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MARTIN MARIETTA

Sensitivity Analysis of the Emission Module of the "Commercial and Residential Energy Use and Emissions Simulation System" (CRESS)

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ABSTRACT

A sensitivity analysis of MODEL6, the final component of the Argonne National Laboratory's Commercial and Residential Energy Use and Emissions Simulation (CRESS) has been carried out using automated sensitivity analysis tools developed at Oak Ridge National Laboratory. MODEL6 projects emissions of five fossil energy-related atmospheric pollutants by assuming emission will be proportional to a related economic activity level adjusted for changes in emission factors. Sensitivities of projections of aggregated emissions to the economic driver parameters and to parameters related to emission factor changes are presented in this report.

1. INTRODUCTION

CRESS, the Commercial and Residential Energy Use and Emissions Simulation System,[1] models the emissions of five atmospheric pollutants in the continental United States over the period 1980 to 2030. It was designed to provide the commercial and residential sector emission projections for a more comprehensive set of models sponsored by the National Acid Precipitation Assessment Program (NAPAP). This sensitivity study was undertaken with the support of the Department of Energy's Office of Planning and Environment and is supplementary to the Argonne National Laboratory (ANL) work on CRESS.

The fundamental task of CRESS is to translate projections of future economic, technological, and geographic parameters into projections of pollutant emissions. CRESS consists of a series of five computer programs which perform various components of this task. Figure 1 diagrams the structure of the CRESS system. The basic functions of the five programs are:

PREP.FOR	Restructure input data sets
HOME2.FOR	Residential Sector Energy Use projections
CSEM2.FOR	Commercial Sector Energy Use projections
REGION.FOR	Disaggregate HOME2 and CSEM2 output by state
MODEL6.FOR	Project pollutant emissions from energy use and 1980 pollution data

The main computational work of the CRESS system is done in the HOME2, CSEM2 and MODEL6 modules. It is intended that a sensitivity analysis be conducted on these three modules separately. This report will concern itself with just one of the modules, however, MODEL6.

Should the analysis of the three major modules appear to warrant such a course of action, selected sensitivities will be propagated through the entire CRESS network.

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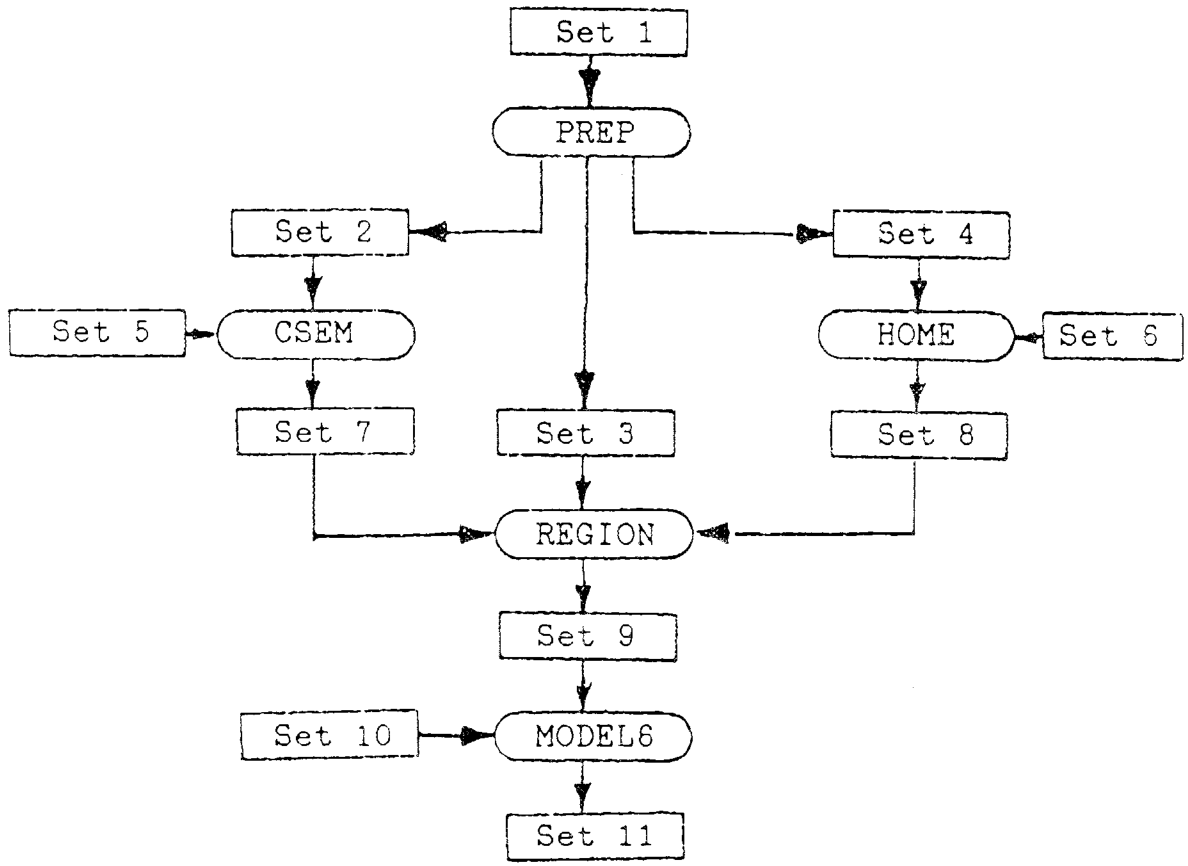

Oval blocks represent the FORTRAN programs comprising CRESS. Rectangular blocks represent one or more data files used by the system. Information flow is indicated by direction of arrows.

Fig. 1. Schematic of CRESS (Commercial and Residential Energy use and Emissions Simulation System).

2. CRESS BACKGROUND

The CRESS system consists of 5 separate FORTRAN programs and 42 input data files containing on the order of 200,000 data elements. The system produces one permanent and 6 temporary output files. The full CRESS system can be conceptually divided into 5 separate modules, each consisting of a single program and its associated input and output files, as depicted in Fig. 1. For the purposes of using Oak Ridge National Laboratory's (ORNL) automated sensitivity analysis system (named GRESS -- an unfortunate coincidence of acronyms for this study), separate examination of the system modules is necessary. Coupling of sensitivities between modules at present requires manual intervention. This paper will discuss sensitivities in the final module, MODEL6.FOR, which converts energy usage and other geographic projections into forecasts of pollutant emissions.

MODEL6 consists of two parallel models, one for projecting VOC (volatile organic compound) emissions, and another for projecting emissions of 4 other energy-related atmospheric pollutants, SO_2, NOx, CO and TSP (total suspended particulates). Projections of emission levels are made using recent historical data on economic activity and pollution levels, and projections of future activity and changes in pollution factors. The details of the projection algorithm will be discussed later in this paper.

3. ENVIRONMENT

The CRESS programs were run at ANL on an IBM 3033 system. While IBM 3033's are available at ORNL, for logistic reasons (cost, turnaround time, and availability of the most recent version of GRESS), the runs at ORNL were conducted on the Scientific and Technical Computing system, which contains (among others) a VAX 8600 on which this work was done. Both systems obstensibly operate the same version of Fortran, but inevitably slight differences in implementation were encountered. Thus, simply to run the CRESS programs, a few slight changes to the code were necessary, in addition to altering the IBM JCL to the corresponding VAX DCL. These changes involved only the alteration of a few FORMAT statements in REGION.FOR and MODEL6.FOR, and addition of the appropriate parameter list to calls to the ENTRY points "VOCTAB" and "POLTAB" in MODEL6.FOR (required by the VAX FORTRAN implementation but apparently not by IBM's). To facilitate separate examination of the modules of CRESS, the control language logic was altered to preserve intermediate data files that are discarded when the full CRESS system is run.

With the above alterations, the CRESS was run on the VAX 8600 for the "Reference" economic growth case (as opposed to "high" and "low" growth cases) and the results compared to the file REFCASE.RESULT, the output file created on ANL's IBM 3033 for the identical case. Substantially the same results were produced by the VAX version as were listed in the IBM-generated output file. Of the approximately 27,000 numbers listed as output in RESULT.TAB, a moderate proportion of the numbers was not identical between the two versions. This seemed to be due to differences in the round-off error produced by the two implementations of FORTRAN. Obstensibly, neither version is accurate to more than about 6 significant digits on a single precision real value, and arithmetic operations can further degrade this precision in the final answer. In general, the largest errors were on the order of 0.02% to 0.03% of the listed result, and the VAX results were somewhat more internally consistent (i.e. the computed sum of a list of values was closer to the actual sum of the list), as exemplified by Table 1.

Table 1. Sample Comparison of CRESS REFCASE.RESULT Precision - MODEL6.FOR

TSP Annual Tonnage - Commercial Sector - Sum of State Totals vs. National Totals

	1980	1985	1990	1995	2000	2010	2020	2030
IBM 3033 (ANL)								
Listed Sum	1873799	1914037	1952961	1978450	1998525	2035707	2052353	2056334
Sum of List	1873799	1914183	1953110	1978615	1998672	2035869	2052513	2056496
Difference	0	146	149	165	147	162	160	162
ppm error	0	76	76	83	74	80	78	79
VAX 8600 (ORNL)								
Listed Sum	1873799	1914186	1953120	1978625	1998687	2035879	2052537	2056524
Sum of List	1873799	1914186	1953116	1978625	1998687	2035883	2052537	2056520
Difference	0	0	-4	0	0	4	0	-4
ppm error	0	0	-2	0	0	2	0	-2

4. MODEL ALGORITHMS

The model for projection of emission quantities consists of essentially two equations, one for VOC emissions and another for the other four pollutants treated by the model. These two equations will be referred to in this paper as "Q-functions". SOx, NOx, CO, and TSP emissions are projected with the formula:

$$Q = C \left[B\ (1-A) + A\ (1-R)^t + A\ E\ (B-(1-R)^t) \right] \tag{1}$$

where the parameters internal variable array names and definitions are:

- Q = TPYSO2, TPYNOX, etc. : tons of pollutant/yr
- C = TPYSO2, TPYNOX, etc. : tons of pollutant/yr in 1980
- A = GROWTH : fraction of new equipment/activity subject to new emission factors
- E = ERATIO : ratio of pollution factors (new:old)
- R = FRACRR : annual replacement rate for old equipment/activity
- B = driver variable (based on RESEGY, CMIEGY and DRIVAR)
- t = years since 1980

Complementing the above equation are several logic checks which impose boundary conditions on the applicability of the equation. The variables (Q) and (C) are read from the POINT.DAT and AREA.DAT files, which contain the NAPAP data base on point and area emission sources. Each entry in these files is categorized according to its source classification and state. Each such category is associated with values for the parameters (A), (E), and (R), read from other data files. The source category will likewise determine which of 18 parameters the driver variable will be based upon. These parameters are derived from internal variables in arrays named RESEGY, CMIEGY, and DRIVAR. Most are fuel usage projections generated in the HOME2 and CSEM2 modules of CRESS, but a few are geographic in nature (forest acreage; total and rural population). CRESS includes only emissions directly attributed to the commercial and residential sectors. The commercial and residential sector emissions do not include contributions from emissions due to transporation or electric utility generation from which they (partly) benefit; the residential sector in CRESS does, however, get credit for certain natural phenomena (e.g forest fires) but apparently not others (e.g. vulcanism). These driver parameters are the only data elements used by MODEL6 which derive from the first 4 modules of CRESS.

The driver variable (B) is defined as the ratio of the parameter value in time (t) to its value in 1980:

$$B = \frac{\text{Driver}(t)}{\text{Driver}(1980)} \quad .$$

The above formula in essence says that pollution will change at the same rate as the selected driver variable, with appropriate corrections made for improvements in equipment and emission regulations. This assumed relationship between pollution and driver variable is not necessarily intended to be either comprehensive or causal. Pollution due to a particular type of activity will be driven by a single driver variable, even though obvious (or subtle) relationships may exist between that driver variable and other driver variables. The model authors have simply chosen what they deemed to be the most appropriate available datum on which to base projections. A particular model result will be formally sensitive only to its own driver variable. There may be a host of relationships implicit in the value of a particular driver variable that will not be evident in this sensitivity analysis on MODEL6. For example, pollution due to residential use of natural gas is driven (quite reasonably) by projections of residential usage of natural gas. Gas usage certainly is related to population (another driver variable), but this relationship will not be evident from this sensitivity analysis. Some of these "invisible" relationships may appear in analyses of other modules of CRESS, and where warranted can be manually linked through all the CRESS modules. Others, however, may be implicit in data imported into the CRESS system as a whole, which is driven by economic and geographic projections made by other models.

VOC emissions are treated conceptually in the same manner, but using a different equation:

$$Q = A\ (1/B)\ (D\ E + C) \tag{2}$$

where the internal variable array names and meanings are:

Q	=	TPYVOC	:	tons of pollutant/yr
A	=	TPYVOC	:	tons of pollutant/yr in 1980
B	=	VOCBYR	:	1980 emission factor
C	=	VOCOLD	:	projected emission factor for existing and replacement sources
E	=	VOCNEW	:	projected emission factor for new sources
D	=	driver variable (based on DRIVAR, RESEGY, and CMIEGY)		

Some differences in definition in this equation should be noted. The driver variable is, as before, based on an appropriate fuel use or other parameter, but is defined as:

$$D = \frac{\text{Driver(t)} - \text{Driver(1980)}}{\text{Driver(1980)}} .$$

Secondly, the parameter (C) encompasses the estimates of replacements (and possible improvement) of 1980 equipment which were at least partially calculated using (R), (t), (E) and (A) in the SOx equation.

The parameters used in the above two equations are read from a number of input files. The names of the files and the associated variable names from which they are derived are listed in Table 2.

Table 2. Input File List for MODEL6.FOR

File #	Name	Variable	Description
08	VOC1980.DAT	VOCBYR	VOC Emission factors by
09	VOC1985.DAT	VOCOLD	source for old
10	VOC1990.DAT	"	equipment/activities
11	VOC1995.DAT	"	
12	VOC2000.DAT	"	
13	VOC2010.DAT	"	
14	VOC2020.DAT	"	
15	VOC2030.DAT	"	
	/ AREA.DAT	TPYxxx	NAPAP 1980 emission
17	POINT.DAT	"	source data base
18	VOCDATA1.NTM	RESEGY;CMIEGY	Driver
19	VOCDATA2.NTM	DRIVAR	variables
20	SOXFRR.DAT	FRACRR	SOx,NOx,CO,TSP
21	SOXNCP.DAT	GROWTH	parameters
22	SNCPFACT.DAT	ERATIO	
23	VCN1985.DAT	VOCNEW	VOC Emission factors by
24	VCN1990.DAT	"	source for new
25	VCN1995.DAT	"	equipment/activities
26	VCN2000.DAT	"	
27	VCN2010.DAT	"	
28	VCN2020.DAT	"	
29	VCN2030.DAT	"	

The basic function which MODEL6 performs is to read each of the 33,000 non-zero source terms in the NAPAP data base, project pollution via the appropriate Q-function for that source in each model period, and add the result to appropriate subtotals (which categorize pollution by sector, aggregated source categories, pollutant, state, region, and national total). This output is written to a single file, RESULT.TAB.

Counter-intuitive behavior is potentially possible with certain combinations of parameter values. An example of such behavior might be emission increasing when emission factors of new equipment decline. Such potential problems were searched for in some detail, but in all cases examined, such behavior was either trapped by program logic or was rendered moot by reason of the specific values of the data.

