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EFFECT OF DIESEL VEHICLES ON VISIBILITY IN CALIFORNIA

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ABSTRACT

The effect of diesel vehicle elemental carbon on visibility in California is estimated for 1980 and projected to the early 1990's. An emissions budget model indicates that heavy-duty diesel trucks contributed nearly one-half of statewide elemental carbon emissions in 1980 and about 5-15% of statewide light extinction (visibility reduction). A lead tracer model indicates somewhat larger extinction contributions from heavy-duty diesel trucks, about 5 to 25% statewide in 1980. Even greater visibility impacts (too large to be reasonable) are suggested by a CO tracer model. Because of increased diesel usage -- due to both overall traffic growth and partial conversion of the vehicle fleet to diesels (10% of light-duty, 20% of medium-duty, and 60% of currently gasoline heavy-duty) -- visibility in California is projected to decrease significantly (about 9 to 35%) from 1980 to the early 1990's under a "no control" scenario. Diesel vehicle elemental carbon would then contribute 13 to 40% of statewide visibility reduction. Even in the early 1990's, heavy-duty trucks would account for about three-fourths of the emissions from the entire diesel fleet. The most uncertain aspect of the conclusions is the overall magnitude of the visibility effect predicted by the emission budget and Pb tracer models. The partition of visibility impacts among light-, medium-, and heavy-duty vehicles is more definite. The conclusions are rather insensitive to reasonable changes in the assumptions regarding emission factors, traffic growth, and dieselization percentages. The findings indicate that, in order to be effective in protecting visibility, the current California standards for light- and medium-duty vehicles would have to be extended to include regulations for heavy-duty trucks.

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INTRODUCTION

In 1982 the California Air Resources Board sponsored a study to investigate the potential impact of light-duty diesels on visibility in California. That study indicated that light-duty diesels could have severe effects on visibility (Trijonis 1982a). For the scenario of "likely dieselization" (20% of the light-duty fleet) and "no-control" (0.4 gm/mile particulate emission rate), a 10 to 30% decrease in statewide visibility was forecasted for the early 1990's.

Discussions of that study as well as recent developments in diesel sales suggested areas where the investigation could be expanded and revised. For one, it was considered worthwhile to check the lead tracer modeling results of the initial study with a carbon monoxide tracer model. Second, the initial study pointed out a critical need to investigate medium- and heavy-duty diesel trucks as well as light-duty diesels. Third, it was of interest to examine current impacts from heavy-duty diesel trucks as well as future impacts from the expanded diesel fleet. Finally, very recent projections indicated that percentage dieselization of the light-duty fleet was likely to be significantly less than originally anticipated. Accordingly, the Air Resources Board funded a project to expand and improve upon the prior study. This paper is the final report for the follow-up project.

The follow-up study indeed resulted in some important new conclusions. For one, our revised estimates of future visibility impacts from light-duty diesels are less than half those in the prior study, basically because it is now projected that dieselization of the light-duty fleet is likely to be around 10% rather than 20%. The visibility impact of the total diesel vehicle fleet, however, is found to be very large. As demonstrated in the remainder of this paper, our calculations indicate that elemental carbon emissions from heavy-duty diesel trucks contribute significantly (~5-20%) to current visibility reduction in California, and that elemental carbon emissions from an expanded diesel fleet will contribute greatly (~13-40%) to future visibility reduction in the state.

EMISSION BUDGET MODEL OF CURRENT DIESEL TRUCK IMPACTS

Variations in regional visibility are basically governed by the concentration and nature of ambient particles, with gaseous NO_2 also playing a minor role. Particles in the air reduce visibility by scattering and absorbing light. The most important particles with respect to light scattering are those in the optically critical size range of 0.1 to 1.0 micron diameter; secondary (chemical reaction formed) particles, such as sulfates and nitrates, are especially significant in this regard because they tend to accumulate in the optically critical size range and because they can attract substantial amounts of water vapor into the aerosol phase. Elemental carbon is by far the most important type of light absorbing particle. In light of the above considerations, the air pollution emissions of greatest relevance to visibility are hydrocarbons (precursor of secondary organic particles), nitrogen oxides (gaseous NO_2 and precursor of nitrate particles), sulfur oxides (precursor of sulfate particles), and primary particulate matter (especially elemental carbon).

The first row of Table 1 lists the contribution of heavy-duty diesel trucks to statewide totals of visibility-related emissions during 1980. This compilation is based on the references presented in the first footnote to the table. The most important general references are the California ARB statewide inventories for HC, NO_x, SO_x, and TSP (ARB 1982; Yotter 1983) and the elemental carbon inventory for Los Angeles compiled by Cass et al. (1982). The most critical assumption concerns the elemental carbon emission rate from heavy-duty diesels. Based on a thorough review of the literature, we have assumed that, on the average, heavy-duty diesels currently emit 1.8 gram/mile of particulate matter, seventy percent of which is in the form of elemental carbon.

The first row of Table 1 demonstrates that heavy-duty diesels are a significant but not a dominant source category for HC, NO_x, SO_x or TSP. In the statewide inventory, heavy-duty diesels currently contribute about ½%

TABLE 1 ESTIMATED CONTRIBUTION OF HEAVY-DUTY DIESELS TO CURRENT EMISSIONS AND VISIBILITY REDUCTION IN CALIFORNIA

	GASEOUS EMISSIONS			PARTICULATE EMISSIONS	
	HC	NO_x	SO_x	Total	Elemental Carbon
Fraction of statewide emissions from heavy-duty diesels in 1980:*	½%	13%	6%	½%	40-50%
Approximate contribution of emission type to current haze levels at various California locations:**	5-20%	10-40%	15-65%	†	10-30%
Approximate contribution of heavy-duty diesel emissions to current visibility reduction in California.	<0.1%	1-5%	1-4%	†	5-15%

*Based on ARB (1980, 1981, 1982), Yotter (1982, 1983), Summerfield (1982, 1983), Cass et al. (1982), Williams (1981, 1982, 1983), Williams and Chock (1979), General Motors (1982a), Pierson (1979, 1982, 1983), Pierson and Brachaczek (1976, 1983), Kittleson (1982, 1983), Baines et al. (1979), Ingalls and Bradow (1981), Hare and Black (1981), NRC (1981), and EPA (1981).

