quantities of interest are $\overline{R}$, the average bag error for all the vehicles, and σ_R, the standard deviation of the individual bag errors about the mean value. A test of significance can then be applied to determine whether $\overline{R}$ represents a bias or is most likely a consequence of random measurement errors. Other statistics of interest are the root mean square deviation of the bag error

$$RMS = \sqrt{\bar{R}^2 + \sigma_R^2}$$

and the magnitudes of $\bar{R}$, σ_R and RMS relative to the average observed bag value $\bar{O}$. See the NOTATION insert for terms used in this report to discuss model performance.

NOTATION

CBAR	=	Mean of the calculated amount of the given pollutant
OBAR	=	Mean of the observed amount of the given pollutant
RBAR	=	Mean bag error (Bag error = Calculated Amount - Observed Amount)
SIGR	=	Standard deviation of the bag error
PSIG	=	(SIGR/OBAR) X 100%
RMSR	=	Root Mean Square deviation of the bag error
PERR	=	(RMSR/OBAR) X 100%

3. FACTORS AFFECTING MODEL PERFORMANCE

As a result of applying the model to data from the FY 71, FY 73, and FY 74 Emission Factors Programs, a backlog of experience has accumulated from which it is possible to isolate some of the factors which influence model performance. Most notable are those associated with the emission measurement process and its effect on the quality of the modal input data. To provide the necessary perspective for meaningful interpretation of the results reported in Section 5, it will be instructive to review this experience, as well as certain aspects of emission measurement.

3.1 MODEL INPUT DATA

First, let us consider the nature of the input data required by the emission model. The model uses modal data as computed from each mode or time segment of the total 1054 seconds of the SDS to predict the actual total output of pollutant over any driving sequence. The SDS is divided into 65 time intervals or modes, 32 acceleration-deceleration modes, and 33 zero-acceleration modes. **Table 1** lists all 32 acceleration-deceleration modes with their corresponding speeds, distances traveled, and times in mode.

Each acceleration-deceleration segment in the SDS is followed by a cruise-mode segment. The second-by-second emission rate response of a vehicle in executing the SDS is recorded by a strip-chart recorder. The strip-chart response is then divided into segments corresponding to each of the 65 modes of the SDS. The area under the emission response curve corresponding to each of the 32 accel/decel modes is measured and is used as input for the $\dot{e}_A$ portion of the emissions model. The areas corresponding to the 33 cruise modes of the SDS are <u>not</u> input to model. Instead, separate tests are performed at constant speeds for periods of 60 seconds. These stabilized steady state emission rates are computed from the 60-second intervals, and are then used as input for the $\dot{e}_S$ portion of the model.

Table 1

MODE VERSUS TIME IN MODE

MODE NO.	FROM-TO (MPH)	DISTANCE (MILES)	TIME (SEC)
2	00-30	0.0602	12
4	30-00	0.0741	16
6	00-15	0.0201	8
8	15-30	0.0705	11
10	30-45	0.1360	13
12	45-30	0.1268	12
14	30-60	0.2163	17
16	60-45	0.1716	12
18	45-60	0.2043	14
20	60-15	0.3367	30
22	15-60	0.3136	26
24	60-00	0.1973	21
26	00-60	0.3313	32
28	60-30	0.2994	23
30	30-15	0.0579	9
32	15-00	0.0173	8
34	00-45	0.1759	22
36	45-15	0.1392	16
38	15-45	0.1528	18
40	45-00	0.1304	19
42	00-60	0.2654	25
44	60-00	0.2634	28
46	00-30	0.0737	15
48	30-60	0.3134	25
50	60-30	0.2362	18
52	30-00	0.0444	10
54	00-60	0.4009	38
56	60-00	0.3293	35
58	00-30	0.0886	18
60	30-60	0.2599	21
62	60-30	0.1813	14
64	30-00	0.0592	13

3.2 REVIEW OF FY 71 AND FY 73 RESULTS

As initially developed the modal analysis model consisted of a composite emission rate function consisting of an $\dot{e}_A$ function based on steady-state modes. The composite model with 12 basis functions had given good performance in the FY 71 Emission Factors Program in the evaluation of 1020 light-duty vehicles in six cities (see EPA Report No. EPA-460/3-74-005) though in subsequent analysis there was found some evidence of significant bias between observed and computed bag values (see EPA Report No. EPA-460/3-74-024). As a starting point in the analysis of the FY 73 Emission Factors Program, therefore, the model in its initial form was applied to the FY 73 modal emissions data. Performance statistics for this form of the model as applied to the SDS and FTP driving sequences for FY 73 data, however, revealed that the mean emissions calculated from the model (CBAR) were consistently lower than the observed means (OBAR) obtained by averaging the observed bag values for the 450 vehicles. Statistical tests of significance indicated that, for the most part, these differences could not be attributed to chance and consequently suggested that the model was producing biased results.

The following figure is offered as representative of a slice through the emissions surface at constant speed.

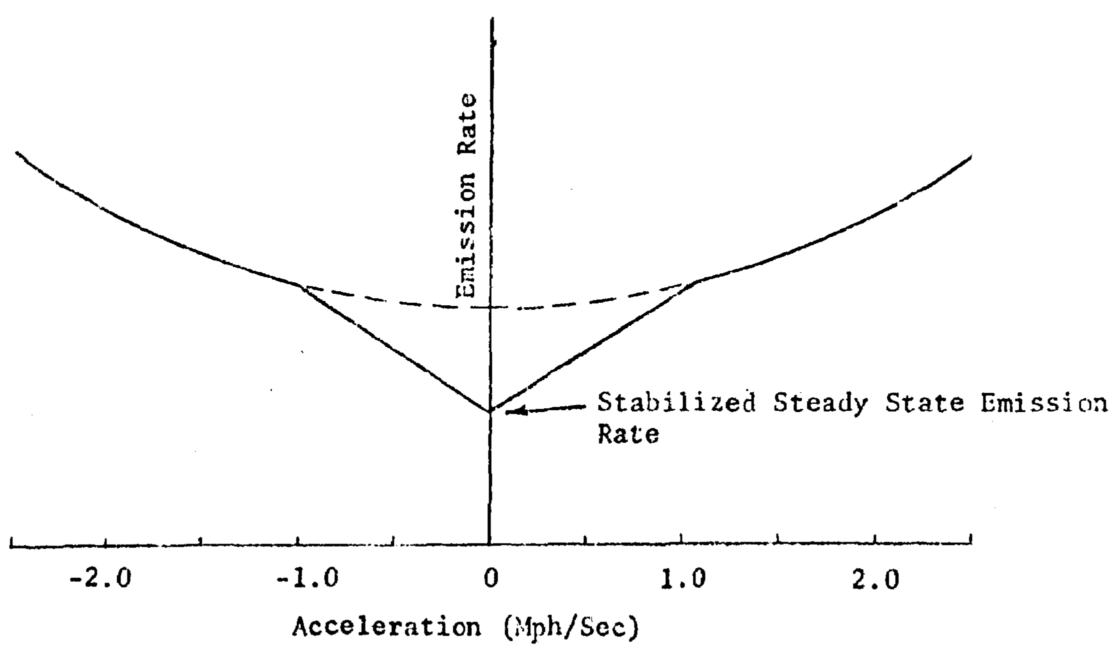


Figure 1

Notice that the emissions rate vs. acceleration profile is discontinuous at accelerations of -1 and +1. This discontinuity is a result of the fact that the emissions surface is configured from two functions which are blended together between accelerations of -1 and +1. The above figure is slightly exaggerated to emphasize the fact that the steady state point at $a = 0$ is the lowest point on the curve. Since the model was negatively biased, it was postulated that the steady state value was not representative of the constant-speed operation during the SDS cycle. In particular, it was conjectured that the cruise modes of the SDS did not afford sufficient time for the emission rate to settle to a stable value truly indicative of constant speed operation and that the use of constant-speed data based on periods of 60-second operation might be inappropriate.

An alternative to the initial form of the model was therefore proposed. Compute the $\dot{e}_A$ portion of the surface from the 32 A/D modes and employ this surface to compute emission rates for all portions of the (v,a)-plane, <u>including</u> those locations in which $a = 0$. The argument here is that $\dot{e}_A$ certainly yields emission rates for $a = 0$ and that these rates, being based on transient performance, are more likely to be consistent with the constant-speed portions of the SDS than are emission rates derived from tests made under unrealistically stabilized conditions. When this alternative form of the model was applied to the FY 73 emission factors data, it was found that for both the SDS and FTP driving sequences the negative biases affecting the computed emissions were, for the most part, adjusted in the positive sense. In other words, large negative biases tended to be transformed into smaller negative biases or, in some cases, into positive biases. These results suggested that the FY 71 data be recomputed using the simplified version of the model and that both versions of the model be compared with regard to group emissions computed for both FY 73 and FY 71 data. For purposes of reference the original version of the model, which employs a composite emission rate function with both $\dot{e}_A$ and $\dot{e}_S$ components is called the "composite" model. The new version of the model which employs only the $\dot{e}_A$ emission rate function is referred to as the "simple" model.

The results using the composite and simplified forms of the model for FY 71 and FY 73 data are summarized in the Tables 2 and 3. In these tables, statistics are presented for homogeneous vehicle groups.

As may be seen in Tables 2-A and 3-A, with a high degree of consistency, biases tend to be adjusted in the positive sense when the steady state function $\dot{e}_S$ is eliminated from the model. Equally important, however, is the fact that there is an associated tendency for the percent standard deviation to increase, as may be seen in Tables 2-B and 3-B. These results suggested the need for a definitive test to assess the importance of the postulated stabilization effect.

3.3 DIRECT TESTING OF EMISSION RATES

In order to evaluate the impact that variances in measurements of input data would have on model performance, tests were conducted to determine the difference between the emission rates of the cruise modes of the SDS and the emission rates of the stabilized steady states. These tests were conducted in such a way that emission rate could be monitored on a second-by-second basis rather than being computed from total emissions and time in mode.

The continuous effluent response of two light-duty vehicles were investigated over the SDS. Particular attention was focused on the time required for each effluent to stabilize after reaching each cruise condition within the SDS. For purposes of this study, therefore, the cruise portions of the SDS were lengthened in time to 60 seconds duration to assure that stabilization had been achieved, and to allow comparison of stabilized emission rates with actual cruise mode emission rates during the zero-acceleration modes of the SDS.