4.1. ANALYTICAL SENSITIVITIES OF Q-FUNCTIONS

Since the fundamental model for emission in MODEL6 is simple, it is straightforward to analytically (and manually) derive the sensitivities of (Q) with respect to its variables. Figures 2 through 4 display the sensitivities of the basic Q function in the SOx model as the Driver variable is varied for variations in the parameters (E), (A), and (Fo), respectively. For purposes of these figures, the parameters (R) and (t) have been combined into the variable (Fo) which is defined as the fraction of old equipment remaining, namely:

$$Fo = (1-R)^t \quad .$$

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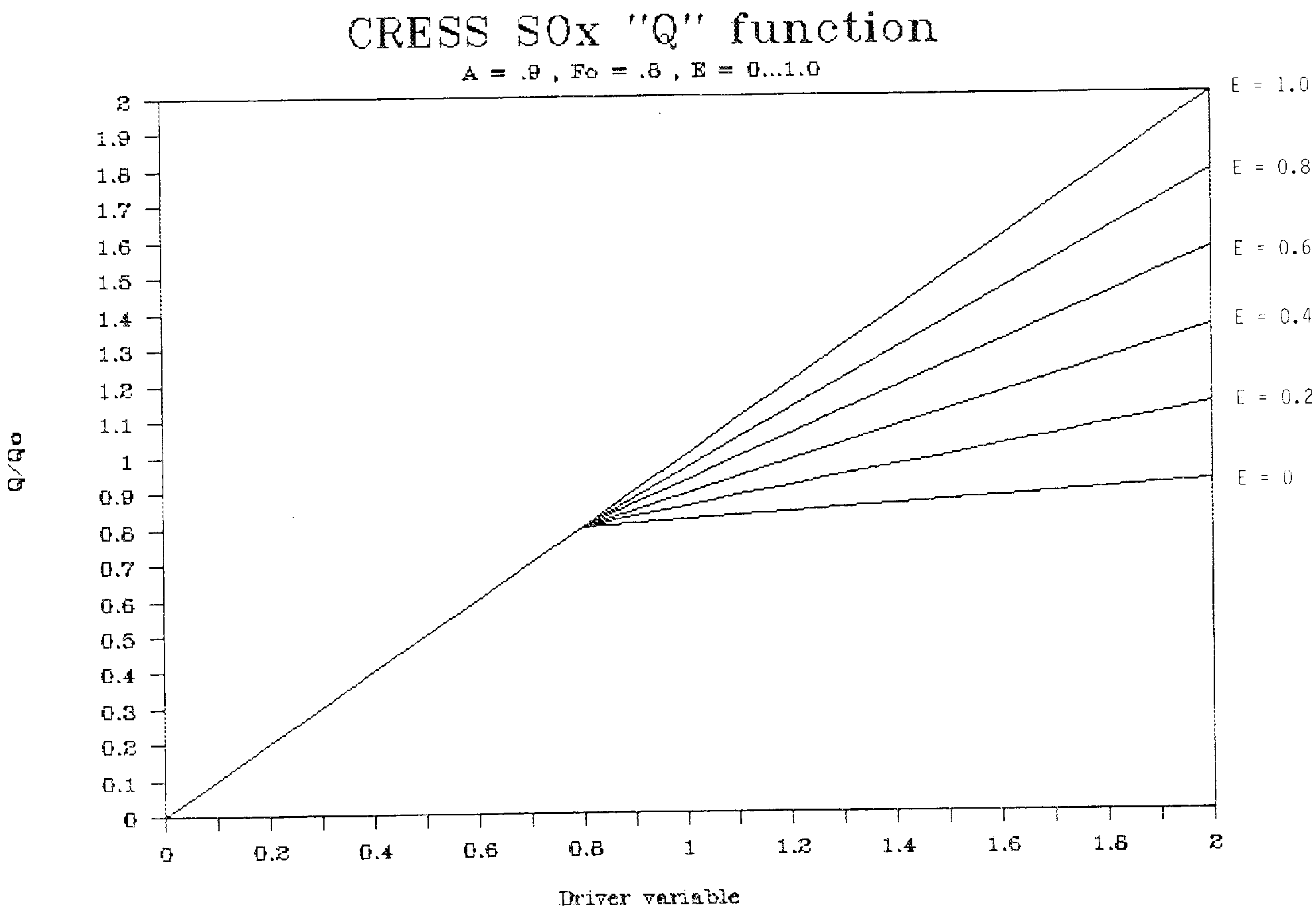

Parameters (A) and Fo) are held constant at 0.9 and 0.8 respectively. The contours are for variaton of (E) from 0 to 1 in steps of 0.2.

Fig. 2. Response of SOx/NOx/CO/TSP model to variation in driver variable (B) and Emission Ratio (E).

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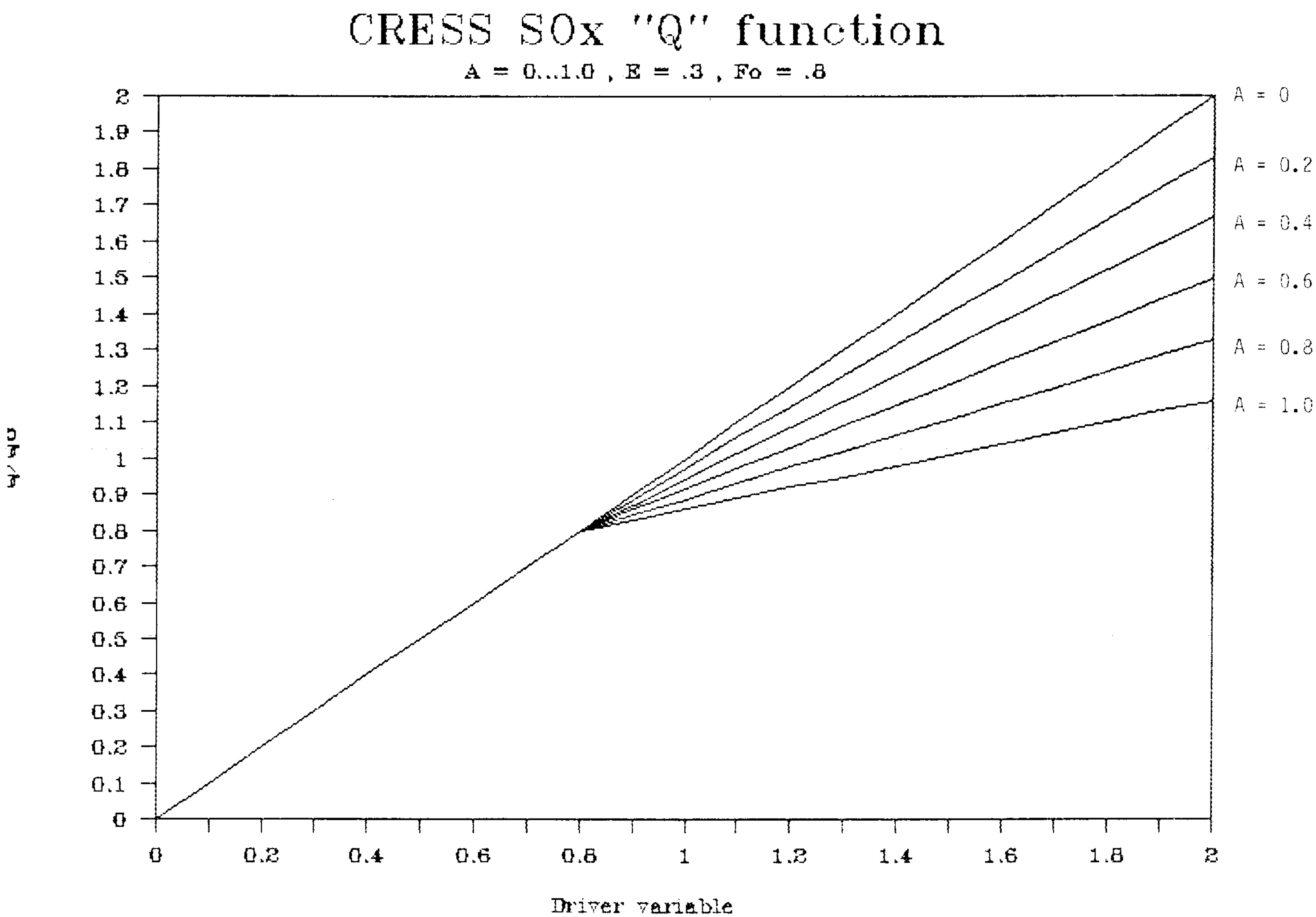
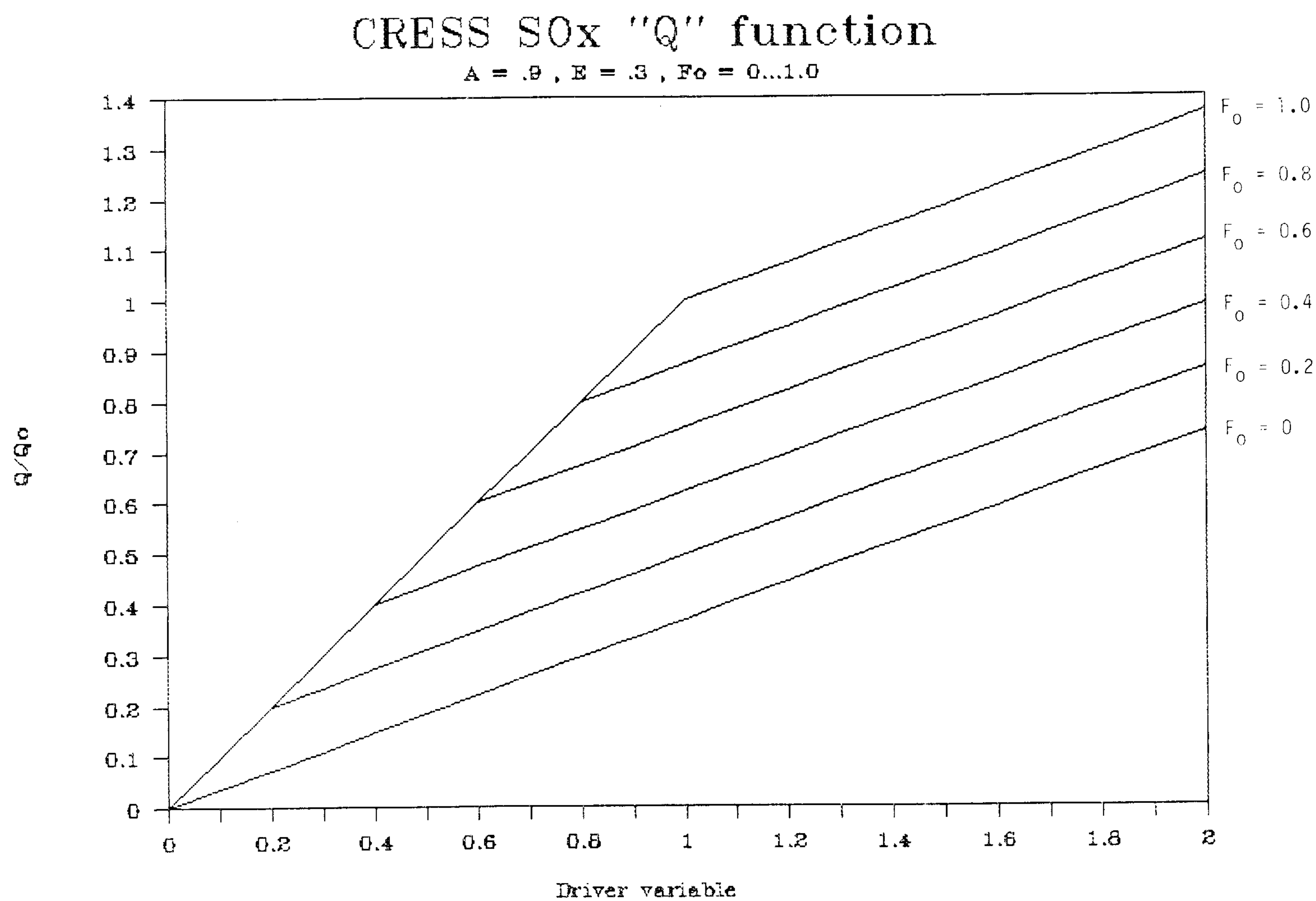


Parameters (E) and (Fo) are held constant at 0.3 and 0.8 respectively. The contours are for variation of (A) from 0 to 1 in steps of 0.2.

Fig. 3. Response of SOx/NOx/CO/TSP model to variation in driver variable (B) and GROWTH parameter (A).

ORNL DWG NO. 86-18133



Parameters (A) and (E) are held constant at 0.9 and 0.3 respectively. The contours are for variation of (Fo) from 0 to 1 in steps of 0.2.

Fig. 4. Response of SOx/NOx/CO/TSP model to variation in driver variable (B) and fraction of old equipment remaining (Fo).

Figure 2 illustrates the behavior of the SOx Q-function over a wide range of values of the parameter E (emission factor for new equipment/activities) and driver variable. The driver variable ranges from 0 (no driving activity) to 2 (doubling of driving activity). The parameter (E) ranges in value from 1.0 (new standard = old standard) to 0.0 (new standard = no emission). In this illustration, the parameter (A), fraction of new activity subject to new emission standards, is held constant at 0.9 and the fraction of old equipment still in use (Fo) is taken to be 0.8. Above a driver variable value of 0.8, the Q-function varies linearly with both driver variable and (E). Below this point, a boundary condition (not directly embodied in the formula displayed above for Q) is imposed, and the parameter (E) has no further effect. The effect of this boundary condition is to say that if an activity (i.e. the driver variable) declines faster than its associated old equipment would normally suffer attrition, that no new equipment will be used. Figures 3 and 4 display similar behavior for variation of other combinations of parameters in the SOx/NOx/CO/TSP Q-function.

Figures 5 and 6 display similar sensitivity contours for the VOC Q-function. In both figures, the driver variable ranges from -1.0 to 1.0. Due to the difference in definition of driver variable between the VOC and SOx equations, this covers the same range of behavior as before, namely "no activity" to "doubling of activity". Figure 5 varies (E), the emission factor for new sources, from 0.0 to 1.0; Fig. 6 varies (C), the emission factor for existing and replacement sources, over the same range. In both cases the parameter (B), the base year emission factor, is fixed at 1.0. As in the SOx/NOx/etc. case, the response of the Q-function is linear to these parameters. The break in the slope of the contours at (Driver = 0.0) is due to a boundary condition preventing new equipment from being used when existing and replacement equipment exceeds the demanded capacity for a given activity.

The above description of analytical sensitivities of MODEL6 apply to any single entry in the POINT and AREA emission data base. Since MODEL6's output consists of variously categorized subtotals and totals of these results, overall sensitivities to a particular parameter will be the sum of the corresponding sensitivities (appropriately normalized) of the subset of results which uses that parameter.

The analysis discussed so far was not conducted with the assistance of automated sensitivity analysis tools. MODEL6 does not (and was not intended to) carry out a complex mathematical processing of its input data. The complexity of CRESS and MODEL6 is in the aggregation/disaggregation and categorization of emissions from the large number of emission sources. In this task, automated sensitivity computation is of considerable assistance.