**Based on Trijonis et al. (1982) as well as on a general visibility literature review.

†The visibility effects of diesel particles other than elemental carbon are negligible compared to the effects of diesel elemental carbon.

of HC, 13% of NO_x, 6% of SO_2, and ½% of TSP. With respect to elemental carbon, however, heavy-duty diesel vehicles are the predominant source, contributing about 40 to 50% of total elemental carbon emissions. Incidentally, the specific estimate that we obtained for statewide elemental carbon emissions from diesel trucks in 1980 is 26.2 tons per day.

The second row of Table 1 indicates the approximate contribution of each type of emission to current light extinction (haze) levels in California. By multiplying together the first and second rows of the table, we obtain an estimate of the fraction of statewide visibility reduction produced by heavy-duty diesels via each exhaust component. The estimated contribution to statewide haze levels is currently very small for diesel HC (less than 0.1%), moderately small for diesel NO_x ($\sim$1-5%) and diesel SO_x ($\sim$1-4%), but rather significant for diesel elemental carbon ($\sim$5-15%). The remainder of this paper will focus on the visibility effects produced specifically by the elemental carbon from diesel road vehicles.

LEAD AND CARBON MONOXIDE TRACER MODELS OF CURRENT DIESEL TRUCK IMPACTS

Because of uncertainties in the emission inventory data for elemental carbon (Cass et al. 1982), and because of uncertainties in the contribution of elemental carbon to current visibility reduction (Trijonis et al. 1982), the estimated visibility impacts from diesel elemental carbon in Table 1 must be regarded as rather approximate. Faced with these uncertainties, it is worthwhile to examine alternative methods for calculating diesel visibility impacts. This section considers two alternative methods -- a lead tracer model and a carbon monoxide tracer model. Actually, we will focus mainly on the Pb tracer model, with the CO tracer model used to check the Pb tracer results.

Appendix A presents a detailed discussion of the emission input data for our Pb tracer model. The emission data are based on a comprehensive assessment of lead emissions from light-, medium-, and heavy-duty vehicles, taking into account long-term trends in the percentage of non-catalyst (leaded-full) traffic and yearly fluctuations in the average Pb content of leaded gasoline. Stationary source lead emissions are also included in the emissions assessment. In toto, the emission data consist of statewide lead emission inventories as a function of calendar year.

Basically, the Pb tracer model estimates diesel elemental carbon concentrations according to the equation:

$$[C]_{jy} = \frac{EC_y}{EPb_x} \cdot [Pb]_{jx}, \qquad (1)$$

where

$[C]_{jy}$ = annual mean elemental carbon concentration from diesel vehicles at site "j" in year "y" (y=1980 for current impacts),

EC_y = statewide total elemental carbon emissions from diesel vehicles in year "y",

EPb_x = statewide total lead emissions from all sources in year "x",

and $[Pb]_{jx}$ = annual mean lead concentration at site "j" in year "x".

Once elemental carbon concentrations from diesels have been estimated by Equation (1), the computation of visibility impacts is straightforward. The extinction efficiency for fine elemental carbon is rather well known: 12 ± 3 m^2/g or $.12 \pm .03$ $(10^{-4}m^{-1})/(\mu g/m^3)$, approximately 9 m^2/g absorption and 3 m^2/g scattering, (Wolff et al. 1980; Wolff 1981; Waggoner and Weiss 1980; Groblicki et al. 1981; Conklin et al. 1981; Scherrer et al. 1981; Pierson 1979; Klausmeier 1981; NRC 1981; Kittelson 1982). The light extinction due to diesel carbon is simply the product of the elemental carbon concentration, $[C]_{jy}$, and the extinction efficiency, 12 m^2/g. To compute percentage contributions of diesels to total light extinction, we use the baseline visual ranges given in Figure 1 and relate extinction to visual range according to the formula:

$$\text{extinction} = 3.0/\text{visual range}. \qquad (2)$$

As discussed by Trijonis et al. (1982), the proportionality constant of 3.0 in this equation is appropriate when using airport visibility data (as used in Figure 1). Furthermore, as noted previously (Trijonis 1982a), the visibilities of Figure 1 should continue to represent baseline visibilities through the 1990's because California visibility is likely to change very little in the future without increased dieselization.

The way we have chosen to compare the Pb tracer model with a CO tracer model is to predict annual mean CO concentrations using the Pb tracer model