Two cars were selected for the tests: a 1972 Chevrolet Impala and a 1976 Chevrolet Malibu. These two vehicles were chosen as representative of cars built before and after the use of NOX controls and catalytic converters. The 1972 Impala was previously used on EPA Contract No. 68-02-0698

Table 2-A

PERCENT BIAS FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS
FOR FY 73 PROGRAM

Group		N	SDS DRIVING SEQUENCE HC	SDS DRIVING SEQUENCE CO	SDS DRIVING SEQUENCE CO_2	SDS DRIVING SEQUENCE NOX	FTP DRIVING SEQUENCE * HC	FTP DRIVING SEQUENCE * CO	FTP DRIVING SEQUENCE * CO_2	FTP DRIVING SEQUENCE * NOX	MODEL
1	1973 and 1974 Denver	45	-16.4	-26.5	-5.9	+15.3	-16.5	-5.6	-11.7	0.0	C
			+9.0	-1.4	-2.2	+4.7	+14.5	+41.1	-4.0	-5.5	S
2	1972 Denver	30	-22.9	-32.8	-8.6	+15.2	15.7	-0.8	-14.9	-5.6	C
			+3.8	-6.0	-2.8	+3.1	+21.9	+54.7	-6.4	-12.0	S
3	1973 and 1974 Los Angeles	45	-12.7	-5.5	-4.4	+5.2	-27.5	-16.7	-4.7	+3.1	C
			+5.9	-7.9	-4.4	+18.6	-5.5	-14.2	-3.4	+19.4	S
4	1972 Los Angeles	30	-6.8	+2.2	-6.6	+15.2	-21.5	-10.4	-6.6	+14.2	C
			+8.1	+8.4	-7.0	+33.4	-3.0	+4.7	-5.6	+34.1	S
5	1973 and 1974 low altitude cities	180	-15.5	-25.6	-10.6	-10.4	-17.8	-12.0	-8.8	-15.4	C
			+6.2	-4.6	-4.6	-3.9	+9.0	+21.9	+0.3	-4.6	S
6	1972 low altitude cities	120	-18.3	-24.1	-8.8	-9.0	-16.9	14.0	-8.0	-16.6	C
			+7.9	-6.6	-3.3	-2.7	+18.1	+11.7	+0.5	-5.9	S
Pooled		450	-17.1	-25.0	-9.0	-4.3	-18.5	-11.5	-8.7	-9.7	C
			+6.8	-4.3	-4.1	+2.2	+11.4	+24.1	-1.2	-0.9	S

*First 505 seconds

C = Composite

S = Simple

Table 2-B

PERCENT STANDARD DEVIATION FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS FOR FY 73 PROGRAM

Group		N	SDS DRIVING SEQUENCE HC	SDS CO	SDS CO_2	SDS NOX	FTP DRIVING SEQUENCE * HC	FTP CO	FTP CO_2	FTP NOX	MODEL
1	1973 and 1974 Denver	45	15.4	21.5	5.7	18.3	29.4	29.6	8.1	22.2	C
			14.7	10.9	6.1	12.6	40.7	54.0	7.2	30.6	S
2	1972 Denver	30	15.2	20.2	9.8	23.7	17.3	30.5	11.6	18.1	C
			7.6	9.2	11.6	9.1	22.9	51.6	13.8	23.1	S
3	1973 and 1974 L.A.	45	21.6	16.4	5.8	13.5	25.5	20.8	6.1	18.9	C
			24.1	21.9	9.3	18.9	28.7	43.6	10.8	27.4	S
4	1972 L.A.	30	28.8	49.4	13.4	23.3	17.3	69.7	17.4	16.0	C
			13.8	100.9	21.5	23.8	30.5	131.1	26.3	24.0	S
5	1973 and 1974 low altitude cities	180	23.1	29.9	10.3	18.4	31.1	45.2	8.5	24.2	C
			23.3	22.0	11.4	21.8	33.7	61.7	10.4	31.8	S
6	1972 low altitude cities	120	29.7	32.6	15.0	16.4	29.2	30.6	9.0	22.6	C
			23.9	25.4	13.8	17.4	48.2	40.2	11.5	26.1	S
Pooled		450	25.7	35.2	11.6	21.8	28.0	37.9	9.1	22.1	C
			20.6	22.8	12.4	23.1	39.2	67.4	12.3	31.2	S

* First 505 seconds

C = Composite

S = Simple

Table 3-A

PERCENT BIAS FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS

FOR FY 71 PROGRAM

Group		N	SDS DRIVING SEQUENCE HC	CO	CO_2	NOX	FTP DRIVING SEQUENCE * HC	CO	CO_2	NOX	MODEL
1	1957-1967 Denver	97	-14.2	-6.3	-19.3	+24.5	-15.3	+1.8	-22.3	+2.1	C
			+3.1	+10.4	-36.5	+12.9	+7.9	+27.7	-38.1	-7.4	S
2	1957-1967 low altitude cities	458	-12.9	-6.8	-2.9	+4.4	-12.6	-7.7	-6.2	-1.5	C
			+5.7	+2.3	-3.1	+10.0	+12.2	+6.6	-3.5	+7.9	S
3	1966 and 1967 California	33	-14.8	-15.0	-11.0	+0.2	-13.8	-13.8	-9.7	-7.8	C
			-6.2	-14.5	-11.3	+8.4	-4.4	-10.8	-7.8	+3.5	S
4	1968 low altitude cities	84	-8.0	+1.9	-3.2	-1.8	-7.9	-0.9	-4.5	-9.1	C
			+11.4	+4.1	-2.0	+8.3	+15.8	+8.0	-1.1	+3.8	S
5	1969 low altitude cities	89	-9.3	-6.5	-3.5	+5.5	-9.9	-7.1	-4.2	+0.0	C
			+9.4	-0.9	-2.1	+15.2	+15.2	+4.5	+0.2	+13.7	S
6	1970 low altitude cities	86	-10.1	-8.9	-5.4	+3.1	-11.4	-10.1	-6.4	-3.1	C
			+3.8	-2.4	-4.3	+12.0	+7.2	+3.4	-1.9	+8.4	S
7	1971 low altitude cities	101	-9.9	-7.7	-5.8	+2.3	-6.8	+11.5	-8.7	-4.1	C
			+3.9	-6.1	-4.0	+14.3	+12.8	+20.2	-3.5	+11.0	S
8	1968 Denver	18	-22.2	-9.5	-25.2	+37.0	-21.1	+5.8	-23.1	+12.2	C
			-11.3	+7.5	-43.2	+21.2	-6.2	+35.3	-42.4	-2.1	S
9	1969 Denver	17	-30.1	-1.7	-23.3	+16.8	-31.6	+2.1	-25.2	-7.0	C
			-27.6	+7.4	-38.4	+28.9	-26.1	+20.2	-38.5	+6.0	S
10	1970 Denver	17	-27.6	-10.3	-19.3	+26.6	-23.7	+3.5	-23.2	-5.6	C
			-13.9	+12.7	-31.3	+20.8	-4.5	+41.9	-33.1	-7.9	S
11	1971 Denver	20	-15.9	-11.8	-14.9	+34.8	-14.9	+7.2	-15.9	-4.8	C
			-0.1	+15.7	-20.7	+28.0	+7.6	+54.5	-20.3	-9.4	S
Pooled		1020	-13.5	-6.9	-6.2	+5.6	-13.3	-4.3	-8.9	-2.7	C
			+4.1	+3.9	-8.1	+11.9	+10.0	+13.3	-7.8	+7.1	S

* First 505 seconds

C = Composite
S = Simple

Table 3-8

PERCENT STANDARD DEVIATION FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS

FOR FY 71 PROGRAM

Group		N	SDS DRIVING SEQUENCE HC	SDS CO	SDS CO_2	SDS NOX	FTP DRIVING SEQUENCE * HC	FTP CO	FTP CO_2	FTP NOX	MODEL
1	1957-1967 Denver	97	16.6	12.5	19.4	43.1	18.2	17.2	19.4	33.8	C
			18.7	13.5	33.2	46.0	18.3	26.8	34.3	53.2	S
2	1957-1967 low altitude cities	458	21.4	24.9	9.9	29.4	27.2	29.3	18.3	29.3	C
			30.7	33.8	12.8	37.0	42.3	40.5	21.1	42.9	S
3	1966 and 1967 California	33	15.8	23.6	14.7	36.8	49.4	21.0	15.6	33.2	C
			29.4	24.1	24.4	56.9	68.7	28.9	27.5	51.6	S
4	1968 low altitude cities	84	17.8	28.2	11.8	21.8	40.3	28.0	13.1	31.1	C
			31.0	33.2	14.2	29.4	55.6	38.9	16.3	42.3	S
5	1969 low altitude cities	89	17.2	25.9	10.4	20.7	24.6	23.3	14.9	24.8	C
			27.1	43.5	14.3	33.8	44.5	44.7	17.4	37.6	S
6	1970 low altitude cities	86	17.0	31.5	13.0	19.1	37.9	47.6	12.0	22.7	C
			22.3	55.7	17.7	33.1	48.0	76.5	18.7	40.6	S
7	1971 low altitude cities	101	31.3	29.5	12.2	20.7	30.1	55.2	30.5	22.2	C
			26.3	43.1	15.9	27.7	62.8	85.1	31.8	33.4	S
8	1968 Denver	18	22.1	11.6	23.4	19.8	22.4	15.3	21.2	38.6	C
			35.1	11.4	38.5	20.3	39.8	29.4	33.3	38.3	S
9	1969 Denver	17	27.2	9.9	21.0	12.9	19.9	24.2	17.4	15.9	C
			41.3	13.3	36.9	34.1	35.9	30.0	35.0	30.8	S
10	1970 Denver	17	24.8	21.1	18.9	28.3	21.6	25.0	18.0	23.9	C
			29.6	14.9	34.3	37.1	37.7	32.2	34.0	38.1	S
11	1971 Denver	20	22.1	13.6	18.9	24.2	14.8	24.1	17.2	27.7	C
			29.4	14.0	30.4	33.9	26.8	41.9	29.1	32.6	S
Pooled		1020	22.4	22.9	13.7	26.5	29.1	28.9	20.0	28.0	C
			30.4	30.5	21.3	36.2	43.4	45.1	26.7	42.3	S