4.2 GRESS ENHANCEMENT

GRESS (GRadient Enhanced Software System)[2] is a tool for automating sensitivity analyses of FORTRAN programs. It is used as a precompiler on source code to produce an enhanced source code and library which has the capability of propagating (via the chain rule of differentiation) partial derivatives with respect to any real parameter. This enhancement to the original code allows the calculation of the sensitivity of any variable with respect to any other without (in principle) detailed examination or knowledge of the intermediate processing the code may perform. Multiple sensitivities may be calculated

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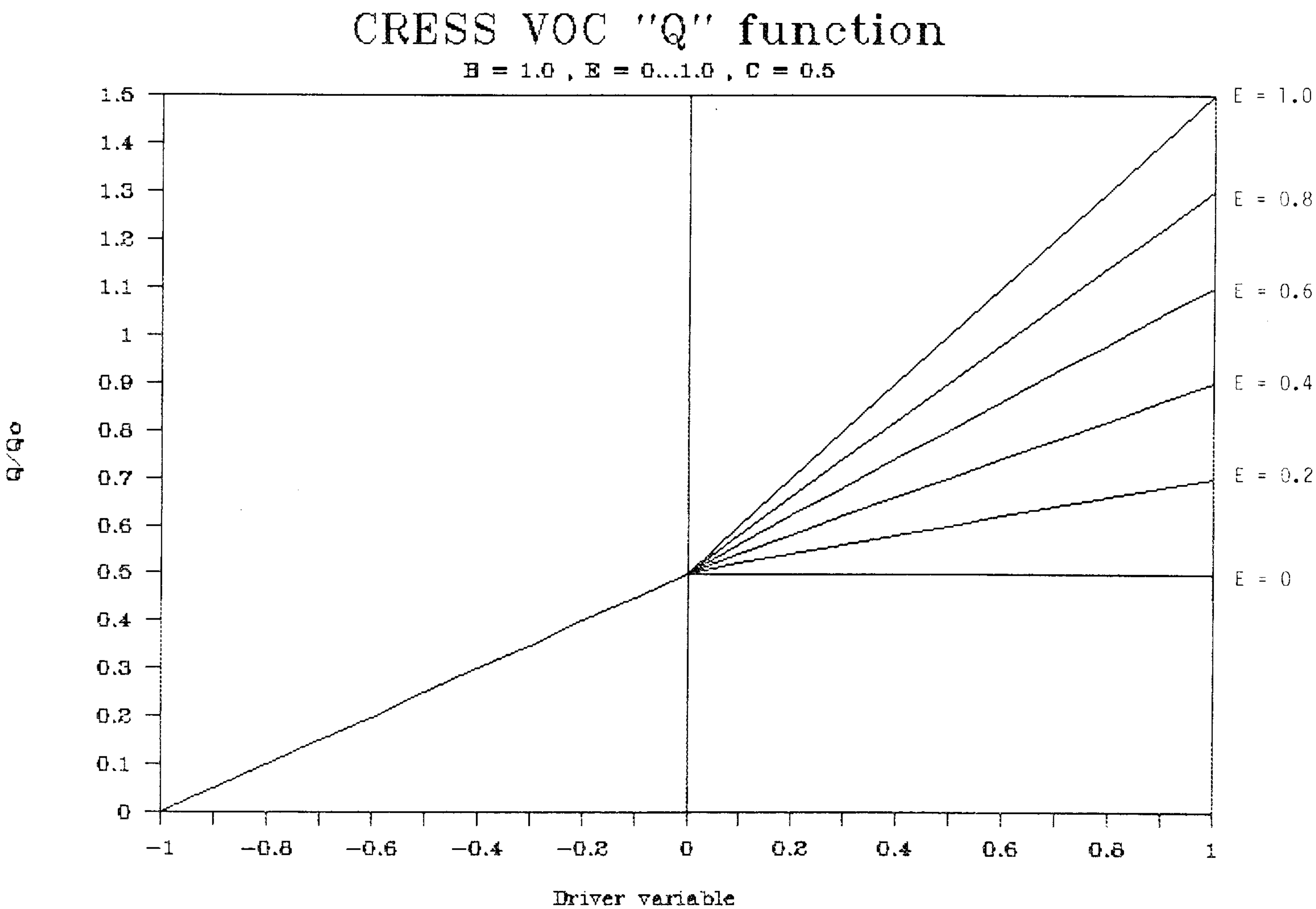

Parameters (B) and (C) are held constant at 1.0 and 0.5 respectively. The contours are for variation of (E) from 0 to 1 in steps of 0.2.

Fig. 5. Response of VOC model to variation in driver variable (D) and emission factor new equipment (E).

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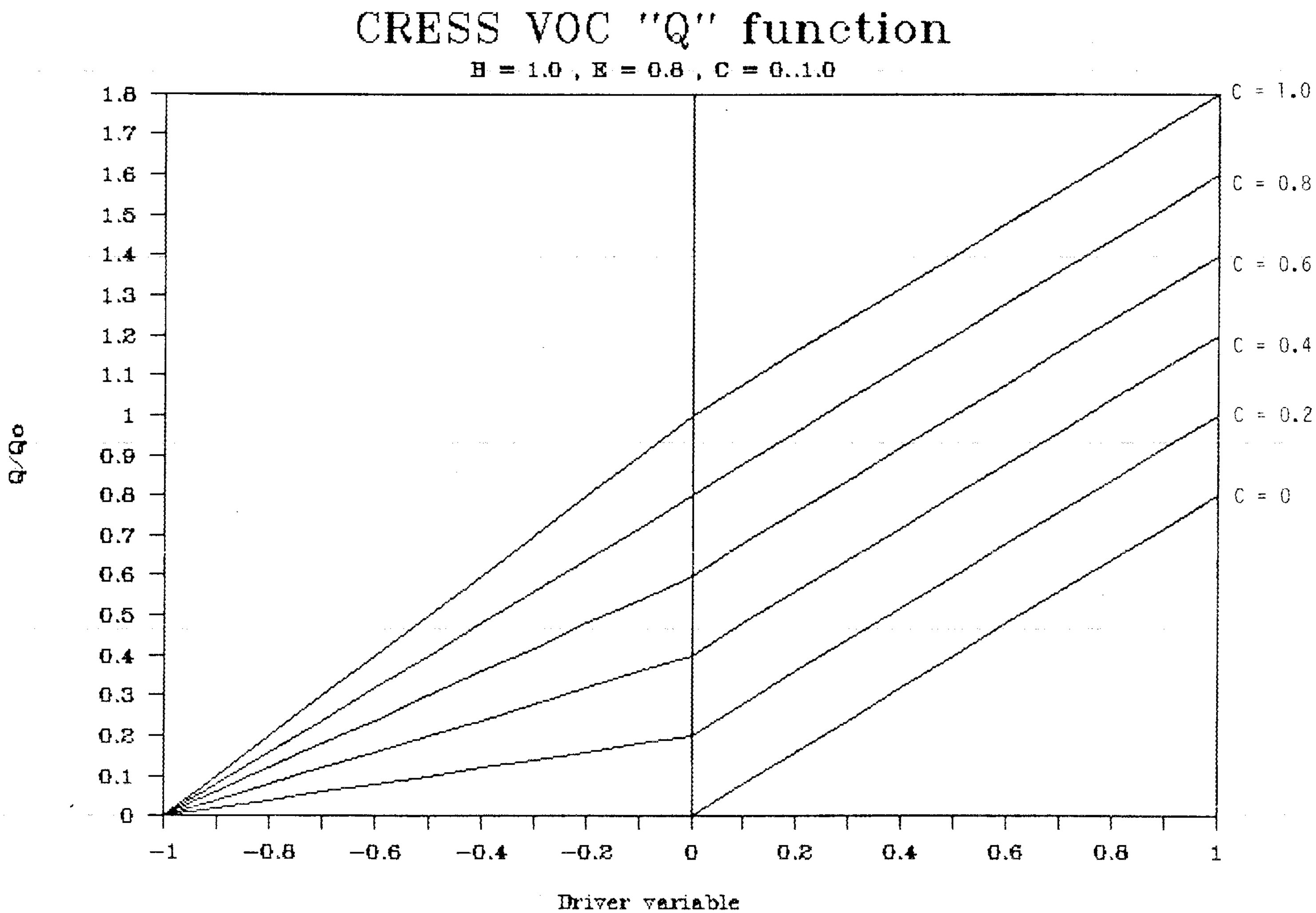

Parameters (B) and (E) are held constant at 1.0 and 0.8 respectively. The contours are for variation of (C) from 0 to 1 in steps of 0.2.

Fig. 6. Response of VOC model to variation in driver variable (D) and emission factor for existing/replacement equipment (C).

using this tool (limited by computer memory and run time), in contrast to perturbation methods, which generally permit only a single variable to be varied per run. Calculated sensitivities from GRESS are for the particular solution point only; development of a detailed response surface would require re-run of the subject program with altered input values.

Aside from the modification and recompilation required, there is typically a CPU-time penalty associated with running a GRESS-enhanced program. In the case of MODEL6, the enhanced version required about 3 times as long to run as the original version. Typical factors for other programs are 10 to 30; the low factor in MODEL6 is due to the fact that it contains relatively little mathematical data manipulation.

GRESS as presently formulated is nearly compatible with FORTRAN-77 standards. A recent addition in this direction which aided the present study significantly is the ability to process arrays up to the FORTRAN-77 limit of 7 dimensions. Automated propagation of sensitivities between series of programs (such as the modules of the CRESS system) is not available at this writing, but is under development.

Typically, the procedure for utilizing GRESS on an existing model requires modification of the model's source code to solve any incompatibility problems that may exist, precompiling the model through GRESS, and then conducting a limited verification of the GRESS-enhanced version. This verification involves performing a limited sensitivity study on the original model using a parameter perturbation technique, and comparing the resulting response to that calculated using the GRESS-enhanced model. In this case, the parameter used for the perturbation analysis was FRACRR(8), the annual fractional replacement rate for residential natural gas equipment in the SOx model.[3] 20 sensitivities were calculated for national total emissions, one for each of 4 pollutants in each of 5 time periods. The same sensitivities were computed by perturbing the value of FRACRR(8) by +1%. The GRESS- and perturbation-calculated sensitivities varied by less than 2% of their values, which represents very good agreement.

The model outputs examined in this study were the national total pollutant emissions. Thus the sensitivity

$$\frac{\partial Q/Q_0}{\partial P/P_0}$$

of each of 40 values for Q(time,pollutant) (8 time periods $\times$ 5 pollutants) is examined with respect to various input parameters (P). In the above definition of sensitivity coefficient, both (Q) and (P) are normalized with respect to their base values, (Qo) and (Po). Many less aggregated outputs are available and could have been examined. As previously mentioned, there are approximately 27,000 output results and subtotals. Combined with the number of input parameters used by the model, there is, to say the least, a large number of permutations possible.

Input items were those elements that control the Q-functions: driver variables, replacement rates, etc. MODEL6 reads parameters into arrays of varying dimensions. For example, the variable FRACRR (the fractional replacement rate per year for old polluting equipment/activities) has 46 components, one for each of the SCCs (Source Category Codes) in the SOx section of the model. Another set of parameters, ERATIO from the file SNCPFACT (ratios of emission factors for new versus old equipment/activities), has one entry for each of the 49 states in each of the 46 SCCs.

The influence of a change in any one member of such an array is likely to be quite small on national totals, and in perturbation studies may be lost in the round-off error inherent in the single precision FORTRAN used in CRESS. Because of inability to compare GRESS-calculated derivatives with those calculated by perturbation, and again to create a tractable number of sensitivities for the study, most of the sensitivities were calculated by use of aggregation parameters. In this technique, the computer code is modified to multiply each initial definition of a parameter which belongs to the aggregate group by an aggregation parameter which has been given a value of "1.0", e.g. for a parameter array, P:

```
    A = 1.0
    DO 100 I=1,10
    P(I) = P(I)*A
100 CONTINUE
```

The gradients and sensitivities of the final result are then taken with respect to this aggregation parameter. The effect is to determine the sensitivities of the results with respect to proportional changes in the values of the entire aggregate group. A sample of such a modification is shown below. In this example, an array of 12 aggregation parameters (PRMIDR) is defined, one for each driver variable block.

Source code modifications which define aggregation parameters:

```
      COMMON/PRMCOM/PRMIDR(12)

      DO 80210 IPRM=1,4
      CALL DEFIYY (PRMIDR(IPRM),1)
80210 CONTINUE

      DO 70701 IPRM=1,12
      PRMIDR(IPRM)=1.0
70701 CONTINUE
```

Source code is modified immediately after reading in pollution quantities (TPYxxx : Tons per Year):

```
14    READ(17,5,END=29) STCODE,SCCNAP,TPYSO2,TPYNOX,TPYVOC,
     .                  TPYTSP,TPYCO
      IPRM = DRIVER(IBLOCK)
      TPYSO2 = TPYSO2*PRMIDR(IPRM)
```

Modification made to capture gradient of interest; inserted immediately after the results of interest (TAB(...)) are printed out. This sequence extracts gradient of TAB(...) with respect to PRMIDR(...) and stores the result in PRMOUT(...) for later printing.

```
      DO 80200 K=1,NYRSS
      DO 80200 IPRM=1,4
      CALL GETPYY(TAB(3,11,15,K),1,PRMIDP(IPRM),1,PRMOUT(IPRM,K))
80200 CONTINUE
```

The subroutines DEFIYY and GETPYY are GRESS procedures for defining parameters and extracting gradients. A list of the actual parameter additions made during analysis of MODEL6 is shown in Table 3.

Table 3. Aggregation Parameter Definitions

Parameter	Multiplies	Used in Q as	Q version
PRMRES(7)	RESEGYiver)	both	
PRMCMI(7)	CMIEGY	(driver)	both
PRMDRI(4)	DRIVAR	(driver)	both
PRMFRR	FRACRR	R	SOx
PRMERA	ERATIO	E	SOx
PRMREG	GROWTH	A	SOx
PRMEFAV	VOCBYR	B	VOC
PRMEXIV	VOCOLD	C	VOC
PRMNEWV	VOCNEW	E	VOC
PRMIDR(12)	TPYSO2, ..NOX,...	C/A	both

5. RESULTS

Three groups of sensitivity analyses have been conducted on MODEL6 using GRESS. The first group of analyses examines the effect on total projected emissions of the parameters of the two Q-functions. The second and third groups study aspects of the sensitivity of emission projections to the economic or geographic driver variables and source groupings. All the analyses use some degree of aggregation of parameters.

5.1 SOx MODEL PARAMETERS

The SOx model (used for all pollutants except VOCs) contains several parameters of potential interest. The three that are examined here are FRACRR, ERATIO, and GROWTH (the "R", "E", and "A" of the SOx Q-function); the driver variable (B) will be examined later. The cumulative sensitivities of total national emissions (for each of the four pollutants in each period) with respect to all elements of these parameter arrays have been computed using the parameter aggregation technique. The results are listed in Table 4 and displayed in Figs. 7 through 9.

5.1.1 FRACRR (Fractional Replacement Ratio of Old Equipment) Fig. 7:

This array contains 46 elements, one for each SCC in the SOx model, most of which have a value of 0.02/yr or 0.0222/yr. Since FRACRR is used in the model in a power function of (t), its influence grows through time. NOx and SOx emissions are most sensitive to FRACRR, but even they show sensitivities of only -0.02 and -0.01 respectively in 2030. CO and TSP emissions are much less sensitive to FRACRR, as they are driven primarily by activities which are projected to remain constant with time (e.g. forest fires).

5.1.2 GROWTH (That Fraction of New Activity/Equipment Subject to New Emission Standards) Fig. 8:

Sensitivities of emissions to this parameter are fairly small (0 to -0.05) and increase in magnitude with time. This is due to increasing contributions with time from new equipment/activities. NOx emissions are most sensitive to this parameter, again because a relatively larger proportion is driven by sources subject to changed emission factors.

5.1.3 ERATIO (Ratio of Emission Factors of Activity/Equipment New to Old) Fig. 9:

Sensitivities of emissions to this parameter are small (<0.03) except in the case of NOx emissions, where it is as high as 0.29 in 2030. All the sensitivities grow in time due to growing contributions from new equipment/activities. NOx emissions are most sensitive to this parameter because a relatively larger proportion is driven by sources subject to changed emission factors. An examination of the file SNCPFACT, which contains the source data for the ERATIO array, reveals that only a small fraction of the source categories is projected to have reduced emission factors in the future. These represent pollution attributed to subsets of natural gas usage and of commercial coal and oil usage. As will be shown later, these categories are the most important drivers of NOx projections, but are of lesser importance in driving other pollution projections.