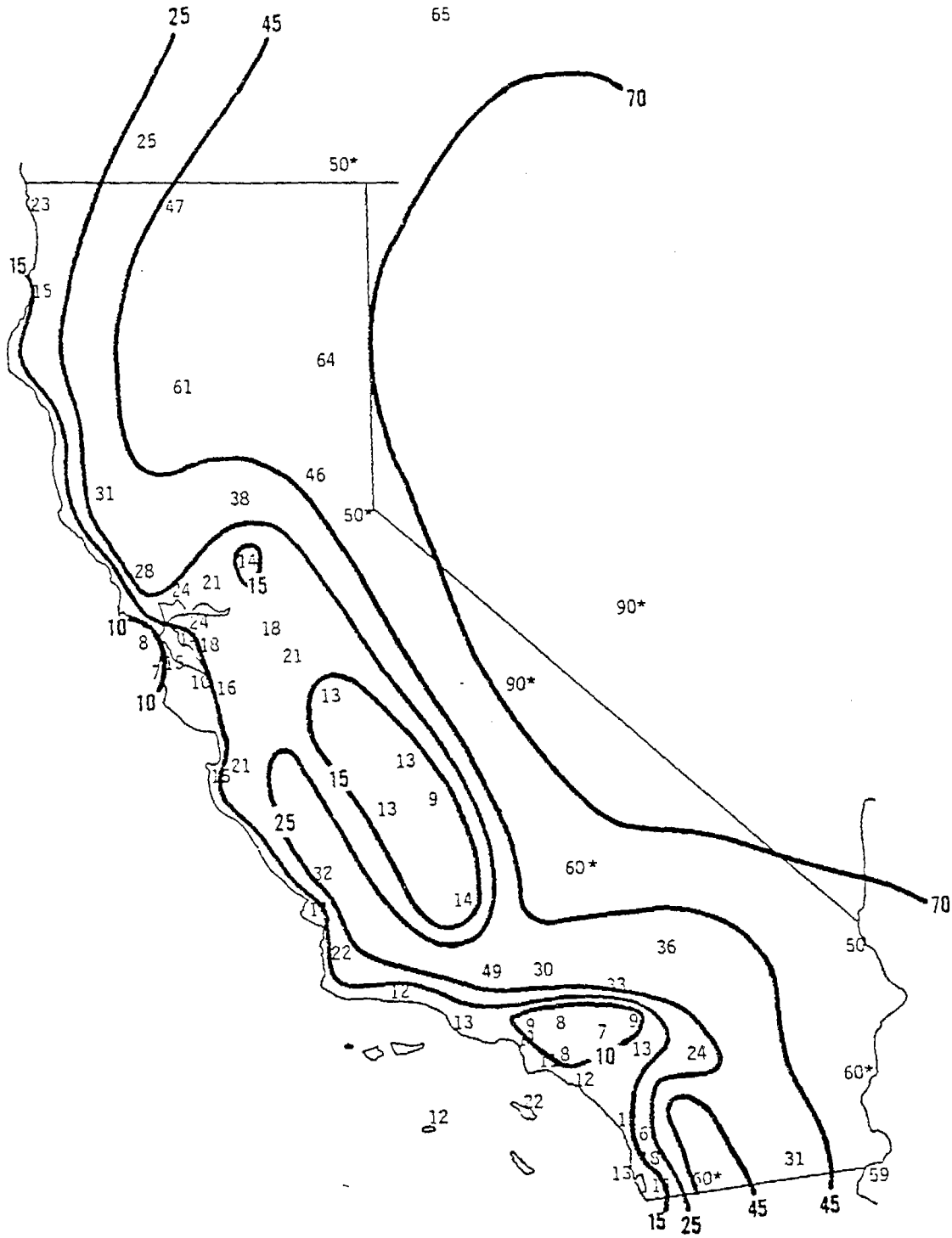

Figure 1 Median annual 1 PM visibilities (in miles) and visibility isopleths for California, 1974-1976.

and statewide CO emissions data as reported in the California state inventories (ARB 1982; Yotter 1982, 1983), and then to test these predictions against actual CO concentrations. Figure 2 shows the results of this test for 166 site-years of data (all site-years in California from 1976 through 1980 with at least 30 days of Hi-Vol Pb data and at least 7500 hours of nondispersive infrared CO data).* Although the correlation between the predicted and actual CO data is fair, R = 0.66, there is an obvious bias in the sense that the Pb tracer model underpredicts ambient CO concentrations, typically by a factor of 1.0 to 2.5.** This implies that a CO tracer model would generally predict elemental carbon concentrations about 1.0 to 2.5 times greater than predicted by the Pb tracer model.

The reason for the disagreement between the Pb and CO tracer models is very puzzling. The possibility of biases in either the emissions inventory data or the ambient data have been discussed with ARB personnel (Cackette 1983; Crowe 1983), but no plausible explanation has been identified.

The results of the carbon monoxide test of the Pb tracer model have been examined within individual air basins. Generally, the Pb tracer model underpredicts ambient CO in all parts of California with one notable exception -- the Central Valley. As illustrated by the open dots in Figure 2, the Pb tracer model tends to overpredict CO somewhat in the Central Valley. The explanation is that gasoline in the Central Valley contains unusually high amounts of lead because the Central Valley is serviced by smaller refiners who are permitted to use higher lead contents (Crowe 1983). Later, we will adjust the Pb tracer model in the Central Valley in order to make the model consistent throughout California.

It should be noted that both the Pb and CO tracer models are likely to overestimate visibility impacts because the tracer (and elemental carbon) concentrations at ground-level monitors are likely to be somewhat greater

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*We did not include flame ionization CO data in this study because such data are considered inaccurate (Crowe 1983).

**The annual means of CO and Pb used for Figure 2 are not a perfect match in the sense that CO is measured every day while Pb is sampled only about 30-60 days per year. This mismatch might account for some of the scatter observed in Figure 2, but it would not produce any general biases.