* First 505 seconds

C = Composite
S = Simple

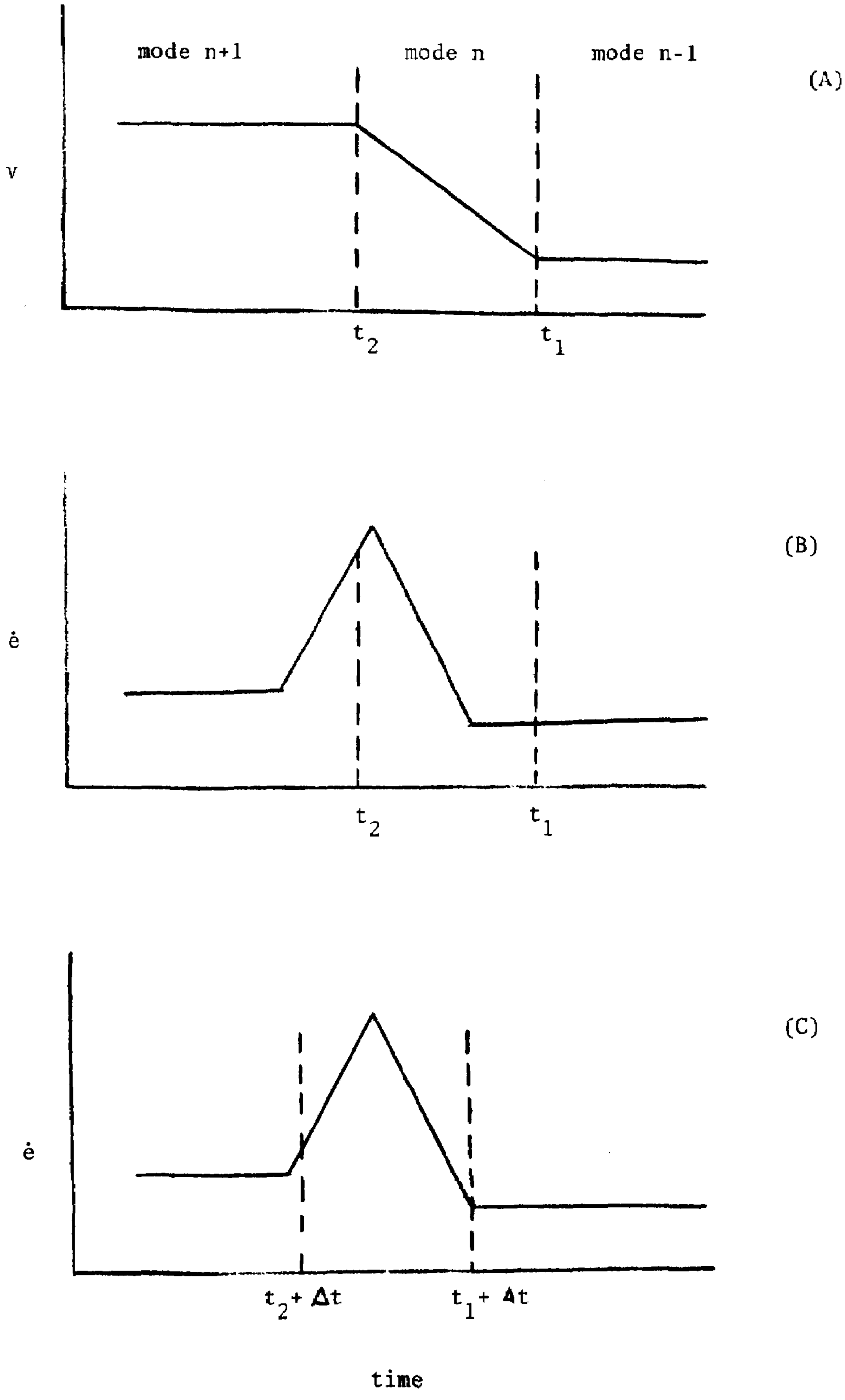
and had been driven 20,000 miles on unleaded indolene and EPA reference fuel. This car was equipped with a 350 CID V-8 engine, a two-barrel carburetor, and an automatic transmission. The 1976 Malibu was equipped with a 305 CID V-8 engine, a two-barrel carburetor, automatic transmission, and an oxidation catalyst. This vehicle had been driven about 1000 miles.

All testing was done in Calspan's Vehicle Emissions Research Laboratory. In each of the tests, the gas sample to be analyzed was drawn from a location in the stabilized flow stream established by the constant volume pump. Consequently, the sample was proportional to the instantaneous mass emissions of the vehicle. Therefore, it was possible to measure emission rates on a continuous basis.

Results obtained from these tests made it apparent that measuring system delay times were of greater magnitude than stabilization times. These results further suggested that integrated modal outputs would be correctly predicted by the model if the modal input data were more appropriately phased in relation to the modal speed profile.

For purposes of clarifying the results of this investigation, the following sketches are offered as a simplified representation of the emission response during a steady-state (mode n-1), acceleration (mode n), steady state (mode n+1) sequence. The emission rate responses in the following sketches approximate the actual emission rate response observed on the strip chart recordings referred to in Section 3.1.

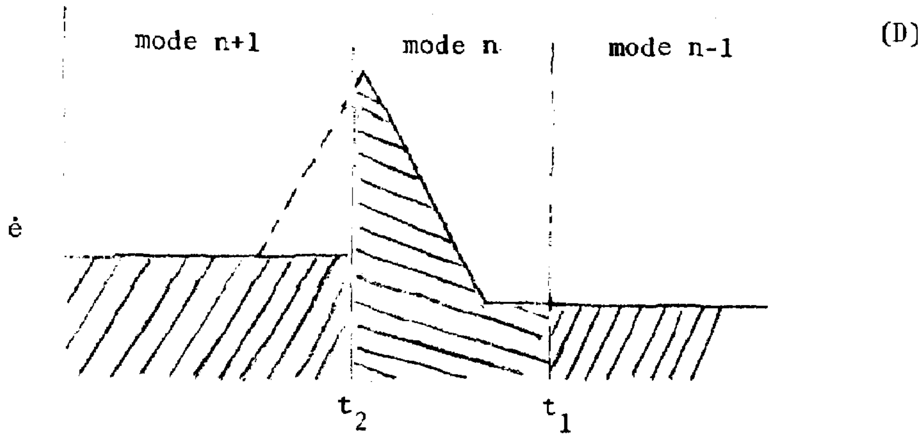
Sketch A shows a portion of the SDS as executed by the driver in accelerating from a 30 mph cruise mode to a 60 mph cruise mode. An idealized version of the emission response to this maneuver is postulated in Sketch B. Though the triangular shape of the emission-response pulse is deliberately oversimplified for convenience in presentation, it is reasonable to believe that during acceleration the emission first increases, then reaches a maximum, and finally decreases to an essentially constant level.

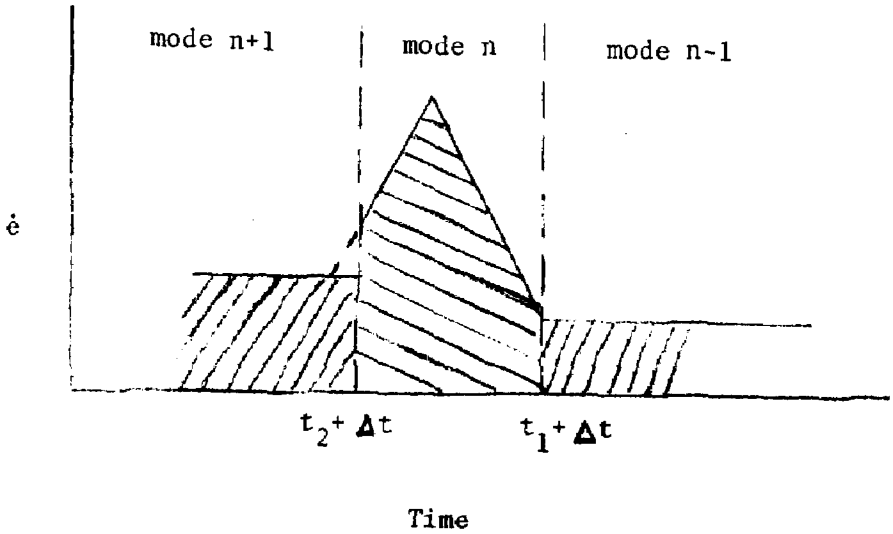

mode n+1
mode n
mode n-1
(A)
v
t2
t1
(B)
ė
t2
t1
(C)
ė
t2+ Δt
t1+ Δt
time

In terms of the driver maneuver, the times denoting the beginning and the end of the acceleration mode are as shown by the event markers at t_1 and t_2 in Sketch A. The time elapsed between these two markers constitutes a modal "window" corresponding to the actual acceleration of the vehicle. Note, however, that in Sketch B the emission pulse does not begin until some time $t_1 + \Delta t$, where Δt denotes a delay time associated with sample transport time and instrument response time. Consequently, only a portion of the emission response pulse falls within the clock-time interval between t_1 and t_2, and the integrated emission during this interval is unrepresentative of the actual acceleration response.

Now consider Sketch C, in which the modal window, of time duration $t_2 - t_1$, is shifted by the delay time Δt. Now most of the emission response pulse falls within the time interval between $t_1 + \Delta t$ and $t_2 + \Delta t$, and the integrated emission during this interval is much more representative of the actual emission response. The fact that the emission has not come to a constant level at time $t_2 + \Delta t$ can be interpreted to mean that the vehicle requires an additional period of time for stabilization to a new steady-state mode of operation. As represented in Sketch C, however, this "stabilization time" is short relative to the delay time Δt and introduces relatively little error in the integrated emission over either the acceleration mode or the cruise mode immediately following it.

Now consider that the inputs to the emission model are the stabilized steady states as computed apart from the SDS, and the acceleration-deceleration emission rates as computed from the SDS. Thus, if acceleration-deceleration values were computed without regard to delay times of the measuring system, the shaded portion of the following Sketch D would represent the input to the emissions model. On the other hand, if modal values were computed by re-positioning the modal time window to adjust for measuring system delay time, the corresponding representation of the input to the model would look like the Sketch E below.





Note that in both cases (Sketches D and E), some area under the actual response curve of the vehicle during acceleration is deleted. The extent to which the predicted values vary from the observed values depends upon both the measuring system delay time and the time it takes the vehicle response to stabilize once it has reached steady state. Measuring system delay times appear to be of the order of 7 to 20 seconds, whereas stabilization times appear to be between 0-4 seconds. Stabilization times can only be defined and measured after the appropriate correction for the measuring system delay time has been made.

Table 4

Test of 1972 Chevrolet Impala

MODE	Relative Area Assuming No Delay Time Due To Instrumentation	Relative Area Assuming Constant Delay Between Vehicle Response and Instrument Response
HC		Assuming 7.5 Sec Delay
14	850	1330
15	1460	960
16	192	102
17	780	840
18	294	504
19	1136	1050
20	420	360
CO		Assuming 18 Sec Delay
14	850	1108
15	4080	3660
16	768	744
17	3480	3600
18	882	1064
19	3960	3780
20	1860	1710
NOX		Assuming 12 Sec Delay
14	51	680
15	1948	1680
16	336	156
17	600	480
18	712	756
19	2025	1800
20	660	167

Table 4 (CONT'D.)