Table 4. Sensitivities of National Pollution Totals with respect to aggregation parameters for all FRACRR (fractional replacement rate), ERATIO ("new" to "old" pollution factor ratio), and GROWTH (fraction of new activity subject to new regulations)

Parameter: (Q Fn:)	FRACRR (R)	ERATIO (E)	GROWTH (A)	Parameter: (Q Fn:)	FRACRR (R)	ERATIO (E)	GROWTH (A)
SOx Emissions				CO Emissions			
1980	--	--	--	1980	--	--	--
1985	-1.14E-03	5.79E-03	-3.99E-03	1985	-8.42E-05	1.08E-03	-1.42E-04
1990	-3.23E-03	1.02E-02	-5.79E-03	1990	-1.57E-04	2.21E-03	-3.07E-04
1995	-4.07E-03	1.54E-02	-7.97E-03	1995	-2.10E-04	3.15E-03	-4.23E-04
2000	-4.89E-03	1.81E-02	-9.17E-03	2000	-2.48E-04	3.73E-03	-5.03E-04
2010	-6.54E-03	2.06E-02	-1.04E-02	2010	-2.92E-04	4.36E-03	-6.06E-04
2020	-8.19E-03	2.13E-02	-1.08E-02	2020	-3.08E-04	4.86E-03	-7.10E-04
2030	-9.29E-03	2.24E-02	-1.14E-02	2030	-3.08E-04	5.45E-03	-8.25E-04
NOx Emissions				TSP Emissions			
1980	--	--	--	1980	--	--	--
1985	-4.85E-03	4.90E-02	-8.24E-03	1985	-3.38E-04	1.10E-03	-1.19E-03
1990	-8.63E-03	1.00E-01	-1.69E-02	1990	-1.31E-03	2.26E-03	-1.69E-03
1995	-1.12E-02	1.36E-01	-2.28E-02	1995	-1.75E-03	3.48E-03	-2.51E-03
2000	-1.34E-02	1.63E-01	-2.73E-02	2000	-2.09E-03	4.15E-03	-2.88E-03
2010	-1.66E-02	2.05E-01	-3.45E-02	2010	-2.53E-03	4.72E-03	-2.99E-03
2020	-1.84E-02	2.46E-01	-4.20E-02	2020	-2.77E-03	5.09E-03	-2.89E-03
2030	-1.87E-02	2.88E-01	-4.95E-02	2030	-2.82E-03	5.64E-03	-2.94E-03

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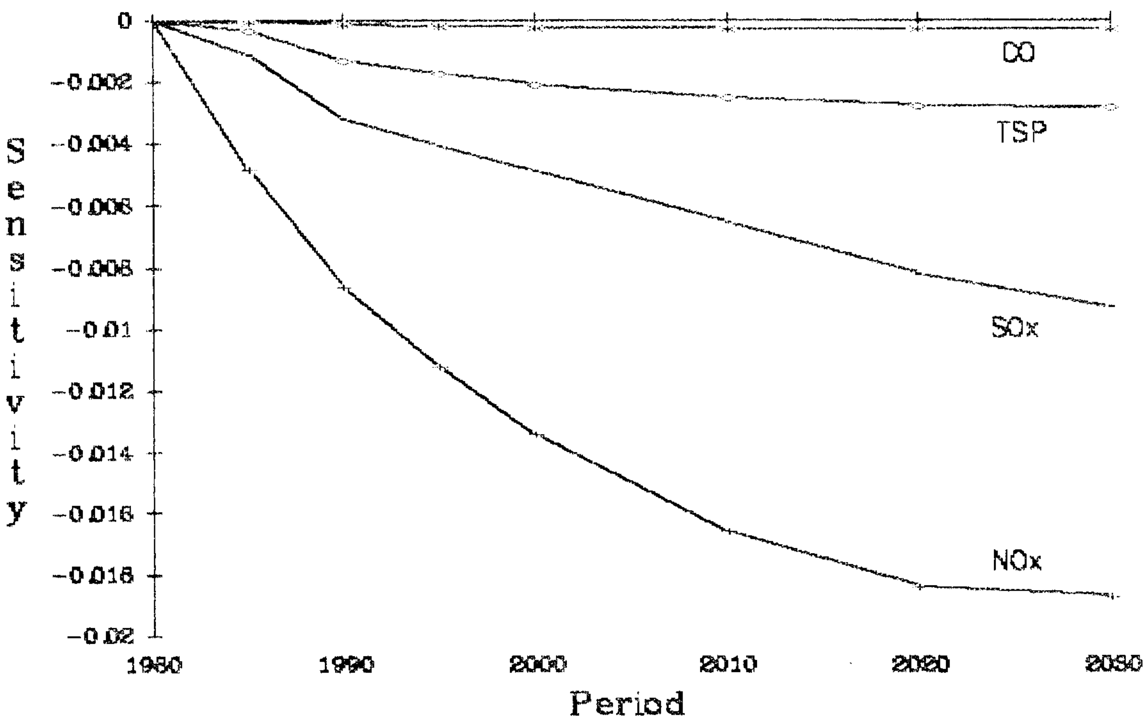

Fig. 7. Sensitivity of national total emissions to aggregated parameter for FRACRR (annual fractional replacement rate for old equipment).

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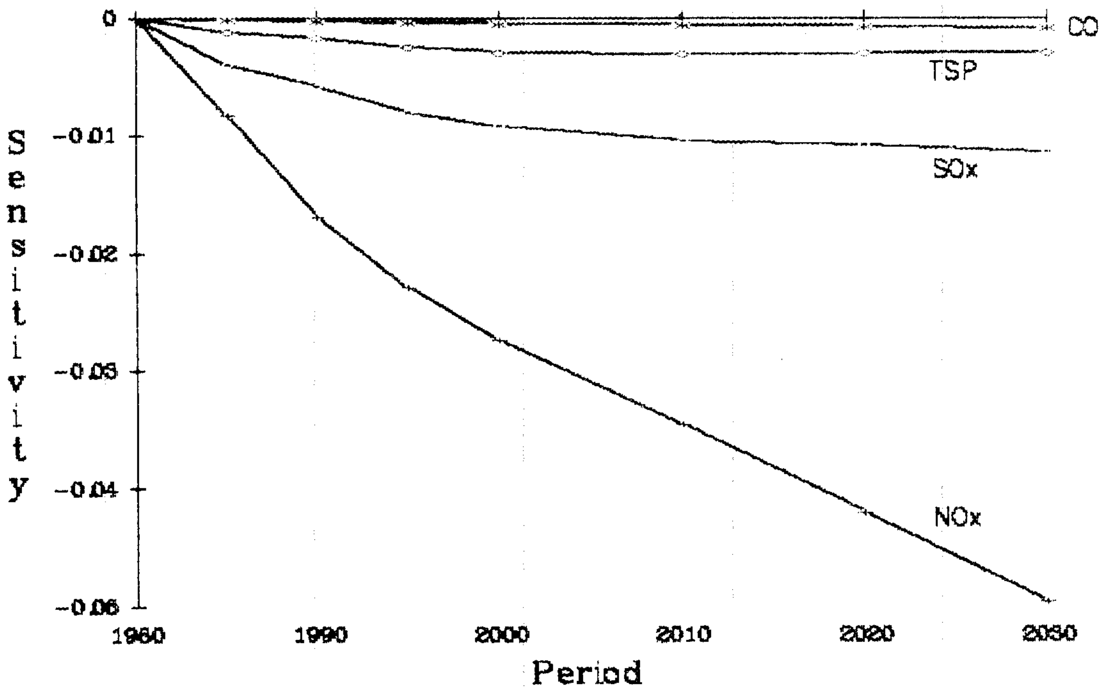

Fig. 8. Sensitivity of national total emissions to aggregated parameter for GROWTH (fraction of new equipment subject to new emission factors).

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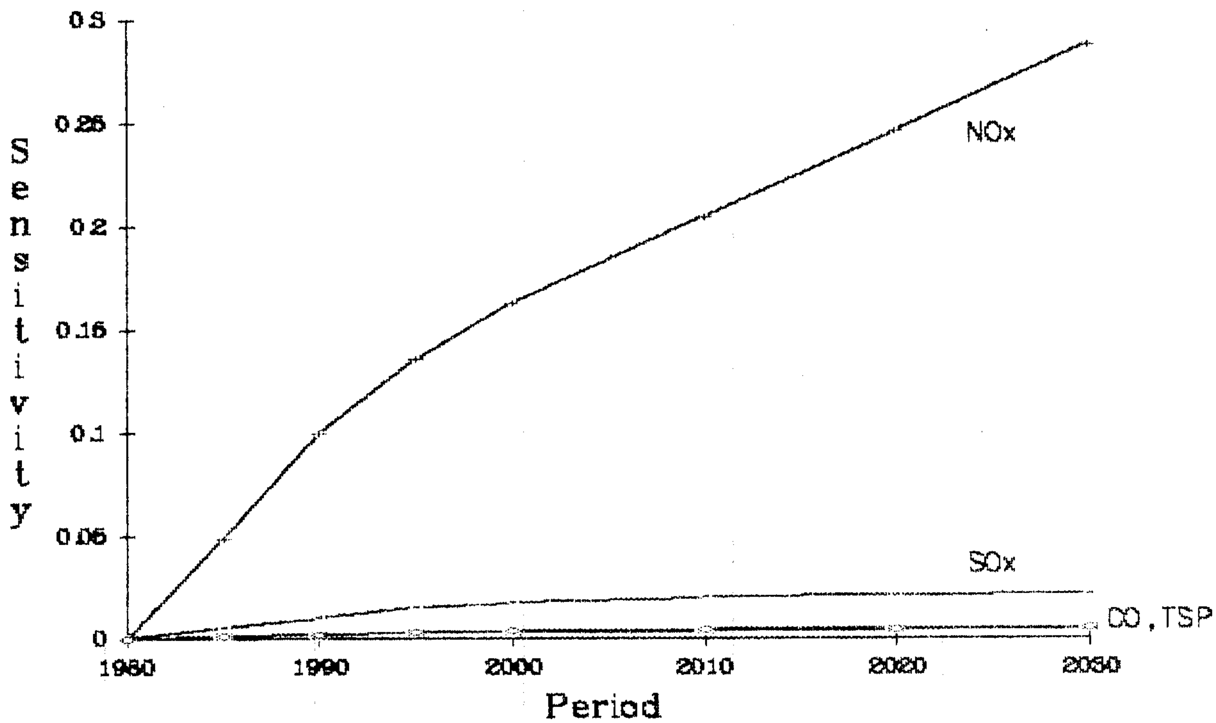

Fig. 9. Sensitivity of national total emissions to aggregated parameter for ERATIO (ratio of emission factors -- new:old).

The method of calculating normalized sensitivities may conceal important parameters for certain data values. This is the case in the above calculations. The method used in the input data to "switch off" use of a new emission factor, namely setting (A) to zero, renders the results insensitive to (E) and (Fo) for many of the entries. For only a very few SCCs are actual reductions in emission factors present in the data. Thus the sensitivity

$$\frac{\partial Q}{\partial E} = \sum_{\text{Sources}} CA(B - F) \tag{3}$$

will be very small, as most terms in the summation have "A" set to zero. A modification was made to MODEL6 to investigate the effect of this pattern of data. For those SCCs which would ordinarily use a value of (A=0) in combination with (E=1), the value of (A) was altered to be equal to one. Inspection of the SOx Q-function shows either combination should yield the same result; the calculated sensitivities, however, are significantly different. The altered sensitivity results for total emissions with respect to the ERATIO aggregation parameter are listed in Table 5 and displayed in Fig. 10. For SOx, CO, and TSP emissions, the sensitivities all have increased by an order of magnitude; the NOx sensitivity also increased, but was fairly large already. All the ERATIO sensitivities grow with time to be in the realm of 0.1 to 0.5. This indicates that, contrary to the initial sensitivity calculations, the emission factor ratio will be fairly important when more complete data is available.

Table 5. Sensitivities of National Pollution Totals with respect to aggregation parameters for all FRACRR (fractional replacement rate), ERATIO ("new" to "old" pollution factor ratio), and GROWTH (fraction of new activity subject to new regulations)*

Parameter: (Q Fn:)	FRACRR (R)	ERATIO (E)	GROWTH (A)	Parameter: (Q Fn:)	FRACRR (R)	ERATIO (E)	GROWTH (A)
SOx Emissions				CO Emissions			
1980	--	--	--	1980	--	--	--
1985	-2.37E-03	1.06E-01	-9.65E-03	1985	-8.42E-05	4.85E-02	-1.42E-04
1990	-5.46E-03	2.34E-01	-1.17E-02	1990	-1.57E-04	8.33E-02	-3.07E-04
1995	-6.91E-03	3.35E-01	-1.42E-02	1995	-2.10E-04	1.11E-01	-4.23E-04
2000	-8.31E-03	3.86E-01	-1.57E-02	2000	-2.48E-04	1.36E-01	-5.03E-04
2010	-1.11E-02	4.38E-01	-1.75E-02	2010	-2.92E-04	1.85E-01	-6.06E-04
2020	-1.38E-02	4.66E-01	-1.87E-02	2020	-3.08E-04	2.18E-01	-7.10E-04
2030	-1.57E-02	5.02E-01	-1.99E-02	2030	-3.08E-04	2.40E-01	-8.25E-04
NOx Emissions				TSP Emissions			
1980	--	--	--	1980	--	--	--
1985	-4.85E-03	8.54E-02	-8.24E-03	1985	-5.75E-04	4.75E-02	-2.25E-03
1990	-8.63E-03	1.87E-01	-1.69E-02	1990	-1.75E-03	8.49E-02	-2.85E-03
1995	-1.12E-02	2.62E-01	-2.28E-02	1995	-2.34E-03	1.16E-01	-3.74E-03
2000	-1.34E-02	3.09E-01	-2.73E-02	2000	-2.79E-03	1.42E-01	-4.13E-03
2010	-1.66E-02	3.69E-01	-3.45E-02	2010	-3.37E-03	1.89E-01	-4.23E-03
2020	-1.84E-02	4.18E-01	-4.20E-02	2020	-3.68E-03	2.21E-01	-4.14E-03
2030	-1.87E-02	4.67E-01	-4.95E-02	2030	-3.74E-03	2.43E-01	-4.18E-03

*These results are the result of modifying entries for which "A=0, E=1" to "A=1, E=1" in order to highlight sensitivity to pollution ratio E, even when it didn't change from the 1980 rate.