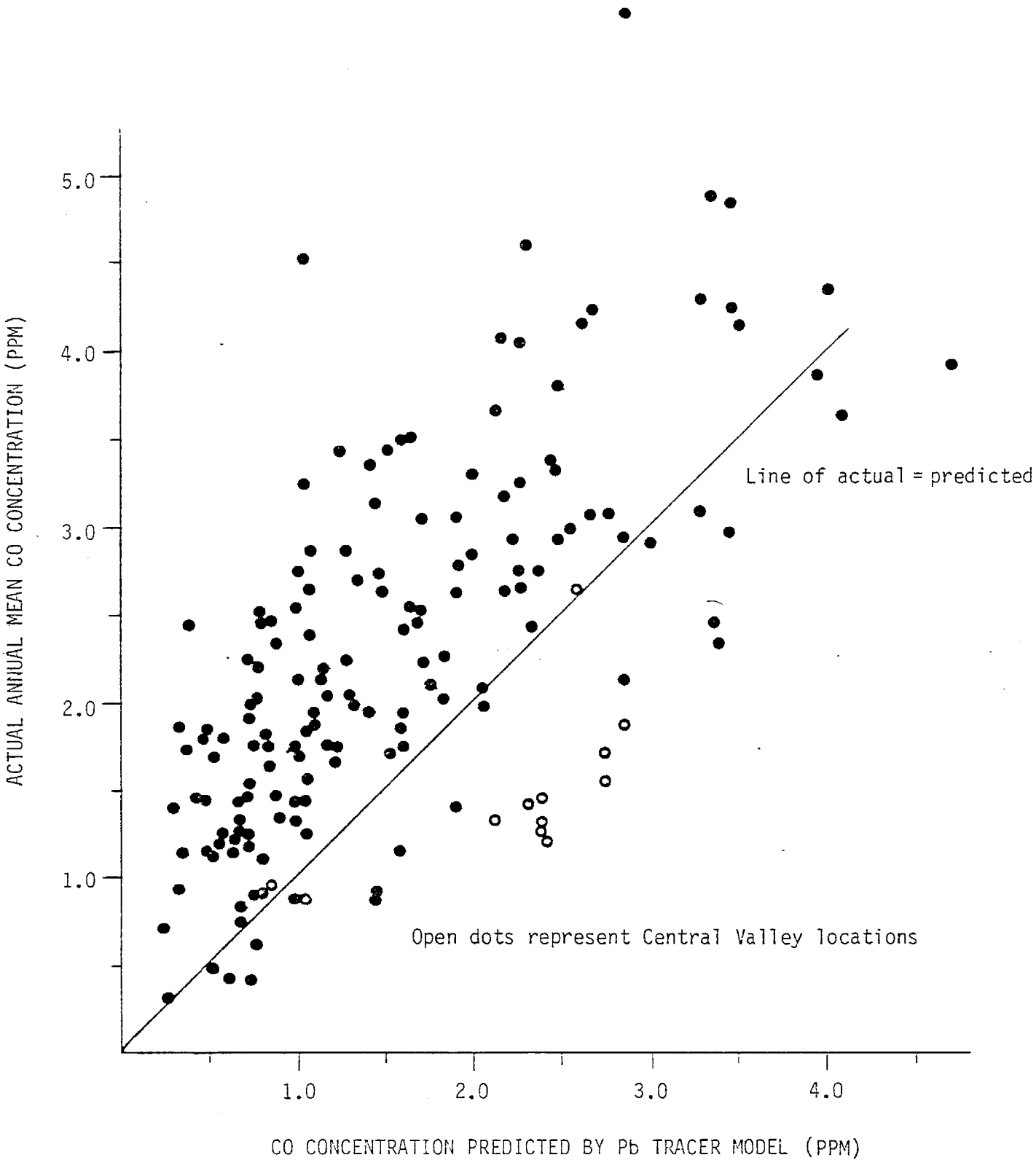

Figure 2 Comparison of actual CO concentrations against predictions by a Pb tracer model.

than the tracer (and elemental carbon) concentrations averaged over the entire line of sight. It is difficult to determine the exact magnitude of this potential error, but some three-dimensional field studies suggest that it should only be about 10 to 20% (Blumenthal 1982), assuming a horizontal sight path and assuming that the ground monitor is not dominated by local traffic sources. The error is likely to be greater for nonurban locations than for urban locations because the ground monitor is more likely to be sited relatively nearer to traffic sources in the former case (i.e. the monitor may be located in a small town surrounded by relatively traffic-free areas). A very approximate adjustment will be made later for this bias in the Pb tracer model.

Because the Pb tracer model can be applied to data from many monitoring sites, one might expect it to be a straightforward task to obtain the entire geographical pattern of current diesel impacts in California. This is not the case, however, because there are strong geographical biases in the state-wide Pb tracer model as represented by Equation (1). Specifically, the ratio of heavy-duty diesel traffic to leaded-vehicle traffic -- and consequently the ratio of diesel elemental carbon emissions to lead emissions -- varies by as much as a factor of three among California air basins and by even larger factors among smaller subareas of California (ARB 1982). Thus, the Pb tracer model would have to be greatly refined geographically before it could be considered accurate in a spatially resolved sense.

In light of the limitations discussed in the last three paragraphs, the following adjustments and procedures will be followed in applying the Pb tracer model:

- Because of the unusual gasoline lead content in the Central Valley, the Pb tracer model predictions will be reduced by one-half in the southern Central Valley and by one-third in the northern Central Valley.
- Because the Lennox site in southern California is known to be severely influenced by local traffic, it will be omitted from the study. As an approximate way to account for line-of-sight concentration biases at other locations, we will reduce the Pb tracer predictions by a factor of 1.2.

- The geographical pattern of current diesel impacts will not be considered. Rather, we will attempt only to estimate the general magnitude of statewide visibility impacts.

It should be stressed that the two quantitative adjustments are both in the direction of reducing the estimated visibility impacts from heavy-duty diesels.

The Pb tracer model has been applied to ambient Pb concentration data for the 83 sites illustrated in Figure 3. Calculations have been made at each site for every year of available Pb data from 1976 to 1980. Because traffic levels, the percentage of non-catalyst VMT, and gasoline lead contents vary considerably from 1976 to 1980, the lead emission factor in Equation (1) changes greatly from year to year. It is very encouraging that approximately the same elemental carbon concentration due to heavy-duty diesels was estimated at each site for the predictions based on various years of Pb data.

Figure 4 presents a histogram showing the distribution of estimated visibility impacts for the 83 study sites. The impacts are specified in terms of the percent contribution by heavy-duty diesels to visibility reduction (light extinction) in 1980. The (adjusted) Pb tracer model indicates that heavy-duty diesels currently account for about 5 to 25% of visibility reduction in California, with an average contribution of 14% over the 83 study sites.

To summarize, we have now considered three alternative methods of determining current visibility effects from heavy-duty trucks. The emission budget model indicates that heavy-duty diesel elemental carbon accounts for about 5 to 15% of visibility reduction statewide. A modified Pb tracer model suggests about 5 to 25% contributions from heavy-duty diesels. A CO tracer model would indicate about 10 to 50%. These last results from the CO tracer model actually seem highly unreasonable in light of the findings from numerous visibility studies conducted in California and elsewhere (Hidy et al. 1974; White and Roberts 1977; Cass 1979; EPA 1979; Trijonis 1980, 1982b; Trijonis et al. 1982; Groblicki et al. 1981; Ouimette and Flagan 1982). Later, we will average the results of the emission budget model and Pb tracer model and refer to a 5 to 20% contribution to visibility reduction from current heavy-duty trucks.

