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Emission Factors for Small Utility Engines

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Abstract

A major gap exists in available baseline emissions data on the small utility engine population between the mid-1970's and present day. As part of the input required for a standard-setting process, the California Air Resources Board has funded limited laboratory emission measurements on a number of modern small engines, both 2-stroke and 4-stroke designs. Exhaust constituents characterized in this study include total hydrocarbons, reactive hydrocarbons (RHC), methane, CO, NO_x, CO_2, O_2, aldehydes, and particulate matter. A total of nine engines were evaluated, spanning the range from the smallest widely-used 2-strokes (about 20 cc displacement) to 4-strokes approaching 20 hp.

THE CALIFORNIA CLEAN AIR ACT OF 1988 (Assembly Bill 2595)(1)* requires that the Air Resources Board (ARB) consider adoption of measures to reduce vehicle and other mobile source reactive organic gases by 55 percent and oxides of nitrogen by 15 percent; plus achieve the maximum feasible reductions for carbon monoxide, particulate mater, and toxic air contaminants; by January 1, 1992. To meet these requirements, the ARB is required to hold hearings on off-road vehicle regulations by November, 1991. Utility engines are one of the six off-road categories for which ARB is required to develop regulations. Utility engines are broadly defined by ARB as internal combustion engines of 25 horsepower or less used on lawn and garden equipment and small industrial equipment.

Much of the existing small engine emissions data comes from studies performed in the early to mid-1970's by various engine manufacturers and Southwest Research Institute (SwRI)(2-4). Due to the length of time which has passed since these prior studies, and ARB's desire to base their proposed emissions standards on data derived from current technology engines ARB contracted with Booz, Allen and Hamilton, Inc. and SwRI to update the small utility engine emissions inventory. This paper presents the results of emission tests of nine different small utility engines typical of current production. Both 2-stroke and 4-stroke designs were evaluated. Data obtained include total hydrocarbons (THC), methane, reactive hydrocarbons (RHC), carbon monoxide (CO), oxides of nitrogen (NO_x), carbon dioxide (CO_2), particulate matter (PM), and aldehydes.

THE TEST PROGRAM was designed by ARB to provide information about the emission levels of modern small engines to support California's emission standard setting process. Engine selection criteria included engine population by application and usage rates, as well as the range of available designs and manufacturers. Design variables which were considered include operating cycle (2-stroke or 4-stroke), displacement, number of cylinders, crankshaft orientation (vertical, horizontal, or all-position), and for 4-strokes, cylinder head/valve actuation design (overhead valve or side valve). While it was not possible to address every combination in this program, a wide range of engine types were selected. They are described in Table 1. Generic product identifications are used in place of manufacturer names.

*Numbers in parentheses designate references at the end of the paper.

Table 1. Description of Engines Tested

Engine Type	Rated Power, hp	Displacement-cm^3	Operating Cycle	Shaft Orientation
WBM[a], Side Valve	4	190	4-stroke	Vertical
WBM, OHV	4	148	4-stroke	Vertical
WBM, OHV	4.5	135	4-stroke	Vertical
WBM, OHV, Propane	4.5	135	4-stroke	Vertical
Utility, OHV	11	338	4-stroke	Horizontal
Side Valve	12	465	4-stroke	Vertical
Side Valve, 2-cylinder	18	782	4-stroke	Horizontal
WBM	5	145	2-stroke	Vertical
Trimmer	0.8	24	2-stroke	All-position
[a] WBM means "walk behind mower"				

TEST PROCEDURES

SAE Recommended Practice J1088[5] was used as the basis for emission measurement. This is a steady-state modal procedure based on raw exhaust gas analysis. As J1088 was under revision by the SAE Small Engine and Powered Equipment Standards Committee during the performance of this project, the version considered current during the summer of 1990 was used. Differences between this draft version of J1088 and its expected final form are anticipated to be minor. In any case, ARB will issue its own version of the J1088 procedure along with the appropriate additions and modifications. It is the ARB procedure which will govern small engine emission certification in California.

Test modes applicable to small engines were defined initially by ARB in its May 2, 1990, workshop notice, "A Preliminary Proposal to Establish Exhaust Emission Standards and Test Procedures for Utility and Lawn and Garden Equipment," (Mail-Out #90-38)[6]; and were revised in its August 28, 1990, notice, "Second Preliminary Proposal to Establish Exhaust Emission Standards and Test Procedures for Utility and Lawn and Garden Engines," (Mail-Out #90-57)[7]. Full details of ARB proposed regulations and test procedures are published in the October 16, 1990, document, "Notice of Public Hearing To Consider Regulations Regarding The California Exhaust Emission Standards And Test Procedures For 1994 And Subsequent Model Utility And Lawn And Garden Equipment Engines," (Mail-Out 90-64)[8]. The version published in the October 16, 1990, notice was used for calculation of results presented in this paper. It is shown in Table 2.

SAE J1088 has no provisions for particulate measurement. As has been well established with diesel engines, dilution and cooling of the exhaust stream is necessary for accurate determination of particulate mass rates. To provide particulate rate data as requested by ARB, we constructed a dilution and sampling system incorporating a dilution tunnel and a positive displacement pump (PDP) type blower. A particulate sampling procedure was developed using techniques previously established for diesel and gasoline engine exhaust particulate measurement.

Table 2. ARB J1088 Mode Applications and Weighting Factors

J1088 Mode	1	2	3	4	5	6	7
Speed	Idle	Rated	85% of Rated	85% of Rated	85% of Rated	85% of Rated	85% of Rated
Load	0	Full	Full	75% of Full	50% of Full	25% of Full	Minimum
Handheld	10%	90%	–	–	–	–	–
Non-Handheld	5%	–	9%	20%	29%	30%	7%

TEST EQUIPMENT

Three dynamometers were used in this program. They were a 30 hp vertical-shaft eddy current dynamometer; a 30 hp horizontal-shaft eddy current dynamometer; and a 1½ hp variable-orientation electric (alternator) dynamometer. Dynamometer test stands were installed in rails in the test cell floor and instrumented for measurement of engine speed, dynamometer load, and a variety of pressures and temperatures. The dynamometer control systems were designed to operate in either speed control or torque control mode. A Jordan actuator was used to provide remote actuation of the engine throttle. Details of the three dynamometer installations are shown in Figures 1-3.

THE RAW EXHAUST ANALYTICAL SYSTEM was constructed in accordance with recommendations in J1088. Laboratory grade emissions instruments of the type normally employed for certification were used, as listed below:

Figure 1. 30-Hp Vertical Shaft Dynamometer

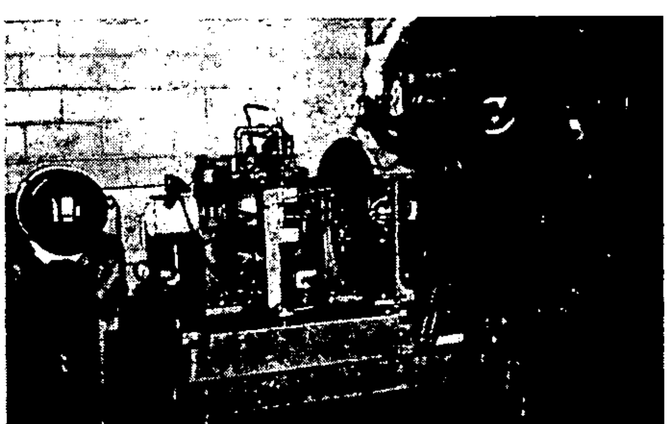

Figure 2. 30-Hp Horizontal Shaft Dynamometer

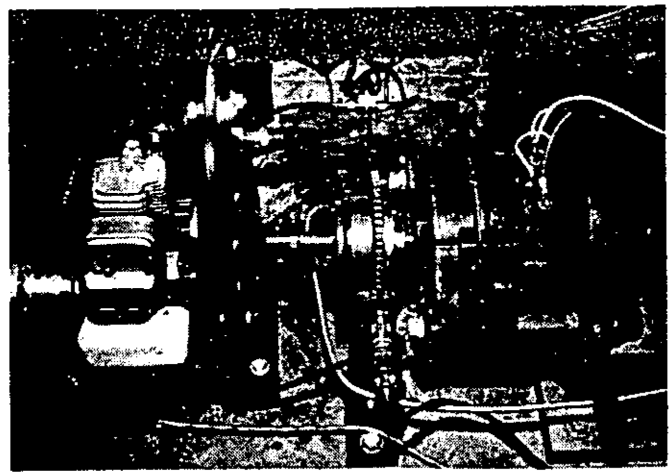

Figure 3. 1½-Hp Alternator Dynamometer

- HC Beckman Model 402 heated FID analyzer
- CO Beckman Model 868 NDIR analyzer
- NO_x SwRI heated chemiluminescent analyzer
- CO_2 Beckman Model 315 NDIR analyzer
- O_2 Beckman Model OM-11 polarographic analyzer

A heated filter (375°F) removed particulate matter from the raw exhaust gaseous sample. Hydrocarbon analysis was performed wet. The balance of the exhaust sample was passed through a cold trap to remove water prior to analysis for CO, CO_2, and NO_x. The raw exhaust analytical system is shown in Figure 4.

PRIMARY COMPONENTS OF THE DILUTE EXHAUST SYSTEM are shown in Figure 5. Dilution air and engine exhaust were mixed (turbulent flow) using an orifice plate in an 8-inch diameter 7-feet long dilution tunnel. The dilution tunnel is shown in Figure 6. Dilution air was filtered and flow measured with a laminar flow element (LFE) before entering the tunnel. Provision was also made for electrically preheating the dilution air to achieve the desired 110°F particulate filter sample zone temperature in low-exhaust-flow modes such as idle. Particulate was measured using fluorocarbon-coated glass fiber 90mm filters, Pallflex Type T60A20 (primary and back-up), installed in a housing through which a portion of the dilute exhaust was withdrawn. The particulate filter housing assembly is shown in Figure 7. Particulate filter

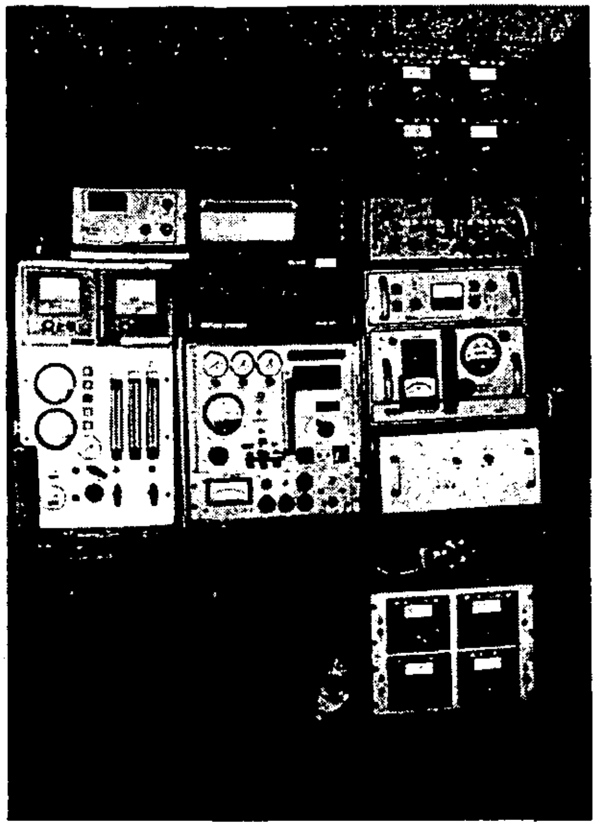

Figure 4. Raw Exhaust Analytical System

sample flow was measured using a calibrated gas meter. A PDP-type constant volume sampling (CVS) blower was used to draw the dilute exhaust through the dilution tunnel. The blower was sized to provide a maximum anticipated flow rate approximately 20 times the maximum engine exhaust flow rate. A variable speed drive enabled setting the blower to different flow rates for different modes. The CVS blower is shown in Figure 8. A heat exchanger was installed to control inlet temperature to the CVS blower. This control may not be required when testing is conducted exclusively on steady-state modes. A 2-inch diameter line was used to pipe the raw exhaust from the engine muffler outlet to the dilution tunnel inlet. This line was insulated and heated to a (outer tube wall) surface temperature of 260°F to minimize the dropout of lubricant aerosol-type particulate.

ENGINE TESTING

Engines tested in this program were supplied by manufacturers already broken-in to stabilize engine power output. Break-ins ranged from 1 to 24 hours, using a variety of cycles. Engines were tested "as received," with basic engine adjustments pre-set by manufacturers prior to receipt.

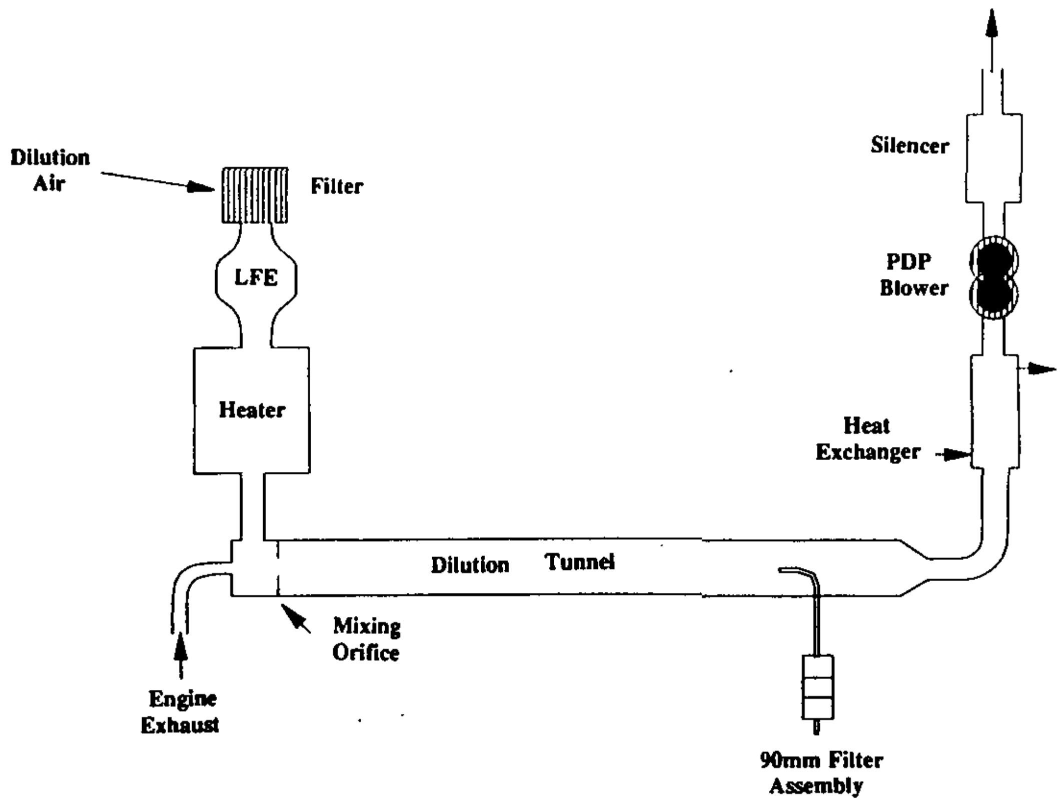

Figure 5. Dilute Exhaust System

The fuel used for gasoline engine testing was an emissions grade, unleaded, certification fuel. Its batch analysis is presented in Table 3. Lubricants used were of the type (and mix ratio for the 2-strokes) recommended by individual engine manufacturers.

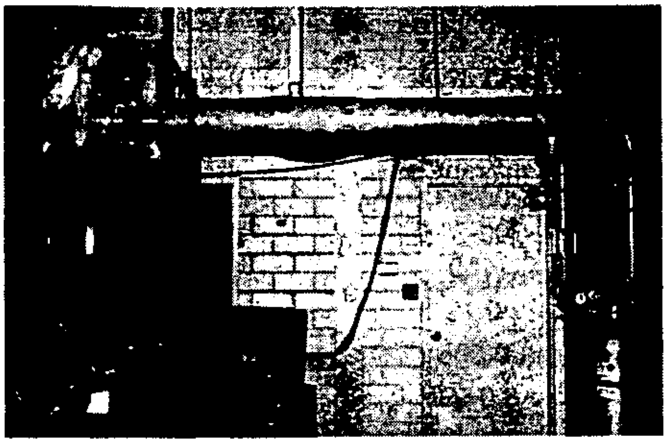

Figure 6. Dilution Tunnel

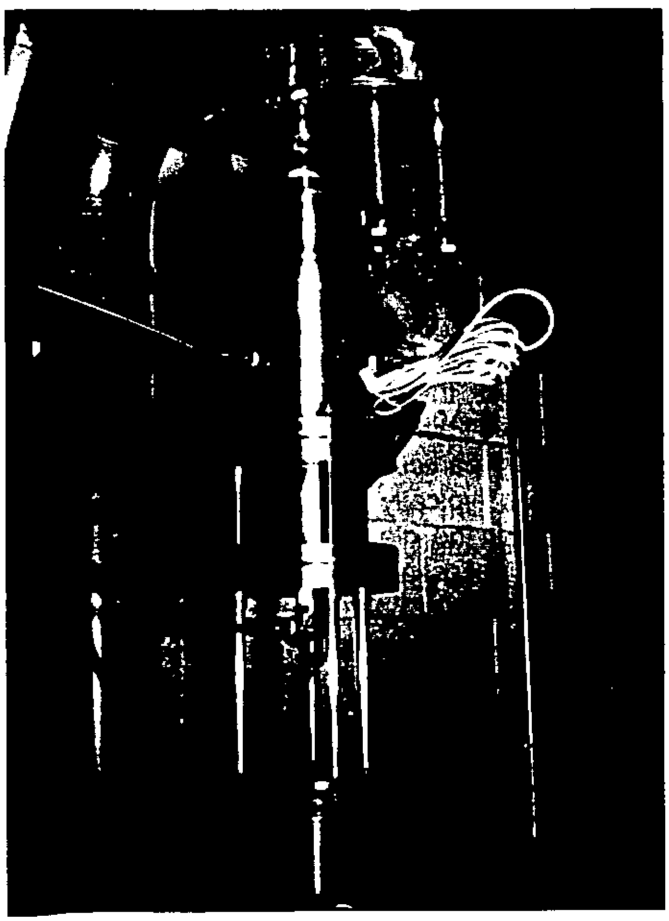

Figure 7. Particulate Filter Housing Assembly

Each engine to be tested was installed on the appropriate test stand and coupled to the dynamometer. The engine was instrumented to measure engine speed, dynamometer load, inlet air temperature, fuel temperature, fuel flow, oil temperature (4-strokes only), spark plug seat temperature, and exhaust temperature and backpressure. Other data obtained included barometric pressure and inlet air humidity, plus the full range of data necessary to determine total dilute sample flow and particulate sample flow. Engines were run with stock air intake and exhaust systems installed. Muffler seams were inspected and, in several cases, welded to prevent leakage. An exhaust mixing chamber was not used. Engine inlet airflow was not measured due to the known adverse effects of intake air flow measurement on both engine performance and emissions. An exhaust line was fabricated, from 2-inch diameter stainless steel tubing, to connect the engine exhaust to the dilution tunnel for particulate measurement and other dilute exhaust analysis. A ¼-inch diameter stainless steel probe was installed in the 2-inch diameter exhaust line to extract the raw exhaust sample for HC, CO, NO_x, CO_2, and O_2 analysis as specified by J1088. The raw exhaust line was heated to 375°F as prescribed by J1088 to prevent the condensation and loss of heavier hydrocarbons in the sample line. The 2-inch diameter exhaust line to the dilution tunnel was heated to 260°F to minimize losses of aerosol particulate while avoiding excessive heating of the dilute