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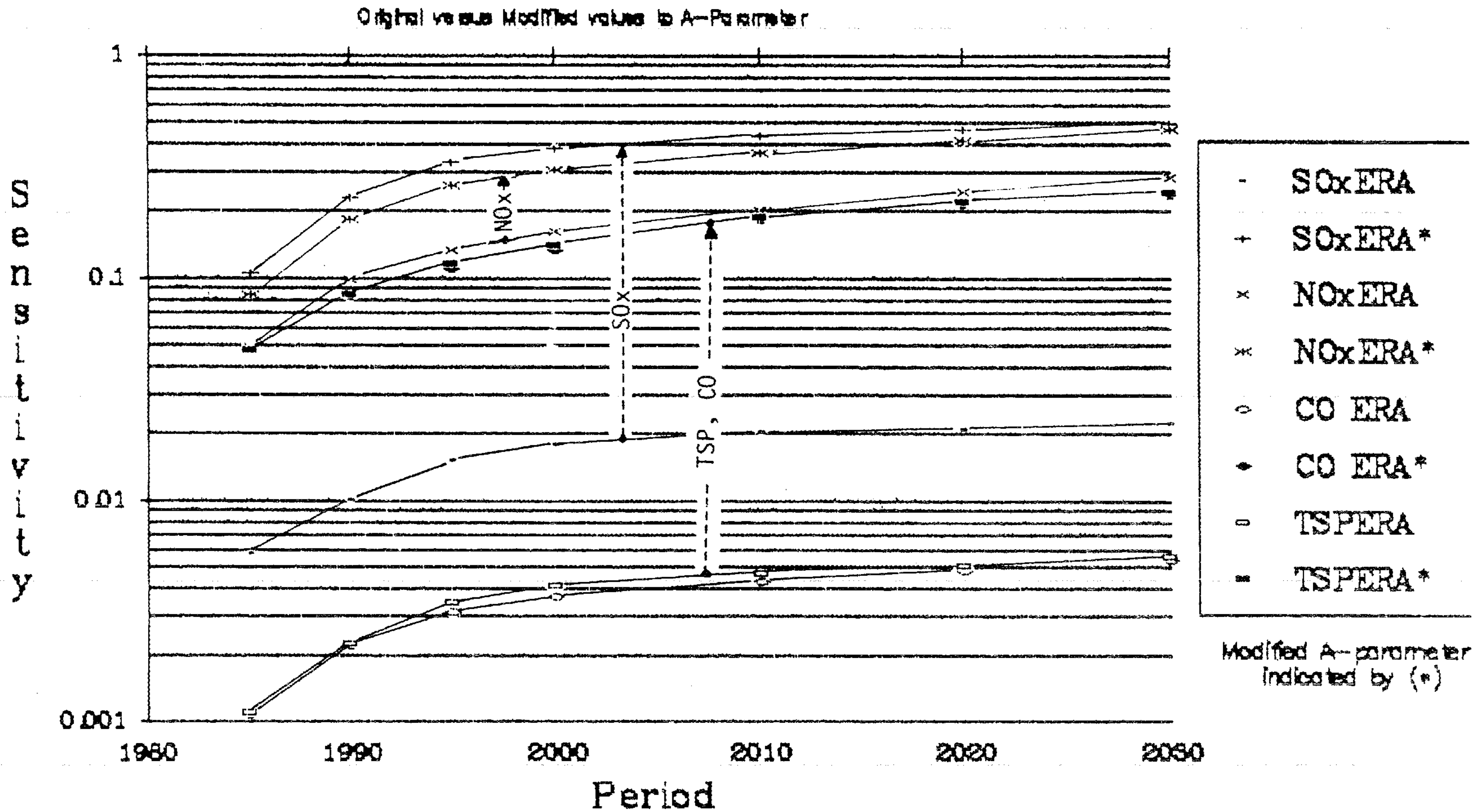

Symbols whose labels are indicated by an asterisk use A = 1.0; others use the original value of A = 0.0.

Fig. 10. Sensitivities of SOx, NOx, CO, and TSP emissions to ERATIO, showing influence on calculated sensitivity of choice of value for (A) for sources projecting no future change in pollution factors.

5.2 VOC MODEL PARAMETERS

The VOC model is structured somewhat differently, and thus its controlling parameters have a different meaning from those previously discussed. As before, the parameters controlling the emission quantity projections were treated by the aggregation technique described earlier, and sensitivity of national total emissions of VOCs is examined with respect to all elements of the arrays VOCBYR, VOCOLD, and VOCNEW. The sensitivity with respect to the driver variable will be examined separately. Sensitivities are listed in Table 6 and displayed in Fig. 11.

VOCOLD values are read from a series of files (one for each period) named VOC1985.DAT, VOC1990.DAT, etc. These values are the pollution factors for old equipment/activities as well as replacement of such equipment. VOCNEW values are read from a similar series of files named VCN1985.DAT, etc. These values are pollution factors for additional equipment/activities. VOCBYR values are base year values for these parameters and come from file VOC1980.DAT.

The sensitivity of VOC emissions to VOCOLD represents the relative contribution made by old and replacement sources. It begins near 1.0 and declines with time to about 80% of its initial value. The sensitivity of emissions with respect to VOCNEW, which represents the relative contribution made by new equipment, conversely grows to about 0.20. The sum of these two sensitivities is (not very profoundly) equal to the negative of the sensitivity of the denominator of their factor in the VOC Q- function, which is VOC-BYR. Using Equation 2 and defining aggregation parameters Pe and Pc (both equal to 1.0) for E and C, VOC emissions are given by

$$Q = \sum_{\text{Sources}} \frac{A}{B}(DEP_e + CP_c) \tag{4}$$

so the gradients with respect to P_e and P_c are

$$\frac{\partial Q}{\partial P_e} = \sum_{\text{Sources}} \frac{A}{B} DE \tag{5}$$

$$\frac{\partial Q}{\partial P_c} = \sum_{\text{Sources}} \frac{A}{B} C \ . \tag{6}$$

Since Pe and Pc are equal to 1,

$$\frac{\partial Q}{\partial P_e} + \frac{\partial Q}{\partial P_c} = Q \ . \tag{7}$$

The equivalent statement for normalized sensitivities is that their sum should be equal to one. Imposition of boundary conditions could reduce this value slightly, but as is evident from Fig. 11, this doesn't occur to an appreciable degree. A similar analysis would indicate that the emission sensitivity with respect to VOCBYR should be equal to -1.

Table 6. Sensitivities of National Pollution Totals with respect to aggregation parameters for all VOCBYR (base year pollution factors), VOCOLD (pollution factors for old and replacement equipment/activity), and VOCNEW (pollution factors for new equipment/activity)

VOC Emissions

Parameter: (Q Fn:)	VOCBYR (B)	VOCOLD (C)	VOCNEW (E)	Total
1980	--	--	--	--
1985	-0.993	0.958	0.035	-0.0004
1990	-0.993	0.926	0.067	-0.0004
1995	-0.993	0.900	0.093	0.0000
2000	-0.993	0.879	0.114	0.0000
2010	-0.993	0.846	0.148	0.0010
2020	-0.994	0.814	0.180	-0.0000
2030	-0.994	0.796	0.198	0.0000

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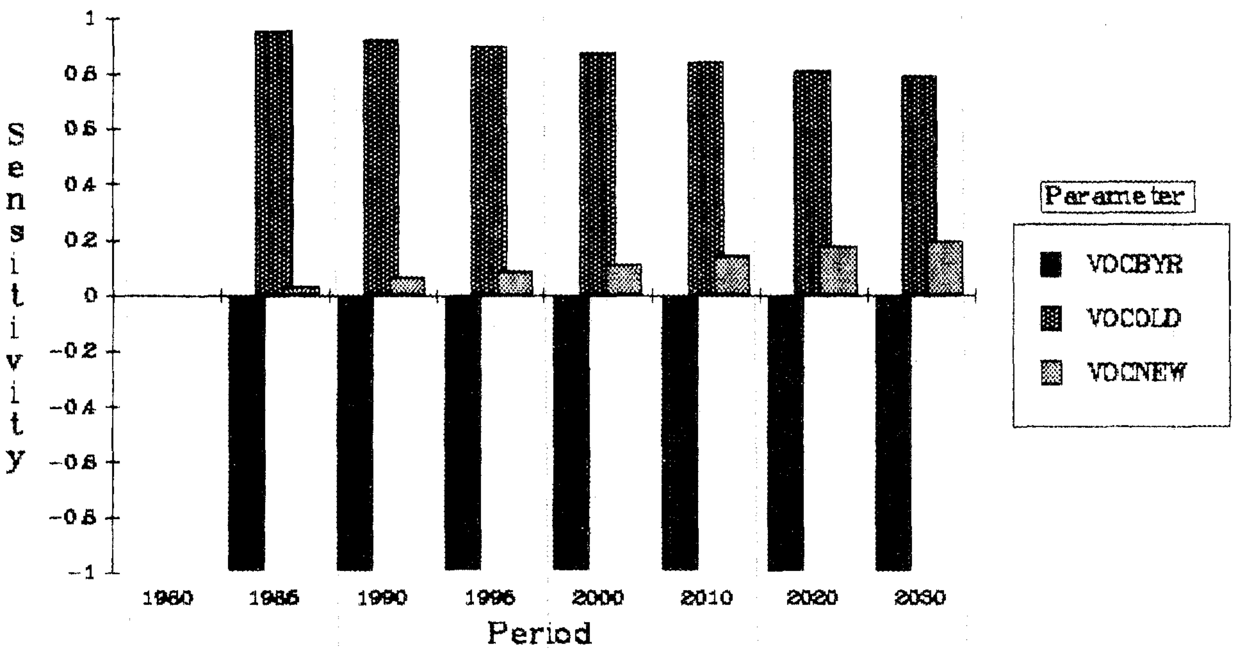

Fig. 11. Sensitivity of national total VOC emissions to aggregated emission factors VOCBYR (base year - old equipment), VOCOLD (old and replacement equipment) and VOCNEW (additions to equipment in excess of replacement rate).

The formulation of the Q-function for VOC emissions makes it difficult to examine sensitivity of emissions to changes in pollution factors, since much of the change (or lack thereof) is combined into data outside of CRESS (into the array VOCOLD). An examination of several of the VOCxxxx and VCNxxxx files suggests that most of the pollution factors contained in the present data are not projected to change.

5.3 SENSITIVITIES TO DRIVER VARIABLES

Each category of pollution source projects future changes in emission levels through use of a driver variable. It is explicitly assumed that the activity which results in emission from that source will change in a manner directly proportional to the selected driver variable. Actual emission levels depend on both the activity and the other factors enumerated above. The driver variables are derived from parameters CMIEGY (an array of commercial fuel usage projections dimensioned with 49 states, 8 periods, and 7 fuels), RESEGY (an array similar to CMIEGY, but for residential sources), and DRIVAR (an array of geographic projections for 49 states, 8 periods, and 4 indices). The four indices of DRIVAR are total population, rural population, forest acreage, and gasoline sales. The precise categories these represent are listed in Table 7 as column headings. These driver variable values comprise the only information passed to MODEL6 from the previous modules (e.g. HOME2, CSEM2,...) of CRESS.

The sensitivity for a particular driver parameter is, due to the linear nature of its use in the Q-functions, proportional to the contribution made to total emission by sources driven by that parameter. Sensitivities calculated here are to the driver parameters read into the arrays RESEGY, CMIEGY and DRIVAR rather than to the actual driver variable derived for the two Q-functions (i.e. "B" in Equation 1 and "D" in equation 2). For the SOx Q-function, the normalized sensitivity of total emissions to the driver (Dn) for a particular source (n) is :

$$\frac{\partial Q}{\partial D_n}\,\frac{D_n}{Q} = \frac{\sum\limits_{\text{Source(n)}} C\,\frac{D_n}{D_n('80)}\,\left|1-A(1-E)\right|}{\sum\limits_{\text{Sources}} C\,\frac{D}{D('80)}\,\left|1-A(1-E)\right| + F_o A(1-E)} \quad (8)$$

For nearly all sources, the term (A(1-E)) in the current data set is zero, so the normalized sensitivity is approximately equal to the fractional share of the pollution driven by source (n), namely:

$$\frac{\partial Q}{\partial D_n}\,\frac{D_n}{Q} \simeq \frac{\sum\limits_{\text{Source(n)}} C D_n/D_n('80)}{\sum\limits_{\text{Sources}} C D/D('80)} \quad (9)$$

Because the sensitivities of driver variables resemble shares of total pollution, the results plotted in the remaining graphs are displayed in stacked-bar format in order to illustrate both the individual and collective sensitivities. In Figs. 12 to 16, the sensitivity of emission to a particular driver variable is given by the height of its portion of the bar; its position on the stacked bar is irrelevant.

Table 7. Sensitivities of National Pollution Totals with Respect to Driver Variable Arrays (DRIVAR, RESEGY, and CMIEGY)*

VARIABLE:	DRIVAR				RESEGY							CMIEGY						
Index:	(1) Gasoline Sales	(2) Total Pop.	(3) Rural Pop.	(4) Forest Area	(1) Coal	(2) Resid. Oil	(3) Distil. Oil	(4) Nat. Gas	(5) LPG	(6) Wood	(7) Electr.	(1) Coal	(2) Resid. Oil	(3) Distil. Oil	(4) Nat. Gas	(5) LPG	(6) Wood	(7) Electr.
SOx Emissions																		
1980	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1985	--	0.0275	0.0100	0.0086	0.0439	--	0.1450	0.0012	--	0.0009	--	0.2090	0.4250	0.1150	0.0017	7.9E-05	--	--
1990	--	0.0260	0.0093	0.0077	0.0344	--	0.1420	0.0012	--	0.0008	--	0.1760	0.4590	0.1250	0.0016	7.2E-05	--	--
1995	--	0.0253	0.0089	0.0071	0.0281	--	0.1320	0.0012	--	0.0008	--	0.1550	0.4930	0.1320	0.0015	6.8E-05	--	--
2000	--	0.0263	0.0091	0.0071	0.0247	--	0.1250	0.0013	--	0.0008	--	0.1470	0.5100	0.1350	0.0015	6.8E-05	--	--
2010	--	0.0307	0.0104	0.0077	0.0208	--	0.1210	0.0014	--	0.0010	--	0.1430	0.5160	0.1350	0.0014	7.6E-05	--	--
2020	--	0.0365	0.0123	0.0087	0.0187	--	0.1310	0.0017	--	0.0012	--	0.1470	0.5010	0.1300	0.0013	8.8E-05	--	--
2030	--	0.0417	0.0141	0.0097	0.0165	--	0.1460	0.0021	--	0.0013	--	0.1490	0.4830	0.1250	0.0012	1.0E-04	--	--
NOx Emissions																		
1980	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1985	--	0.0380	0.0617	0.2110	0.0028	--	0.0786	0.2210	--	0.0081	--	0.0480	0.1060	0.0571	0.1130	6.5E-05	--	--
1990	--	0.0369	0.0599	0.1970	0.0023	--	0.0810	0.2280	--	0.0078	--	0.0425	0.1210	0.0648	0.1090	5.9E-05	--	--
1995	--	0.0366	0.0597	0.1900	0.0019	--	0.0785	0.2320	--	0.0077	--	0.0389	0.1330	0.0707	0.1060	5.6E-05	--	--
2000	--	0.0373	0.0610	0.1900	0.0017	--	0.0740	0.2400	--	0.0080	--	0.0368	0.1360	0.0721	0.1030	5.5E-05	--	--
2010	--	0.0400	0.0659	0.1950	0.0014	--	0.0686	0.2590	--	0.0092	--	0.0343	0.1300	0.0678	0.0939	5.5E-05	--	--
2020	--	0.0433	0.0713	0.2010	0.0011	--	0.0675	0.2870	--	0.0098	--	0.0322	0.1140	0.0592	0.0816	5.5E-05	--	--
2030	--	0.0450	0.0742	0.2040	0.0009	--	0.0692	0.3170	--	0.0100	--	0.0296	0.1000	0.0521	0.0707	5.4E-05	--	--

*Sensitivities identically equal to zero are indicated by dashes (--).