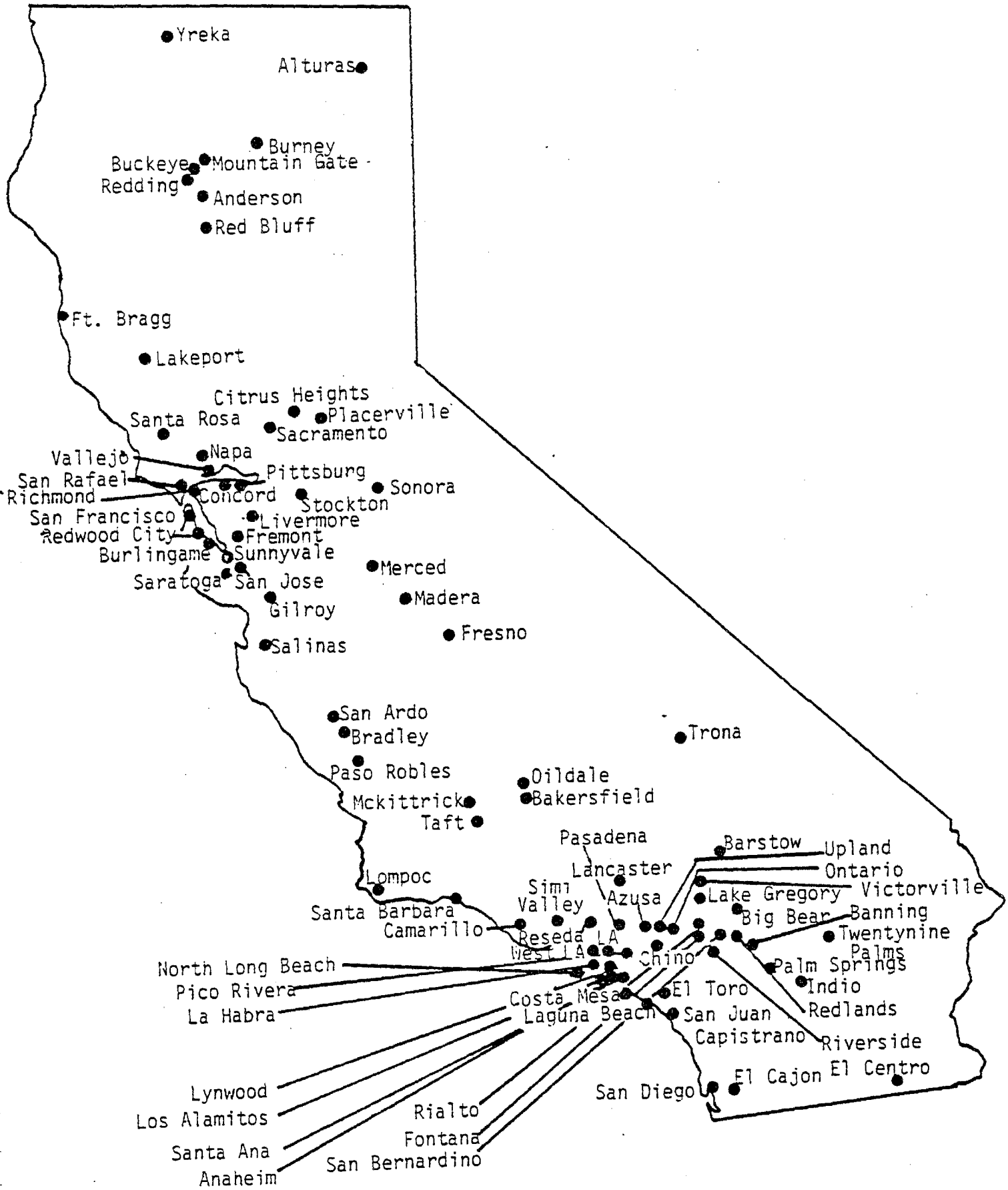

Figure 3. Monitoring sites used for the Pb-tracer model.