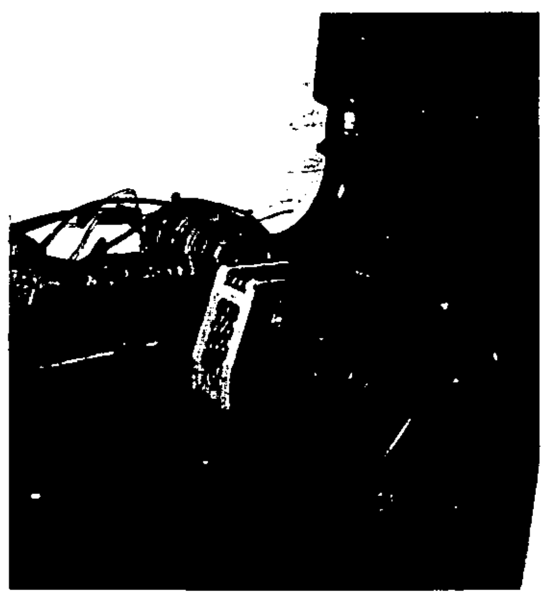

Figure 8. CVS Blower

Table 3. Fuel Batch Analysis

Item	CFR Specification[a]		SwRI Analyses
	ASTM	Unleaded	
Octane, research (min.)	D2699	93	97.2
Sensitivity (min.)		7.5	9.9
Pb (organic), gm/U.S., gal.		0.05[b]	<0.001
Distillation Range:			
IBP Distillation Range:			
IBP °F	D86	75-95	95
10% Point, °F	D86	120-135	122
50% Point, °F	D86	200-230	218
90% Point, °F	D86	300-325	320
EP, °F (max.)F	D86	415	391
Sulfur, wt. % (max.)	D1266	0.10	0.012
Phosphorus, gm/U.S., gal. (max.)		0.005	<0.0001
RVP, psi	D323	8.0-9.2	9.2
Hydrocarbon Composition:			
Olefins, %, (max.)	D1319	10	4.5
Aromatics, % (max.)	D1319	35	28.6
Saturates	D1319	c	66.9

a Gasoline fuel specification as in CFR 86.113-87(b)(2) for light-duty gasoline vehicles and CFR 86.113-87(b)(2) for heavy-duty gasoline engines.
b Maximum
c Remainder

exhaust stream. A comparison of engine performance was made with and without the connection of the line to the dilution tunnel to confirm that this sampling technique did not alter engine power or emissions.

Engines were warmed up at an intermediate speed and load prior to testing. A quick check of maximum power (WOT at rated speed) was made to verify proper engine operation. The J1088 test sequence was run on each engine a minimum of two times. Raw exhaust analysis for HC, CO, NO_x, CO_2, and O_2 was run first for each test mode. Three complete sets of data were recorded for each test mode, as prescribed by the J1088 test procedure. These three readings were subsequently averaged to determine mean values for each mode.

Following raw exhaust analysis for each mode, the raw sample flow was turned off to direct 100 percent of the engine exhaust stream to the dilution tunnel for particulate measurement and methane and aldehydes analysis. The PDP blower flow rate was adjusted initially for each test mode to a nominal dilution ratio of approximately 15. Total flow rate was determined by summing measured dilution air flow and exhaust flow calculated using a fuel-based (carbon balance) technique. Total flow was then fine-tuned at each mode to give a dilute sample temperature at the inlet face of the primary particulate filter of 110°F ± 5°F. Dilution air was typically preheated to achieve this temperature in the idle mode. Sampling times were adjusted as necessary to achieve reasonable filter loadings. One set of particulate filters was loaded for each test mode. Particulate filter pre- and post-conditioning, handling, and weighing were all done in accordance with procedures specified in Subpart N of 40 CFR Part 86[9].

While particulate sampling was underway, a bag sample of dilute exhaust was taken downstream of the particulate filter assembly. This sample was analyzed to determine exhaust methane concentration using a gas chromatographic technique. A second sample of dilute exhaust was taken for aldehydes analysis. The sample was bubbled through two impingers containing a dinitrophenylhydrazine (DNPH) solution. Aldehyde species concentrations were determined using a liquid chromatographic technique.

CALCULATIONS

Mass emissions results were calculated using the Fuel Flow Method – Section 6.2.2.2 of J1088. The applicable equations are:

HC, g/hr = MHC/MF • Fuel, g/hr / (TC) • HC, ppmC • 1/10000

CO, g/hr = MCO/MF • Fuel, g/hr / (TC) • CO, % wet

NO_X, g/hr = MNO_X/MF • Fuel, g/hr / (TC) • NO_X, ppm • K_h • 1/10000

where:

1. (TC) = CO, % wet + CO_2, % wet + HC, % wet
2. MHC = Molecular weight of exhaust HC species = 13.88 for fuel H/C = 1.85
3. MF = Molecular weight of fuel = 13.88 for fuel H/C = 1.85
4. MCO = Molecular weight of CO = 28.01
5. MNO_X = Molecular weight of NO_2 = 46.00
6. K_h = Federal factor to correct for the effect of humidity on NO_X formation.

$$= \frac{1}{(1-0.0047[H-75])} \text{ (4-stroke engines)}$$

$$= 1 \text{ (2-stroke engines)}$$

H = Absolute humidity, grains H_2O/lb. dry air

Individual modal results are in units of unweighted g/hr. To determine emission rates on a brake specific basis, ARB modal weighting factors must be applied.

For Non-Handheld Weighting

$$X, g/hr_{(wtd)} = X, g/hr_{(1)} * 0.05 + X, g/hr_{(3)} * 0.09 + X, g/hr_{(4)} * 0.20 + X, g/hr_{(5)} * 0.29 + X, g/hr_{(6)} * 0.30 + X, g/hr_{(7)} * 0.07$$

and:

$$hp_{(wtd)} = hp_{(1)} * 0.05 + hp_{(3)} * 0.09 + hp_{(4)} * 0.20 + hp_{(5)} * 0.29 + hp_{(6)} * 0.30 + hp_{(7)} * 0.07$$

For Handheld Weighting

$$X, g/hr_{(wtd)} = X, g/hr_{(1)} * 0.1 + X, g/hr_{(2)} * 0.9$$

and:

$$hp_{(wtd)} = hp_{(1)} * 0.1 + hp_{(2)} * 0.9$$

where:

$X, g/hr_{(i)}$ = HC, CO, NO_X, or PM, g/hr in $mode_{(i)}$

$hp_{(i)}$ = Indicated hp in $mode_{(i)}$

Thus, the final weighted brake specific result is:

$$X, g/hp\text{-}hr_{(wtd)} = \frac{X, g/hr_{(wtd)}}{hp_{(wtd)}}$$

Particulate Calculations

Small engine particulate results are calculated on a mass basis, as follows:

$$PM, g/hr = \frac{PM, mg * \left(\frac{Exh\ Q, scfm + Dil\ Q, scfm}{90\ mm\ Q, scfm}\right) * 3.6}{90\ mm\ t, sec}$$

where:

PM, mg = Total mg particulate (front + rear filter)

Dil Q, scfm = Dilution air flowrate, scfm

90 mm Q, scfm = 90 mm sample flowrate, scfm

90 mm t, sec = 90 mm sample time, seconds

Exh Q, scfm = Exhaust flowrate, scfm

$$Exh\ Q, scfm = \frac{100}{\left(CO\%w + CO_2\%w + \frac{HC\ ppmCw}{10{,}000}\right)} * \frac{Exh\ MW}{13.88} * \frac{Fuel\ \dot{M}, lb/hr}{4.513}$$

where:

Fuel $\dot{M}$, lb/hr = Fuel flowrate, lb/hr

CO%w = Raw CO%, wet basis

CO_2%w = Raw CO_2%, wet basis

HC ppmCw = Raw HC ppmC, wet basis

Exh MW = Exhaust gas molecular weight

$$\text{Exh MW} = \frac{13.88 * \text{HC ppmCw}}{10^6} + \frac{28.01 * \text{CO\%w}}{10^2}$$

$$+ \frac{44.01 * \text{CO}_2\text{\%w}}{10^2} + \frac{46.00 * \text{NO}_x \text{ ppmw}}{10^6}$$

$$+ \frac{32.00 * \text{O}_2\text{\%w}}{10^2} + \frac{2.016 * \text{H}_2\text{\%} * K}{10^2}$$

$$+ 18.01 * (1 - K) + \left[28.10 * \left(100 - \frac{\text{HC ppmCw}}{10^4} \right.\right.$$

$$- \text{CO\%w} - \text{CO}_2\text{\%w} - \frac{\text{NO}_x \text{ ppmw}}{10^4} - \text{O}_2\text{\%w}$$

$$\left.\left. - (\text{H}_2\text{\%} * K) - 100 * (1 - K) \right) \right] \Big/ 10^2$$

where:

$$K = \frac{1}{1 + 0.005 * (\text{CO\%d} + \text{CO}_2\text{\%d}) * y - 0.01 * \text{H}_2\text{\%d}}$$

$$\text{H}_2\text{\%d} = \frac{0.5 * y * \text{CO\%d} * (\text{CO\%d} + \text{CO}_2\text{\%d})}{\text{CO\%d} + 3 * \text{CO}_2\text{\%d}}$$

$$y = \text{H/C ratio of the fuel}$$

For 2-stroke engines, it is assumed no residual H_2 is present and the K and molecular weight equations are modified by deleting the H_2 terms. The above equations calculate PM for individual modes. Weighted PM in g/h and weighted PM in g/hp-hr are calculated with the same equations used for gaseous emissions.

RESULTS AND DISCUSSION

Results of small engine emission tests are presented in Table 4, grouped according to engine type and displacement. ARB weighting factors, described in Table 2, were applied to modal data to calculate weighted total results. Results are presented in brake-specific units, based on observed (uncorrected) power.

Emission results for 4-stroke engines of less than 225 cm^3 displacement are summarized in Table 4. Reactive hydrocarbon (RHC) levels are determined by subtracting methane emissions from total hydrocarbon (THC) emissions. The sum of THC plus NO_x is presented to provide for convenient comparison with proposed ARB standards. Weighted power and air/fuel ratio (A/F) are included with the emissions data to provide insight into engine operating conditions. Air/fuel is derived from measured fuel flow and calculated (fuel based) exhaust flow.

The third engine listed (4.5 hp, WBM, OHV) was refitted with a manufacturer-supplied propane kit following gasoline-fueled testing. Results of propane-fueled testing of this engine are listed fourth in the table. Laboratory-grade propane (99.9% min C_3H_8) was used as the test fuel. It should be

Table 4. Small Engine Emissions Results

Engine Type	Weighted J1088, g/hp-hr							Weighted	
	THC	CH4	RHC	NO_x	THC + NO_x	CO	PM	HP	A/F
4-Stroke Engines, <225 cm^3									
4-hp, WBM, Side valve	49.2	1.65	47.5	1.16	50.4	476	0.85	1.20	11.6
4-hp, WBM, OHV	18.5	1.82	16.7	1.99	20.5	360	0.33	1.40	11.7
4.5-hp, WBM, OHV	10.0	1.11	8.9	2.54	12.5	372	0.69	1.21	11.5
4.5-hp, WBM, OHV, Propane	6.2	0.95	5.3	6.28	12.5	168	0.60	1.15	13.6
4-Stroke Engines, >225 cm^3									
11-hp, Utility, OHV	6.0	0.75	5.2	2.16	8.1	255	0.03	4.13	12.0
12-hp, Side valve	6.5	1.03	5.5	5.01	11.5	274	0.06	4.36	12.6
18-hp, Side valve, 2-cyl.	6.7	0.94	5.7	2.80	9.5	354	0.20	7.09	12.0
2-Stroke Engines									
5-hp WBM	190	3.70	186	0.31	190	444	7.1	1.30	10.7
0.8-hp, Trimmer	169	1.20	168	0.94	170	284	4.5	0.71	11.7

noted that this propane conversion system had not been optimized and was not production ready. It was included to explore the potential benefits of an alternate fuel.

Total hydrocarbon emissions of the three gasoline-fueled 4-stroke walk-behind-mower (WBM) engines varied from 10.0 to 49.2 g/hp-hr. Hydrocarbon emission levels of small engines tend to be high due to the rich calibrations used to provide fuel cooling. The overhead valve design engines both emitted less THC than the side valve design engine. Carbon monoxide emission levels were also very high for all three engines, ranging from 360 to 476 g/hp-hr. Carbon monoxide production is primarily a function of air/fuel ratio. The stoichiometric air/fuel ratio for the gasoline used was 14.6. Weighted A/F ratios for these three engines were all very rich, ranging from 11.5 to 11.7 so that CO emissions, as well as HC emissions, were elevated by the rich carburetor calibrations employed. NO_x emissions, on the other hand, tended to be low, ranging from 1.16 to 2.54 g/hp-hr. NO_x production is a function of peak combustion temperature and requires the presence of oxygen. The rich calibrations used typically result in cool combustion and low residual oxygen levels, and so produce low NO_x emissions.

Methane emission levels ranged from 1.11 to 1.82 g/hp-hr, and represent from 3.4 to 11.1 percent of total HC levels, so reactive HC levels (the balance of THC) range from 96.6 to 88.9 percent of total HC levels.

Particulate emissions from these gasoline-fueled engines were low compared to those from 2-stroke engines, ranging from 0.33 to 0.85 g/hp-hr. Particulate filters collected exhibited colors ranging from tan to black, suggesting particulate creation perhaps from unburned lubricant in the case of the lighter colored filters, and perhaps particulate soot from overly rich combustion in the case of the darker colored filters.

The conversion of the 4.5 HP WBM engine to propane operation provides an interesting comparison with its gasoline-fueled operation. The primary differences are related to the leaner operation achieved using propane. This resulted in substantially reduced THC and CO emissions, 38 percent and 55 percent respectively, but NO_x which was higher by 147 percent. With this tradeoff of increased NO_x for decreased HC, the combined HC + NO_x level is precisely the same as it was for gasoline-fueled operation. Thus, meeting a combined HC + NO_x standard may require more than simple enleanment.

Emission results for 4-stroke engines greater than 225 cm^3 displacement are also summarized in Table 4. Since these engines employ rich calibrations like the smaller displacement 4-stroke engines, there is considerable similarity in emission levels and trends. THC levels ranged from 6.0 to 6.7 g/hp-hr, and CO levels ranged from 255 to 354 g/hp-hr. NO_x emissions ranged from 2.16 to 5.01 g/hp-hr. One significant difference noted between the larger and smaller displacement 4-stroke engines is in THC emissions. The larger displacement engines emit much less THC than their smaller counterparts. Since hydrocarbon formation is strongly a function of combustion chamber surface area, it is reasonable to conclude that the increased combustion chamber surface-to-volume ratio of the smaller engines is a primary cause of their increased THC emissions.

Emission results for the 2-stroke engines tested are also summarized in Table 4. A striking difference between 2-stroke and 4-stroke engines is in the extremely high levels of THC emitted by the 2-stroke engines. Levels of 190 and 169 g THC/hp-hr were observed for the 5 hp WBM engine and 0.8 hp trimmer engine, respectively. Like the 4-stroke engines, the 2-stroke engines employ rich calibrations for fuel cooling and smooth operation. A greater factor, however, is the design of the 2-stroke engine which permits a fraction of the intake charge to short-circuit directly to the exhaust port, uncombusted. These factors combine such that brake specific HC emissions for 2-stroke engines are typically 10-20 times the level of 4-stroke engines.

Two-stroke engine CO emissions are similar to 4-stroke engine levels, as would be expected for engines operating at similar air/fuel ratios, with 444 and 284 g/hp-hr observed for the WBM engine and trimmer engines, respectively. Two-stroke engine NO_x emissions were very low, ranging from 0.31 g/hp-hr for the WBM engine to 0.94 g/hp-hr for the trimmer engine. Although sufficient oxygen is present, 2-stroke engine combustion temperatures typically tend to be too low to produce large amounts of NO_x. Both a rich mixture and "incidental EGR," or residual exhaust gases, contribute to the low combustion temperatures.

Two-stroke engine particulate emissions tend to be very high. Levels of 7.1 and 4.5 g/hp-hr were determined for the WBM engine and trimmer engine, respectively. Lubrication of the comparatively inexpensive two-stroke engines tested was provided by mixing the lubricant with the fuel. A certain amount of this lubricant passes through the combustion chamber unburned and is emitted as an aerosol-type particulate. This is also reflected by 2-stroke engine particulate filter appearance, which was different from 4-stroke engine filters, tending to be light tan in color.

Modal data for all engines tested is included in the Appendix. Results are presented in terms of both g/hr and g/hp-hr, and show the relative contributions of individual modes to the final weighted total.

ALDEHYDE RESULTS

Aldehyde emissions were measured for all nine engines tested. Aldehydes were determined by bubbling a proportional sample of diluted exhaust through two impingers containing a dinitrophenylhydrazine (DNPH) solution with subsequent analysis by liquid chromatography. Primary plus back-up impinger samples were taken in every J1088 mode. These data are summarized in Table 5.

The analytical technique used provided speciation for formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, isobutraldehyde, benzaldehyde, and hexanaldehyde. For simplification, only the major components (formaldehyde, acetaldehyde, acrolein, and benzaldehyde) are included in the table. Note that the total is generally greater than the sum of the components due to the contribution of unlisted components.

Typically, formaldehyde was the species present in highest concentration, representing from 40 percent to over 90 percent of total aldehyde emissions. Aldehyde emissions seem to roughly follow the pattern set by HC emissions. Within the 4-stroke engine group, the side-valve engines emitted more aldehydes than the OHV engines. Two-stroke engines emitted much higher levels of aldehydes than the 4-stroke engines, again, roughly in proportion to the corresponding THC emission levels.