Table 7. (Cont'd)

Index:	(1) Gasoline Sales	(2) Total Pop.	(3) Rural Pop.	(4) Forest Area	(1) Coal	(2) Resid. Oil	(3) Distil. Oil	(4) Nat. Gas	(5) LPG	(6) Wood	(7) Electr.	(1) Coal	(2) Resid. Oil	(3) Distil. Oil	(4) Nat. Gas	(5) LPG	(6) Wood	(7) Electr.
CO Emissions																		
1980	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1985	--	0.1160	0.0916	0.6090	0.0077	--	0.0019	0.0039	--	0.1280	--	0.0014	0.0012	0.0013	0.0027	1.6E-05	--	--
1990	--	0.1200	0.0939	0.6000	0.0067	--	0.0021	0.0043	--	0.1320	--	0.0013	0.0015	0.0016	0.0028	1.5E-05	--	--
1995	--	0.1230	0.0960	0.5940	0.0059	--	0.0021	0.0045	--	0.1330	--	0.0012	0.0016	0.0018	0.0029	1.5E-05	--	--
2000	--	0.1250	0.0975	0.5880	0.0051	--	0.0020	0.0046	--	0.1370	--	0.0011	0.0017	0.0018	0.0028	1.5E-05	--	--
2010	--	0.1290	0.0997	0.5730	0.0039	--	0.0017	0.0047	--	0.1490	--	0.0010	0.0015	0.0016	0.0025	1.5E-05	--	--
2020	--	0.1330	0.1030	0.5650	0.0031	--	0.0016	0.0050	--	0.1520	--	0.0009	0.0013	0.0013	0.0021	1.5E-05	--	--
2030	--	0.1360	0.1050	0.5610	0.0024	--	0.0016	0.0054	--	0.1520	--	0.0008	0.0011	0.0011	0.0018	1.5E-05	--	--
TSP Emissions																		
1980	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1985	--	0.1200	0.1320	0.5240	0.0065	--	0.0059	0.0035	--	0.1100	--	0.0238	0.0266	0.0061	0.0062	1.6E-05	--	--
1990	--	0.1230	0.1340	0.5130	0.0056	--	0.0064	0.0038	--	0.1120	--	0.0221	0.0276	0.0071	0.0063	1.6E-05	--	--
1995	--	0.1260	0.1370	0.5070	0.0049	--	0.0064	0.0040	--	0.1130	--	0.0206	0.0306	0.0078	0.0062	1.[illegible]E-05	--	--
2000	--	0.1280	0.1390	0.5020	0.0043	--	0.0060	0.0041	--	0.1160	--	0.0193	0.0308	0.0078	0.0060	1.5E-05	--	--
2010	--	0.1320	0.1430	0.4920	0.0033	--	0.0053	0.0042	--	0.1280	--	0.0170	0.0275	0.0069	0.0051	1.5E-05	--	--
2020	--	0.1370	0.1490	0.4890	0.0026	--	0.0050	0.0045	--	0.1310	--	0.0153	0.0230	0.0058	0.0041	1.6E-05	--	--
2030	--	0.1410	0.1530	0.4880	0.0020	--	0.0051	0.0049	--	0.1310	--	0.0139	0.0200	0.0050	0.0034	1.6E-05	--	--
VOC Emissions																		
1980	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1985	0.0678	0.6420	0.1450	0.1210	1.0E-03	--	3.1E-04	1.4E-03	--	1.4E-03	--	1.7E-04	2.4E-04	2.6E-04	1.1E-03	5.8E-06	--	--
1990	0.0536	0.6610	0.1490	0.1200	8.8E-04	--	3.4E-04	1.6E-03	--	1.5E-03	--	1.6E-04	2.9E-04	3.1E-04	1.1E-03	5.5E-06	--	--
1995	0.0508	0.6680	0.1500	0.1170	7.6E-04	--	3.3E-04	1.6E-03	--	1.5E-03	--	1.4E-04	3.2E-04	3.4E-04	1.1E-03	5.3E-06	--	--
2000	0.0514	0.6710	0.1500	0.1140	6.5E-04	--	3.1E-04	1.6E-03	--	1.5E-03	--	1.3E-04	3.3E-04	3.4E-04	1.1E-03	5.2E-06	--	--
2010	0.0523	0.6750	0.1500	0.1100	4.9E-04	--	2.7E-04	1.6E-03	--	1.6E-03	--	1.2E-04	2.9E-04	3.0E-04	9.5E-04	5.0E-06	--	--
2020	0.0507	0.6810	0.1520	0.1050	3.7E-04	--	2.4E-04	1.7E-03	--	1.5E-03	--	1.0E-04	2.3E-04	2.5E-04	7.8E-04	4.9E-06	--	--
2030	0.0516	0.6820	0.1520	0.1030	2.9E-04	--	2.4E-04	1.8E-03	--	1.5E-03	--	9.0E-05	2.0E-04	2.1E-04	6.6E-04	4.9E-06	--	--

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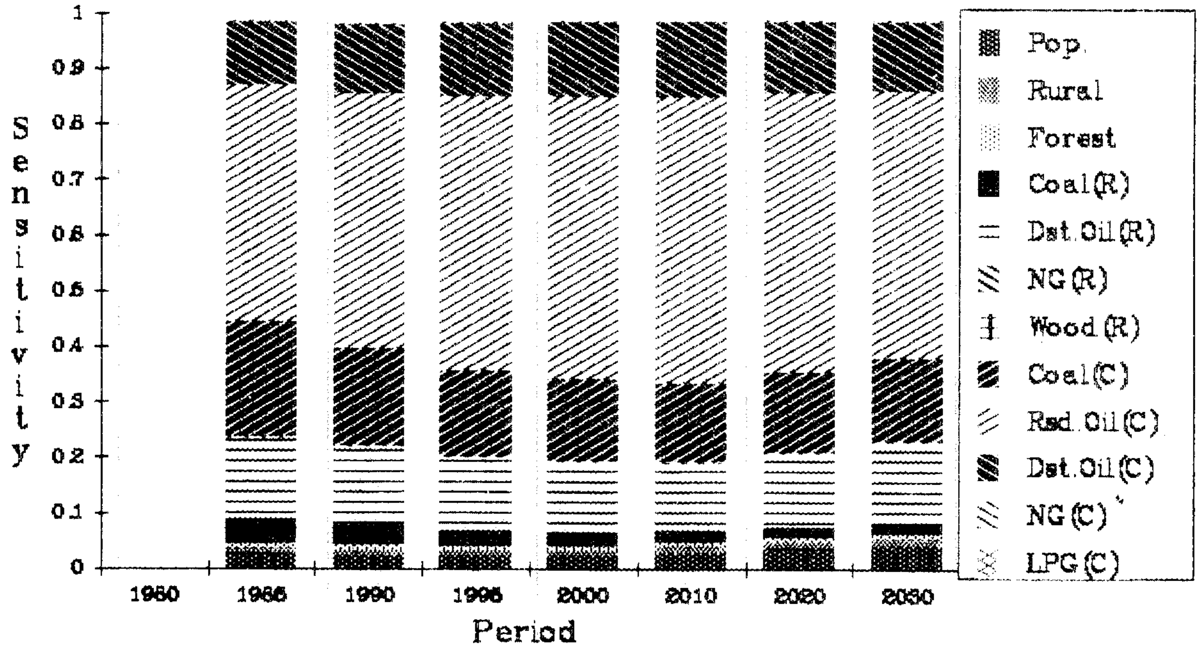

Fig. 12. Sensitivities of SOx national total emission to driver variable input parameters (RESEGY, CMIEGY, and DRIVAR).

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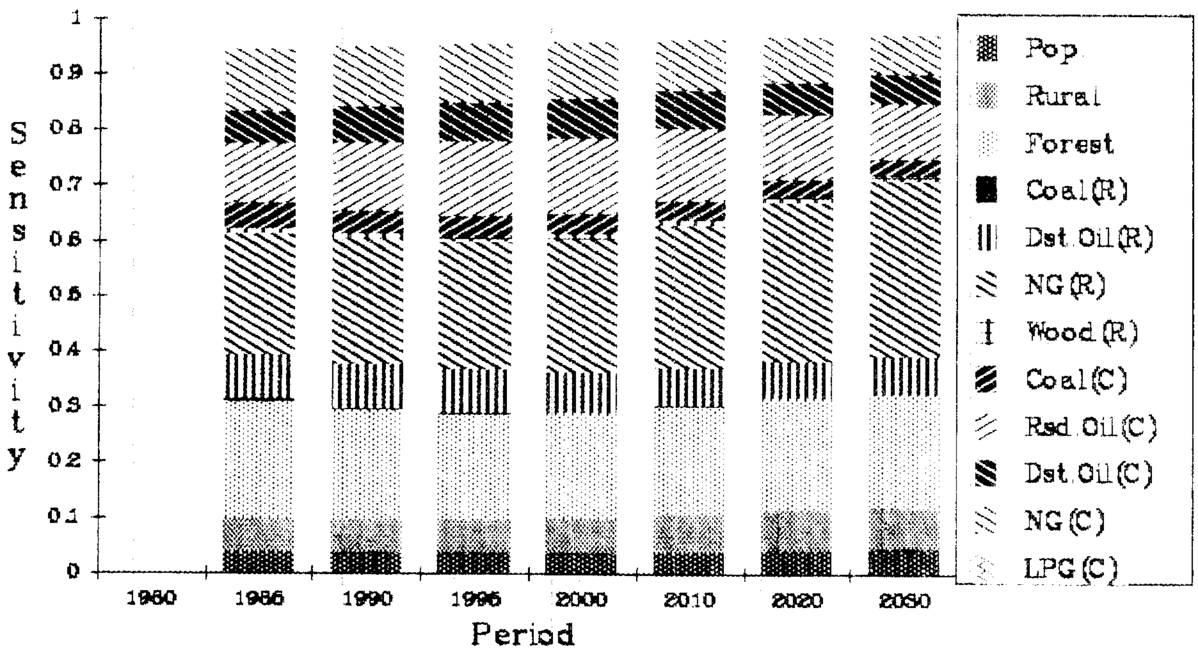

Fig. 13. Sensitivities of NOx national total emission to driver variable input parameters (RESEGY, CMIEGY, and DRIVAR).

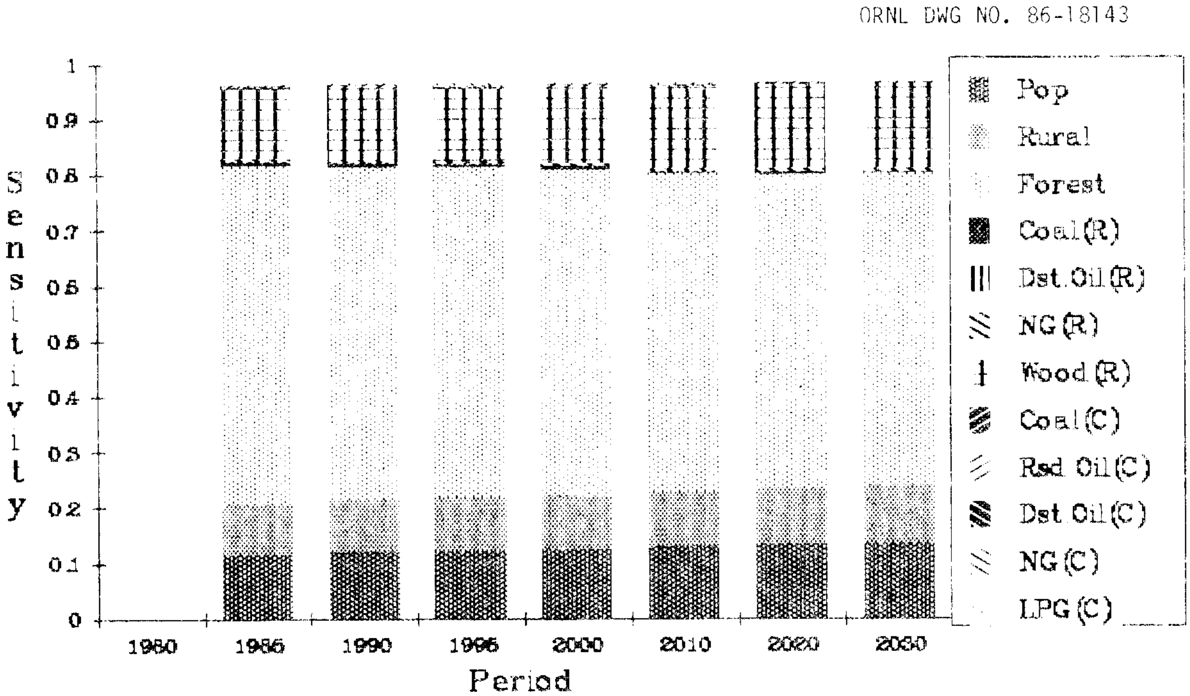

Fig. 14. Sensitivities of CO national total emission to driver variable input parameters (RESEGY, CMIEGY, and DRIVAR).

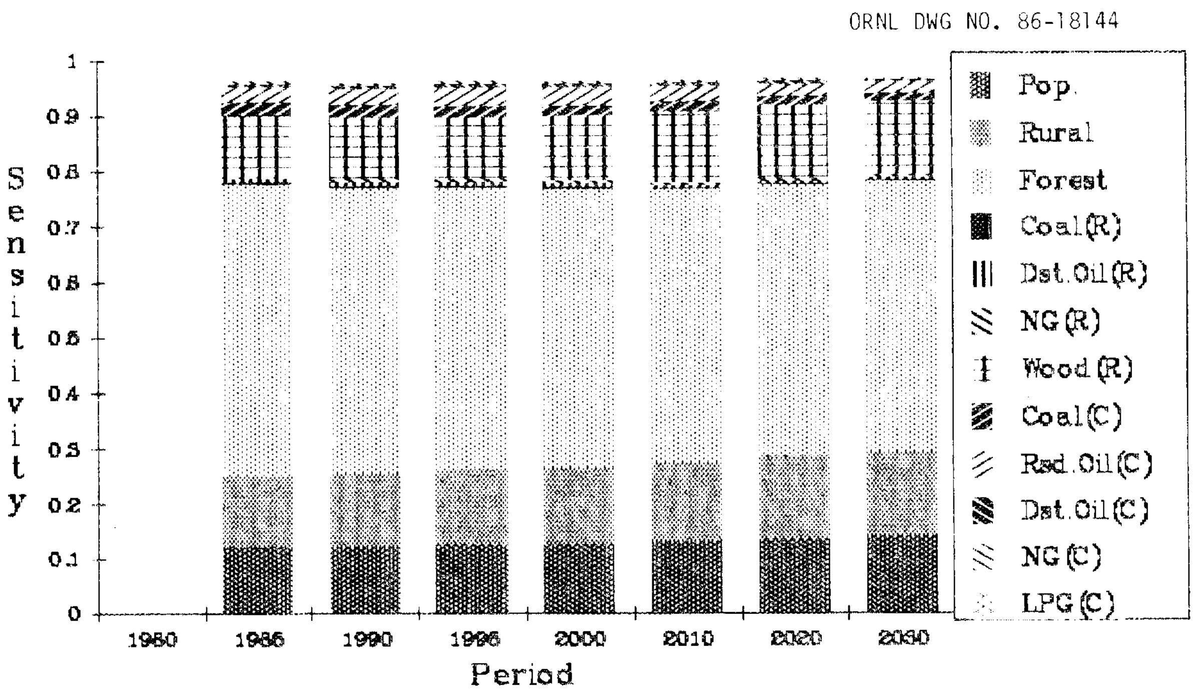

Fig. 15. Sensitivities of TSP national total emission to driver variable input parameters (RESEGY, CMIEGY, and DRIVAR).