Test of 1976 Chevrolet Malibu

	Relative Area Assuming No Time Delay	Relative Area With Delay
HC		7.5 Sec Delay
14	160	700
15	1200	600
16	24	800
17	750	128
18	14	100
19	250	180
20	300	300
CO		12 Sec Delay
14	150	800
15	3200	2100
16	24	480
17	800	400
18	40	400
19	2400	2200
20	960	600
NOX		18 Sec Delay
14	51	306
15	3600	4800
16	1200	300
17	1400	660
18	170	560
19	2000	1900
20	600	60

Table 4 represents the relative areas under the emission rate response as measured on the actual strip chart recordings for HC, CO, and NOX for tests conducted on a 1972 Chevrolet Impala and a 1976 Chevrolet Malibu.

Relative areas are presented for the case when measuring system delay times are ignored and for the case when appropriate system delay time shifts are taken into account. Relative areas reported in Table 4 were only approximated and are presented only for comparison. Note that the areas as measured with and without a time shift can differ considerably. Also, note that the greater the delay time shift, the more this difference is exaggerated. Differences in relative areas of each modal segment are also a function of the length of time defining a modal segment. Delay times of 15 seconds or more that are not applied to modal segments of less than 15 seconds duration imply that the entire emission response of that modal segment may be mistakenly added to another mode.

The areas corresponding to cruise modes in Table 4 are areas computed over the 60 second time duration of the extended SDS. The effect of ignoring measuring system delay times during the normal 15 second duration cruise modes of the SDS can result in greater differences in relative areas than are noted in Table 4. Areas for each mode segment of the emission response could increase or decrease after adjustment of the modal window by the delay time, depending on the time duration of the successive modes relative to the delay times involved.

3.4 DISCUSSION OF DRIVING SEQUENCES

It is indicated from results obtained from tests of the 1972 Impala and the 1976 Malibu over the SDS cycle that if adjustments of the modal windows by appropriate delay times are not applied to the emission response for each acceleration and deceleration mode, then errors will occur in the measurement of the modal response of these A/D modes. Since stabilization times are of much smaller magnitude than measuring system delay times, little or no errors occur in the use of stabilized steady state emission values for the cruise mode portions of the SDS.

Inspection of the velocity-time profile of the SDS sequence shows that every acceleration and deceleration segment of the SDS cycle is followed by a steady-state period of approximately 15 seconds. That is, almost half of the SDS cycle, which may be regarded as a "training sequence" is composed of steady-state or cruise mode periods over which little or no errors occur in the measurements of emissions.

Inspection of the velocity-time profile of the Federal Test Procedure (FTP), which may be regarded as a "test sequence," shows that less than twenty percent of the FTP cycle is composed of cruise mode or zero-acceleration segments. All cruise mode segments of the FTP are idle modes where the velocity is zero. When comparing the SDS cycle performance with the FTP cycle performance, it is evident why the SDS cycle performs more accurately in predicting total emissions. The SDS contains more steady-state portions and measurements of these portions are accurately representative of the zero-acceleration modes. Measurements of acceleration-deceleration segments, however, may be inaccurate due to phasing problems as discussed in Section 3.

Also, since the regression coefficients are obtained from inputs from the SDS, calculation of SDS bag values from these coefficients involves an element of "reciting" what was input or "learned" in the training phase. When the same coefficients are employed to compute total emissions for the FTP sequence, however, no such reciting is involved because the FTP constitutes an independent test.

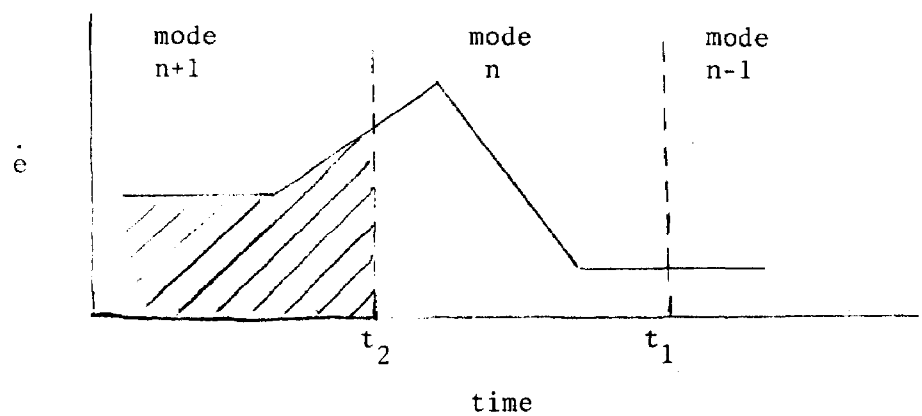
4. FY 74 RESULTS

Results of the continuous emission response test reported in Section 3.3 indicated that the measuring system delay times could introduce a phase lag between driver actions and the actual emission response as recorded by the instrumentation strip charts. The result of the phase lag was that the emission outputs could be associated, in part, with the wrong nominal mode of the SDS. The second finding, however, led to a completely different cause for the negative bias observed in the model. If the driver maneuvers and emission responses are properly phased, there may be only minor differences between stabilized steady state emission rates and cruise mode emission rates. According to this second finding, it is reasonable to believe that the stabilized steady state values as input to the composite model are representative of the cruise mode or zero-acceleration portions of the SDS.

The result of the first finding from the continuous emission rate tests of two vehicles implies that the acceleration-deceleration modes, as reported, are not representative of the emission response of the vehicle in executing an accel or decel segment. If we now return to the sketches in Section 3.3, it will be helpful in demonstrating an approximate method for correcting the A/D input data. If the phasing lag has not been removed, then the emission response of a vehicle in accelerating from a 30 mph cruise mode to a 60 mph cruise mode, as seen in sketch A, might be represented by approximation in sketch B.

As pointed out in Section 3, if the phase lag was not accounted for, the input to the model would be represented by the shaded portions of sketch D. In sketch D, the shaded areas of mode n+1 and mode n-1 are the stabilized steady state values that are input to the model. Mode n is an acceleration mode. Sketch D graphically demonstrates that because mode n was misaligned due to the phase lag, the unshaded portion of mode n+1 was mistakenly omitted from mode n.

If the phase lag was properly accounted for, the emission response to the acceleration sequence shown in sketch A might look like the approximated curve in Sketch C. Although not used as input to the emission model, the cruise mode data from Washington is available. If the phase lag was not accounted for, the shaded area of mode n+1 in Sketch F below would correspond to the "cruise" mode as measured from the strip chart recording.



(F)

If the phase shift was not made, part of the emission output from mode n could be incorrectly associated with mode n+1. Even if the phase lag was not adjusted, however, the emission output from mode n can be adjusted to a first approximation. If the stabilized steady state output from mode n+1 in Sketch D is subtracted from the cruise mode output from mode n+1 in Sketch F, the resulting delta output is reclassified as belonging to mode n. Table 5 gives a comparison of the 32 accel-decel modes before and after adjustment by the above method for one vehicle from Washington. Note that, in most cases, the A/D modal values have been increased after adjustment and, in some cases, decreased in magnitude after adjustment. The decrease corresponds to adjustments of deceleration modes as the same argument above applies.

Table 5

COMPARISON OF ORIGINAL A/D MODES AND CORRECTED A/D MODES - VEHICLE 5011* -- WASHINGTON

	Original A/D Modes				A/D Modes Corrected for Phasing Error			
Mode	HC	CO	CO2	NOX	HC	CO	CO2	NOX
1	2.66	16.35	1012.9	9.55	3.18	16.79	1471.4	10.26
2	0.83	12.18	310.0	0.73	0.96	17.58	359.9	0.83
3	3.51	18.35	838.0	11.32	5.41	28.08	1340.5	13.06
4	1.49	8.80	559.3	8.06	1.90	10.59	996.4	8.73
5	0.89	4.14	485.7	7.69	1.06	7.37	742.1	9.59
6	0.48	4.89	299.1	3.80	1.23	7.87	291.0	4.17
7	2.20	41.02	655.3	11.18	3.38	49.82	842.9	12.84
8	0.36	4.92	295.4	2.16	2.14	8.41	235.3	2.72
9	0.85	12.81	631.7	10.60	1.06	16.77	773.3	11.80
10	1.70	7.14	347.9	0.91	2.08	9.19	347.1	0.90
11	1.36	34.96	782.6	14.62	1.49	35.36	872.8	15.26
12	2.32	8.48	404.2	1.48	2.50	11.46	421.3	1.52
13	1.26	17.16	826.5	14.94	1.37	17.51	928.9	15.68
14	2.01	5.94	344.2	1.42	2.24	6.96	321.8	1.36
15	0.67	6.95	363.2	1.34	1.52	19.10	358.6	1.38
16	2.31	19.81	712.2	1.27	3.47	50.59	871.2	1.70
17	1.56	8.51	878.9	11.60	1.70	9.04	984.9	11.89
18	1.12	7.29	326.8	0.49	1.47	11.49	324.9	0.54
19	1.33	10.38	700.1	13.48	1.60	10.67	928.3	14.11
20	1.23	9.03	383.5	0.67	1.38	13.00	411.9	0.73
21	2.05	57.14	930.9	15.15	2.39	59.14	1046.2	16.07
22	2.25	7.38	336.0	1.15	2.49	9.40	346.4	1.18
23	2.44	13.09	557.1	9.44	2.86	14.12	779.8	9.71
24	0.99	9.75	607.5	10.61	1.17	11.44	701.9	11.39
25	1.73	5.72	321.9	1.18	2.64	7.37	306.9	1.16
26	0.91	10.39	436.4	0.76	1.30	22.38	498.3	0.93
27	1.05	7.91	536.7	12.02	1.16	8.18	585.0	12.69
28	1.75	6.04	369.7	0.72	1.82	7.55	377.1	0.74
29	1.92	9.37	836.5	8.17	2.27	9.91	993.1	8.34
30	2.12	19.45	523.9	12.50	2.79	21.76	660.9	14.07
31	1.34	5.97	339.4	1.19	2.15	8.66	302.4	1.20
32	0.88	8.48	448.5	1.22	1.13	17.01	500.4	1.35

*This table is representative of corrected input data for one vehicle from Washington. Input data for all 35 vehicles from Washington were corrected in the same manner.