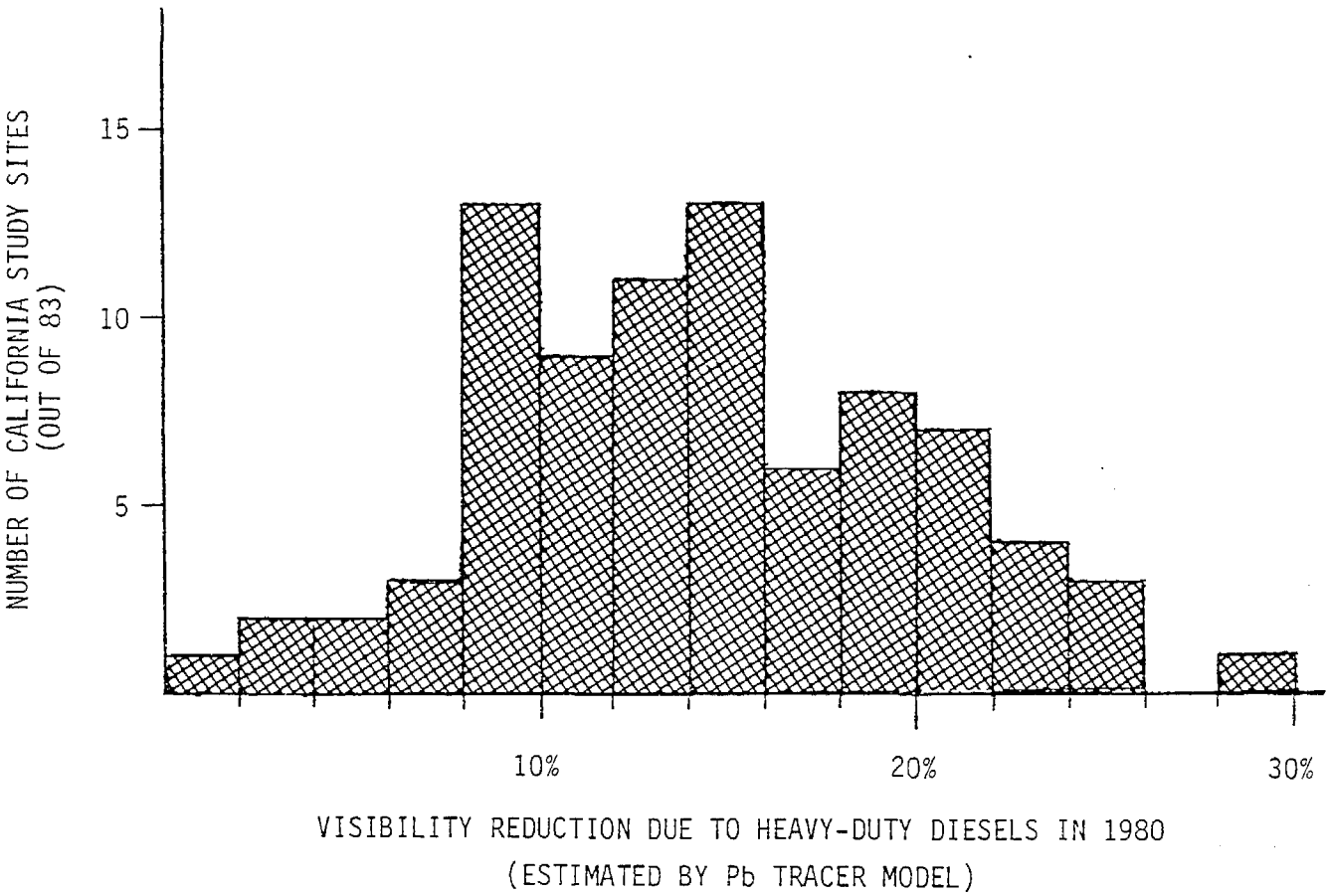

Figure 4 Frequency distribution among California sites of percentage visibility reduction from heavy-duty diesels, as estimated by a lead tracer model.

SCENARIOS OF FUTURE DIESEL USAGE

Table 2 summarizes our assumptions regarding future diesel use in California. The most important references for Table 2 are the California Energy Commission (CEC 1983), the California Air Resources Board (Yotter 1982, 1983), and General Motors documents (GM 1982a,b). Basically, it is assumed that total traffic in California will increase by 2.6% per year from 1980 to the early 1990's (1992-1993), with growth rates relatively higher in the heavier vehicle classes. Furthermore, we have assumed that 10% of the light-duty fleet, 20% of the medium-duty fleet, and 60% of the currently-gas-powered heavy-duty fleet will become diesel powered by the early 1990's.

It should be noted that, in a previous paper dealing with light-duty diesels (Trijonis 1982a), it was assumed that 20% of the light-duty fleet would become diesel powered by the early 1990's. The revised value of 10% reflects more recent studies which indicate that dieselization of the light-duty fleet will be significantly less than originally anticipated.

For the <u>no control</u> scenario, we have adopted the following total particulate emission rates for diesels:*

light-duty cars and trucks . . . . . 0.4 gm/mile,

medium-duty trucks . . . . . 0.7 gm/mile,

heavy-duty-G trucks (smaller type that was gasoline powered in 1980) . . . . . 1.3 gm/mile,

and heavy-duty-D trucks (larger type that was already diesel powered in 1980). . . . . 1.8 gm/mile,

For each vehicle class, we furthermore assume that 70% of the emissions are elemental carbon. The above "no control" emission factors pertain to average emission rates over the life of the vehicle and therefore include deterioration factors. We have assumed emission factors that are slightly in the high side of the typical range found in the literature because of

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*Based on a review of the following references: Summerfield (1982, 1983), Cass et al. (1982), Williams (1981. 1982, 1983), Williams and Chock (1979), General Motors (1982a,b, 1983), Pierson (1979, 1982, 1983), Pierson and Brachaczek (1976, 1983), Kittelson (1982, 1983), Baines et al. (1979), Klausmeier (1981), Ingalls and Bradow (1981), Hare and Black (1981), NRC (1981), and EPA (1981).

TABLE 2 PROTECTION OF DIESEL USAGE IN THE EARLY 1990's

VEHICLE CLASS	TOTAL STATEWIDE VMT BY VEHICLE CLASS		AVERAGE YEARLY VMT GROWTH, 1980 to early 1990's	DIESELIZATION PROJECTION (Fraction of VMT* in vehicle class contributed by diesels)	
	1980	Early 1990's		1980	Early 1990's
Light-duty cars and trucks (GVW* ≤ 6000 lbs)	88.5%	87.0%	2½%	0%	10%
Medium-duty trucks (6000 < GVW ≤ 8500 lbs)	4.2%	4.4%	3%	0%	20%
Heavy-Duty-G trucks (GVW > 8500 lbs, and were gasoline powered type in 1980)	2.7%	3.2%	4%	0%	60%
Heavy-duty-D trucks (GVW > 8500 lbs, and were diesel powered type in 1980)	4.6%	5.4%	4%	100%	100%
All Vehicles	$150 \times 10^9 \frac{\text{miles}}{\text{year}}$	$208 \times 10^9 \frac{\text{miles}}{\text{year}}$	2.6%	4.6%	16.9%
	A		A	B	

* GVW = Gross Vehicle Weight, VMT = Vehicle Miles Travelled

A: These columns based on Yotter (1982, 1983), ARB (1980, 1981), and CEC (1983).

B: These columns based on CEC (1983), Miller (1983), GM (1982a,b), Sacramento Bee (1982), Automotive News (1982), and Ingalls and Bradow (1981).

the critical trade-off between NO_x and particulate emissions from diesels, and because rather stringent NO_x standards are expected in California. In a later section, we will consider other emission rates as part of a sensitivity analysis.

FUTURE DIESEL VISIBILITY IMPACTS

As noted previously, heavy-duty diesel vehicles in California emitted about 26.2 tons per day of elemental carbon in 1980. The resulting contribution to visibility reduction in 1980 was estimated as 5-20%, averaging the results of the emission budget and Pb tracer models. Under the scenario outlined in the previous section, it can be demonstrated that diesel vehicles will emit about 71.8 tons per day of elemental carbon in the early 1990's. Based on these emission changes, the emission budget and Pb tracer models imply that statewide light extinction will increase 9-35% from 1980 to the early 1990's, and that diesel vehicle elemental carbon would then contribute about 13-40% of statewide light extinction. In other words, according to the scenario outlined in the previous section, diesel vehicles will produce a very significant reduction in visibility during the next decade and will become the predominant individual source category affecting visibility in California.