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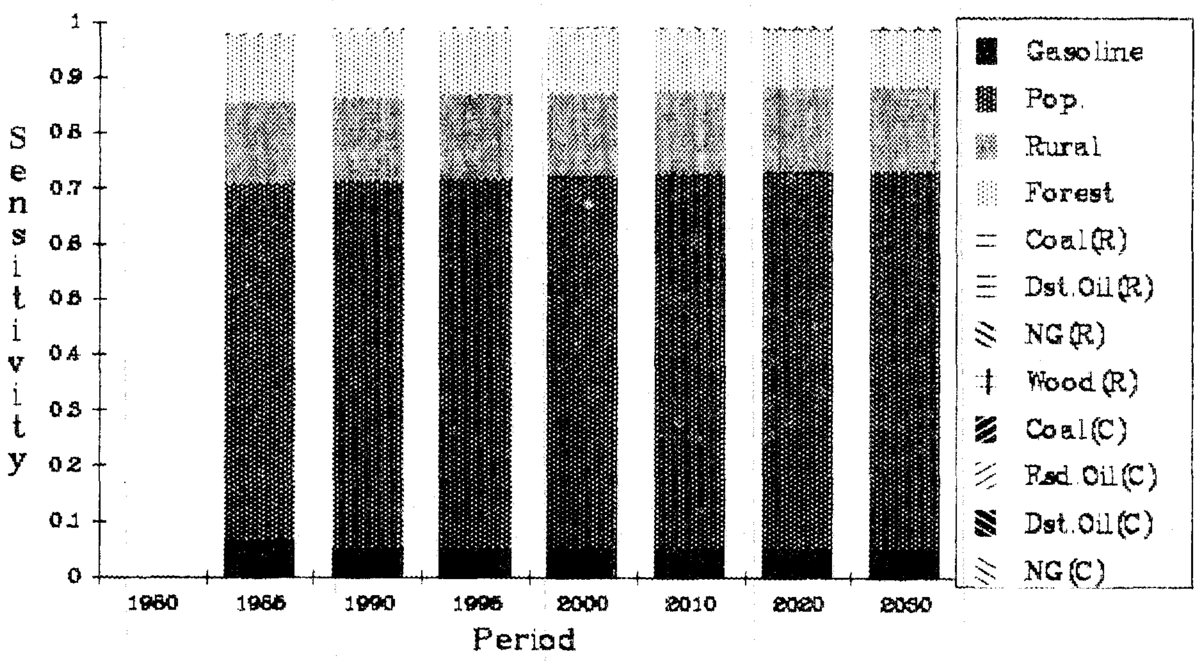

Fig. 16. Sensitivities of VOC national total emission to driver variable input parameters (RESEGY, CMIEGY, and DRIVAR).

The SOx module uses driver parameters differently from the VOC module, as has been described previously, but the intent and effect is similar. The aggregation parameter technique was used on the driver variables to examine combined sensitivities to emissions at the national level. Thus 18 sensitivities were calculated (7 for each of the RESEGY and CMIEGY fuel types and 4 for the DRIVAR variables) for each of the 5 pollutants in each of the 8 model periods.

The sensitivity of the national emission totals to the driver variables are listed in Table 7 and displayed in Figs. 12 through 16. In Table 7, sensitivities which were found to be equal to zero are portrayed with dashes (--). These are:

1. All 1980 results -- these are directly read in as data and not projected using driver variables.
2. Electric energy use: This data is read in but never referred to by any source block or code. Presumably pollution due to electric power generation is credited to a utility sector
3. Residential Residual Oil use: This driver parameter is "zero" in the file VOCDATA1.
4. Commercial Wood use: This driver parameter is "zero" in the file VOCDATA1.

5. Residential LPG use: In VOC1980 and similar files, all sources referring to LPG are attributed to the commercial sector. While there are residential LPG projections in the driver parameter file VOCDATA1, these values are never referred to in MODEL6.
6. SOx, NOx, TSP, CO vs. gasoline sales: A check of the source data base (POINT and AREA) revealed that those source codes corresponding to gasoline sales listed only VOC pollution.

All of the other driver parameters had at least a moderate influence on one or more pollutants (i.e. above a few percent) with the exception of commercial LPG use. Its maximum sensitivity to any pollutant total was 0.0001.

A second general observation is that the emission projections do not change very much over time. This seems to be inherent in the data (both the driver projections and in the relatively unchanging nature of other parameters, such as pollution factors).

SOx emission projections (Fig. 12) are driven largely by commercial oil and coal usage. Residential oil usage also contributes moderately to SOx projections; other variables make only relatively small contributions.

NOx emissions (Fig. 13) are driven by a more diverse mixture of parameters, with approximately equal contributions from commercial energy use, residential energy use, and geographic parameters.

CO and TSP emissions (Figs. 14 and 15) exhibit similar patterns of sensitivity, being driven primarily by geographic variables (mainly forest acreage), with a moderate contribution from residential wood usage, and only small contributions from other sources.

VOC emissions (Fig. 16) are driven almost exclusively by geographic projections, the most important of which is total population. It is the only pollutant to utilize the gasoline sales projections as a driver, and this contributes only minimally to total emissions (ca 5%).

5.4 SENSITIVITIES TO SOURCE DRIVER BLOCKS

An aggregation parameter was defined for the base year emission quantities (e.g. variables TPYSO2, TPYNOX, etc.) belonging to each of the 12 driver blocks into which the SCCs are subdivided. These 12 driver blocks are listed as column headings in Table 8. The sensitivities of total emissions with respect to these parameters were calculated. The resulting sensitivities represent the share of total emission due to each driver block.

Detailed results are listed in Table 8 and displayed in Figs. 17 through 21. These results show the relative contribution to the model output of various driver variables/fuel sources. As such, the sensitivities displayed are very similar to those for the driver variables themselves, discussed in the previous section. In this case, the residential fuel usage contributions are combined with the corresponding commercial/institutional usage. The mathematical difference between these sensitivities and those of the previous discussion is that the previous sensitivities are reduced by effects of pollution abatement. Overall this reduction is very slight, as was also evident in the determination of sensitivities to ERATIO. As before, no dramatic changes in distribution are projected through time for any of the significant contributors to emission.

Table 8. Sensitivities of National Pollutional Totals with Respect to PRMIDR*

Sensitivities of National Pollution Totals with respect to PRMIDR. This parameter has the effect of listing the fraction of total pollution driven by particular blocks of driver variables as defined by index to the variable DRIVER. Sensitivities calculated to be identically zero are shown as dashes (--).

DRIVER BLOCK:	(1) Gasoline Sales	(2) Total Pop.	(3) Rural Pop.	(4) Forest Area	(5) Coal	(6) Resid. Oil	(7) Distil. Oil	(8) Nat Gas	(9) Wood	(10) LPG	(11) Compo-ite	(12) Constant	Total
SOx Emissions													
1980	--	0.0262	0.0098	0.0087	0.2240	0.4390	0.2870	0.0032	8.7E-04	7.9E-05	3.8E-04	6.2E-04	0.9998
1985	--	0.0275	0.0100	0.0086	0.2590	0.4300	0.2600	0.0030	9.5E-04	7.5E-05	3.9E-04	6.1E-04	1.0001
1990	--	0.0260	0.0093	0.0077	0.2160	0.4690	0.2670	0.0028	8.8E-04	6.8E-05	3.8E-04	5.4E-04	0.9996
1995	--	0.0253	0.0089	0.0071	0.1880	0.5020	0.2640	0.0027	8.2E-04	6.4E-05	3.8E-04	5.1E-04	0.9998
2000	--	0.0263	0.0091	0.0071	0.1760	0.5170	0.2600	0.0026	8.6E-04	6.5E-05	3.8E-04	5.0E-04	1.0000
2010	--	0.0307	0.0104	0.0077	0.1680	0.5230	0.2560	0.0027	1.0E-03	7.2E-05	3.8E-04	5.5E-04	1.0005
2020	--	0.0365	0.0123	0.0087	0.1700	0.5070	0.2600	0.0030	1.2E-03	8.4E-05	3.7E-04	6.2E-04	0.9998
2030	--	0.0417	0.0141	0.0097	0.1680	0.4890	0.2720	0.0032	1.4E-03	9.6E-05	3.6E-04	6.9E-04	1.0002
NOx Emissions													
1980	--	0.0371	0.0595	0.2130	0.0420	0.1120	0.1490	0.3690	0.0074	5.9E-05	8.5E-04	0.0107	1.0006
1985	--	0.0380	0.0617	0.2110	0.0507	0.1060	0.1360	0.3760	0.0083	5.6E-05	8.6E-04	0.0106	0.9992
1990	--	0.0369	0.0599	0.1970	0.0448	0.1210	0.1460	0.3750	0.0081	5.1E-05	8.1E-04	0.0099	0.9994
1995	--	0.0366	0.0597	0.1900	0.0408	0.1330	0.1500	0.3720	0.0079	4.8E-05	8.3E-04	0.0096	1.0004
2000	--	0.0373	0.0610	0.1900	0.0385	0.1360	0.1460	0.3720	0.0082	4.7E-05	8.2E-04	0.0095	0.9994
2010	--	0.0400	0.0659	0.1950	0.0356	0.1300	0.1370	0.3770	0.0094	4.7E-05	7.7E-04	0.0098	1.0005
2020	--	0.0433	0.0713	0.2010	0.0333	0.1140	0.1270	0.3890	0.0100	4.7E-05	6.8E-04	0.0101	0.9997
2030	--	0.0450	0.0742	0.2040	0.0305	0.1000	0.1210	0.4040	0.0102	4.6E-05	6.0E-04	0.0102	0.9997

*This parameter has the effect of listing the fraction of total pollution driven by particular blocks of driver variables as defined by index to the variable DRIVER. Sensitivities calculated to be identically zero are shown as dashes (--).

Table 8. (Cont'd)

DRIVER BLOCK:	(1) Gasoline Sales	(2) Total Pop.	(3) Rural Pop.	(4) Forest Area	(5) Coal	(6) Resid. Oil	(7) Distil. Oil	(8) Nat Gas	(9) Wood	(10) LPG	(11) Compo-ite	(12) Constant	Total
CO Emissions													
1980	--	0.1140	0.0901	0.6240	0.0088	0.0012	0.0035	0.0066	0.1160	--	0.0010	0.0348	0.9999
1985	--	0.1160	0.0916	0.6090	0.0091	0.0011	0.0031	0.0067	0.1280	--	0.0010	0.0339	0.9995
1990	--	0.1200	0.0939	0.6000	0.0080	0.0014	0.0035	0.0070	0.1320	--	0.0011	0.0335	1.0003
1995	--	0.1230	0.0960	0.5940	0.0070	0.0015	0.0036	0.0072	0.1330	--	0.0012	0.0331	0.9996
2000	--	0.1250	0.0975	0.5880	0.0062	0.0016	0.0035	0.0071	0.1370	---	0.0012	0.0327	0.9998
2010	--	0.1290	0.0997	0.5730	0.0049	0.0014	0.0031	0.0068	0.1500	--	0.0011	0.0319	1.0009
2020	--	0.1330	0.1030	0.5650	0.0039	0.0012	0.0028	0.0067	0.1520	--	0.0010	0.0315	1.0001
2030	--	0.1360	0.1050	0.5610	0.0032	0.0010	0.0026	0.0069	0.1520	--	0.0008	0.0313	0.9998
TSP Emissions													
1980	--	0.1170	0.1290	0.5350	0.0279	0.0323	0.0141	0.0114	0.0997	1.3E-05	1.6E-04	0.0326	0.9992
1985	--	0.1200	0.1320	0.5240	0.0325	0.0270	0.0120	0.0103	0.1100	1.3E-05	1.6E-04	0.0319	0.9999
1990	--	0.1230	0.1340	0.5130	0.0297	0.0314	0.0135	0.0106	0.1130	1.3E-05	1.7E-04	0.0313	0.9997
1995	--	0.1260	0.1370	0.5070	0.0272	0.0340	0.0141	0.0107	0.1130	1.3E-05	1.9E-04	0.0309	1.0001
2000	--	0.1280	0.1390	0.5020	0.0252	0.0338	0.0137	0.0104	0.1170	1.3E-05	1.9E-04	0.0306	0.9999
2010	--	0.1320	0.1430	0.4920	0.0216	0.0299	0.0121	0.0096	0.1280	1.3E-05	1.7E-04	0.0300	0.9983
2020	--	0.1370	0.1490	0.4890	0.0189	0.0250	0.0107	0.0089	0.1320	1.3E-05	1.5E-04	0.0298	1.0004
2030	--	0.1410	0.1530	0.4880	0.0168	0.0216	0.0100	0.0085	0.1320	1.3E-05	1.3E-04	0.0297	1.0007
VOC Emissions													
1980	0.0956	0.6400	0.1350	0.1170	1.1E-03	2.2E-04	5.2E-04	0.0021	0.0013	--	3.3E-04	0.0071	1.0002
1985	0.0678	0.6530	0.1450	0.1210	1.2E-03	2.1E-04	5.0E-04	0.0023	0.0015	--	3.8E-04	0.0074	1.0002
1990	0.0536	0.6640	0.1490	0.1200	1.0E-03	2.6E-04	5.7E-04	0.0025	0.0016	--	3.9E-04	0.0073	1.0001
1995	0.0508	0.6690	0.1500	0.1170	8.9E-04	2.8E-04	5.9E-04	0.0025	0.0015	--	4.3E-04	0.0071	1.0001
2000	0.0514	0.6710	0.1500	0.1140	7.8E-04	2.9E-04	5.6E-04	0.0025	0.0015	--	4.3E-04	0.0070	0.9994
2010	0.0523	0.6750	0.1500	0.1100	6.0E-04	2.5E-04	4.9E-04	0.0023	0.0016	--	3.9E-04	0.0067	0.9996
2020	0.0507	0.6810	0.1520	0.1050	4.7E-04	2.1E-04	4.3E-04	0.0023	0.0016	--	3.2E-04	0.0064	1.0004
2030	0.0516	0.6820	0.1520	0.1030	3.7E-04	1.7E-04	4.0E-04	0.0023	0.0015	--	2.8E-04	0.0062	0.9999

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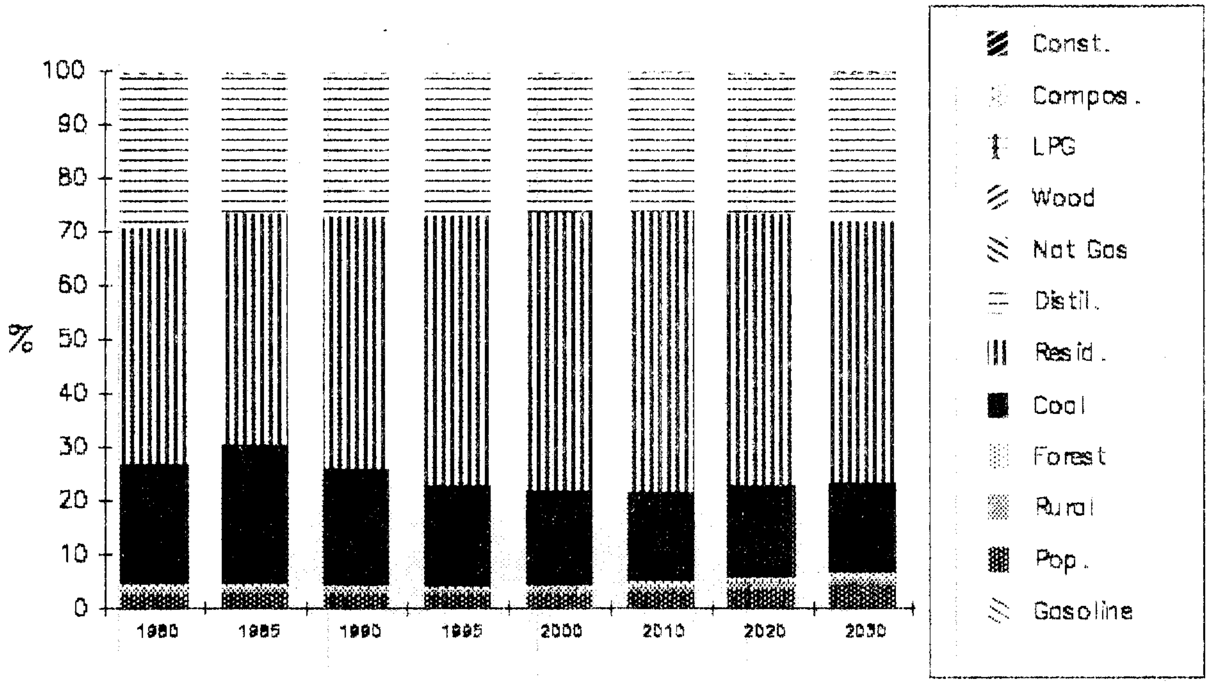

Fig. 17. Sensitivities of SOx national total emission to source quantities categorized by driver block.