SUMMARY AND CONCLUSIONS

Baseline emissions of the nine small engines tested using the SAE J1088 recommended practice are summarized in Figures 9 through 12. Small utility engines emit high levels of HC and CO, and in the case of 2-stroke engines, high particulate. Among the 4-stroke engines, the smaller displacement WBM-type engines produced higher brake-specific HC emissions than the larger dis-

Table 5. Small Engine Aldehyde Emissions

Engine Type	Weighted J1088, g/hp-hr				
	Formaldehyde	Acetaldehyde	Acrolein	Benzaldehyde	Total Aldehydes
4-Stroke Engines, <225 cm^3					
4-hp, WBM, Side valve	0.32	0.05	0.04	0.07	0.54
4-hp, WBM, OHV	0.28	0.04	0.00	0.06	0.47
4.5-hp, WBM, OHV	0.10	0.01	–	0.02	0.14
4.5-hp, WBM, OHV, Propane	0.11	0.01	–	0.00	0.13
4-Stroke Engines, >225cm^3					
11-hp, Utility, OHV	0.04	0.01	0.00	0.02	0.10
12-hp, Side valve	0.23	0.03	0.05	0.05	0.41
18-hp, Side valve, 2-cyl.	0.08	0.02	0.00	0.02	0.12
2-Stroke Engines					
5-hp WBM	0.82	0.23	0.18	0.31	1.85
0.8-hp, Trimmer	0.67	0.17	0.08	0.20	1.35
Totals include contribution of other unreported species.					

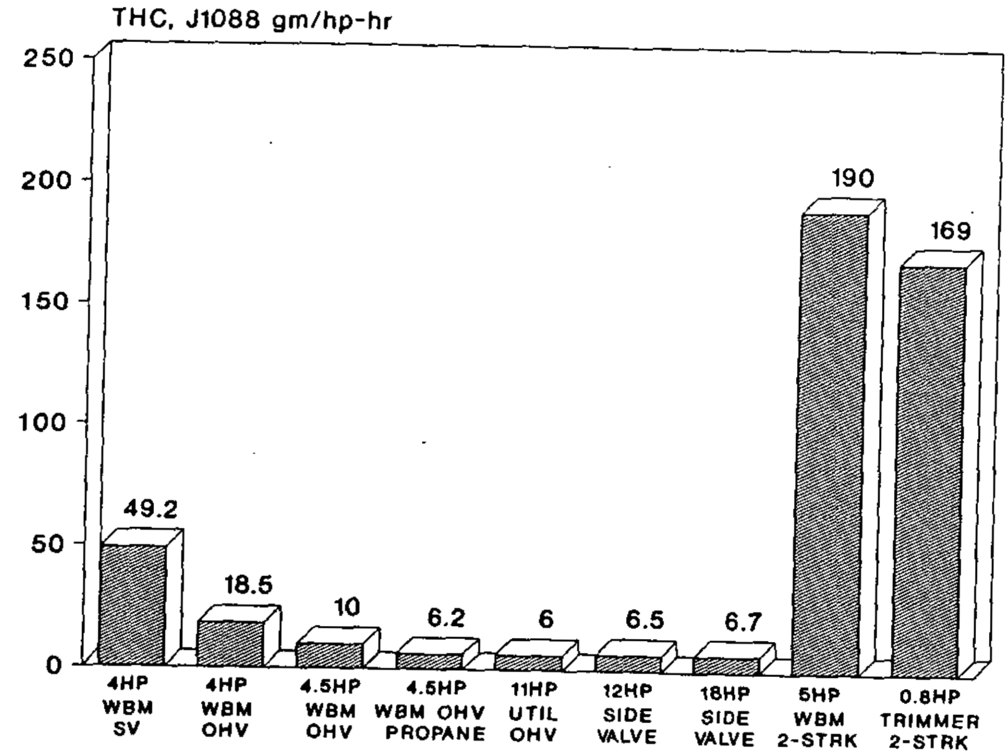

Figure 9. Small Engine Hydrocarbon Emissions

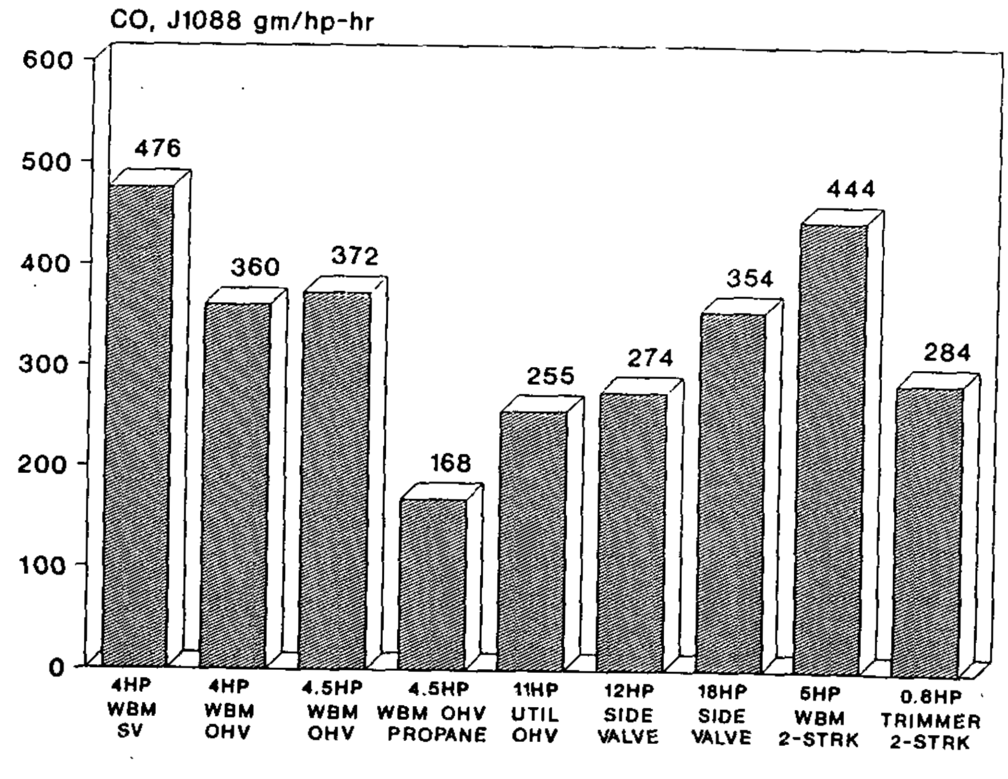

Figure 10. Small Engine Carbon Monoxide Emissions

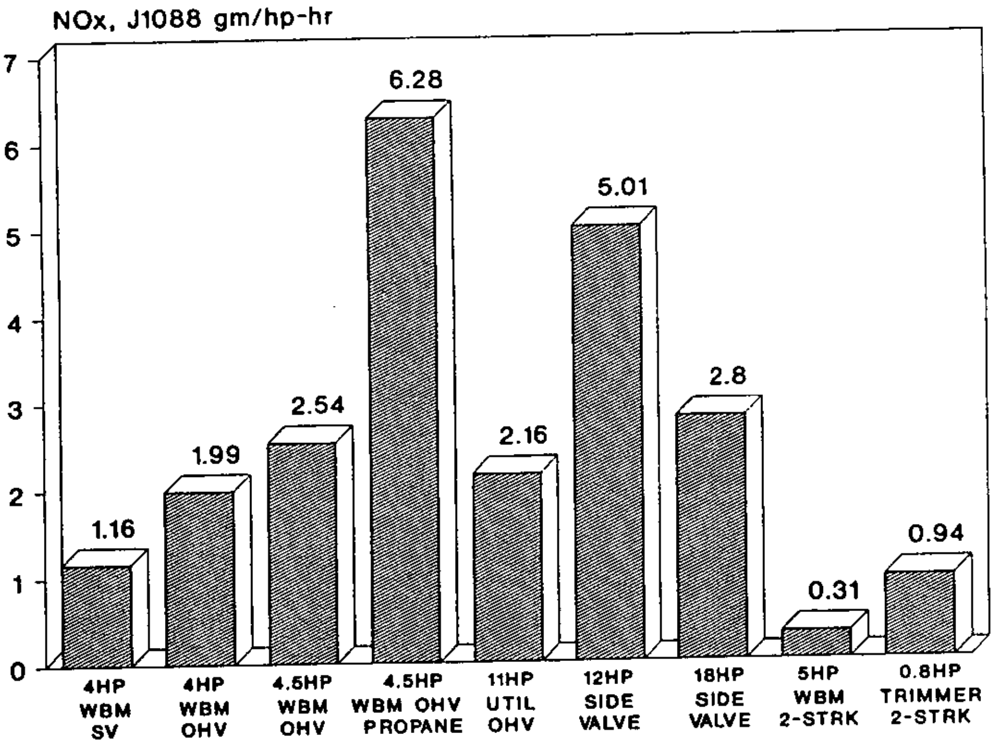

Figure 11. Small Engine Nitrogen Oxides Emissions

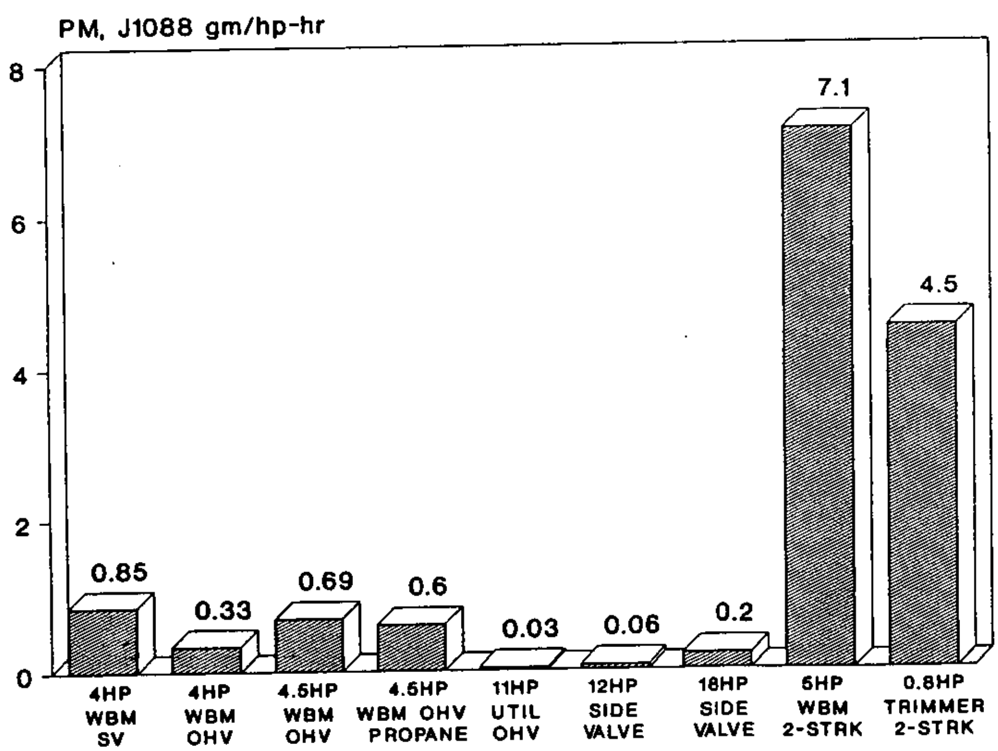

Figure 12. Small Engine Particulate Emissions

placement utility and riding-mower engines. The older side-valve 4-stroke design also produced higher HC emissions than engines employing OHV technology. Two-stroke engines emitted on the order of ten times as much HC as the 4-stroke engines due to incomplete combustion and the short-circuiting inherent to the crankcase-scavenged 2-stroke engine design.

Carbon monoxide emissions were high for all engines tested (Figure 10). This is a result of the rich calibrations which are typically used to provide fuel cooling and smooth operation. NO_X emissions were low for all engines tested (Figure 11). This is primarily due to their rich (oxygen deficient) operation. Two-stroke engine NO_X levels are even lower than those from the 4-stroke engines due to the cooler combustion associated with the 2-stroke design. Particulate emissions (Figure 12) were highest from the 2-stroke engines. Most of this particulate matter is an aerosol from uncombusted lubricant which is mixed with the fuel.

A comparison of results from this study with those from earlier studies (3, 4) suggests emission levels of engines produced in 1990 are not greatly different from those of engines produced over 15 years ago. For at least engines to be sold in California, this is expected to change with the introduction of California emission standards for small engines. How quickly use of low-emissions technology will spread to other areas depends on numerous economic and political factors.

ACKNOWLEDGEMENTS

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REFERENCES

1. **Assembly Bill No. 2595**, California Legislature, March 6, 1987, Amended in Senate, August 26, 1988.
2. Donohue, J. A., Hardwick, G. C., Newhall, H. K., Sanvordenker, K. S., Woelffer, N. C., "Small Engine Exhaust Emissions and Air Quality in the United States," SAE Paper No. 720198 presented at the Automotive Engineering Congress, Detroit, Michigan, January 10-14, 1972.
3. Hare, C. T. and Springer, K. J., "Exhaust Emissions from Uncontrolled Vehicle and Related Equipment Using Internal Combustion Engines - Part 4, Small Air Cooled Spark Ignition Utility Engines," EPA Report under Contract EHS-70-108, May 1973.
4. Hare, C. T., Springer, K. J., Oliver, W. R., Houtman, W. H., "Small Engine Emissions and Their Impact," SAE Paper No. 730859 presented at the National Combined Farm, Construction & Industrial Machinery and Fuels and Lubricants Meetings, Milwaukee, Wisconsin, September 10-13, 1973.
5. "Test Procedure for the Measurement of Exhaust Emissions from Small Utility Engines - SAE Recommended Practice J1088 JUN83," Society of Automotive Engineers, June 1983.
6. "A Proposal to Establish Exhaust Emission Standards and Test Procedures for Utility and Lawn and Garden Equipment," California Air Resources Board, Mail-Out #90-38, May 2, 1990.
7. "Second Preliminary Proposal to Establish Exhaust Emission Standards and Test Procedures for Utility and Lawn and Garden Engines," California Air Resources Board, Mail-Out #90-57, August 28, 1990.
8. "Notice of Public Hearing To Consider Regulations Regarding The California Exhaust Emission Standards And Test Procedures For 1994 And Subsequent Model Utility And Lawn And Garden Equipment Engines," California Air Resources Board, Mail-Out #90-64, October 16, 1990.
9. Code of Federal Regulations 40, Part 86, Subpart N, July 1, 1989.

Appendix A-1. 4-Hp Side Valve WBM Engine

Engine # / run #	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
4HP, WBM, Side Valve #1							
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	13.0	11.2	11.6	11.1	11.9	12.1	11.6
Fuel flow rate, lb/h	0.31	2.52	2.06	1.75	1.28	1.18	1.63
Engine speed, rpm	1033	3190	3200	3200	3200	3230	3093
Engine torque, lb-ft	0.18	4.12	3.13	2.09	1.02	0.37	1.94
Power output, hp	0.04	2.50	1.91	1.27	0.62	0.23	1.18
Air inlet temp, F	92.3	88.0	85.7	82.0	76.0	79.3	81.6
Humidity, grains/lb	62.1	62.4	63.3	62.8	63.5	62.6	63.0
Total engine hours, h	2.9	3.5	4.0	4.8	5.4	6.1	6.1
HC ppmc wet	17683	15500	15173	12567	8567	8663	12135
CO % wet	2.03	6.56	5.88	6.79	5.41	4.95	5.81
CO2 % wet	10.8	8.00	8.35	8.21	9.14	9.49	8.72
NOx ppm wet	28.4	139	122	76.1	67.5	59.3	84.8
O2 % wet	1.94	1.83	1.66	1.26	0.97	0.89	1.31
RAW J1088							
HC, g/h	17.0	110	90.2	61.3	32.3	30.2	58.4
HC, g/hp-h		44.1	47.3	48.1	51.9		49.5
CH4, g/h	0.26	3.27	2.33	2.15	1.60	1.56	1.99
CH4, g/hp-h		1.31	1.22	1.69	2.57		1.68
RHC, g/h	16.7	107	87.9	59.1	30.7	28.6	56.4
RHC, g/hp-h		42.7	46.1	46.4	49.4		47.8
CO, g/h	39.4	942	706	669	412	349	570
CO, g/hp-h		376	371	525	663		483
NOx, g/h	0.09	3.10	2.28	1.17	0.80	0.65	1.36
NOx, g/hp-h		1.24	1.20	0.92	1.29		1.16
CO2, g/h	330	1804	1576	1270	1094	1049	1264
CO2, g/hp-h		721	827	998	1760		1072
Fuel, lb/h	0.31	2.52	2.06	1.75	1.28	1.18	1.63
Fuel, lb/hp-h		1.01	1.08	1.37	2.06		1.38
DILUTE PARTICULATE							
PM, g/h	0.22	3.08	1.86	0.92	0.35	0.22	1.05
PM, g/hp-h		1.22	0.97	0.73	0.56		0.89

Engine # / run #	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
4HP,WBM, Side Valve #2							
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	13.0	11.2	11.5	11.3	11.8	12.0	11.6
Fuel flow rate, lb/h	0.34	2.56	2.06	1.76	1.32	1.13	1.65
Engine speed, rpm	1110	3200	3190	3200	3200	3227	3095
Engine torque, lb-ft	0.13	4.27	3.25	2.16	1.06	0.35	2.01
Power output, hp	0.03	2.60	1.97	1.32	0.65	0.22	1.22
Air inlet temp, F	89.3	81.7	77.0	81.7	74.0	74.0	78.3
Humidity, grains/lb	64.6	63.0	61.2	72.7	61.9	61.8	65.1
Total engine hours, h	7.2	7.7	8.1	8.1	8.5	9.0	9.0
HC ppmc wet	20803	16700	15900	11533	8800	8667	12315
CO % wet	1.60	6.48	5.57	6.81	5.57	5.01	5.77
CO2 % wet	10.9	7.97	8.67	8.01	9.11	9.48	8.72
NOx ppm wet	25.6	130	131	78.7	68.6	59.5	86.7
O2 % wet	2.40	1.86	1.70	1.28	0.970	0.895	1.35
RAW J1088							
HC, g/h	21.7	120	93.9	57.5	33.9	29.0	59.6
HC, g/hp-h		46.3	47.6	43.7	52.6		48.8
CH4, g/h	0.31	3.25	2.27	2.28	1.50	1.49	1.98
CH4, g/hp-h		1.25	1.15	1.73	2.33		1.62
RHC, g/h	21.4	117	91.6	55.3	32.4	27.5	57.6
RHC, g/hp-h		45.0	46.4	42.0	50.2		47.2
CO, g/h	33.6	944	664	686	434	338	572
CO, g/hp-h		363	336	521	672		469
NOx, g/h	0.08	2.95	2.41	1.29	0.83	0.62	1.42
NOx, g/hp-h		1.13	1.22	0.98	1.28		1.16
CO2, g/h	361	1823	1625	1269	1115	1006	1280
CO2, g/hp-h		701	823	964	1727		1049
Fuel, lb/h	0.34	2.56	2.06	1.76	1.32	1.13	1.65
Fuel, lb/hp-h		0.98	1.04	1.34	2.05		1.35
DILUTE PARTICULATE							
PM, g/h	0.156	2.80	1.67	1.02	0.31	0.20	1.00
PM, g/hp-h		1.07	0.85	0.78	0.48		0.82

Appendix A-2. 4-Hp OHV WBM Engine

Engine # / run #	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	WEIGHTED
4HP, WBM, OHV #1	MODE 1	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.25	12.6	12.2	11.6	12.2	11.3	11.7
Fuel flow rate, lb/h	0.49	1.96	1.78	1.59	1.17	1.06	1.44
Engine speed, rpm	773	3200	3193	3210	3210	3147	3080
Engine torque, lb-ft	0.25	5.02	3.73	2.53	1.25	0.44	2.35
Power output, hp	0.04	3.06	2.27	1.55	0.76	0.26	1.43
Air inlet temp, F	86.0	88.7	86.3	84.7	82.7	81.0	84.6
Humidity, grains/lb	80.2	64.6	64.7	74.3	75.3	71.0	71.9
Total engine hours, h	10.1	10.8	11.4	11.8	12.3	12.7	12.7
HC ppmc wet	66800	6033	5500	5633	4600	5833	8405
CO % wet	11.0	4.22	5.28	6.95	5.93	7.69	6.32
CO2 % wet	4.56	9.98	9.33	8.20	8.69	7.61	8.51
NOx ppm wet	11.2	504	282	116	104	74.4	172
O2 % wet	2.40	0.92	0.95	1.02	1.15	1.22	1.12
J1088 RESULTS							
THC, g/h	67.0	36.2	29.3	25.8	16.3	17.7	26.1
THC, g/hp-h		11.8	12.9	16.7	21.3		18.3
CH4, g/h	8.81	2.64	2.64	2.36	1.71	1.94	2.54
CH4, g/hp-h		0.86	1.16	1.53	2.24		1.78
RHC, g/h	58.2	33.5	26.6	23.5	14.5	15.7	23.5
RHC, g/hp-h		11.0	11.7	15.2	19.0		16.5
CO, g/h	222	511	568	644	423	471	517
CO, g/hp-h		167	250	416	554		362
NOx, g/h	0.04	9.55	4.77	1.75	1.23	0.74	2.74
NOx, g/hp-h		3.13	2.10	1.13	1.61		1.92
CO2, g/h	145	1898	1577	1193	974	733	1183
CO2, g/hp-h		621	695	771	1275		829
Fuel, lb/h	0.49	1.96	1.78	1.59	1.17	1.06	1.44
Fuel, lb/hp-h		0.64	0.78	1.03	1.54		1.01
DILUTE PARTICULATE							
PM, g/h	0.31	a	1.04	0.29	0.10	0.09	a
PM, g/hp-h		a	0.46	0.19	0.13		a

a Mode 3 Particulate loading improbably high, no weighted average calculated.