Table 3 disaggregates the projected diesel elemental carbon emissions among the vehicle classes. The salient feature of Table 3 is the continued domination of diesel emissions through the early 1990's by heavy-duty trucks (GVW 8,500 lb). In the early 1990's, heavy-duty vehicles will still contribute three-fourths of the elemental carbon emissions from the diesel fleet. In fact, the ultra-heavy vehicles, the vehicles that are already diesel powered, will alone still account for 60% of the diesel fleet emissions.

Another way of viewing Table 3 is as follows. Of the 71.8 TPD of diesel elemental carbon expected in the early 1990's, 26.2 TPD (37%) already exists with the current 1980 heavy-duty diesel fleet. Another 16.7 TPD (23%) will be added from projected growth in the use of these (ultra) heavy-duty vehicles. About 10.9 TPD (15%) will result from the 60% dieselization of heavy-duty vehicles that are currently gasoline powered. About 15.3 TPD (21%) will arise from the 10% dieselization of light-duty vehicles (GVW 6,000 lbs). Only 2.7 TPD (4%) will come from the 20% dieselization of medium-duty vehicles (6,000 GVW 8,500 lbs).

TABLE 3 STATEWIDE ELEMENTAL CARBON EMISSIONS BY DIESEL VEHICLE CLASS

VEHICLE CLASS	STATEWIDE ELEMENTAL CARBON EMISSIONS TONS PER DAY (PERCENT OF DIESEL TOTAL)	
	1980	Early 1990's
Light-duty cars and trucks	--	15.3 (21%)
Medium-duty trucks	--	2.7 (4%)
Heavy-duty-G trucks (were gasoline powered in 1980)	--	10.9 (15%)
Heavy-duty-D trucks (were diesel powered in 1980)	26.2 (100%)	42.9 (60%)
Total	26.2	71.8

It would be of great interest to examine the geographical distribution (within California) of the above forecasted 9 to 35% increase in haze levels from 1980 to the early 1990's. To formulate a spatially resolved Pb tracer model, however, would require several types of data:

- Spatially resolved information on traffic splits by vehicle class in the late 1970's.
- Spatially resolved data on lead contents in gasoline during the late 1970's.
- Spatially resolved projections of traffic growth by vehicle class.
- Spatially resolved projections of dieselization by vehicle class.

Although information gaps now preclude such an analysis (Yotter 1983), it may be possible to conduct a spatially resolved study with data to become available one or two years hence.

OTHER SCENARIOS

Table 4 summarizes diesel visibility impacts for study scenarios other than the one discussed above. The top part of the table addresses the sensitivity of our conclusions to changes in some of the basic assumptions.

TABLE 4 DIESEL VISIBILITY IMPACTS FOR ALTERNATIVE SCENARIOS

SCENARIOS	STATEWIDE DIESEL ELEMENTAL CARBON EMISSIONS IN EARLY 1990's (TONS/DAY)	PERCENT CONTRIBUTION OF DIESEL ELEMENTAL CARBON TO STATEWIDE VISIBILITY REDUCTION IN EARLY 1990's (AVERAGE OF EMISSION BUDGET AND Pb-TRACER MODELS)
ORIGINAL NO CONTROL SCENARIO	71.8	13-40%
ALTERNATIVE NO CONTROL SCENARIOS		
A.1 Lower uncontrolled particulate emission factors: Assume .3 instead of .4 gm/mi for light-duty, .4 instead of .7 gm/mi for medium-duty, .9 instead of 1.3 gm/mi for heavy-duty-G, and 1.3 instead of 1.8 gm/mi for heavy-duty-D.	51.6	10-32%
A.2 Lower traffic growth: Assume increase in traffic levels from 1980 to early 1990's will be only half as much as now forecasted for each vehicle class.	59.0	11-35%
A.3 Low dieselization: Assume 5% instead of 10% dieselization for light-duty, 10% instead of 20% for medium-duty, and 30% instead of 60% for heavy-duty-G.	57.4	11-34%
CONTROL SCENARIOS		
C.1 Current California Air Resources Board standards for light- and medium-duty diesels: Assume on-road particulate emission rates for light- and medium-duty diesels will average 0.2 gm/mi in the early 1990's.	62.2	11-36%
C.2 Add stringent control of heavy-duty diesels to CARB standards for light- and medium-duty diesels: Assume on-road particulate emission rates will average 0.7 gm/mi for heavy-duty diesels and 0.2 gm/mi for light- and medium-duty diesels in the early 1990's.	31.0	6-22%

The bottom part of the table shows the effect of particulate control strategies for diesel vehicles.

As indicated by the results for the three alternative "no control" scenarios, our conclusions are rather insensitive to reasonable changes in the scenario specifications. For example, assuming lower uncontrolled emission rates (Scenario A.1) would decrease projected fleet emissions in the early 1990's by only 28%. Cutting the assumed traffic growth in half (Scenario A.2) would lower projected emissions by only 18%. Reducing the dieselization percentages in half (Scenario A.3) would decrease projected emissions by only 20%. The basic reason for this insensitivity is because the diesel visibility "problem" stems not from a single factor but from several factors: the inherently high elemental carbon emissions of diesel vehicles; the importance of the existing heavy-duty diesel fleet; the conversion of more light-, medium-, and heavy-duty vehicles to diesel power; and future growth in overall traffic levels. Because none of these individual factors totally predominates, and because one critical factor (emissions from the existing heavy-duty fleet) is already fairly well known, our results are intrinsically insensitive to reasonable changes in the assumptions about single specific factors.