The adjusted A/D modes were then employed with the stabilized steady state modes as input to the composite model. These results are presented in Table 7 of Section 4.1. Note that the biases as well as the percent RMS errors are lower than the composite model employing the original data in Table 6. Since both biases and RMS errors are lower when the adjusted A/D modes are used in the model, one must conclude that the adjusted A/D modal values are more representative of actual modal responses than the original A/D values.

The results presented suggest that a phasing error exists for the Washington data. Manipulation of the accel/decel data is possible to a first approximation by employing the cruise mode emission rates. This manipulation reduces the phasing error and improves model performance. Although improvement of model performance is possible by the above method, proper adjustment of the phase lag before accel-decel data is computed is greatly desirable in improving model performance.

4.1 MODEL COEFFICIENTS AND ERROR STATISTICS

Unfortunately, the "cruise mode" values available for Washington are not available for any of the remaining data for FY 74. Presented in the Tables 8-23, therefore, are model performance statistics for individual cities as well as the pooled group of cities excluding Los Angeles. Coefficients for the pooled group and Los Angeles are also presented.

At this point it is well to consider results particular to the FY 74 data. Most vehicles within this data set were equipped with catalytic converters. As a result, in general, all the modal values for FY 74 were much lower than the values for FY 73 and FY 71. Upon examination of the individual model predictions for each of the vehicles using the simple form of the model, it was discovered that some vehicles had negative predicted emissions. Further, upon examination of the observed modal steady-state values for these vehicles with negative predictions, it was discovered that all or almost all steady state raw input values were reported as "true" zeroes. It is conjectured that the

Table 6

MODEL COEFFICIENTS AND ERROR STATISTICS

PERFORMANCE STATISTICS FOR WASHINGTON

SDS Driving Sequence

Composite Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.867	20.586	556.124	4.935
OBAR =	0.898	21.857	567.466	4.778
REAR =	-0.031	-1.271	-11.342	0.157
PRBR =	-3.458	-5.815	-1.999	3.279
SIGR =	0.161	5.830	22.109	0.532
PSIG =	17.974	26.675	3.896	11.141
RMSR =	0.164	5.967	24.848	0.555
PERR =	18.304	27.302	4.379	11.614

Table 7

PERFORMANCE STATISTICS FOR WASHINGTON

SDS

A/D Modes Adjusted

Composite Model

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.911	22.404	576.489	5.057
OBAR =	0.898	21.857	567.466	4.778
RBAR =	0.013	0.547	9.023	0.278
PRBR =	1.457	2.503	1.590	5.825
SIGR =	0.137	4.346	19.666	0.307
PSIG =	15.290	19.885	3.466	6.420
RMSR =	0.138	4.381	21.637	0.414
PERR =	15.359	20.042	3.813	8.669

Table 8

PERFORMANCE STATISTICS FOR WASHINGTON

SDS Driving Sequence

Simple Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	1.016	19.881	603.600	6.073
OBAR =	0.898	21.857	567.466	4.778
RBAR =	0.119	-1.975	36.134	1.294
PRBR =	13.204	-9.038	6.368	27.087
SIGR =	0.258	7.508	34.443	0.958
PSIG =	28.698	34.350	6.070	20.054
RMSR =	0.284	7.763	49.920	1.610
PERR =	31.589	35.519	8.797	33.702

Table 9

PERFORMANCE STATISTICS FOR CHICAGO

SDS

Composite Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.700	23.724	545.629	3.188
OBAR =	0.811	28.170	561.643	3.224
RBAR =	-0.112	-4.446	-16.013	-0.036
PRBR =	-13.778	-15.781	-2.851	-1.122
SIGR =	0.139	4.150	18.881	0.377
PSIG =	17.142	14.731	3.362	11.686
RMSR =	0.178	6.081	24.757	0.378
PERR =	21.993	21.588	4.408	11.740

Table 10

PERFORMANCE STATISTICS FOR CHICAGO

SDS
SIMPLE FUNCTION
(UNITS = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

		HC	CO	CO2	NOX
CBAR	=	0.770	23.649	572.171	3.629
OBAR	=	0.811	28.170	561.643	3.224
RBAR	=	-0.041	-4.521	10.528	0.406
PRBR	=	-5.110	-16.050	1.875	12.587
SIGR	=	0.156	6.824	25.016	0.620
PSIG	=	19.210	24.226	4.454	19.242
RMSR	=	0.161	8.186	27.141	0.741
PERR	=	19.878	29.060	4.832	22.993

Table 11

PERFORMANCE STATISTICS FOR HOUSTON

SDS Driving Sequence

Composite Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

		HC	CO	CO2	NOX
CBAR	=	0.623	15.316	546.917	4.094
OBAR	=	0.711	17.199	566.700	4.163
RBAR	=	-0.088	-1.883	-19.783	-0.070
PRBR	=	-12.333	-10.949	-3.491	-1.671
SIGR	=	0.151	3.366	15.184	0.397
PSIG	=	21.194	19.572	2.679	9.528
RMSR	=	0.174	3.857	24.938	0.403
PERR	=	24.521	22.426	4.401	9.674

Table 12

PERFORMANCE STATISTICS FOR HOUSTON

SDS Driving Sequence

Simple Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR	0.724	15.169	569.158	4.739
OBAR =	0.711	17.199	566.700	4.163
RBAR =	0.013	-2.030	2.458	0.575
PRBR =	1.881	-11.801	0.434	13.813
SIGR =	0.147	4.846	13.846	0.586
PSIG =	20.640	28.177	2.443	14.072
RMSR =	0.147	5.254	14.063	0.821
PERR =	20.725	30.548	2.482	19.718

Table 13

PERFORMANCE STATISTICS FOR ST. LOUIS

SDS

Composite Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.591	11.969	507.309	3.881
OBAR =	0.598	13.186	521.331	4.093
RBAR =	-0.007	-1.217	-14.023	-0.212
PRBR =	-1.147	-9.229	-2.690	-5.191
SIGR =	0.307	3.582	25.280	0.469
PSIG =	51.254	27.165	4.849	11.458
RMSR =	0.307	3.783	28.909	0.515
PERR =	51.267	28.690	5.545	12.579

Table 14

PERFORMANCE STATISTICS FOR ST. LOUIS

SDS

Composite Function

(Excluding One Outlier)

(Units = GMS/MI)

Number of cars in this group = 34 (Model Year 75)

		HC	CO	CO2	NOX
CBAR	=	0.547	11.829	507.684	3.885
OBAR	=	0.603	13.427	521.426	4.091
RBAR	=	-0.055	-1.598	-13.743	-0.205
PRBR	=	-9.205	-11.903	-2.636	-5.016
SIGR	=	0.108	2.824	25.605	0.474
PSIG	=	17.916	21.033	4.911	11.590
RMSR	=	0.121	3.245	29.060	0.517
PERR	=	20.143	24.168	5.573	12.629

Table 15

PERFORMANCE STATISTICS FOR ST. LOUIS

SDS

Simple Function

(Units = GMS/MI)

Number of cars in this group = 35 (Model Year 75)

		HC	CO	CO2	NOX
CBAR	=	0.568	11.521	527.425	4.434
OBAR	=	0.598	13.186	521.331	4.093
RBAR	=	-0.030	-1.665	6.093	0.341
PRBR	=	-5.075	-12.627	1.169	8.328
SIGR	=	0.122	4.900	44.557	0.480
PSIG	=	20.421	37.164	8.547	11.732
RMSR	=	0.126	5.176	44.971	0.589
PERR	=	21.042	39.251	8.626	14.388

Table 16

PERFORMANCE STATISTICS FOR PHOENIX

Composite Function

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.727	20.918	503.700	3.994
OBAR =	0.861	25.101	522.429	4.107
RBAR =	-0.135	-4.184	-18.728	-0.113
PRBR =	-15.626	-16.667	-3.585	-2.747
SIGR =	0.141	8.302	12.762	0.471
PSIG =	16.351	33.072	2.443	11.472
RMSR =	0.195	9.296	22.663	0.484
PERR =	22.617	37.035	4.338	11.796

Table 17

PERFORMANCE STATISTICS FOR PHOENIX

Simple Function

Number of cars in this group = 35 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.833	22.629	523.767	4.429
OBAR =	0.861	25.101	522.429	4.107
RBAR =	-0.028	-2.473	1.338	0.323
PRBR =	-3.275	-9.851	0.256	7.862
SIGR =	0.148	4.895	11.499	0.514
PSIG =	17.228	19.499	2.201	12.526
RMSR =	0.151	5.484	11.577	0.607
PERR =	17.536	21.846	2.216	14.789

Table 18

POOLED PERFORMANCE STATISTICS FOR ABOVE CITIES

Composite Function

Number of cars in this group = 175 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.701	18.502	531.939	4.018
OBAR =	0.776	21.103	547.914	4.073
RBAR =	-0.074	-2.600	-15.978	-0.055
PRBR =	-9.587	-12.321	-2.916	-1.347
SIGR =	0.195	5.498	19.402	0.464
PSIG =	25.089	26.054	3.541	11.384
RMSR =	0.208	6.082	25.134	0.467
PERR =	26.858	28.820	4.587	11.464

Table 19

POOLED PERFORMANCE STATISTICS FOR ABOVE CITIES

Simple Function

Number of cars in this group = 175 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.782	18.570	559.224	4.661
OBAR =	0.776	21.103	547.914	4.073
RBAR =	0.006	-2.533	11.310	0.588
PRBR =	0.822	-12.002	2.064	14.431
SIGR =	0.181	5.928	31.155	0.743
PSIG =	23.290	28.090	5.686	18.240
RMSR =	0.181	6.446	33.145	0.947
PERR =	23.305	30.547	6.049	23.258

Table 20

POOLED COEFFICIENTS FOR ABOVE CITIES

	Basis Function	HC	CO	CO2	NOX
$\dot{e}_A$ Function	1	0.00806836	0.21578518	2.28404948	0.01081596
	v	-0.00040017	-0.01257778	-0.02627984	-0.00122498
	a	0.00090038	0.05147729	0.06559008	-0.00073537
	av	0.00006497	-0.00234263	0.05392222	0.00053943
	v^2	0.00000663	0.00016779	0.00212888	0.00004444
	a^2	-0.00073571	-0.00157560	-0.16557200	-0.00329725
	va^2	0.00008982	0.00028233	0.03023214	0.00052657
	v^2a^2	-0.00000028	0.00012527	-0.00009010	0.00000312
	v^2a^2	-0.00000058	0.00004850	-0.00041269	-0.00000840
$\dot{e}_S$ Function	1	0.00538160	0.11655782	1.46895685	0.00265085
	v	-0.00014550	-0.00462987	0.00706689	-0.00035369
	v^2	0.00000205	0.00006995	0.00161369	0.00002341