Engine # / run #	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	WEIGHTED
4HP, WBM, OHV #2	MODE 1	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.00	12.9	12.2	11.6	12.4	11.5	11.8
Fuel flow rate, lb/h	0.50	2.00	1.70	1.56	1.11	1.07	1.41
Engine speed, rpm	873	3200	3200	3200	3197	3207	3083
Engine torque, lb-ft	0.17	4.85	3.65	2.39	1.21	0.43	2.26
Power output, hp	0.03	2.96	2.22	1.45	0.74	0.26	1.37
Air inlet temp, F	86.7	98.0	99.0	86.7	89.3	90.3	91.2
Humidity, grains/lb	71.2	73.1	63.4	59.2	63.3	68.0	63.8
Total engine hours, h	13.6	14.0	14.4	14.8	15.2	15.7	15.7
HC ppmc wet	83700	5200	5933	5300	4433	5333	9080
CO % wet	9.99	3.78	5.17	7.04	5.58	7.51	6.11
CO2 % wet	4.55	10.3	9.36	8.14	8.90	7.65	8.59
NOx ppm wet	17.5	578	268	118	111	78	180
O2 % wet	3.62	0.90	0.98	1.00	1.16	1.32	1.19
J1088 RESULTS							
THC, g/h	82.7	32.3	30.3	23.9	14.9	16.4	25.7
THC, g/hp-h		10.9	13.6	16.4	20.3		18.7
CH4, g/h	10.3	2.67	2.25	2.34	1.69	2.26	2.55
CH4, g/hp-h		0.90	1.01	1.61	2.29		1.86
RHC, g/h	72.4	29.7	28.0	21.6	13.2	14.2	23.1
RHC, g/hp-h		10.0	12.6	14.8	18.0		16.8
CO, g/h	199	475	533	641	379	468	492
CO, g/hp-h		161	240	441	515		358
NOx, g/h	0.06	11.82	4.30	1.65	1.18	0.77	2.81
NOx, g/hp-h		4.00	1.94	1.13	1.60		2.05
CO2, g/h	143	2029	1516	1166	951	748	1169
CO2, g/hp-h		686	682	802	1292		851
Fuel, lb/h	0.50	2.00	1.70	1.56	1.11	1.07	1.41
Fuel, lb/hp-h		0.68	0.77	1.07	1.50		1.02
DILUTE PARTICULATE							
PM, g/h	1.18	1.13	0.61	0.37	0.19	0.07	0.45
PM, g/hp-h		0.38	0.28	0.25	0.26		0.33

Appendix A-3. 4.5-Hp OHV WBM Engine

Engine # / run # 4.5HP, WBM, OHV #1	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	10.2	11.6	11.6	11.3	11.5	10.8	11.4
Fuel flow rate, lb/h	0.42	1.80	1.53	1.29	0.96	0.75	1.20
Engine speed, rpm	2023	3200	3200	3207	3200	3203	3143
Engine torque, lb-ft	0.03	4.27	3.20	2.15	1.07	0.06	1.97
Power output, hp	0.01	2.60	1.95	1.31	0.65	0.03	1.20
Air inlet temp, F	110	131	136	124	115	114	123
Humidity, grains/lb	84	82	74	88	76	72	80
Total engine hours, h	2.1	2.7	3.2	3.7	4.1	4.6	4.6
HC ppmc wet	12700	2467	2567	3633	4267	9300	4355
CO % wet	8.34	6.61	6.46	6.91	6.25	7.38	6.70
CO2 % wet	7.67	8.92	9.01	8.77	9.19	8.32	8.87
NOx ppm wet	35.6	423	279	241	139	70.1	212
O2 % wet	0.45	0.12	0.11	0.13	0.13	0.27	0.15
J1088 RESULTS							
THC, g/h	13.9	12.8	11.3	13.3	11.7	19.0	12.8
THC, g/hp-h		4.91	5.80	10.1	18.0		10.6
CH4, g/h	1.18	1.47	1.29	1.51	1.15	2.21	1.39
CH4, g/hp-h		0.57	0.66	1.15	1.76		1.15
RHC, g/h	12.8	11.3	10.0	11.7	10.5	16.8	11.4
RHC, g/hp-h		4.34	5.14	8.95	16.2		9.48
CO, g/h	185	691	575	509	345	304	459
CO, g/hp-h		266	295	388	531		382
NOx, g/h	0.14	7.52	4.05	3.10	1.27	0.47	2.81
NOx, g/hp-h		2.89	2.08	2.36	1.95		2.33
CO2, g/h	267	1464	1260	1015	798	538	969
CO2, g/hp-h		563	647	773	1228		806
Fuel, lb/h	0.42	1.80	1.53	1.29	0.96	0.75	1.20
Fuel, lb/hp-h		0.69	0.78	0.98	1.47		1.00
DILUTE PARTICULATE							
PM, g/h	0.30	2.52	1.67	0.69	0.54	0.94	1.01
PM, g/hp-h		0.98	0.86	0.53	0.83		0.84

Engine # / run # 4.5HP, WBM, OHV #2	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	10.4	11.7	11.9	11.5	11.6	10.7	11.5
Fuel flow rate, lb/h	0.41	1.79	1.51	1.27	0.94	0.74	1.19
Engine speed, rpm	1967	3200	3210	3200	3207	3197	3142
Engine torque, lb-ft	0.14	4.26	3.23	2.15	1.05	0.08	1.98
Power output, hp	0.05	2.60	1.97	1.31	0.64	0.05	1.21
Air inlet temp, F	106	133	136	129	120	114	126
Humidity, grains/lb	76	79	86	86	70	74	79
Total engine hours, h	5.5	6.2	6.6	7.0	7.3	7.7	7.7
HC ppmc wet	11467	2300	1700	3300	3833	10867	3988
CO % wet	8.24	6.27	5.98	6.48	6.23	7.37	6.44
CO2 % wet	7.75	9.19	9.29	9.01	9.16	8.35	9.02
NOx ppm wet	41.8	449	374	282	139	66.5	245
O2 % wet	0.37	0.09	0.09	0.13	0.15	0.27	0.15
J1088 RESULTS							
THC, g/h	12.5	11.9	7.53	12.0	10.4	21.6	11.3
THC, g/hp-h		4.59	3.82	9.15	16.2		9.37
CH4, g/h	1.53	1.54	1.14	1.26	1.08	2.14	1.28
CH4, g/hp-h		0.59	0.58	0.96	1.68		1.06
RHC, g/h	11.0	10.4	6.40	10.7	9.29	19.5	10.0
RHC, g/hp-h		4.00	3.24	8.19	14.5		8.31
CO, g/h	181	657	536	476	340	296	436
CO, g/hp-h		253	272	363	531		361
NOx, g/h	0.15	7.88	5.79	3.58	1.22	0.44	3.31
NOx, g/hp-h		3.03	2.94	2.73	1.90		2.74
CO2, g/h	268	1512	1307	1041	786	527	985
CO2, g/hp-h		582	663	793	1226		816
Fuel, lb/h	0.41	1.79	1.51	1.27	0.94	0.74	1.19
Fuel, lb/hp-h		0.69	0.77	0.97	1.47		0.98
DILUTE PARTICULATE							
PM, g/h	0.07	1.97	1.14	0.49	0.25	0.59	0.67
PM, g/hp-h		0.76	0.58	0.38	0.39		0.55

Appendix A-4. 4.5-Hp OHV WBM Propane Engine

Engine # / run #	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
4.5HP, OHV, Propane #1							
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	10.0	14.2	14.4	14.4	12.8	10.8	13.5
Fuel flow rate, lb/h	0.45	1.30	1.24	0.84	0.84	0.68	0.93
Engine speed, rpm	2130	3200	3200	3200	3200	3167	3144
Engine torque, lb-ft	0.00	4.19	3.11	2.13	1.05	0.017	1.93
Power output, hp	0.00	2.55	1.90	1.30	0.64	0.01	1.18
Air inlet temp, F	111	133	134	129	118	112	125
Humidity, grains/lb	98	98	90	90	90	91	91
Total engine hours, h	2.3	2.9	3.3	3.8	4.3	5.0	5.0
HC ppmc wet	19400	1400	1300	1300	2100	8400	2951
CO % wet	8.50	2.59	2.16	2.20	5.01	8.03	3.79
CO2 % wet	5.50	9.70	9.99	9.93	8.10	6.16	8.89
NOx ppm wet	5.69	1098	1097	718	109	23.9	561
O2 % wet	0.99	0.13	0.08	0.13	0.13	0.42	0.18
J1088 RESULTS							
THC, g/h	25.0	6.64	5.97	4.05	6.04	17.2	7.23
THC, g/hp-h		2.60	3.15	3.13	9.47		6.14
CH4, g/h	5.30	0.56	0.98	0.34	0.93	3.20	1.11
CH4, g/hp-h		0.22	0.51	0.26	1.46		0.94
RHC, g/h	19.7	6.08	4.99	3.71	5.11	14.0	6.12
RHC, g/hp-h		2.38	2.63	2.87	8.01		5.20
CO, g/h	208	234	189	131	274	314	212
CO, g/hp-h		92	100	101	430		180
NOx, g/h	0.03	18.4	16.9	7.53	1.06	0.17	7.55
NOx, g/hp-h		7.18	8.93	5.81	1.66		6.42
CO2, g/h	212	1377	1374	926	698	378	914
CO2, g/hp-h		539	724	715	1094		776
Fuel, lb/h	0.45	1.30	1.24	0.84	0.84	0.68	0.93
Fuel, lb/hp-h		0.51	0.66	0.65	1.32		0.79
DILUTE PARTICULATE							
PM, g/h	0.04	2.40	2.83	0.41	0.11	0.06	0.94
PM, g/hp-h		0.94	1.48	0.32	0.18		0.80

Engine # / run #	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
4.5HP, OHV, Propane #2							
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	9.38	14.2	14.5	14.7	13.0	11.1	13.6
Fuel flow rate, lb/h	0.59	1.19	1.05	0.76	0.72	0.65	0.83
Engine speed, rpm	2197	3200	3200	3200	3200	3220	3151
Engine torque, lb-ft	0.00	4.02	3.03	1.98	1.00	0.00	1.84
Power output, hp	0.00	2.45	1.84	1.20	0.61	0.00	1.12
Air inlet temp, F	105	136	135	130	123	116	127
Humidity, grains/lb	86	87	83	83	82	81	83
Total engine hours, h	5.9	6.5	6.9	7.3	7.7	8.1	8.1
HC ppmc wet	26600	1167	1100	1233	2167	7167	3164
CO % wet	9.03	2.31	1.96	1.57	4.80	7.66	3.48
CO2 % wet	5.04	9.98	10.1	10.4	8.19	6.34	9.09
NOx ppm wet	2.65	1054	1055	949	105	31.6	615
O2 % wet	1.10	0.07	0.08	0.13	0.17	0.39	0.19
J1088 RESULTS							
THC, g/h	42.4	5.06	4.31	3.53	5.39	14.4	7.09
THC, g/hp-h		2.06	2.34	2.93	8.83		6.32
CH4, g/h	8.74	0.66	0.47	0.31	0.77	2.43	1.08
CH4, g/hp-h		0.27	0.25	0.26	1.25		0.96
RHC, g/h	33.7	4.40	3.85	3.22	4.63	12.0	6.01
RHC, g/hp-h		1.80	2.09	2.68	7.57		5.36
CO, g/h	274	191	146	85.7	228	294	174
CO, g/hp-h		78.1	79.4	71.1	372		155
NOx, g/h	0.01	15.2	13.5	8.83	0.84	0.21	6.89
NOx, g/hp-h		6.20	7.31	7.33	1.38		6.14
CO2, g/h	241	1296	1189	893	610	382	835
CO2, g/hp-h		529	645	741	998		744
Fuel, lb/h	0.59	1.19	1.05	0.76	0.72	0.65	0.83
Fuel, lb/hp-h		0.48	0.57	0.63	1.19		0.74
DILUTE PARTICULATE							
PM, g/h	0.02	1.34	1.03	0.35	0.08	0.06	0.46
PM, g/hp-h		0.55	0.56	0.29	0.13		0.41

Appendix A-5. 11-Hp OHV Utility Engine

Engine # / run #	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	WEIGHTED
11HP, Utility, OHV #1	MODE 1	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.3	11.1	12.0	12.5	12.7	10.1	11.9
Fuel flow rate, lb/h	0.92	6.30	4.36	3.31	2.46	2.35	3.35
Engine speed, rpm	1060	3600	3607	3600	3607	3637	3479
Engine torque, lb-ft	0.05	12.9	9.69	6.52	3.23	0.38	5.99
Power output, hp	0.01	8.86	6.65	4.47	2.22	0.26	4.11
Air inlet temp, F	84.0	86	91	85	81	81	85
Humidity, grains/lb	92.3	71	63	83	78	79	76
Total engine hours, h	4.9	1.5	2.3	2.9	3.4	4.1	4.1
HC ppmc wet	56200	1700	1400	1583	1707	5767	4618
CO % wet	10.8	7.71	5.25	4.35	3.73	9.47	5.33
CO2 % wet	5.99	8.34	9.99	10.5	10.9	7.41	9.87
NOx ppm wet	5.86	179	377	328	168	45.4	240
O2 % wet	1.31	0.07	0.06	0.07	0.07	0.13	0.13
J1088 RESULTS							
THC, g/h	105	29.9	18.0	15.9	12.9	35.3	22.5
THC, g/hp-h		3.38	2.71	3.55	5.80		5.47
CH4, g/h	0.12	5.04	2.49	1.99	1.75	6.96	2.55
CH4, g/hp-h		0.57	0.37	0.44	0.79		0.62
RHC, g/h	105	24.9	15.5	13.9	11.1	28.3	19.9
RHC, g/hp-h		2.81	2.33	3.11	5.01		4.85
CO, g/h	407	2741	1365	881	569	1170	1048
CO, g/hp-h		309	205	197	256		255
NOx, g/h	0.04	10.2	15.2	11.3	4.26	0.94	8.60
NOx, g/hp-h		1.16	2.29	2.54	1.92		2.09
CO2, g/h	355	4661	4081	3336	2600	1439	3102
CO2, g/hp-h		526	614	746	1172		755
Fuel, lb/h	0.92	6.30	4.36	3.31	2.46	2.35	3.35
Fuel, lb/hp-h		0.71	0.66	0.74	1.11		0.81
DILUTE PARTICULATE							
PM, g/h	0.00	0.28	0.15	0.07	0.08	0.05	0.10
PM, g/hp-h		0.03	0.02	0.02	0.04		0.03

Engine # / run #	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	AVERAGE	WEIGHTED
11HP, Utility, OHV #2	MODE 1	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.3	11.1	12.1	12.5	12.8	10.2	12.0
Fuel flow rate, lb/h	0.92	6.24	4.48	3.33	2.42	2.35	3.36
Engine speed, rpm	1060	3600	3600	3590	3607	3593	3472
Engine torque, lb-ft	0.05	13.1	9.80	6.50	3.31	0.317	6.04
Power output, hp	0.01	8.95	6.72	4.44	2.28	0.217	4.14
Air inlet temp, F	84.0	79	84	83	82	80	82
Humidity, grains/lb	92.3	80	81	81	80	79	81
Total engine hours, h	4.9	5.2	5.8	6.2	6.6	7.2	7.2
HC ppmc wet	56200	2320	1973	1900	2000	6233	5001
CO % wet	10.8	7.55	5.14	4.37	3.90	9.35	5.34
CO2 % wet	5.99	8.49	9.94	10.41	10.57	7.24	9.75
NOx ppm wet	5.86	200	377	345	161	42.8	245
O2 % wet	1.31	0.08	0.09	0.09	0.09	0.14	0.15
J1088 RESULTS							
THC, g/h	105	40.3	26.2	19.2	14.9	38.7	26.9
THC, g/hp-h		4.50	3.90	4.31	6.57		6.49
CH4, g/h	8.14	7.01	3.69	2.48	1.93	8.36	3.66
CH4, g/hp-h		0.78	0.55	0.56	0.85		0.88
RHC, g/h	96.8	33.3	22.5	16.7	13.0	30.3	23.2
RHC, g/hp-h		3.72	3.35	3.75	5.72		5.61
CO, g/h	407	2652	1379	889	589	1171	1051
CO, g/hp-h		296	205	200	259		254
NOx, g/h	0.04	11.8	17.1	11.9	4.10	0.897	9.22
NOx, g/hp-h		1.32	2.55	2.67	1.80		2.23
CO2, g/h	355	4683	4193	3331	2506	1426	3095
CO2, g/hp-h		523	624	750	1102		748
Fuel, lb/h	0.92	6.24	4.48	3.33	2.42	2.35	3.36
Fuel, lb/hp-h		0.70	0.67	0.75	1.06		0.81
DILUTE PARTICULATE							
PM, g/h	0.08	0.35	0.17	0.12	0.07	0.08	0.13
PM, g/hp-h		0.04	0.03	0.03	0.03		0.03