The results of the control strategy analysis show that the recently promulgated California standards for particulate emissions from light- and medium-duty diesels will be marginally effective in protecting California visibility from the diesel-caused deterioration. The current light- and medium-duty emission standards (Scenario C.1)* should reduce elemental carbon emissions by diesel vehicles from the uncontrolled 71.8 tons/day in the early 1990's to 62.2 tons/day. To be really effective in protecting visibility, however, the control program would have to be extended to cover heavy-duty vehicles. Light- and medium-duty diesel particulate emissions of 0.2 gm/mile and heavy-duty emissions of 0.7 gm/mile (Scenario C.2) would,

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*Section 1960.1, Title 13 of the California Administrative Code as amended on 26 August 1982 specifies 50,000 mile particulate exhaust standards for light- and medium-duty diesels of 0.4 gm/mile in 1985, 0.2 gm/mile in 1986, and 0.08 gm/mile in 1989. An on-road, fleet-averaged emission rate of 0.2 gm/mile in the early 1990's seems reasonable, taking into account the phasing of standards, deterioration of emissions, and real-world durability of controls.

in fact, limit diesel elemental carbon emissions to 31.0 tons/day in the early 1990's, and essentially preserve current overall visibility levels. To improve visibility in California would require even stricter standards for light-, medium-, and heavy-duty diesels than those of Scenario C.2.

CONCLUSIONS

A fundamental conclusion of this paper is that -- if the emission budget model and Pb tracer are reliable -- then heavy-duty diesels contribute significantly (~5-20%) to current haze (light extinction) levels in California, and the total diesel fleet will contribute greatly (~13-40%) to future haze levels. Furthermore, because of growth in diesel elemental carbon emissions, overall haze in California will increase by 9-35% from 1980 to the early 1990's under the assumed "no control" scenario. These effects are quite substantial, considering that haze increases (visibility decreases) of 5 to 10% are perceptible by human observers in short-term experiments.

As indicated by the qualifier in the first sentence above, the preceding conclusions are tempered by uncertainties in the emission budget model and the Pb tracer model. Although the emission budget and Pb tracer models are in approximate agreement, and although a carbon monoxide model suggests even higher diesel impacts, we cannot be sure of the rather large magnitude of the projected effects. Further study regarding concentrations and sources of elemental carbon in California should help to resolve the uncertainty.

With respect to other conclusions, there is much more certainty. For current projections of dieselization (10% of light-duty vehicles, 20% of medium-duty trucks, and 60% of heavy-duty-G trucks) and for "no control" conditions, we can be fairly sure that heavy-duty diesels will continue to dominate total fleet emissions, contributing about three-fourths of diesel vehicle elemental carbon in the early 1990's. The policy implication of this finding is obvious -- in order to be effective in protecting visibility, the current California standards for light- and medium-duty vehicles would have to be extended to include emission regulations for heavy-duty trucks. Furthermore, we are secure that all of the conclusions are insensitive to the specific assumptions of the "no control" scenario. That is, the findings

change rather little with reasonable variations in assumed emission factors, traffic growth rates, and dieselization percentages.

It is important to remark that the above analysis does not encompass all of the visibility impacts from diesel vehicles. We have neglected the visibility effects from diesel nitrogen oxides, sulfur oxides, and the non-elemental carbon fraction of particulate matter as well as from the possible catalysis effects of elemental carbon on atmospheric sulfate formation. Furthermore, all of the above calculations pertain only to annual average conditions; for worst-case days or hours, the visibility effects could be significantly higher.

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APPENDIX A

EMISSIONS DATA FOR THE Pb TRACER MODEL

This appendix outlines the emissions data for the Pb tracer model used in this paper. The emissions data consist of statewide lead emission inventories for the years 1976 to 1980. The data sources cited here are listed in the main reference section of the paper.

1. Emission Factors

Suspendible ($\lesssim 20\ \mu m$ in size) lead emission factors in [gm/mile] are assumed to be as follows:

light-duty cars and trucks . . . $0.025\ \{Pb\}_L$,

medium-duty trucks . . . $0.034\ \{Pb\}_M$,

and heavy-duty (gasoline) trucks . . . $0.066\ \{Pb\}_H$,

where $\{Pb\}_i$ is the concentration of Pb in leaded gasoline each year for vehicle type "i". These emission factors are based on a review of the following references: Ter Haar et al. (1972), Habibi (1973), Trijonis et al. (1975), Pierson and Brachaczek (1976), Cass and McRae (1980), Hare and Black (1981), ARB (1980, 1981), Yotter (1982, 1983), and Cass et al. (1982).

2. Pb Content in Leaded Gasoline

Based on DOE (1971-1980), ARB (1980, 1981), Suer et al. (1982), and Cass and McRae (1980), the concentrations of Pb in leaded gasoline were approximately as follows from 1976 to 1980:

Year	Average Pb concentration in leaded gasoline used by light- and medium-duty California vehicles (weighted by yearly usage of regular versus premium gasoline)	Average Pb concentration in leaded gasoline used by heavy-duty California vehicles (regular gasoline only)
1976	2.0 gm/gal	1.6 gm/gal
1977	1.8	1.4
1978	1.5	1.2
1979	1.3	1.0
1980	1.0	0.7

3. Traffic Data

The following yearly traffic data for estimating statewide vehicular Pb emissions are based on ARB (1980, 1981), Yotter (1982, 1983), Cass et al. (1982), and CEC (1983).

Year	Statewide Total Traffic by All On-Road Vehicles	Traffic Percentage Contributed by Leaded Gasoline Vehicle Class		
		Non-Catalyst Light-duty	Non-Catalyst Medium-Duty	Non-Catalyst Heavy-Duty
1976	130 ($\times 10^9$ miles/year)	70.5%	4.1	2.6
1977	134	58.2	4.0	2.6
1978	139	48.0	3.7	2.7
1979	144	38.9	3.1	2.7
1980	150	30.5	2.5	2.7

4. Stationary Sources

Based on Suer et al. (1982) and Suer (1983), total statewide emissions of Pb from non-highway mobile sources and stationary sources were approximately 1.0 tons/day from 1976 to 1980.

5. Estimate of Statewide Emissions

From the above, our estimate of the statewide Pb emission inventory from 1976 to 1980 is as follows:

Year	California Statewide Lead Emissions
1976	17.0 tons/day
1977	13.6
1978	10.2
1979	7.9
1980	5.5