Table 21

PERFORMANCE STATISTICS FOR LOS ANGELES

Composite Function

Number of cars in this group = 33 (Model Year 75)

	HC	CO	CO2	NOX
CBAR =	0.233	7.106	576.160	3.291
OBAR =	0.241	8.947	594.936	3.318
RBAR =	-0.008	-1.841	-18.776	-0.028
PRBR =	-3.321	-20.577	-3.156	-0.831
SIGR =	0.111	4.291	22.326	0.401
PSIG =	46.106	47.958	3.753	12.087
RMSR =	0.111	4.669	29.171	0.402
PERR =	46.226	52.186	4.903	12.115

Table 22

PERFORMANCE STATISTICS FOR LOS ANGELES

Simple Function

Number of cars in this group = 33 (Model Year 75)

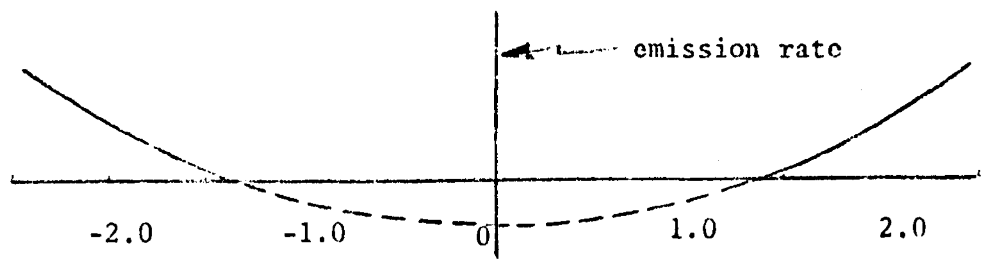
	HC	CO	CO2	NOX
CBAR =	0.199	6.012	590.584	3.544
OBAR =	0.241	8.947	594.936	3.318
RBAR =	-0.042	-2.935	-4.353	0.225
PRBR =	-17.255	-32.804	-0.732	6.792
SIGR =	0.055	4.768	27.507	0.391
PSIG =	23.046	53.290	4.624	11.772
RMSR =	0.069	5.599	27.849	0.451
PERR =	28.790	62.577	4.681	13.591

Table 23

COEFFICIENTS FOR LOS ANGELES

	Basis Function	HC	CO	CO2	NOX
$\dot{e}_A$ Function	1	-0.00090547	0.04637532	2.21799416	0.00921564
	v	0.00012708	-0.00331952	-0.00712464	-0.00070116
	a	0.00033065	0.03405101	0.10090503	0.00029334
	va	-0.00002369	-0.00423590	0.05336254	0.00038903
	v^2	-0.00000186	0.00002119	0.00185543	0.00002696
	a^2	0.00055315	0.01143820	-0.09739484	-0.00198106
	va^2	-0.00005786	-0.00182000	0.02457471	0.00031261
	v^2a	0.00000121	0.00013682	-0.00022188	0.00000196
	v^2a^2	0.00000162	0.00007624	-0.00026850	-0.00000375
$\dot{e}_S$ Function	1	0.00104760	0.00859732	1.70297875	0.00206893
	v	-0.00000516	-0.00056630	0.01441993	-0.00016999
	v^2	0.00000013	0.00001144	0.00155828	0.00001728

observed modal steady state values for these vehicles could actually have been negative emission values (i.e., emissions lower than ambient), but were reported as zero.

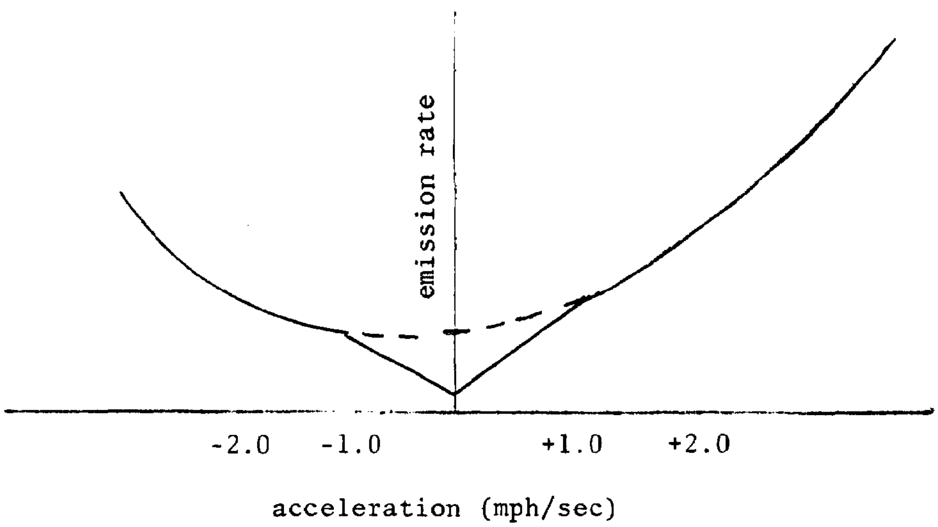


As seen in the above figure, the utilization of the simple model could result in the prediction of a negative emission, since the simple model does not use steady state values (which, in this case, would be zero but not negative) as input to calculate coefficients which define the emissions surface. The negative emission is possible for the SDS (or even the FTP) sequence because, even though part of the emission surface is positive, the majority of the driving sequence takes place in the region where the surface is negative.

The simple, although arbitrary, procedure to solve this problem is to set all negative emissions predicted by the model to zero. This was done before model performance statistics were computed for all cities using the simple model. Examination of the FTP driving sequence shows that while there are no steady state models other than v = 0, negative values predicted by the model are certainly possible since many accelerations in the FTP are very small and very close to zero (i.e., between -1 and +1 mph/sec -- see above figure).

4.2 DISCUSSION

Perhaps it would be best to review the emissions model results for FY 71, FY 73, and FY 74 data by observing, as we have previously, a slice through the emissions surface at constant velocity. For FY 71 and FY 73 data, all coefficients produced by the emissions model have resulted in an emissions surface entirely above the velocity-acceleration plane. As the effect of emissions controls succeeded in limiting the amounts of pollutants emitted by a vehicle, the emissions surface has come closer to the velocity-acceleration plane, at the same time retaining its essential shape for FY 71 and FY 73. The shape of this surface in emission rate acceleration space is closely represented by a skewed parabola approximated below in **Sketch G.**

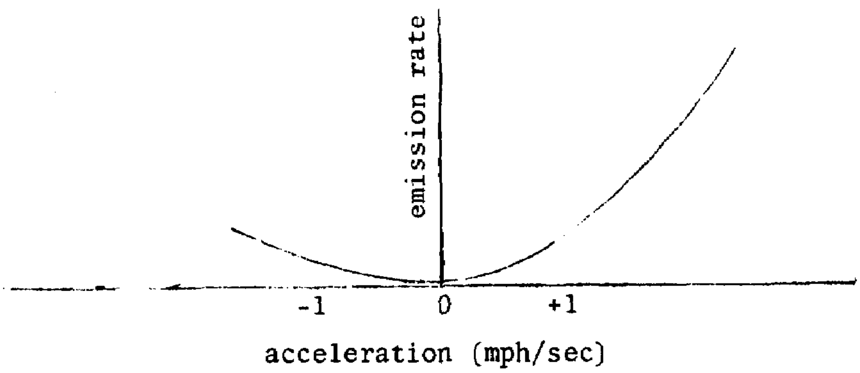


(G)

The solid curve represents the composite form of the model and the dotted line the simple form of the model, both of which are blended together at approximately ± 1 mph/sec. As the emission surface descends and finally touches and intersects the v-a plane, as it does for FY 74 data, its shape changes. The surface represented by the composite model gets "squashed" against the v-a plane as a rubber ball would get squashed upon impact against a hard surface. We have mentioned that the reason the composite surface is effectively squashed, stems from the fact that any modes measured during the SDS as having emissions below ambient get reported as zero.

Examine for a moment the plot of the test design points on the average speed and acceleration plane in the following figure. If all or most all of the steady state emissions are reported as zero and if the steady state portion of the model $\dot{e}_S$ is blended into the model between accelerations of ± 1, then the surface will eventually flatten out or squash between ± 1 mph/sec as it descends into the v-a plane. There is no such restriction on the simple form of the model (only as long as no negative emissions for A/D modes are measured). The simple model certainly predicts a surface at $a = 0$, but the simple model has no prior inputs between $a = \pm 1$ mph/sec that would alter the form of the surface from the form determined by the "outer" design test points (i.e., $-1 > a > +1$).

For FY 71 and FY 73 data, it is apparent that the lowest point on the emission surface, for the composite model, is the stabilized steady state point. It appears as if the stabilized SS point causes a distortion in the emissions surface. As we have shown, however, it is the A/D modal values or "outer" design test points that are in error. In fact, when the A/D modal data are corrected as by the approximation reported for the FY 74 Washington data, the effect is to appropriately increase or in some cases (especially for decelerations) decrease the A/D values, such that the emission rate surface for the composite model using adjusted data from Washington now appears as in Sketch H.



(H)

For corrected A/D input data, steady state values are "naturally" blended into the form of the emissions surface. That is, as long as the emissions surface is entirely above the v-a plane, there is no difference between the shape of the surface for the composite model and the simple model. Performance statistics for the two models should be the same except perhaps for the fact that the simple model may have a slightly higher standard deviation because of a reduced number of degrees of freedom.

The above discussion attempts to describe the effects on the emission surface and thereby on the emissions model as the input data is changed from FY to FY to reflect the changes in vehicle population, emissions regulation (i.e., catalytic converter for FY 74), vehicle group structure, and even emissions measuring procedure; for the reporting of emission rates lower than ambient as zero is arbitrary at best. This procedure coupled with measurements of A/D modal values that are uncorrected can have deleterious effects upon model performance. Model performance for Washington, for instance, was very good indeed even prior to adjustment of the A/D modes. This favorable model performance indicated that measurement of A/D values was conscientious and all, or most, steady state values were positive values. For Los Angeles, however, model performance is not comparable to Washington. First of all, Los Angeles was statistically determined to be presented separately from the rest of the city groups. Examination of the pollution levels for Los Angeles show pollutant levels much lower than other low-altitude cities. A third of the predicted emissions for the 33 vehicles in Los Angeles were negative predictions for CO. The percent bias for CO was -20.6% when using the composite model and -32.8% when using the simple model. The percent RMSR error was 52.5% for the composite model and 62.6% for the simple model. We can see that the simple model no longer reduces the percent bias or changes the bias in a positive sense. Instead, both percent bias and percent RMS error increase when the simple model is used.