Appendix A-6. 12-Hp Side Valve Engine

Engine # / run # 12HP, Side Valve #1	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	11.6	12.6	13.3	13.1	11.9	13.1	12.7
Fuel flow rate, lb/h	0.87	6.50	4.99	4.19	3.52	2.48	4.07
Engine speed, rpm	1397	3500	3500	3500	3500	3467	3393
Engine torque, lb-ft	0.26	14.3	10.6	7.10	3.51	0.26	6.54
Power output, hp	0.07	9.50	7.04	4.73	2.34	0.17	4.35
Air inlet temp, F	78	83	81	78	77	74	78
Humidity, grains/lb	63	53	50	49	52	52	51
Total engine hours, h	2.1	3.6	4.6	5.2	5.8	6.2	6.2
HC ppmc wet	15400	2200	1833	2100	3100	3400	3112
CO % wet	6.60	4.47	3.01	4.03	6.36	3.89	4.68
CO2 % wet	7.43	10.1	11.0	10.1	8.70	10.1	9.74
NOx ppm wet	27.0	940	1176	539	114	81.8	517
O2 % wet	2.71	0.39	0.48	0.60	0.70	1.02	0.72
J1088 RESULTS							
THC, g/h	38.8	43.9	29.1	27.8	32.2	26.8	31.3
THC, g/hp-h		4.62	4.14	5.87	13.8		7.19
CH4, g/h	3.19	7.06	3.88	3.82	4.54	3.26	4.27
CH4, g/hp-h		0.74	0.55	0.81	1.94		0.98
RHC, g/h	35.6	36.8	25.3	24.0	27.6	23.5	27.0
RHC, g/hp-h		3.88	3.59	5.06	11.8		6.21
CO, g/h	336	1802	967	1078	1333	618	1128
CO, g/hp-h		190	137	228	570		259
NOx, g/h	0.21	56.4	55.5	21.1	3.54	1.93	23.5
NOx, g/hp-h		5.94	7.89	4.46	1.51		5.40
CO2, g/h	595	6383	5568	4244	2866	2520	3985
CO2, g/hp-h		672	791	897	1225		916
Fuel, lb/h	0.87	6.50	4.99	4.19	3.52	2.48	4.07
Fuel, lb/hp-h		0.68	0.71	0.88	1.50		0.93
DILUTE PARTICULATE							
PM, g/h	0.08	0.64	0.32	0.24	0.21	0.08	0.26
PM, g/hp-h		0.07	0.05	0.05	0.09		0.06

Engine # / run # 12HP, Side valve #2	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	11.6	12.2	12.9	12.6	12.1	13.0	12.5
Fuel flow rate, lb/h	0.87	6.54	5.13	4.26	3.59	2.50	4.15
Engine speed, rpm	1403	3500	3500	3500	3500	3540	3398
Engine torque, lb-ft	0.12	14.2	10.6	7.09	3.56	0.147	6.54
Power output, hp	0.03	9.47	7.07	4.73	2.37	0.099	4.36
Air inlet temp, F	72	84	81	80	77	75	79
Humidity, grains/lb	77	65	59	60	56	57	59
Total engine hours, h	7.2	12.0	9.5	10.0	10.4	11.0	11.0
HC ppmc wet	15167	1850	1897	2200	1600	1600	2534
CO % wet	6.38	5.05	3.95	4.63	6.21	4.55	5.09
CO2 % wet	7.73	9.97	10.5	9.99	8.76	9.65	9.59
NOx ppm wet	29.5	821	924	447	116	79.3	430
O2 % wet	2.55	0.46	0.55	0.66	0.80	1.11	0.79
J1088 RESULTS							
THC, g/h	38.0	38.1	30.1	28.6	17.2	12.6	25.5
THC, g/hp-h		3.81	4.26	6.06	7.27		5.86
CH4, g/h	2.74	6.62	4.58	4.20	5.10	3.83	4.67
CH4, g/hp-h		0.70	0.65	0.89	2.15		1.07
RHC, g/h	35.3	29.4	25.6	24.4	12.1	8.81	20.9
RHC, g/hp-h		3.11	3.62	5.17	5.11		4.79
CO, g/h	323	1989	1267	1219	1351	725	1258
CO, g/hp-h		210	179	258	569		289
NOx, g/h	0.25	50.7	45.2	18.0	3.82	1.91	20.1
NOx, g/hp-h		5.35	6.40	3.81	1.61		4.62
CO2, g/h	616	6171	5295	4130	2996	2419	3911
CO2, g/hp-h		652	749	874	1263		898
Fuel, lb/h	0.87	6.54	5.13	4.26	3.59	2.50	4.15
Fuel, lb/hp-h		0.69	0.73	0.90	1.51		0.95
DILUTE PARTICULATE							
PM, g/h	0.03	0.69	0.36	0.19	0.13	0.10	0.24
PM, g/hp-h		0.07	0.05	0.04	0.06		0.05

Appendix A-7. 18-Hp Side Valve 2-Cylinder Engine

Engine # / run # 18HP, Side Valve, 2 Cyl. #1	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	11.6	11.5	11.5	12.4	12.2	11.9	12.0
Fuel flow rate, lb/h	1.84	12.5	10.09	7.31	5.87	4.79	7.45
Engine speed, rpm	1570	3600	3600	3600	3600	3667	3503
Engine torque, lb-ft	0.04	22.7	17.2	11.3	5.51	0.08	10.4
Power output, hp	0.01	15.6	11.8	7.75	3.77	0.05	7.15
Air inlet temp, F	69	80	85	86	83	82	83
Humidity, grains/lb	74	75	82	82	80	77	80
Total engine hours, h	9.1	10.1	10.7	12.0	12.6	13.2	13.2
HC ppmc wet	17600	1653	1780	1783	2650	3893	2970
CO % wet	4.75	7.05	6.80	4.58	5.01	5.47	5.44
CO2 % wet	9.34	8.65	8.83	10.3	9.95	9.63	9.65
NOx ppm wet	39.4	348	257	346	134	89.4	232
O2 % wet	1.33	0.08	0.09	0.10	0.10	0.22	0.17
J1088 RESULTS							
THC, g/h	92.8	59.0	51.6	39.4	46.4	54.6	49.4
THC, g/hp-h		3.79	4.37	5.08	12.3		6.92
CH4, g/h	5.27	13.4	9.09	5.49	5.33	7.08	6.97
CH4, g/hp-h		0.86	0.77	0.71	1.41		0.98
RHC, g/h	87.5	45.7	42.5	33.9	41.0	47.5	42.4
RHC, g/hp-h		2.93	3.60	4.37	10.9		5.94
CO, g/h	505	5086	3977	2042	1770	1549	2510
CO, g/hp-h		327	337	263	469		351
NOx, g/h	0.69	41.3	25.5	26.2	8.00	4.20	19.2
NOx, g/hp-h		2.66	2.16	3.38	2.12		2.68
CO2, g/h	1562	9808	8119	7188	5529	4285	6628
CO2, g/hp-h		630	688	927	1465		927
Fuel, lb/h	1.84	12.5	10.1	7.31	5.87	4.79	7.45
Fuel, lb/hp-h		0.80	0.86	0.94	1.56		1.04
DILUTE PARTICULATE							
PM, g/h	0.70	8.65	2.40	0.83	0.35	0.25	1.66
PM, g/hp-h		0.55	0.20	0.11	0.09		0.23

Engine # / run # 18HP, Side valve, 2 Cyl. #2	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	12.2	11.4	11.6	12.5	12.2	11.4	12.0
Fuel flow rate, lb/h	1.86	12.5	9.88	7.39	5.84	4.52	7.41
Engine speed, rpm	1627	3600	3600	3600	3600	3510	3495
Engine torque, lb-ft	0.09	22.2	16.7	11.1	5.49	0.14	10.2
Power output, hp	0.03	15.2	11.5	7.64	3.76	0.09	7.02
Air inlet temp, F	74	86	86	86	85	85	85
Humidity, grains/lb	107	113	108	107	106	106	107
Total engine hours, h	14.4	15.6	16.3	16.9	17.5	18.1	18.1
HC ppmc wet	13967	1593	1677	1567	2253	4860	2648
CO % wet	4.05	7.04	6.56	4.50	5.07	7.93	5.53
CO2 % wet	9.81	8.73	9.01	10.3	9.95	7.28	9.55
NOx ppm wet	33.2	327	255	308	114	66.0	210
O2 % wet	1.20	0.08	0.08	0.09	0.11	0.28	0.16
J1088 RESULTS							
THC, g/h	77.2	56.7	47.7	35.2	39.2	63.5	44.9
THC, g/hp-h		3.72	4.17	4.61	10.4		6.40
CH4, g/h	4.47	10.5	7.85	4.98	5.30	8.25	6.35
CH4, g/hp-h		0.69	0.69	0.65	1.41		0.90
RHC, g/h	72.7	46.3	39.9	30.2	33.9	55.3	38.6
RHC, g/hp-h		3.04	3.48	3.96	9.01		5.50
CO, g/h	453	5066	3773	2042	1780	2093	2506
CO, g/hp-h		333	329	267	473		357
NOx, g/h	0.72	47.2	28.6	27.1	7.68	3.35	20.4
NOx, g/hp-h		3.10	2.49	3.55	2.04		2.91
CO2, g/h	1725	9871	8141	7315	5492	3021	6584
CO2, g/hp-h		648	710	958	1460		938
Fuel, lb/h	1.86	12.5	9.88	7.39	5.84	4.52	7.41
Fuel, lb/hp-h		0.82	0.86	0.97	1.55		1.06
DILUTE PARTICULATE							
PM, g/h	0.32	4.30	1.67	0.67	0.51	0.35	1.11
PM, g/hp-h		0.28	0.15	0.09	0.13		0.16

Appendix A-8. 5-Hp 2-Stroke WBM Engine

Engine # / run # 5HP, WBM #1	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.79	11.1	10.4	10.4	11.0	10.6	10.5
Fuel flow rate, lb/h	0.52	3.05	2.64	2.02	1.20	0.87	1.84
Engine speed, rpm	963	3250	3250	3253	3243	3250	3135
Engine torque, lb-ft	0.03	4.46	3.39	2.25	1.11	0.08	2.07
Power output, hp	0.01	2.76	2.10	1.40	0.69	0.05	1.28
Air inlet temp, F	86	147	139	115	99	94	115
Humidity, grains/lb	81	96	82	78	89	99	85
Total engine hours, h	1.1	2.0	2.5	2.9	3.4	3.9	3.9
HC ppmc wet	130900	54300	53900	51833	42900	58700	54223
CO % wet	5.17	4.61	6.06	6.43	5.50	4.91	5.74
CO2 % wet	3.26	6.26	5.77	5.62	6.69	6.17	5.95
NOx ppm wet	7.83	48.7	24.5	21.9	13.6	11.7	20.9
O2 % wet	9.32	5.94	5.22	4.93	4.30	5.74	5.17
J1088 RESULTS							
THC, g/h	143	461	375	276	141	136	256
THC, g/hp-h		167	179	198	206		199
CH4, g/h	5.82	2.39	4.57	5.60	3.64	3.74	4.40
CH4, g/hp-h		0.87	2.18	4.01	5.29		3.43
RHC, g/h	137	458	371	270	138	132	251
RHC, g/hp-h		166	177	194	200		196
CO, g/h	114	791	851	692	366	230	574
CO, g/hp-h		287	406	496	532		447
NOx, g/h	0.03	1.37	0.57	0.39	0.15	0.09	0.40
NOx, g/hp-h		0.50	0.27	0.28	0.22		0.31
CO2, g/h	113	1686	1275	949	699	454	929
CO2, g/hp-h		611	608	680	1017		724
Fuel, lb/h	0.52	3.05	2.64	2.02	1.20	0.87	1.84
Fuel, lb/hp-h		1.11	1.26	1.45	1.74		1.43
DILUTE PARTICULATE							
PM, g/h	4.53	15.3	10.3	9.70	6.02	5.94	8.70
PM, g/hp-h		5.56	4.91	6.91	8.69		6.78

Engine # / run # 5HP, WBM #2	AVERAGE MODE 1	AVERAGE MODE 3	AVERAGE MODE 4	AVERAGE MODE 5	AVERAGE MODE 6	AVERAGE MODE 7	WEIGHTED J1088
Weighting Factor	5%	9%	20%	29%	30%	7%	
Air/fuel ratio	7.31	10.9	10.4	10.3	12.4	10.5	10.9
Fuel flow rate, lb/h	0.52	3.07	2.64	1.91	1.24	0.88	1.82
Engine speed, rpm	970	3250	3250	3250	3250	3257	3136
Engine torque, lb-ft	0.04	4.64	3.48	2.31	1.15	0.10	2.14
Power output, hp	0.01	2.87	2.15	1.43	0.71	0.06	1.32
Air inlet temp, F	85	139	134	127	95	92	115
Humidity, grains/lb	84	74	72	88	70	88	78
Total engine hours, h	4.4	4.9	5.3	5.7	6.1	6.4	6.4
HC ppmc wet	138067	55600	54100	51200	26400	60567	49735
CO % wet	5.58	4.89	6.01	6.50	5.54	5.00	5.82
CO2 % wet	3.27	6.17	5.77	5.75	6.73	6.00	5.98
NOx ppm wet	2.75	45.4	26.0	21.7	15.4	11.2	21.1
O2 % wet	8.98	5.83	5.27	4.74	4.25	5.82	5.09
J1088 RESULTS							
THC, g/h	145	466	377	256	100	141	239
THC, g/hp-h		162	175	179	140		181
CH4, g/h	6.15	2.48	5.01	6.50	5.03	4.37	5.23
CH4, g/hp-h		0.862	2.33	4.56	7.07		3.96
RHC, g/h	138	464	372	249	95	137	233
RHC, g/hp-h		162	173	174	133		177
CO, g/h	118	829	846	655	422	236	583
CO, g/hp-h		289	393	459	593		441
NOx, g/h	0.01	1.27	0.60	0.36	0.19	0.09	0.40
NOx, g/hp-h		0.44	0.28	0.25	0.27		0.30
CO2, g/h	109	1642	1278	910	806	445	946
CO2, g/hp-h		572	594	638	1133		716
Fuel, lb/h	0.52	3.07	2.64	1.91	1.24	0.88	1.82
Fuel, lb/hp-h		1.07	1.23	1.34	1.74		1.38
DILUTE PARTICULATE							
PM, g/h	6.99	21.9	12.3	9.67	6.24	5.37	9.83
PM, g/hp-h		7.60	5.72	6.74	8.77		7.44

Appendix A-9. 0.8-Hp 2-Stroke Trimmer Engine

Engine # / run #	AVERAGE	AVERAGE	WEIGHTED
0.8HP, Trimmer #1	MODE 1	MODE 2	J1088
Weighting Factor	10%	90%	
Air/fuel ratio	11.6	12.4	12.3
Fuel flow rate, lb/h	0.33	0.97	0.91
Engine speed, rpm	2613	7200	6741
Engine torque, lb-ft	0.16	0.59	0.55
Power output, hp	0.08	0.81	0.73
Air inlet temp, F	74	88	86
Humidity, grains/lb	72	73	73
Total engine hours, h	2.3	2.8	2.7
HC ppmc wet	61600	45100	46750
CO % wet	3.74	3.22	3.27
CO2 % wet	5.78	7.25	7.10
NOx ppm wet	13.5	92.8	84.9
O2 % wet	7.63	5.67	5.87
J1088 RESULTS			
THC, g/h	58	133	126
THC, g/hp-h		165	171
CH4, g/h	1.12	0.87	0.89
CH4, g/hp-h		1.08	1.22
RHC, g/h	57	132	125
RHC, g/hp-h		164	170
CO, g/h	72	192	180
CO, g/hp-h		238	245
NOx, g/h	0.04	0.91	0.82
NOx, g/hp-h		1.13	1.12
CO2, g/h	174	679	629
CO2, g/hp-h		843	857
Fuel, lb/h	0.33	0.97	0.91
Fuel, lb/hp-h		1.21	1.24
DILUTE PARTICULATE			
PM, g/h	1.22	5.52	5.09
PM, g/hp-h		6.98	6.94

Engine # / run #	AVERAGE	AVERAGE	WEIGHTED
0.8HP, Trimmer #2	MODE 1	MODE 2	J1088
Weighting Factor	10%	90%	
Air/fuel ratio	11.6	11.9	11.9
Fuel flow rate, lb/h	0.28	0.98	0.91
Engine speed, rpm	3403	7200	6820
Engine torque, lb-ft	0.07	0.59	0.54
Power output, hp	0.05	0.81	0.73
Air inlet temp, F	73	79	79
Humidity, grains/lb	71	63	64
Total engine hours, h	3.8	4.3	4.3
HC ppmc wet	71367	44300	47007
CO % wet	3.20	4.04	3.96
CO2 % wet	5.35	7.03	6.86
NOx ppm wet	16.0	81.8	75.2
O2 % wet	8.87	5.30	5.65
J1088 RESULTS			
THC, g/h	57.9	127	120
THC, g/hp-h		157	164
CH4, g/h	0.84	0.82	0.82
CH4, g/hp-h		1.01	1.12
RHC, g/h	57.1	126	119
RHC, g/hp-h		156	163
CO, g/h	52.4	234	216
CO, g/hp-h		290	295
NOx, g/h	0.04	0.78	0.71
NOx, g/hp-h		0.96	0.96
CO2, g/h	138	640	589
CO2, g/hp-h		791	805
Fuel, lb/h	0.28	0.98	0.91
Fuel, lb/hp-h		1.21	1.24
DILUTE PARTICULATE			
PM, g/h	0.90	2.79	2.60
PM, g/hp-h		3.46	3.55

Engine # / run #	AVERAGE	AVERAGE	WEIGHTED
0.8HP, Trimmer #3	MODE 1	MODE 2	J1088
Weighting Factor	10%	90%	
Air/fuel ratio	10.2	11.2	11.1
Fuel flow rate, lb/h	0.26	0.91	0.85
Engine speed, rpm	3300	7000	6630
Engine torque, lb-ft	0.09	0.59	0.54
Power output, hp	0.06	0.79	0.71
Air inlet temp, F	73	89	87
Humidity, grains/lb	85	74	75
Total engine hours, h	5.4	6.0	5.9
HC ppmc wet	79867	48167	51337
CO % wet	4.22	4.23	4.22
CO2 % wet	5.21	7.23	7.03
NOx ppm wet	12.5	73.6	67.5
O2 % wet	8.03	5.14	5.43
J1088 RESULTS			
THC, g/h	54.3	123	116
THC, g/hp-h		156	162
CH4, g/h	1.26	0.84	0.88
CH4, g/hp-h		1.07	1.24
RHC, g/h	53.0	122	115
RHC, g/hp-h		155	161
CO, g/h	57.9	217	201
CO, g/hp-h		276	282
NOx, g/h	0.03	0.62	0.56
NOx, g/hp-h		0.79	0.79
CO2, g/h	112	584	537
CO2, g/hp-h		742	752
Fuel, lb/h	0.26	0.91	0.85
Fuel, lb/hp-h		1.16	1.19
DILUTE PARTICULATE			
PM, g/h	0.80	3.25	3.01
PM, g/hp-h		4.13	4.21

Engine # / run #	AVERAGE	AVERAGE	WEIGHTED
0.8HP, Trimmer #4	MODE 1	MODE 2	J1088
Weighting Factor	10%	90%	
Air/fuel ratio	9.9	11.5	11.4
Fuel flow rate, lb/h	0.24	0.98	0.90
Engine speed, rpm	3250	6900	6535
Engine torque, lb-ft	0.03	0.57	0.52
Power output, hp	0.02	0.75	0.68
Air inlet temp, F	71	83	82
Humidity, grains/lb	78	70	70
Total engine hours, h	7.4	8.0	7.9
HC ppmc wet	82533	46700	50283
CO % wet	4.10	4.09	4.09
CO2 % wet	5.63	7.17	7.02
NOx ppm wet	12.4	73.4	67.3
O2 % wet	8.10	5.23	5.51
J1088 RESULTS			
THC, g/h	49.9	130	122
THC, g/hp-h		173	180
CH4, g/h	1.18	0.78	0.82
CH4, g/hp-h		1.0	1.21
RHC, g/h	48.8	129	121
RHC, g/hp-h		172	178
CO, g/h	50.1	229	211
CO, g/hp-h		305	312
NOx, g/h	0.02	0.68	0.61
NOx, g/hp-h		0.90	0.90
CO2, g/h	108	632	580
CO2, g/hp-h		842	856
Fuel, lb/h	0.24	0.98	0.90
Fuel, lb/hp-h		1.30	1.33
DILUTE PARTICULATE			
PM, g/h	0.56	2.53	2.34
PM, g/hp-h		3.41	3.45

is normally used to slow the machine in tight quarters and for changing direction.