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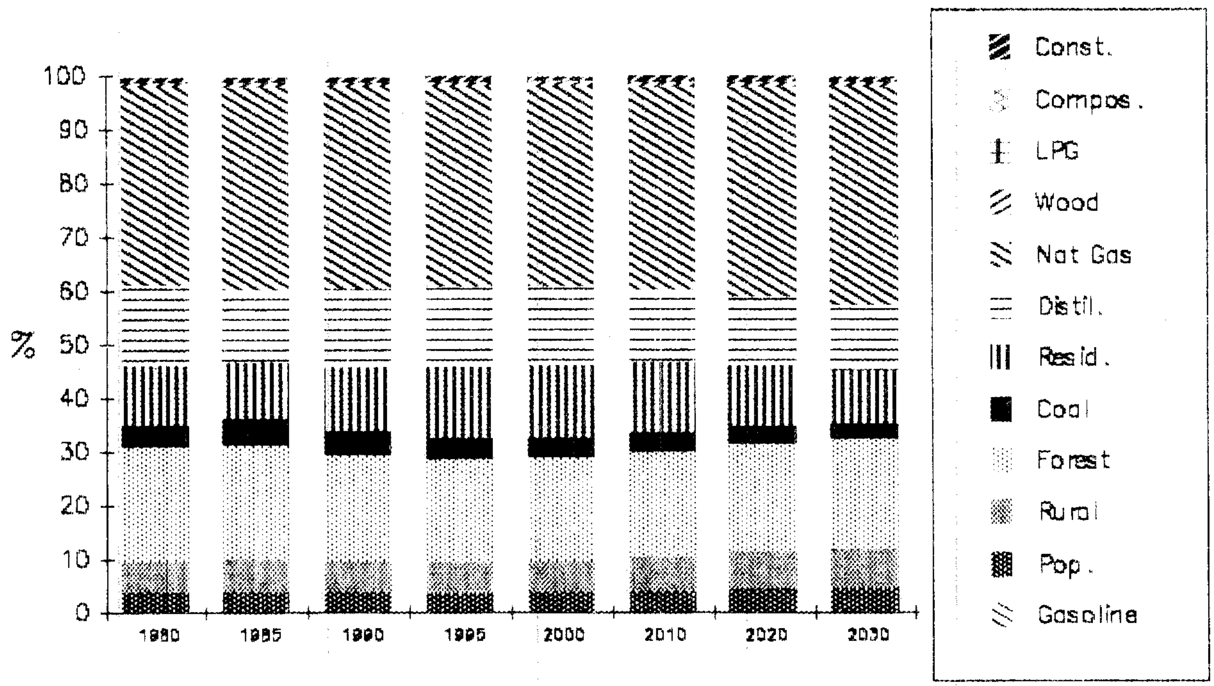

Fig. 18. Sensitivities of NOx national total emission to source quantities categorized by driver block.

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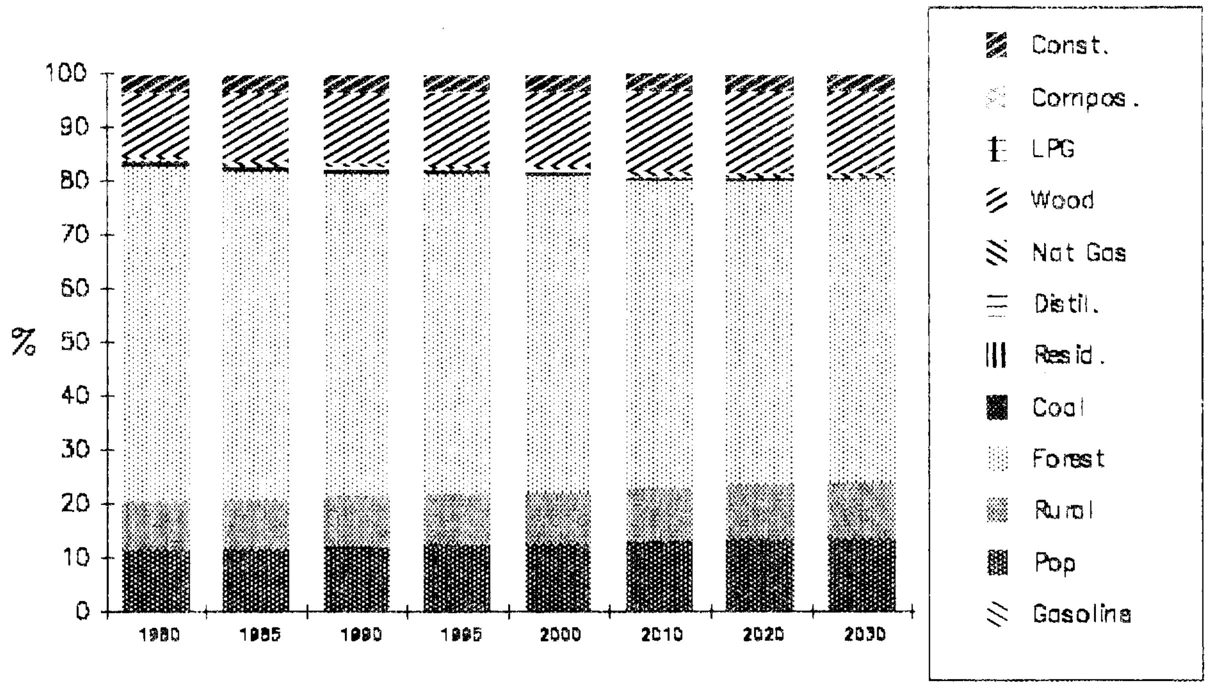

Fig. 19. Sensitivities of CO national total emission of source quantities categorized by driver block.

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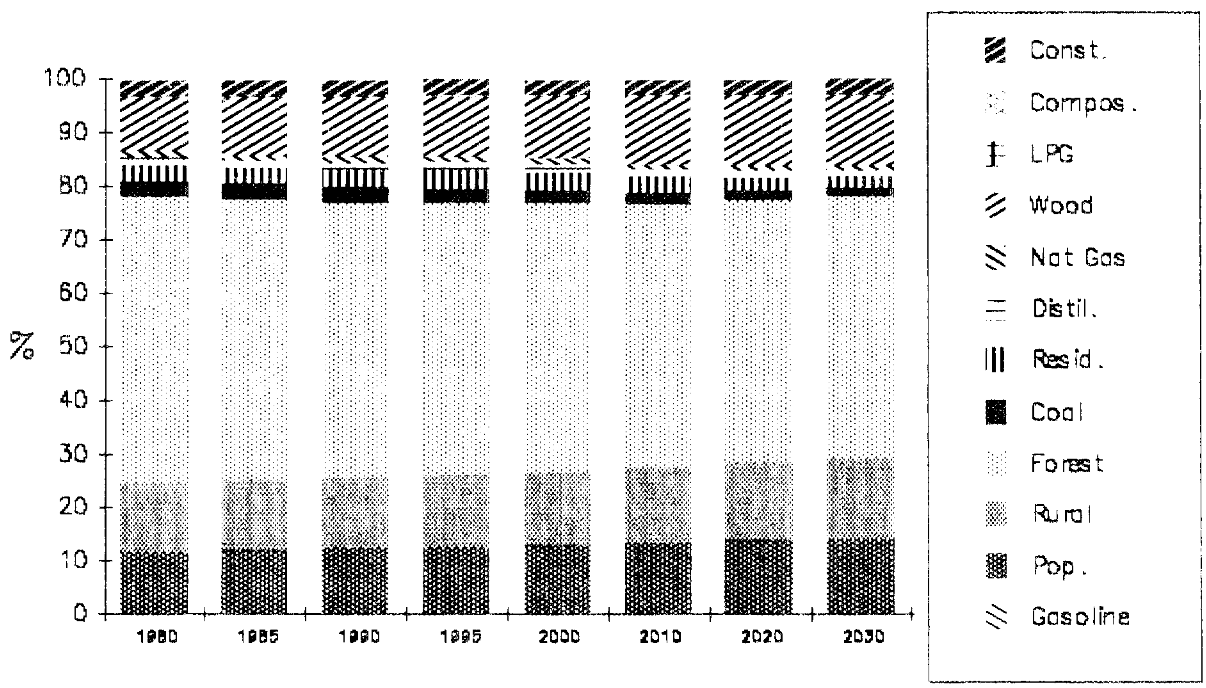

Fig. 20. Sensitivities of TSP national total emission to source quantities categorized by driver block.

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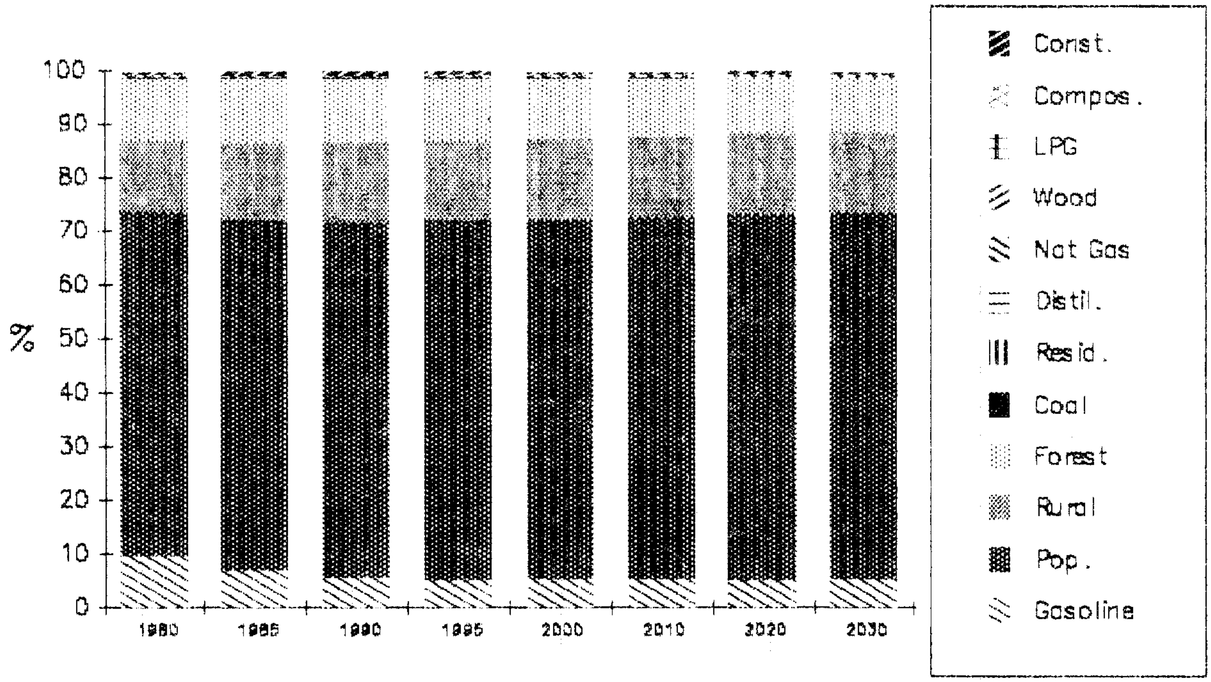

Fig. 21. Sensitivities of VOC national total emission to source quantities categorized by driver block.

SOx emission sensitivities are displayed in Fig. 17. SOx emissions are driven primarily by residual and distillate oil usage, and secondarily by coal usage. Other driver blocks contribute only slightly.

NOx emissions, displayed in Fig. 18, are driven with approximately equal contribution by natural gas usage, distillate/residual oil usage, and geographic driver blocks (primarily forest acreage).

CO and TSP projections (Figs. 19 and 20) have similar patterns of source contributions. About 80% of the contribution of each of these is driven by geographic projections, the largest fraction of which is forest acreage. Wood usage (which is entirely residential) forms a secondary contribution to CO and TSP results; other blocks (e.g. coal and oil usage) make only minor contributions.

For VOC emissions (Fig. 21), the primary determinant (ca. 2/3) is attributed to population and over 90% to the combined geographic driver blocks (population, rural population, and forest acreage). VOC emission projections are the only ones that use the projections of gasoline sales, and these make only a small (ca 5%) contribution to VOC emission projections. The other fuel usage parameters have essentially no influence on the calculated VOC emissions.

6. CONCLUSIONS

Sensitivity analysis of the MODEL6 component of CRESS has been carried out with the aid of an automated sensitivity analysis tool, GRESS. MODEL6 is a computationally straightforward, linear model. Sensitivity analysis results thus tend not to be particularly surprising or revealing. The automated analysis did, however, assist in examining and aggregating the massive quantities of data processed by the model, and in verifying that potential counter-intuitive behavior was not, in fact, taking place. A sensitivity analysis can't, unaided, verify the validity of a model or its input data. This report is not a comprehensive review of MODEL6.

Within the framework of the model design, sensitivities computed have identified the important contributors to projected emissions. Much of this is equivalent to identification of important contributors to subtotals. There are only a few classes of what would ordinarily be regarded as model parameters within MODEL6. Many of the potentially interesting relationships are implicit in the input data to MODEL6. Some such relationships may be created within other modules of CRESS, and thus will be examined in later work, but many potentially sensitive parameters (e.g. population growth rates) are implicit in data imported into the CRESS system as a whole.

Driver variables are the only information imported to MODEL6 from the earlier modules of CRESS. Sensitivities of emissions to driver variables approximate the shares of emission driven by a particular driver parameter. These sensitivities will be useful in propagating sensitivity of parameters in HOME2 and CSEM2 through to emission projections made by MODEL6.

If simplification of either the model or data files is desired, the results of the analyses presented here indicate those elements which are more expendable. It is not clear that there is much to be gained by such a step (the model runs fairly quickly as is), but some possibilities are:

1. VOC emission is already calculated by a separate model. Most of the driver data (the 14 x 49 fuel usage arrays CMIEGY and RESEGY) have virtually no influence on VOC results, and could be dropped from the VOC part of the model in favor of a more general parameter such as population.
2. The VOC model reads in a very large number of data elements to reflect changes in VOC emission factors, but only a relatively small proportion contains actual changes. For example, between 1980 and 1990, the only emission factor changes in the VOCOLD files are for emissions due to "dry-cleaning" related categories. The data files could be simplified if there is no intent to update input parameters.
3. In both VOC and SOx models, certain categories of input parameters are unused and presumably could be dropped. For example, energy usage due to electricity, residential LPG, and commercial wood usage are not used by the model.

Again, these changes are not necessary, and may even be undesirable from the standpoint of completeness or cost effectiveness of such a change.

Some low values for sensitivities may be the result of incomplete data rather than mathematical insensitivity. Emission factor variables in the model equations shouldn't be discarded just because their computed sensitivity for this reference case has proven to be small. In the SOx model, most of the potential sensitivity of the emission factor ratio (E), the equipment replacement rate (R) and the fraction subject to new emission levels (A) is erased by choice of the value (A=0) for those categories where no change in emission factors is anticipated. Should the data be updated, these parameters could become much more important than they are at present. In addition, projected emission factors for the future are likely to be fairly uncertain. The letter describing the model [Ref 1] implies that the projected emission factors are equal to projected regulatory mandates. Cases could be made for actual emission factors being either higher or lower than those anticipated.

Only a highly aggregated subset of the model results have been examined in this analysis. Many alternative sensitivities could have been examined. Some may be indicated by analysis of the earlier modules in CRESS (which create the Driver variable arrays); if so further analysis may be conducted on MODEL6 at that time.

ACKNOWLEDGEMENT

I would like to offer sincere thanks to J. E. Horwedel for his helpfulness and responsiveness in upgrading GRESS to accommodate multi-dimensioned arrays. Without that enhancement to GRESS, this work would not have been feasible in the required time-frame.

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