Obviously, measurement of all modal values accurately is essential for good model performance. Degradation of model performance is most likely due to inaccuracies in measurements of the A/D modes. The effect of these inaccuracies is most surely heightened as emission levels decrease, as is evident from examination of model performance statistics for Los Angeles. Although corrections of A/D modal data input is possible, there is no substitution for proper adjustment of the data during the sequence in which the vehicles are tested.

5. SUMMARY AND CONCLUSIONS

The modal emissions model performance is affected by two major phenomena:

1. Measuring system response delay times can introduce a phase lag between driver actions and the emission response to these actions as recorded on the instrumentation strip charts. The result is that emissions outputs resulting from driver maneuvers can be associated, at least in part, with the wrong nominal mode of the Surveillance Driving Sequence (SDS). The modes affected by the time lag are the acceleration-deceleration modes of the SDS.

2. Although constant speed or zero acceleration emissions input data accurately reflect the cruise mode portions of the SDS, model distortion can arise as total emissions from FY to FY decrease, causing a flattening of the emissions surface against the v-a plane. This flattening results because emissions that are measured lower than ambient are reported as zero, constraining the emissions surface to be above the v-a plane. Any errors in correctly measuring the accel-decel emission modes can greatly degrade model performance, since total emissions become smaller from FY to FY.

If A/D modal input was correctly adjusted prior to the emissions model, the emissions surface generated by the simple emissions model (i.e., model without steady state), would be identical or at least very close to the emissions surface generated by the composite model, as long as all modal emissions for all modes were measured greater than ambient.

Presented in the following tables are the summarized results for the FY 74 program. Table 24 compares the percent bias results for both the simple and composite forms of the model and Table 25 compares the percent standard deviation for both forms of the model for all city groups.

Table 24

PERCENT BIAS FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS
FOR THE FY 74 PROGRAM

CITY	N	HC	CO	CO_2	NO_X	MODEL
Washington	35	-3.458	-5.815	-1.999	3.279	C
		13.204	-9.038	6.368	27.087	S
		1.457	2.503	1.590	5.825	C (adjusted)
Chicago	35	-13.778	-15.781	-2.851	-1.122	C
		-5.110	-16.050	1.875	12.587	S
Houston	35	-12.333	-10.949	-3.491	-1.671	C
		1.881	-11.801	0.434	13.813	S
St. Louis	35	-1.147	-9.229	-2.690	-5.191	C
	(34)	-9.205	-11.903	-2.636	-5.016	C (minus outlier)
		-5.075	-12.627	1.169	8.328	S
Phoenix	35	-15.626	-16.667	-3.585	-2.747	C
		-3.275	-9.851	0.256	7.862	S
Pooled	175	-9.587	-12.321	-2.916	-1.347	C
		0.822	-12.002	2.064	14.431	S
Los Angeles	33	-3.321	-20.577	-3.156	-0.831	C
		-17.255	-32.804	-0.732	6.792	S

Table 25

PERCENT STANDARD DEVIATION FOR SIMPLE AND COMPOSITE EMISSION RATE FUNCTIONS FOR FY 74

CITY	N	HC	CO	CO_2	NO_X	MODEL
Washington	35	17.974	26.675	3.896	11.141	C
		15.290	19.885	3.466	6.420	C (Modified A/D Inputs)
		28.698	34.350	6.070	20.054	S
Chicago	35	17.142	14.731	3.362	11.686	C
		19.210	24.226	4.454	19.242	S
Houston	35	21.194	19.572	2.679	9.528	C
		20.640	28.177	2.443	14.072	S
St. Louis	35	51.254	27.165	4.849	11.458	C
	(34)	17.916	21.033	4.911	11.590	C (minus outlier)
	35	20.421	37.164	8.547	11.732	S
Phoenix	35	16.351	33.072	2.443	11.472	C
		17.228	19.499	2.201	12.526	S
Pooled	175	25.089	26.054	3.541	11.384	C
		23.290	28.090	5.686	18.240	S
Los Angeles	33	46.106	47.958	3.753	12.087	C
		23.046	53.290	4.624	11.772	S

6. APPENDIX: AVERAGE GROUP COEFFICIENTS FOR FY 73 AND FY 71

AVERAGE GROUP COEFFICIENTS FOR FY 73 FOR
BOTH SIMPLE & GROUP EMISSION RATE FUNCTIONS

GROUP 1 - 1973 and 1974 Denver - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.03673279	1.10400859	2.60419841	0.00310424
v	-0.00199239	-0.07945388	-0.05360373	0.00001506
a	-0.00088590	0.05630319	0.05482671	-0.00077950
va	0.00037807	0.00170772	0.01517054	0.00018693
v^2	0.00004643	0.00161816	0.00207580	0.00001103
a^2	-0.00412351	-0.17064409	-0.21999308	-0.00058944
va^2	0.00056539	0.01980341	0.02470781	0.00009365
v^2a	-0.00000277	0.00020100	0.00006307	-0.00000053
v^2a^2	-0.00000892	-0.00026382	-0.00035096	-0.00000159
		for composite emission rate function include the following		
1	0.01262324	0.25955878	1.21196048	0.00199461
v	-0.00026730	-0.00759697	0.01720046	-0.00024173
v^2	0.00001149	0.00026727	0.00125049	0.00001981

GROUP 2 - 1972 Denver - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.05405567	1.49310401	2.22999486	0.00144976
v	-0.00268925	-0.10349673	-0.02441241	0.00043599
a	-0.00101342	0.00722273	0.05660318	0.00017710
va	0.00019053	0.00591609	0.00234623	0.00002336
v^2	0.00005623	0.00200536	0.00159217	0.00001192
a^2	-0.00556067	-0.23721019	-0.16246379	0.00018445
va^2	0.00069298	0.02622559	0.01698271	0.00001644
v^2a	-0.00000090	0.00002392	0.00004330	-0.00000066
v^2a^2	-0.00001145	-0.00039850	-0.00024700	-0.00000112
		for composite emission rate function include the following		
1	0.01281331	0.32877001	1.20695927	0.00233554
v	-0.00021308	-0.00917287	0.01750029	-0.00040469
v^2	0.00001241	0.00029820	0.00104091	0.00003392

GROUP 3 - 1973 and 1974 Los Angeles - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.02667524	0.20974290	1.66130810	0.00096731
v	-0.00147237	-0.01284891	0.02272887	-0.00005236
a	0.00338008	0.09685962	0.14670172	-0.00075958
va	0.00008997	-0.00663593	0.05285483	0.00069431
v^2	0.00002910	0.00018599	0.00122293	0.00002439
a^2	-0.00319628	0.02192463	-0.03175795	-0.00102613
va^2	0.00041041	-0.00156859	0.02299226	0.00033396
v^2a	0.00000063	0.00027883	0.00004743	0.00000060
v^2a^2	-0.00000438	0.00012293	-0.00028821	-0.00000449
		for composite emission rate function include the following		
1	0.00884129	0.11387944	1.61624131	0.00194663
v	-0.00007578	-0.00286858	0.02409572	-0.00021615
v^2	0.00000427	0.00004719	0.00118920	0.00002051

GROUP N	GROUP 4 - 1972 Los Angeles - Simple emission rate function			
1	0.02753334	0.28853572	1.54830571	-0.00235249
v	-0.00155636	-0.01231569	0.01658593	-0.00019142
a	0.00407880	0.09240786	0.18629377	-0.00225345
va	0.00000915	-0.00315050	0.04171278	0.00092392
v^2	0.00003079	0.00016614	0.00107667	0.00004448
a^2	-0.00351729	0.00707022	-0.02311154	-0.00126582
va^2	0.00044819	0.00046436	0.01892498	0.00045565
v^2a	0.00000019	0.00014813	0.00016261	0.00000192
v^2a^2	-0.00000565	0.00005659	-0.00021464	-0.00000762
	for composite emission rate function include the following			
1	0.00898459	0.15976294	1.46922220	0.00195007
v	-0.00004908	-0.00652330	0.02363722	-0.00032206
v^2	0.00000568	0.00010359	0.00097246	0.00003236

GROUP N	GROUP 5 - 1973 and 1974 low altitude cities - Simple emission rate function			
1	0.02626262	0.54005560	2.90645519	0.01187600
v	-0.00110580	-0.03959409	-0.05130095	-0.00072420
a	0.00130303	0.02832110	-0.00944663	-0.00077164
va	0.00006337	0.00144263	0.02837012	0.00027149
v^2	0.00002386	0.00070014	0.00237781	0.00003251
a^2	-0.00186747	-0.05709695	-0.25426778	-0.00249363
va^2	0.00025699	0.00732978	0.03370509	0.00034106
v^2a	0.00000033	0.00005355	-0.00005903	0.00000082
v^2a^2	-0.00000311	-0.00008588	-0.00051395	-0.00000539
	for composite emission rate function include the following			
1	0.01045279	0.20601881	1.66736189	0.00298216
v	-0.00019408	-0.00580179	0.01541613	-0.00036151
v^2	0.00000675	0.00008558	0.00131556	0.00002689

GROUP N	GROUP 6 - 1972 low altitude cities - Simple emission rate function			
1	0.04434662	0.57665520	2.61400935	0.01486188
v	-0.00221667	-0.03627741	-0.04138154	-0.00072346
a	0.00068992	0.02157196	-0.02310735	-0.00044333
va	0.00013456	0.00294424	0.02886318	0.00032002
v^2	0.00004133	0.00063650	0.00215970	0.00004031
a^2	-0.00534209	-0.05285343	-0.25081254	-0.00339756
va^2	0.00060573	0.00694145	0.03285040	0.00045425
v^2a	-0.00000183	-0.00001756	-0.00004957	0.00000104
v^2a^2	-0.00000964	-0.00009447	-0.00049582	-0.00000763
	for composite emission rate function include the following			
1	0.01310196	0.25530096	1.49414969	0.00340546
v	-0.00024442	-0.00769485	0.01919612	-0.00050338
v^2	0.00000817	0.00013531	0.00121897	0.00003816