HAULING UNITS, such as scrapers and bottom-dump wagons are normally designed with a single foot accelerator. These machines operate in a variety of conditions, varying mainly in loading methods, materials, length of haul, grades, haul road condition (rolling resistance) and whether loads are discharged quickly or spread in light lifts, as in finishing grading. Self-loading scrapers - elevator or auger type - will be at or near full load and speed during the loading function, while push-loaded scrapers will be operated at reduced throttle, depending on ground conditions, in order to avoid tire slippage and undue wear. The push tractor will do most of the work during loading. Once loaded, both types will operate at highest possible speeds during the haul portion of the cycle, again subject to road conditions - grade, surface condition, traffic and length of haul. All haulers, of whatever type, are limited as to haul distance and speed because of tire heat limitations. Tire rating systems have been worked out, based on ton-mile per hour, to deal with these limitations. Once again, it would be difficult to identify a typical work cycle for scrapers due to the variables involved.

OFF-HIGHWAY TRUCKS generally have a single, foot-operated accelerator-type throttle control. These machines are subject to most of the same variables as scrapers and wagons; grade, rolling resistance tire limitations, etc. Because off-highway trucks are designed to be top loaded by a shovel or wheel-type loader, as opposed to being self-loading, they tend to operate at higher haul speeds over greater haul distances. Also because of their tire design, they operate on improved haul roads, generally, allowing for higher speed operation. Because they are designed with either power shift transmissions or electric drive systems, engine speeds are kept at or near maximum except for maneuvering or during wait periods for loading and dumping.

FRONT END LOADERS range in size from 1 to 15 cubic yards and cover a range of horsepower ratings from 50 to approximately 600. Since these machines are used in loading functions (a limited number may be found in so-called load and carry applications) the cycle is of fairly short duration and the distance travelled usually quite short. These units are employed in loading material out of a stock pile or bank excavation, into hauling unit. Other applications may include sorting or classifying aggregate and charging bins or hoppers in batch plants or paving operations.

Almost all wheel-type front end loaders are designed with a foot-operated accelerator-type throttle control. Track-type loaders will normally have a hand throttle and a foot throttle to override the hand throttle setting. Except in leveling or clean-up work, loaders of both types are employed in production loading where the objective is to operate the unit at maximum output. Wide open throttle is used during most of the work shift, except during maneuvering to dump the load into the hauling unit. Wheel loaders are subject to the same tire slip and excessive tire wear problems as scrapers, particularly where wet and abrasive underfoot conditions are present, resulting in the need to operate at somewhat reduced throttle and load.

EXCAVATORS are designed, for the most part, with a hand throttle and the engine speed is kept at maximum while load is a function of the work being done by the excavator. In a straight trenching or excavating job, the unit will operate for long periods of near full load. In some applications, such as laying pipe, the machine will be operated at low engine speed to permit precise control of the load.

As may be seen, construction machinery operation is widely variable. The nature of the work largely determines the work cycle. With the tremendous variety of machine types and the numerous attachments available, each operation is nearly unique. To select any sort of transient work cycle would be extremely difficult. John Deere provided some numerical data on the typical speed settings, power range, cycle time and load factor for a range of off-road equipment. Of particular relevance to this discussion are the cycle times provided, as shown in Table 3-2. Cycle time is the time between two consecutive work periods, e.g., in a front end loader, it could be the time between two successive periods of filling the loader bucket. Typically, the lowest cycle time provided in Table 3-2 is 10 seconds while a more typical one is in the range of 30 seconds to one minute. In contrast, on-highway trucks have much shorter transients associated with traffic conditions.

One method to address load cycles and duty cycles independent of equipment type is to examine the duty cycle on an engine speed-load map. The throttle control for a diesel sets the governor speed. In a typical "loaded-mode", the throttle will be set to 90 or 100 percent of rated speed (full throttle). The engine accelerates from rest to a rated-speed, rated power point. Typically, the engine is sized for the equipment so that when the machine is working at capacity, it absorbs all the engine horsepower available. As engine RPM drops, the output moves down the full load "lug" line and the equipment's work rate slows (with some delay due to the hydraulic transmission). As the engine slows to near peak engine RPM (typically at 60% of rated RPM) available horsepower is inadequate to continue the work cycle, so that the operator reverses the equipment, allowing the engine to accelerate back to rated RPM, and start a new work cycle. As described earlier, the operator may or may not change throttle position when backing away, depending on the type of transmission.

Another operating mode for the engine is when the equipment is operating unloaded. This can happen when the equipment is moving from one work area to another under "no load" conditions, or, for example, in a load-and-carry work cycle, it returns empty to the work site to pick up another load. Individual equipment manufacturers and the EMA also stated that most off-road equipment had high accessory loads, and that even if the equipment was operating unloaded engines would not be operating at conditions similar to idle on off-

TABLE 3-2
TYPICAL DUTY CYCLES

Machine	Operation	Speed Setting	Power Range	Cycle Time	Load Factor
Backhoe Loader	Backhoe	70-100%	20-80%	10-30 sec.	30-70%
	Loader	80-100%	50-100%	15-30 sec.	40-70%
	Craning	40-60%	10-30%	1-5 min.	15-20%
	Backfilling	60-100%	30-80%	10-30 sec.	30-70%
	Transport	90-100%	80-100%	1-60 min.	60-80%
Excavator	Trenching	70-100%	40-100%	10-30 sec.	40-90%
	Craning	40-60%	10-30%	1-5 min.	15-20%
	Transport	90-100%	90-100%	1-30 min.	80-90%
4WD Loader	Loading	80-100%	60-100%	20-40 sec.	30-60%
	Trenching	80-100%	80-100%	20-45 sec.	60-80%
	Transport	80-100%	80-100%	1-60 min.	60-90%
Crawler Loader	Loading	80-100%	70-100%	20-40 sec.	30-60%
	Trenching	80-100%	90-100%	20-45 sec.	70-90%
	Transport	80-100%	40-80%	1-30 min.	40-60%
Crawler Dozer	Dozing	80-100%	60-100%	.5-5 min.	60-90%
	Ripping	100%	90-100%	.5-5 min.	80-90%
	Backfilling	60-80%	30-60%	10-30 sec.	30-50%
	Transport	80-100%	40-80%	1-30 min.	40-60%
Grader	Rough Grading	80-100%	70-100%	1-10 min.	50-80%
	Finish Grading	50-90%	40-80%	1-10 min.	30-50%
	Ripping	90-100%	80-100%	1-10 min.	70-90%
	Snow Plowing	100%	90-100%	1-60 min.	80-90%
	Transport	80-100%	80-100%	1-60 min.	60-80%
Scraper	Loading	100%	90-100%	1-3 min.	80-90%
	Transport	100%	80-100%	1-5 min.	70-90%
	Unloading	80-100%	70-90%	30-60 sec.	50-60%

Source: John Deere

highway trucks. However, there may be periods such as operator breaks or waiting for job access when the engine is idling. A schematic representation of the operating speeds and loads during a typical working cycle is shown in Figure 3-1.

However, the above discussion must not be understood to imply that all types of off-highway equipment experience engine operation in modes shown in Figure 3-1. For example, motor graders will run at fairly constant intermediate loads that fall between the two regimes described above. Off-highway trucks may see far more variation in load-speed settings than for most other types of off-highway equipment. The enormous variety of equipment and use patterns result in exceptions to any generalized rule formulated.

The discussion does provide two insights particularly useful in formulating a general test cycle for all off-highway applications.

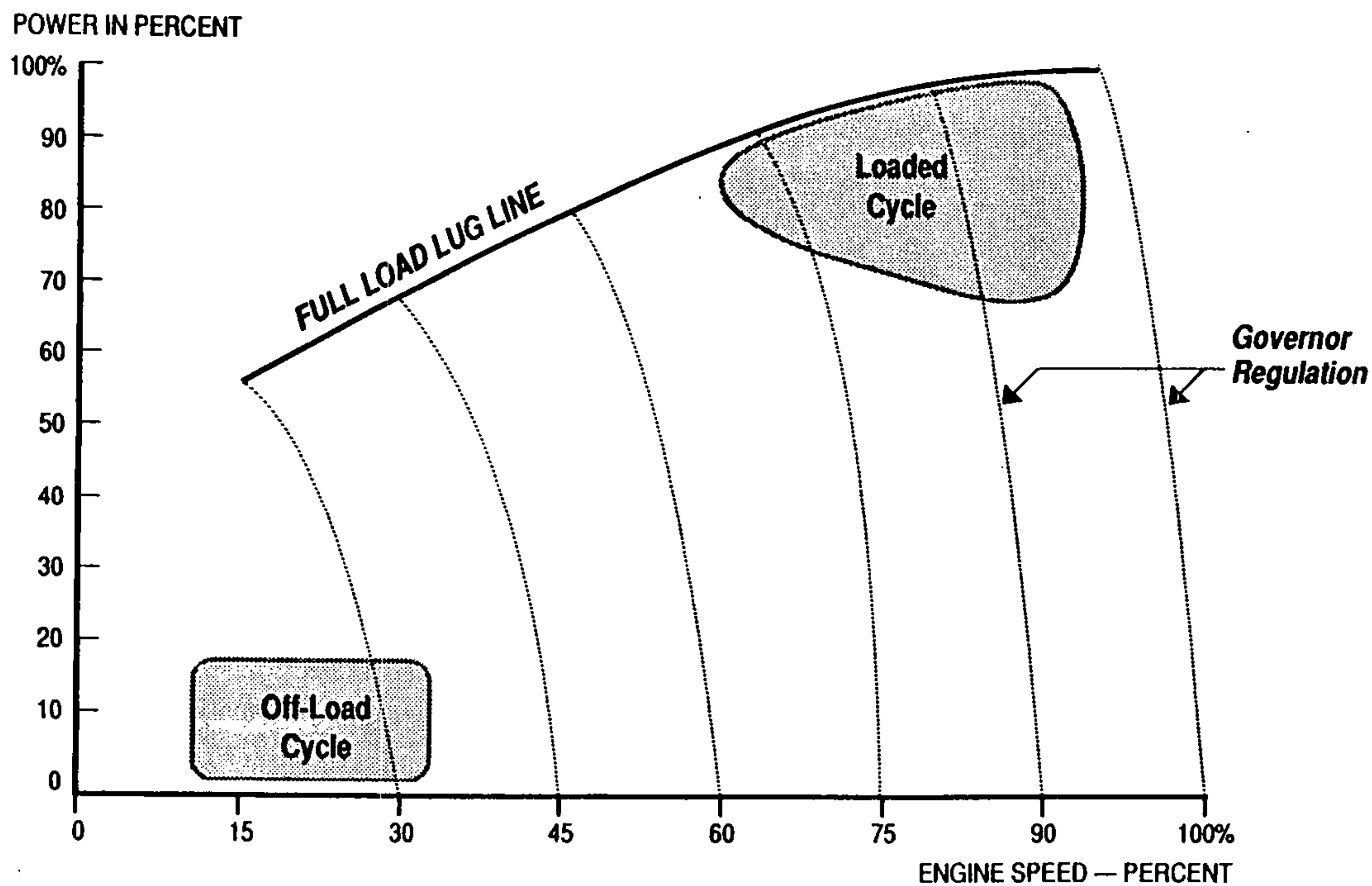
- As a result of a hydraulic interface between engine and drives, most off-highway equipment do not subject the engine to high-frequency transients of load and speed typical of on-highway vehicles. Moreover, the use of hand-throttles and the close match between equipment horsepower requirements and engine size result in operation at fixed throttle under most operating conditions.
- Many, but not all, types of construction equipment usually operate at the engines' rated load/speed point or the full-load "lug down" condition during the loaded part of its working cycle, and at low load/speed conditions during the "off-load" or waiting modes. A test procedure for off-highway construction equipment should emphasize the high load operating points to a greater degree than in the on-highway test procedure.

3.3 RECOMMENDATIONS FOR CERTIFICATION TEST PROCEDURE

The analysis in Section 3.2 has two implications. First, the on-highway transient procedure is not representative of most off-highway engine operation, and a steady-state test is probably a preferred option. This is because slow load-speed variations occurring over a 20 second to 60 second interval

FIGURE 3-1

Schematic Of Construction Equipment Engine Duty Cycles



can be approximated well by a series of steady-state load-speed conditions. Second, a steady-state test for off-highway engines should have a higher average load factor than the load-factor for the on-highway test.

The original CAL/ERT study and the Engine Manufacturer's Association concur with this view. The original CAL/ERT study concluded that the on-highway 13-mode test was an adequate test procedure with reweighting of the individual modes to derive a composite emissions result. Given the extensive experience of many engine manufacturers with the 13-mode test (which was only recently replaced with the transient test) for on-highway engines, it would be economically efficient to transfer the test procedure to the off-highway segment.

More recently, in response to inquiries for EEA, EMA suggested an even more simple 7-mode test procedure. The 7-mode test is essentially the 13-mode test with the very low-load modes (2 and 25 percent load) and two of three idle modes eliminated. In EEA's opinion, the need for three repeated idle modes in the 13-mode sequence was never very well established, as typically in diesel engines the idle mode is quite stable. Based on the engineering analysis of typical off-highway operating conditions, EEA would concur with EMA recommendations of using a simplified test procedure. Table 3-3 compares the 13-mode test, the CAL/ERT study modified 13-mode and the recently recommended 7-mode test, as well as an EEA recommended weighting discussed below.

From the ARB's point of view, the comparability of emissions results from the different test procedures is of interest. Intuitively, it can be seen the brake-specific emissions (g/BHP-hr) will increase with decreasing load factor. As an extreme example, brake specific emissions at idle are infinite as the engine produces no power but emissions are finite. Thus, as the weight factor for emissions at idle is increased in either 13-mode or 7-mode tests, brake specific emissions increase. In addition, combustion tends to be more efficient at higher loads, so the brake-specific HC and CO emissions decrease even between low load operating regimes and high load regimes. As a result,

TABLE 3-3
COMPARISON OF ALTERNATIVE STEADY STATE TESTS

Mode	Speed	Load	13-mode	CAL/ERT	EMA	EEA
			----------Weight Factors, %----------			
1	Idle	0	6.6	5.0	15	15
2	Int.	2	8	5.0	--	--
3	Int.	25	8	5.0	--	--
4	Int.	50	8	10.0	10	10
5	Int.	75	8	5.0	10	10
6	Int.	100	8	5.0	10	10
7	Idle	0	6.6	5.0	--	--
8	Rated	100	8	20.0	20	15
9	Rated	75	8	15.0	20	15
10	Rated	50	8	10.0	15	15
11	Rated	25	8	5.0	--	--
12	Rated	2*	8	5.0	--	10
13	Idle	0	6.6	5.0	--	--
Composite Load Factor			40.3%	52.7%	65.0%	56.45

* EMA has recommended that this mode use a 10 percent load factor for off-highway engine emission tests.

measured HC/CO emissions on either the CAL/ERT 13-mode or the EMA 7-mode test will be lower than on the on-highway 13-mode test. NO_x emissions are not expected to change significantly, as idle and low-load modes have low NO_x emissions.

In the absence of hard data on the statistical distribution of engine load/speed operating conditions for a range of off-highway equipment, a decision on the test-cycle and weight factors would be based primarily on convenience and economic factors, as well as ARB's level of comfort. In providing an inventory of equipment, Power Systems Research also provided EEA an average load factor, derived principally from manufacturer supplied information. These numbers indicate load factors in the range of 0.45 to 0.65 for most equipment types, suggesting that the EMA 7-mode load factor may be too high. EEA concurs with EMA in its selection of 7-modes, but believes that the weights for the lower load points should be increased. Moreover, EEA believes that an eighth mode of rated speed at low load (2 percent) be added to represent machines in the full throttle reverse mode with no load. Komatsu also suggested that this was a mode considered in their internal evaluation. An average load factor in the range of 0.5 to 0.55 also appears appropriate, as suggested by the CAL/ERT study. More recently, EMA has suggested that EEA's eighth mode have a load factor of 10 percent rather than 2 percent to simulate accessory loads. EEA believes this is appropriate; the composite load factor is then 58.75 percent.

South-West Research tested a IH DT-466 engine and used a range of different weights for the individual modes to derive composite emissions. NO_x emissions, as shown in Table 3-4, are only slightly affected by load factors as idle NO_x emissions are typically quite low. However, HC emissions decline significantly as load factor increases, principally because high HC emissions occur at low loads. CO emissions from diesels are very low and not of concern to this analysis. Thus, HC emissions on the proposed 7-mode EMA cycle can be 30 to 50 percent lower than that measured on the 13-mode. Little data is

TABLE 3-4

EFFECT OF DIFFERENT WEIGHT CYCLE ON EMISSIONS
ENGINE: DT-466B - TURBOCHARGED, DIRECT INJECTION

Description of Weighing Cycle	Composite Load Factor	CO	HC	NOx
On-Highway (13-mode)	.40	2.03	1.74	10.02
Proposed EMA Off-Highway	.53	1.38	1.28	9.63
SWRI C-1, Track Tractor	.61	1.16	1.05	9.44
SWRI C-2, Wheel Tractor	.49	1.45	1.40	9.61
SWRI C-3, Wheel Loaders	.62	.99	1.07	9.48
SWRI C-4, Off-Highway Trucks	.58	1.35	1.20	9.59
SWRI Comp. Ag. Tractor	.57	1.07	1.27	9.42
EMA Comp. Ag. Tractor	.54	1.26	1.37	9.45

SOURCE: CAL/ERT Study

available on engine performance currently to set 7-mode based standards, but this is an area recommended for further study. In summary, EEA believes that:

(1) Steady-state test procedures are reasonable for use in off-highway equipment, as such equipment have engine loads and throttle positions typically not subject to high frequency transients

(2) The available on-highway 13-mode steady-state test imposes too low a load factor and includes modes that may not be representative of off-highway engine operation

(3) The EMA suggestion of a simplified 7-mode test appears reasonable if an eighth mode at idle RPM/typical accessory load (10 percent) is added.

In setting standards, however, little data is available to support an analysis of 7-mode or 8-mode based standards. Our analysis of standards and compliance feasibility is based on the 13-mode cycle. If a simplified 7/8 mode cycle is desired, ARB could invite off-highway engine manufacturers to submit 13-mode and 7/8-mode data on the same engine, and a correlation be established so that numerically different standards of equal stringency can be established for the simplified test procedure.*

3.4 POTENTIAL EMISSION STANDARDS

As a result of the experience available in controlling emissions from on-highway diesel engines, as well as the extensive data available on diesel engine emissions capability for on-highway standards, it would be economically efficient to set standards numerically equivalent to previous or current on-highway standards. In order to maximize engine model availability for use in off-highway equipment, EEA believes that standards equivalent to historical or current Federal (rather than California) heavy-duty diesel emissions standards should be considered. The use of emissions standards equivalent to future Federal on-highway standards is examined, but does not yet appear appropriate.

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* EPA followed a similar path in accepting a simplified transient test for heavy-duty gasoline engines (the MVMA cycle).

Three levels of control stringency were chosen for evaluation. All standards are based on 13-mode test.

Level I is the 10 g/BHP-hr HC + NO_x standards in force during the 1979-1983 period. Since carbon monoxide emission levels are relatively low, any standard, such as 10 g/BHP-hr, can be implemented as typically diesel CO emissions are 3 to 5 g/BHP-hr.

Level II is the 13-mode equivalent of the 1.3 g/BHP-hr HC and 6.0 g/BHP-hr NO_x standards based on the transient test that will be in force in 1990 for Federal heavy-duty diesels. EEA developed regressions for relating 13-mode and transient test emissions and they are as follows:

$$HC_t = 0.17 + 1.05\ HC_{13}$$

$$NO_{xt} = 1.70 + 0.75\ NO_{x13}$$

where the t subscript is for transient test emissions and 13 subscript for 13-mode emissions. A 1.3 transient HC standard is equivalent to 1.07 13-mode HC standard and the 6.0 transient NO_x standard is equivalent to a 5.7 g/BHP-hr 13-mode NO_x standard. The EEA developed regressions utilize a larger data base than the one utilized by EPA to develop its regressions; the EPA regressions are generally similar and produce equivalent conclusions.

Level II also envisages a particulate emissions standard equivalent to 0.60 g/BHP-hr transient standard. Unfortunately, transient test particulate emissions are not well correlated to 13-mode particulate emissions (in fact, this was the key rationale for imposing the transient test). Little work has been done in relating particulate emissions on the two test procedures; however, based on a recent study of six engines tested on both transient and 13-mode tests, it appears that particulate emissions on the transient test are always higher than on the 13-mode test. EPA, in its regulatory analysis for the 1987 heavy-duty engine emission regulations, suggested that 13-mode particulate emissions are typically 0.15 to 0.25 g/BHP-hr lower than transient particulate emissions. In any event, a 13-mode standard of 0.60 g/BHP-hr is uniformly less stringent than a numerically identical standard based on the transient test. As a first approximation, we believe that this numerical standard should be retained, although it may be reduced to 0.4 g/BHP-hr based on actual test data if warranted.

Level III is approximately identical in stringency to the proposed 1991 Federal standards of 1.3 HC/5.1 NO_x/0.25 particulate g/BHP-hr. Using the regressions, these transient test standards translate to a 1.07 HC/4.53 NO_x/0.25(?) particulate standard on the 13-mode test. The particulate standard would, of course, be less stringent with the 13-mode test than with a transient test.

All heavy-duty trucks are required to meet a smoke standard for smoke opacity equal to 20 percent in the acceleration mode, 15 percent in the lug mode and 50 percent peak smoke. The smoke standard was principally to solve a public nuisance problem for on-highway vehicles and served as surrogate for limiting particulate emissions until the advent of a particulate standard. One potential rationale for a smoke standard is as a result of our recommendation to adopt a steady-state test procedure for emissions testing. Since off-highway equipment does experience some transient modes, especially the lug mode, a smoke test may serve to limit emissions of particulate in these modes.

The EMA has objected to the use of a smoke test for off-highway engines. EMA comments are provided in the next subsection. If the ARB believes that there is a significant public nuisance problem or does not yet wish to impose particulate standards, it appears reasonable to impose smoke standards, with a potential modification to the acceleration test as suggested by EMA. We also note that California's Health and Safety Code 41701 sets a 40 percent opacity limit for smoke emissions in excess of three minutes, although EEA has learned that it is rarely enforced for off-highway equipment.

3.5 EMA COMMENTS ON THE SMOKE TEST

In EEA's February 9, 1988 letter to Don Dowdall, it was indicated that the existing heavy-duty truck engine smoke standards were chosen as potential standards for off-highway machinery. EMA's comments are as follows:

Depending on the stringency of the particulate standard chosen, the addition of a smoke test and prescribed standards may not be necessary. If smoke standards were determined to be necessary, it is incorrect to assume that these standards can also be applied to heavy-duty off-highway engines for several reasons.

The power requirements and acceleration response criteria for off-highway equipment engines can be considerably different than those of on-highway truck engines. A truck engine is matched to a drive train so that, with the proper low gear ratio, the torque produced by the engine is sufficient to start the truck moving. The higher gear ratios are then used to accelerate to the desired road speed. On turbocharged truck engines, the fuel rate during the initial acceleration must be restricted to prevent excessive exhaust smoke. This restricted fuel rate also limits available torque, thus making it important that proper gear ratios have been selected for the truck. With the wide variety of transmissions and axle ratios available, it is possible to match a truck engine and drive train to meet the performance needs of all truck operators.

For off-highway machinery, however, the power demands on the engine are quite different in that there can be very high hydraulic pump loads and torque converter losses in addition to the power required to move the machine. In order to accelerate the engine against these high parasitic loads, off-highway engines require fuel delivery rates designed to provide an extra boost of power to enable acceleration against the higher initial loading. High initial fueling for acceptable machinery operation may result in higher exhaust smoke levels than those observed from on-highway trucks.

Achieving the same exhaust smoke standards for off-highway engines as required for on-highway engines could significantly degrade the useful operation for which the equipment was designed. Overcoming this degradation would require major design modifications to machinery drive trains and hydraulic systems. Such handicaps could in some cases even require larger displacement engines to enable the machine to accomplish the same work. In this case, machine cost effectiveness and overall emission output could be negatively affected.

The current EPA smoke test cycle was derived from a truck start from rest followed by a gear shift and then a lug down to peak torque. The initial acceleration portion of the test cycle may be similar to off-highway equipment engines, but the second acceleration is not representative of the operating modes of most machines, especially those that operate at fixed throttle settings. Therefore, EMA recommends that, if a smoke test is determined to be necessary, the EPA smoke test be modified by deleting the second acceleration portion of the cycle. The resulting smoke test would then be an acceleration to full load and rated speed followed by a lug down to peak torque or 60% of rated speed, whichever is greater.

In summary, EMA believes that it is inappropriate to apply the same smoke standards to off-highway machinery engines that are currently in place for on-highway truck engines. The acceleration response characteristics and duty cycles of off-highway engines are quite different from those of on-highway engines. For off-highway equipment engines to meet similar smoke standards would severely compromise their ability to function effectively in the majority of construction applications for which they were designed. Smoke puff limiting devices could hinder the immediate power response of such engines during critical maneuvers and lifting functions, which may adversely affect the safety of nearby construction site personnel.

EEA's analysis suggests that the smoke test procedure should be modified to meet EMA's objections which are appropriate. The hydraulic drive in most construction machines does not require the second-acceleration used for the on-highway smoke test. However, EEA does not believe that the on-highway opacity standards are inappropriate for off-highway equipment. The certification data for on-highway engines shows most engines meet the peak smoke and acceleration smoke limits with significant margin. Many manufacturers individually commented that the lug smoke standard may be the more difficult constraint. As a result, it appears appropriate to retain on-highway opacity standards while altering the test procedure as suggested by EMA.

4. TECHNOLOGY ANALYSIS

4.1 OVERVIEW OF TECHNOLOGY REQUIREMENTS

Emission control technology for diesel engines has been studied in detail since the 1970's, primarily for emission control of on-road trucks. With few exceptions, most of the technologies developed for on-road heavy-duty diesel engine emission control can be directly applied to the off-highway diesel engine market. This section summarizes the technological requirements to meet the Level I, II and III for emissions control technology. In addition, comments on the applicability of the technology to off-highway engines are provided wherever appropriate.

Level I standards of 10 g/BHP-hr HC + NO_x are identical to those in force in the 1979-1983 time frame for Federal on-highway standards. However, the natural uncontrolled emission levels for many models of engines is in the range of 10 to 12 g/BHP-hr HC + NO_x at optimum performance and fuel economy. A review of the 1977 certification list shows most engines certified at 9-12 g/BHP-hr HC + NO_x even though the standard in force was 16 g/BHP-hr. For example, all Caterpillar engine families were certified below 10 g/BHP-hr, and all Cummins engine families below 12 g/BHP-hr, in 1977. However, there were a few engine families in the 13-16 g/BHP-hr range. Most engines require only the following technologies to meet Level I standards:

- low sac-volume injectors
- injector timing optimization and control
- optimization of injector fuel spray.

EEA believes that low-sac injectors are used in most off-highway engines rated above 120 HP already, and most engines currently sold in the market rated above 120 HP emit in the range of 10-13 g/BHP-hr HC + NO_x. Smaller engines, where there has been no attempt to develop on-highway versions, still do not utilize low sac volume injectors and emit in the range of 14 to 16 g/BHP-hr HC + NO_x. With the above technological modifications in place, most engines would certify at 7 to 8.0 g/BHP-hr NO_x and 0.7 to 1.2 g/BHP-hr HC at low mileage.

The Level II standards 1.07 HC/5.7 NO_x/0.6 particulate g/BHP-hr require a wide variety of changes. Typically these would include:

- derating of peak output
- decreased injector spray hole sizes
- increased injection pressure
- improvements to injection timing control and duration
- combustion chamber modifications
- turbocharging
- aftercooling

Of course, not all of these technologies are required on any specific engine. While many engines can meet the 5.7 g/BHP-hr NO_x standard in isolation, it is the NO_x/particulate tradeoff that makes it difficult to meet both standards simultaneously. Typically naturally aspirated engines have a more difficult time meeting the standard than turbocharged engines. In addition, small displacement naturally aspirated diesels have even more difficulty because the small cylinder volume makes air utilization for combustion difficult. For these reasons, good control of injector timing, high injector pressure and a well-designed combustion chamber are required. Another option available to some small, naturally aspirated diesels is to convert from direct-injection to a pre-chamber type combustion chamber. Pre-chamber diesels typically have NO_x emissions in the range of 3 to 5 g/BHP-hr, but do require careful design to meet NO_x and particulate standards. Such a design change would require significant rework of the cylinder head and fuel injection system. In 1988, several domestic and foreign engine manufactures have certified naturally aspirated direct-injection and pre-chamber diesels to on-highway standards approximately equivalent to Level II standards. These are listed in Table 4-1.

The Level III standards of 1.07 HC/4.5 NO_x/0.25 particulate g/BHP-hr are principally far more stringent only in the particulate standard. NO_x standards decline by 21 percent from level II, and at these low levels, certification represents a significant technological challenge. The 1988 certification shows several turbocharged and aftercooled engines at 4 to 4.5 g/BHP-hr NO_x, although particulate levels are typically in the 0.4 to 0.6 g/BHP-hr range, twice the required level. One method under investigation to meet the particulate standard is the particulate trap or catalyst/trap. Many prototypes are under development and some are believed to be near commercialization. Extensive literature exists on particulate trap performance.

EEA is also aware that many manufacturers hope to meet Level III standards without the use of a trap, as the trap is considered to be an expensive and potentially unnecessary device by some manufacturers. In the absence of a trap, devices that are being explored include:

- high pressure turbocharging
- very high injector pressures
- air-to-air aftercoolers
- variable fuel injection timing using electronic control systems
- zero-sac injectors (valve covered orifice)
- reduction in piston-ring crevice volume
- lubrication oil loss control

It is possible that by 1991 some engines will certify to Level III standards without a trap. EEA believes that these engines will be advanced, relatively recently designed engines, such as the Cummins L10, GM-DDA Series 60, etc., which have limited or non-existent application for the off-highway market.

TABLE 4-1

LIST OF NATURALLY ASPIRATED
DIESELS MEETING LEVEL II STANDARDS

Engine	Rating (HP @ RPM)	Transient Test HC	CO	NOx	Particulate
Caterpillar 3208	165 @ 2200[1/]	1.20	2.6	6.0	0.60
GM 6.2L[2/]	155 @ 3600	0.42	2.2	3.2	0.54
GM 8.2L	175 @ 2800	0.89	2.9	5.3	0.53
Hino HO7C-F	160 @ 3000	0.40	2.6	5.5	0.40
Nissan FE-6	160 @ 3000	0.84	3.2	5.0	0.48
IH 7.3L[2/]	185 @ 3300	0.94	--	4.7	0.50
Isuzu 6BG1	150 @ 3000	0.87	4.2	5.0	0.53

SOURCE: Draft 1988 Certification Test Results, EPA.

1/ Derated from Federal version

2/ Pre-chamber diesels

EEA interviewed the major manufacturers, who suggested that several on-highway technologies were inappropriate for off-highway use.

High pressure turbocharging results in an engine of given horsepower rating having poor low speed torque, but many off-highway engines require good low end torque to pull against high hydraulic loads.

Air-to-air intercooling requires an extra heat exchanger, and heat exchange surface fouling is common in the dusty off-highway environments. Many manufactures believe that this technology is inappropriate in several equipment applications.

Electronic timing control may or may not survive in the harsh environment of off-highway use. Manufacturers are reluctant to use this technology until its durability characteristics are well understood.

Particulate Traps or Catalysts are not yet proven in an on-highway environment, and manufacturers do not have enough information to evaluate traps in off-highway equipment. Concerns center around the high-load duty cycle, with possible extended operation at full load on the "lug" line. This may aid in trap regeneration, but trap durability may be adversely affected.

The technologies described above are required in combination or singly to certify to Level III standards. Manufacturers have suggested that Level III standards are inappropriate for the off-highway market. EEA believes that the availability of particulate traps with efficiencies over 75 percent could largely solve the problem of meeting Level III standards. EEA concurs with the manufacturers concerns on durability of traps, and suggests that Level III standards not be imposed until there is some experience with trap technology on the heavy-duty truck market, (1991). The use of traps on off-highway equipment must also consider the packaging changes required by the construction equipment manufacturers.

The exact nature of changes, and the costs per engine will depend on the current status of each engine's emission level, and the hardware changes required to meet the changes. This varies considerably among engines and manufacturers. In addition, the effect of imposing emission standards on fuel economy will also vary. Broadly speaking, however, it is incorrect to assume that emission standards always lead to fuel economy reduction. Improvements to technology can improve both fuel economy and emissions. In the on-highway market, diesel engines have managed to reduce brake specific fuel consumption consistently over the years in spite of increasingly stringent emission standards. One concept is the "fuel economy gain foregone," which would specify the gain that would have occurred in fuel economy had the more stringent standard not been imposed. Since this analysis costs technology explicitly, the "gain foregone" is not utilized in the analysis. Four specific manufacturers cases are addressed in the following subsection, and their ability to meet Level I and Level II standards are addressed.

4.2 CASE STUDIES

An evaluation of four major manufactures of engines for off-highway construction equipment is provided; based on comments received from each manufacturer. The purpose of this more in-depth evaluation is to highlight the differences in costs and difficulty in meeting standards between different manufacturers, and the potential differences in strategies in meeting different standards.

4.2.1 John Deere

Deere is a major manufacturer of agricultural and construction equipment, and its strengths in the market are primarily in equipment below 120 HP. Deere offers some equipment rated up to 290 HP, but its sales in the higher horsepower categories are limited.

Deere offers four basic types of engines, with each type having a unique displacement per cylinder. The 300 series is offered in 3, 4 and 6 cylinder versions in turbocharged and naturally aspirated form. Each cylinder has a displacement of 60 cu. in. A long stroke version in four and six cylinders is also offered, with each cylinder having a displacement of 69 cu.in. The 300 series in both versions accounts for 80 percent of Deere's total engine sales.

Deere also manufactures 3 other series, offered only as six cylinder models. The 400 series with a 466 cid displacement is offered in turbocharged and turbocharged/aftercooled versions. The 500 series with a 619 cid displacement is offered in turbocharged/aftercooled versions only as is the 700 series with a displacement of 955 cid. The 400 series accounts for 18 percent of Deere's construction equipment engines, while the 500 and 700 series together account for only 2 percent. Table 4-2 shows Deere engine specifications.

Deere provided baseline information on emission rates of each series with different rated HP. By and large, most engines in the 300 and 400 series had emissions of 13 to 15 g/BHP-hr of HC + NO_x. The 500 series was rated at 1 HC/13 NO_x g/BHP-hr; no information was provided on the 700 series.

Deere certified a turbocharged version of the 300 series - the 6-359 engine - in 1987. Its transient test levels were 0.67 HC/9.1 NO_x g/BHP-hr. Two versions of the turbocharged and aftercooled 400 series are certified for 1987 and 1988, and current certification levels are 0.52 HC/8.6 NO_x/0.38 particulate g/BHP-hr. Both certified engine lines would meet Level I standards.