GROUP AVERAGE COEFFICIENTS FOR FY 71
FOR BOTH SIMPLE & COMPOSITE EMISSION RATE FUNCTIONS

GROUP 1 - 1957-1967 Denver - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.09193082	**1.01939646**	**0.73499392**	-0.00305700
v	-0.00462605	**-0.04771040**	0.01152654	0.00050317
a	0.00392938	0.00074659	0.07536853	0.00082683
va	0.00057714	0.02156825	0.01649186	-0.00001250
v^2	0.00008785	0.00110084	0.00055018	0.00000649
a^2	-0.01177275	-0.15253911	0.00702534	0.00198891
va^2	0.00141214	0.01991216	0.00428403	-0.00016629
v^2a	-0.00000619	-0.00012003	0.00004008	0.00000242
v^2a^2	-0.00002401	-0.00029160	-0.00003355	0.00000281
		for composite emission rate function include the following		
1	0.03057799	0.33671377	0.86639376	0.00297319
v	-0.00022455	-0.00241322	0.01073421	-0.00030207
v^2	0.00001694	0.00032059	0.00124842	0.00002282

GROUP 2 - 1957-1967 low altitude cities* - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.07628901	**0.63519355**	**1.25022438**	0.00463792
v	-0.00335782	**-0.02517176**	**0.02228016**	0.00014202
a	0.00557653	0.03982681	**0.08512990**	0.00007608
va	0.00029385	0.00556602	0.03687863	0.00044335
v^2	0.00006357	0.00047038	0.00091322	0.00002215
a^2	-0.00785867	-0.04830223	0.00303730	-0.00029964
va^2	0.00096193	0.00635515	0.00864681	0.00017920
v^2a	-0.00000303	**-0.00000291**	**0.00002828**	0.00000155
v^2a^2	-0.00001630	**-0.00007479**	**-0.00006759**	-0.00000301
		for composite emission rate function include the following		
1	0.02755122	0.30342393	0.90209652	0.00351627
v	-0.00028560	-0.00273503	0.01276564	-0.00046493
v^2	0.00001451	0.00013472	0.00133361	0.00003240

GROUP 3 - 1966 and 1967 California - Simple emission rate function

GROUP N	HC	CO	CO2	NOX
1	0.02730842	**0.27989996**	**1.86924557**	0.00869070
v	-0.00042395	**-0.00498866**	0.00234203	-0.00059465
a	0.00208875	0.04242040	0.16609689	-0.00070495
va	0.00048092	0.00155372	0.02692388	0.00070165
v^2	0.00001614	0.00011530	0.00116331	0.00003425
a^2	-0.00080988	-0.00235636	-0.05894861	-0.00266144
va^2	0.00022506	0.00101693	0.01433370	0.00048951
v^2a	-0.00000581	0.00000706	0.00011010	-0.00000204
v^2a^2	-0.00000382	-0.00000490	-0.00018606	-0.00000861
		for composite emission rate function include the following		
1	0.01874040	0.22926731	1.28089607	0.00322353
v	0.00022502	-0.00401950	0.02726103	-0.00044518
v^2	0.00000273	0.00012243	0.00102263	0.00002993

*non California 1966, 1967

GROUP 4 - 1968 low altitude cities - Simple emission rate function

GROUP N				
1	0.04931905	0.50832557	1.53914069	0.00478557
v	-0.00216938	-0.01621125	0.02005679	0.00013356
a	0.00373793	0.06054505	0.07708463	-0.00264929
va	0.00009518	-0.00034837	0.04279486	0.00099452
v^2	0.00004014	0.00024459	0.00102066	0.00002869
a^2	-0.00530121	-0.00932161	-0.02495641	-0.00224931
va^2	0.00064703	0.00138680	0.01302565	0.00047462
v^2a	-0.00000122	0.00009970	0.00000086	-0.00000513
v^2a^2	-0.00001054	0.00002778	-0.00013431	-0.00000853

for composite emission rate function include the following

1	0.02159531	0.26295216	1.28117786	0.00407894
v	-0.00023145	-0.00181854	0.00647524	-0.00051323
v^2	0.00000723	0.00008399	0.00139262	0.00003552

GROUP 5 - 1969 low altitude cities - Simple emission rate function

GROUP N				
1	0.05025577	0.50606297	1.98422858	0.00439991
v	-0.00230273	-0.01835328	-0.00308355	0.00058477
a	0.00221975	0.05856576	0.05567749	-0.00563892
va	0.00018041	-0.00165730	0.04615791	0.00164965
v^2	0.00004093	0.00024560	0.00141746	0.00002862
a^2	-0.00626386	-0.01367472	-0.12986334	-0.00293812
va^2	0.00068703	0.00134108	0.02230076	0.00062018
v^2a	-0.00000117	0.00007037	0.00001199	-0.00001269
v^2a^2	-0.00001060	0.00000929	-0.00027903	-0.00001070

for composite emission rate function include the following

1	0.01968456	0.30530330	1.33958437	0.00498771
v	-0.00024682	-0.00702316	0.00812709	-0.00069093
v^2	0.00000801	0.00010784	0.00149789	0.00004657

GROUP 6 - 1970 low altitude cities - Simple emission rate function

GROUP N				
1	0.02778199	0.41314478	2.22024403	0.00507104
v	-0.00106505	-0.01501546	-0.00548294	0.00001130
a	0.00278733	0.05829699	0.13106027	-0.00371813
va	0.00003901	-0.00184962	0.04758484	0.00120519
v^2	0.00002242	0.00019490	0.00131642	0.00003946
a^2	-0.00228885	-0.00812962	-0.09880359	-0.00356645
va^2	0.00030622	0.00066544	0.01927777	0.00067226
v^2a	0.00000089	0.00008331	-0.00008848	-0.00000632
v^2a^2	-0.00000427	0.00003037	-0.00023170	-0.00001220

for composite emission rate function include the following

1	0.01214718	0.24616785	1.41570879	0.00590685
v	-0.00011020	-0.00685289	0.01225111	-0.00077228
v^2	0.00000686	0.00010251	0.00137486	0.00004772

GROUP 7 - 1971 low altitude cities - Simple emission rate function

GROUP N				
1	0.02387170	0.37338899	2.33113963	0.01051507
v	-0.00093892	-0.01503251	-0.01420001	-0.00053625
a	0.00190587	0.06764833	0.07696648	-0.00383698
va	0.00009884	-0.00314375	0.04623667	0.00110935
v^2	0.00001915	0.00020180	0.00149478	0.00004619
a^2	-0.00182555	0.00057390	-0.12730560	-0.00451347
va^2	0.00025134	0.00026241	0.02257528	0.00073942
v^2a	-0.00000010	0.00013265	-0.00008096	-0.00000541
v^2a^2	-0.00000323	0.00004880	-0.00029945	-0.00001357

for composite emission rate function include the following

1	0.01043694	0.22516425	1.45908313	0.00577802
v	-0.00008301	-0.00460959	0.00983462	-0.00070763
v^2	0.00000516	0.00006979	0.00141076	0.00004330

GROUP 8 - 1969 Denver - Simple emission rate function

GROUP N				
1	0.04490182	1.05429790	0.74615791	-0.01341946
v	-0.00227597	-0.06943045	0.02110150	0.00161219
a	0.00128843	0.04712450	-0.01475054	-0.00108798
va	0.00042108	0.01336219	0.02680134	0.00023321
v^2	0.00004992	0.00146910	0.00034770	-0.00000956
a^2	-0.00688266	-0.17414647	-0.02724796	0.00359546
va^2	0.00088194	0.02242855	0.00686935	-0.00033100
v^2a	-0.00000314	0.00007263	-0.00016431	-0.00000234
v^2a^2	-0.00001500	-0.00031433	-0.00008498	0.00000516

for composite emission rate function include the following

1	0.01800833	0.30520380	0.99307769	0.00314808
v	-0.00016620	-0.00658131	0.02028057	-0.00030420
v^2	0.00001437	0.00036294	0.00109975	0.00002452

GROUP 9 - 1969 Denver - Simple emission rate function

GROUP N				
1	0.03357721	0.69682963	1.19717609	0.00306419
v	-0.00160934	-0.05215655	0.00489378	0.00018235
a	0.00136514	0.08151960	-0.00070476	-0.00351125
va	0.00022437	0.00562416	0.02585258	0.00067441
v^2	0.00003290	0.00104908	0.00055116	0.00001946
a^2	-0.00391496	-0.09712129	-0.04984784	-0.00116670
va^2	0.00049794	0.01425001	0.00731408	0.00020889
v^2a	-0.00000095	0.00015691	-0.00009728	-0.00000843
v^2a^2	-0.00000796	-0.00015502	-0.00007255	-0.00000478

for composite emission rate function include the following

1	0.01454846	0.19974257	1.17531764	0.00372786
v	0.00000403	-0.00776361	0.01809230	-0.00046996
v^2	0.00000938	0.00033751	0.00104337	0.00002788

GROUP 10 - 1970 Denver - Simple emission rate function

GROUP N				
1	0.05206897	1.09134300	1.22872281	0.00043387
v	-0.00266509	-0.07413160	0.00254560	0.00046245
a	0.00025524	0.04172969	0.03491994	0.00047938
va	0.00051758	0.01422696	0.02550732	0.00007920
v^2	0.00005281	0.00149024	0.00084449	0.00001353
a^2	-0.00710693	-0.18479960	-0.05919603	0.00092582
va^2	0.00064813	0.02352125	0.01056317	-0.00004556
v^2a	-0.00000485	0.00006572	-0.00006632	0.00000092
v^2a^2	-0.00001418	-0.00032908	-0.00014492	0.00000007
		for composite emission rate function include the following		
1	0.01902037	0.31745494	1.11161829	0.00361932
v	-0.00016942	-0.00970994	0.01235048	-0.00040599
v^2	0.00001115	0.00031332	0.00134523	0.00003196

GROUP 11 - 1971 Denver - Simple emission rate function

GROUP N				
1	0.03976241	1.17291937	1.55096134	-0.00501945
v	-0.00210474	-0.08788155	0.00624295	0.00073873
a	0.00352024	0.07816697	0.10723281	-0.00114299
va	0.00015505	0.00863532	0.03361190	0.00050725
v^2	0.00004473	0.00178530	0.00099627	0.00001002
a^2	-0.00352917	-0.18577261	-0.02833368	0.00150868
va^2	0.00047602	0.02430256	0.01130088	-0.00002108
v^2a	0.00000430	0.00025009	-0.00017174	-0.00000842
v^2a^2	-0.00000553	-0.00032093	-0.00014893	-0.00000094
		for composite emission rate function include the following		
1	0.01265952	0.30541509	1.31557277	0.00346888
v	-0.00001560	-0.00679713	0.02523382	-0.00037850
v^2	0.00000643	0.00022583	0.00107375	0.00003049