The 300 series used a low-cost inlet metered rotary injection pump. Timing retard was the principal method of NO_x control on the certified engine, but the injection pump was also modified to incorporate a light load injection timing advance. This feature is currently available on rotary pumps with "hi-lo" governors that are not widely used in off-highway applications which utilize the all-speed governor. The 300 series cannot incorporate in-line

TABLE 4-2

DEERE ENGINE SPECIFICATIONS

Type	No. of Cylinders	Displacement (CID)	Aspiration	HP
300 Series	3	179	NA	~50
	4	239	NA,T	58-69
	6	359	NA,T	95-110
	4	276	NA,T	73-105
	6	414	T	122-148
400 Series	6	466	T,TA	165-205
500 Series	6	619	TA	275
700 Series	6	955	TA	290

pumps without extensive redesign of the pump gear drive, manifolds and, possibly, the block. The construction equipment versions of the 300 series use injectors with 0.46 mm^3 sac volume but low sac volume injectors are used in the certified version. Deere stated that they were not satisfied with the durability of the low sac injectors.

EEA believes that a modest development effort will be required to certify the naturally aspirated versions of the 300 series to Level I standards. It is assumed that the low sac injectors' durability problems would be solved. Contact with Stanadyne revealed that newer models of rotary pumps could be supplied with the light load advance feature and the all-speed governor. Accordingly, we project that Level I standards should be attainable by the 300 series engines. Deere provided information showing that the incremental cost of low-sac injectors was negligible. Stanadyne representatives estimated the cost of the timing advance feature in the range of $30 to $50.

EEA expects that it will be difficult for Deere to certify the 300 series engines to Level II standards, unless the engines are significantly modified. As noted in Section 4.1, several naturally aspirated engines are certified to Level II equivalent standards, but these tend to be either modern diesels or pre-chamber type diesels. The Deere engines are of dated design, and we anticipate that significant effort in optimizing combustion is required. In addition, Deere will probably need to redesign the pump drive to accept in-line pumps. The incremental cost of in-line pumps over rotary pumps according to data supplied by Deere, is about $150 to $200. In addition, some horse-power ratings of naturally aspirated engines may no longer be available, requiring a turbocharged engine. Engine price data submitted by Deere shows the turbocharger price increment to be $700-$750 for 300 series engines.

Engines in the 400 series are sold only in turbocharged form. The 400 series' certified version utilizes a higher pressure in-line injector pump with an aneroid for smoke/particulate control. The nozzle configuration is different to accommodate the high pressure pump, and have reduced sac volumes. EEA anticipates that these changes can be incorporated into the off-highway versions, so that meeting Level I standards is not a problem. Since the off-highway 400 series engines are rated at lower power than the certified version, it is not clear if new injection pumps are required to meet Level I standards.

For Level II standards, the currently certified engine with turbocharging and aftercooling appears to have relatively low particulate emissions, at the 8.0 g/BHP-hr NO_x levels. It is likely that with timing retard, combustion optimization, use of zero-sac injectors and a higher pressure injector system, the engine will be able to meet the 5.7 g/BHP-hr NO_x and 0.6 g/BHP-hr particulate standard. Deere suggested that the non-aftercooled version of the engine could also meet Level II standards. While technological improvements could improve fuel economy, the overall effect of timing retard and improved technology may raise fuel consumption by 3 to 4 percent, in the turbocharged engine.

The extremely low sales volume of the 500 and 700 series engines suggests that Deere could qualify for any potential low sales volume exemption from Level II standards. Since these engines are turbocharged/aftercooled, EEA anticipates no problems in meeting Level I standards.

Deere was unable to provide specific comments on Level III standards, but suggested that it was not advanced enough technically at this point to evaluate its ability to comply. Even with Level II standards, Deere anticipates problems with its 300 series engines. It is possible that Deere may outsource some engines at the Level II and Level III standard.

4.2.2 Caterpillar

Caterpillar engines are available for off-highway use in five different series. The 3200 series, sold as 4 cylinder and 8 cylinder models is available in the 70 to 200 HP range. The 3200 is a direct injection engine with a separate injection pump. The 3300 series is the most widely used off-highway engine in Caterpillar's line and is available in naturally aspirated, turbocharged and turbocharged/aftercooled versions as a 4-cylinder and 6-cylinder engine. The 3400 series is Caterpillar's on-highway truck engine, but some versions are sold in the off-highway market. Both the 3300 and 3400 series use advanced high pressure fuel injection systems operating at about 15,000 psi in comparison to the 8500 psi system for the 3200 series. The 3300 series covers ratings from 85 HP to 260 HP. The 3400 series covers rating from about 250 HP to 600 HP (in 12-cylinder form). The 3500 series is used on very large equipment, mostly off-highway trucks and the largest of Caterpillar's bulldozers and power equipment requiring 800 to 2000 HP. The 3110 series was recently introduced (in 1986) and covers the same horsepower range as the 3200 series. The 3110 series features an advanced unit injector system, and is expected to replace the 3200 series, which may be phased out in the early 1990's.

Caterpillar provided data on its mix of sales over the past five year period from which EEA estimated the following mix:

3200 series*	3204 NA	7.5
	3204 T	6.0
	3208 NA	2.0
	3208 T	2.5
		18.0
3300 series	3304 NA	2.5
	3304 T	15.8
	3306 NA	6.0
	3306 T	29.2
	3306 TA	2.5
		56.0

* The last 2 digits in the series are the number of cylinders, NA is naturally aspirated, T is turbocharged and TA is turbocharged/after cooled.

3400 series	3406 T	6.0
	3406 TA	2.5
	3408 T	6.3
	3408 TA	2.5
	3412 T	2.0
	3412 TA	2.0
		20.3

All other engines account for less than 6 percent of Caterpillar off-highway sales. Caterpillar provided the emissions based on aspiration for all of their current engines. They are:

- Natural aspirated — 1.5 HC/5.5 CO/9.0 NO_x/0.7 Particulate
- Turbocharged — 0.6 HC/2.0 CO/9.0 NO_x/0.3 Particulate
- Turbocharged/aftercooled — 0.4 HC/2.6 CO/8.0 NO_x/0.4 Particulate

Clearly, the turbocharged engines are already in compliance with Level I standards. From the above figures, it appears that about 18 percent of Caterpillar's engines are naturally aspirated. These would require some modest modifications to attain Level I standards. Caterpillar has certified the 3200 NA series to meet Level I standards for several years. However, the 3300 NA engine has not been certified so its performance is not clear. EEA believes that given the high technology level of the 3306, it should have no difficulty in attaining Level I standards, simply through modest timing optimization.

To meet Level II standards, Caterpillar can utilize existing calibrations for off-highway engines extensively. Table 4-3 lists the certified levels of 1988 or previous model years for equivalent engines. Data from 1977 engines show that on the 13-mode test, Caterpillar 3300 and 3400 engines were meeting or close to meeting Level II standards without aftercoolers, although particulate emissions are not known. EEA believes that technological improvements to the combustion chamber and the incorporation of high pressure injection systems over the past decade has placed the turbocharged non-aftercooled engines at or below Level II standards. The only engine that may have difficulty with Level

TABLE 4-3

EMISSION LEVELS OF 1988 CATERPILLAR ON-HIGHWAY ENGINES
(transient test emissions in g/BHP-hr)

ENGINE	HP	HC	CO	NOx	Particulate
3200 NA	165	1.20	2.6	6.0	0.60
3200 T	240	0.80	1.6	5.4	0.48
(1977)* 3300 T	250	--	1.0	6 $HC+NO_x$	n/a
3300 TA	300	1.10	4.5	5.8	0.46
(1977)* 3400 T	325	--	1.5	7 $HC+NO_x$	n/a
3400 TA	425	0.40	2.0	6.0	0.15
(1977)*3408 TA	450	--	1.0	6 $HC+NO_x$	n/a

* Results from 1977 certification on 13-mode steady-state test. n/a is not available.

II standards is the Caterpillar 3300 naturally aspirated series. The 3300 series is also available in pre-chamber form and Caterpillar provided information on the emissions level of these engines as being at 0.2 HC/1.5 CO/5.5 NO_x/0.5 particulate g/BHP-hr. The pre-chamber engine, however, results in a significant fuel economy penalty in the range of 15 percent.

Caterpillar is planning to attain Level III equivalent emissions for their on-highway engines through the use of particulate traps and electronic timing controls, as well as extensive improvements to the combustion chamber. It already utilizes air-to-air aftercoolers in most of its 3306/3406 line certified for on-highway use. Section 4.1 discussed some of the difficulties with using air-to-air aftercoolers and electronic controls on off-highway engines.

Caterpillar did not provide separate data on the 3500 series and 3110 series. Sales volume of the 3500 series is likely to be so low that it may qualify for any possible low volume exemptions.

The 3110 series is a modern engine that has better emission characteristics than the 3200 series. EEA believes that the 3110 series may be close to meeting Level III standards in turbocharged/aftercooled form without a trap. This observation is based on Caterpillar staff comments but no data is publicly available on the lowest emissions achievable by the 3110 series. Level I and II standards for both naturally aspirated and turbocharged engines should be possible given the performance of the 3200 series.

Since most Caterpillar engines are already complying with Level I Standards, there are no variable component costs associated with meeting the standard. For Level II, Caterpillar will probably have to upgrade its turbocharged non-aftercooled engines, but here again, timing optimization, some degree of derate and improvements to combustion chamber shape (piston bowl) will be the primary methods. We anticipate no increased variable costs in such cases.

Fuel economy on the engines will decline by 3 to 5 percent, compared to existing (Level I) engines. We anticipate no decline in the fuel economy of aftercooled engines, consistent with Caterpillar's on-highway engines. Caterpillar's naturally aspirated 3300 series could potentially be changed to a pre-chamber configuration, with a fuel economy loss of 15 percent. Given that several naturally aspirated diesels are meeting Level II equivalent standards, this is probably a remote possibility. In individual cases, Caterpillar could substitute a turbocharged engine for an existing naturally aspirated engine, or an intercooled engine for one without an intercooler. Based on list prices supplied by Caterpillar, a turbocharger on a 3200 series engine adds $1,000 to the cost, while an intercooler adds $600. In such cases, fuel economy could improve 5 to 10 percent, even with the emission reduction. In summary, Caterpillar engines appear to be capable of meeting Level I and Level II standards with available technology.

4.2.3 Cummins

Cummins offers 5 series of engines for off-highway use. The B-series engines cover the 75 HP - 180 HP range and are built by the Cummins-Case joint venture. The engine is a direct injection diesel with a Bosch-type in-line fuel pump, and is available in 4 and 6 cylinder form. The C-series is available only as 6 cylinder in ratings from 150 to 240 HP. The C and B series diesels are used in medium- and light-heavy trucks respectively. Both engines are of recent design and have come into production in the 1984-1985 time frame. The Cummins NH-855 series was the mainstay of its on-highway engine line-up, and has recently been supplemented by the L-10 engines. Both engines cover the 240 - 480 HP range, but the L-10 is typically used in the lower horsepower categories. Both engines use unit injectors with a unique Cummins fuel injection system. The K and KV series of engines are used in applications over 450 HP to about 800 HP. Cummins also offers some models producing over 1000 HP.

Although Cummins did not provide an estimate of sales by engine type, they provided EEA data that allowed us to estimate the total sales in off-highway use. Our estimates are as follows:

	% Share	% Turbocharged
B and C series	50	80
NH855/L-10	30	80
K/KV	10	100
All Other	10	75

The distribution is similar to that for Caterpillar, since 18.5 percent of Cummins engines are estimated to be naturally aspirated.

Since most of the engine lines are new, they can all easily meet Level I standards. Except for the naturally aspirated engine lines, most can meet Level II standards as well. The 1988 certification levels are shown in Table 4-4. As can be seen, a large majority of Cummins diesels can easily meet Level II standards with existing hardware. In addition, Cummins certified a naturally aspirated NHC-250 in 1977 at 8.0 g/BHP-hr HC + NO_x, relatively close to the Level II standard proposed, although particulate emissions are not available for this engine.

Given the advanced and modern state of most of Cummins naturally aspirated diesels, EEA believes that timing retard and timing optimization are likely to be adequate to meet Level II. As with Caterpillar, we anticipate some engines moving from natural aspiration to turbocharged configuration to meet standards for specific horsepower ratings.

Cummins provided a price list for engines, but even ostensibly identical engines were priced very differently for the truck and construction equipment markets. Cummins provided one comparison of the on-highway NTC-400 and construction equipment NTA-855-C400. Hardware differences are minor, and NO_x

TABLE 4-4

CUMMINS 1988 ON-HIGHWAY ENGINE EMISSION LEVELS
(transient test emissions in g/BHP-hr)

ENGINE*	HP	HC	CO	NOx	Particulate
B Series					
4B3.9 T	105	0.70	--	4.8	0.46
4B3.9 TA	120	0.43	--	4.4	0.45
6B5.9 T	160	0.43	--	5.2	0.43
6B5.9 TA	180	0.87	--	4.3	0.51
C-Series					
6C8.3 T	210	0.50		4.6	0.58
6C8.3 TA	250	0.71	--	5.7	0.50
Other					
L-10 TA	350	0.31	--	5.4	0.38
NT855 TA	444	0.51	--	5.0	0.44
K19 TA	600	0.55	--	7.6	0.60
NHC N (1977)**	250	--	--	8.0 HC+NO_x	n/a

* N - naturally aspirated
T - turbocharged
TA - turbocharged/aftercooled

** Results from 1977 certification on 13-mode test. n/a is not available.

emissions are near identical, but the on-highway version was priced $2000 more than the off-highway. The prices include application specific options that may have been different for the two engines. As a result, we are unable to specify costs for Cummins engines, but believe that costs should be generally similar to those for Caterpillar. (Pricing actions are considered in Section 7.) In summary, Cummins engines are probably already in compliance with Level I standards, and are capable of meeting Level II standards with available technology.

4.2.4 Komatsu

Komatsu offers a wide variety of engine lines, although sales are generally concentrated in the following five engine lines:

95 Series	-	65 HP to 147 HP
105 Series	-	100 HP to 190 HP
125 Series	-	230 HP to 375 HP
140 Series	-	400 HP to 500 HP
170 Series	-	550 HP to 1500 HP.

The 140 and 170 Series are 100 percent turbocharged, while the 95 Series is principally naturally aspirated. The 105 and 125 Series offer a mix of naturally aspirated and turbocharged models. Komatsu also offers two pre-chamber type diesels, the 94 Series and the 130 Series (in 4-cylinder form). In addition, Komatsu offers a "turbulence chamber" version of the 95 Series.

Komatsu provided emissions data on each engine at several different ratings and injection timing settings. The engines are very sensitive to injection timing; for example, one engine - the SA6D-125 - at a timing of BTDC-20° produced 20.8 g/BHP-hr HC + NO_x, and at a timing of BTDC-16° produced less than 7 g/BHP-hr HC + NO_x. It was not clear from their submission as to which engine was used, although the 20.8 figure was an isolated and extreme case. Most other engines in the 95, 105 and 125 Series appeared to have HC + NO_x emissions in the 9 to 13 g/BHP-hr range. The 140, 155 and 170 Series typically reported HC + NO_x emissions between 15 and 17 g/BHP-hr.

However, the emissions capability of the engines are much better than the results reported. Komatsu, in a letter to EEA, stated that Level I standards could be attained by all engine through timing modifications alone, for a HC + NO_x level in the range of 7 to 9 g/BHP-hr. EEA estimates that those standards are attainable at little or no variable component cost increment.

Komatsu also stated that Level II standards could be attained with the following technologies:

- Injection timing retard
- Use of electronic timed injection retard
- Use of high pressure injection pumps
- Improved combustion matching by using
    - lower swirl ratio
    - smaller hole diameters in injector nozzle
    - air-to-air intercoolers or dual circuit intercoolers.

Komatsu provided data, based on the transient test, on several engines in the 105, 125 and 140 Series. These data indicated emission levels ranging from 6.5 to 8.5 g/BHP-hr NO_x and 0.25 to 0.7 g/BHP-hr particulate. As with other manufactures, we anticipate that Komatsu's principal problems in meeting Level II standards will be with their small displacement naturally aspirated engines. The existence of a low emission swirl chamber 95 Series line indicates that Komatsu may opt for replacing the direct injection 95 Series with the swirl chamber version.

Komatsu also offers naturally aspirated 105 and 125 Series engines in their smaller crawler loaders, crawler dozers, wheel loaders and excavators. These engines may have problems with meeting Level II standards. Komatsu currently offers the pre-chamber 4D-130 in some models, and it is possible that the 95 or 130 Series may be substituted for the 105 and 125 naturally aspirated engines.

Komatsu did not provide cost estimates of the pre-chamber engines nor an estimate of fuel economy. EEA believes that pre-chamber and direct-injection engines are approximately equal in cost, but there is a fuel economy penalty associated with the pre-chamber engine of about 12 to 15 percent. For the very large engines over 850 HP, Komatsu stated the high pressure fuel injection pumps were unavailable and too expensive to be designed for the low volume application. Komatsu's statements indicate that they will be able to comply with the proposed Level I and Level II standards with available technology. Komatsu also stated that they could not provide comments on these Level III standards at this time.

4.3 AGGREGATE VARIABLE COST/PRICE ESTIMATES FOR THE INDUSTRY

In this section, aggregate industry-wide variable costs to meet Level I, II and III standards are estimated. The assumptions behind the aggregate cost estimates are (1) that the four case studies cover the range of technological variation in industry and (2) the sales of engines are distributed as follows:

HP Category	% Turbocharged	% Total Market
50-120	60	50
120-240	80	40
240-480	90	9
480+	90	1

This section also covers only these price increases associated with new additional hardware. Research and development costs as well as certification costs are considered in Section 7. These costs are typically expenses in the year that they occur and not associated with specific products.

4.3.1 Level I Standards

Industry indicates that most larger engines in 120 to 480 HP category are close to or are already in compliance with Level I standards. EEA believes that this is largely true for major manufacturers other than Deere and

Komatsu. The case studies indicate that most manufacturers will meet Level I standards by injection timing optimization and the use of low sac injectors. In some equipment, (such as Deere's 300 Series) which uses rotary injection pumps, light load timing advance mechanisms may be required. No variable cost is associated with timing optimization. We have conservatively estimated the 50 percent of all engines will need improved injectors at $10 per engine and 20 percent of all engines may need some light-load advance mechanism for injection timing at $50/engine. The average price increase associated with hardware changes is, therefore, $14. This price does not include the price effects of R&D and certification cost, which are treated separately. A fuel economy loss of 3 percent is expected for approximately half the population, for a weighted effect of 1.5 percent.

4.3.2 Level II Standards

At this level of control, it is believed that many naturally aspirated diesels will require significant changes to meet the standards. In some cases, a naturally aspirated diesel will be replaced by a turbocharged diesel and some turbocharged diesels by turbocharged/aftercooled diesels.. In almost all cases, a variety of changes are required to meet Level II standards including:

- combustion chamber optimization
- increases to injection pressure
- injection timing control.

Unless manufacturers change to a more expensive injection pump, the changes listed above are a result of research and development, and generally do not involve increased component costs. For example, the price of piston is not affected by the exact dimensions of the combustion chamber in the piston bowl. In some cases, as with Deere, the use of high pressure injection pump may require changes to the pump drive gears and mounts to handle the extra load. Again, these involve design costs but variable costs are hardly affected.

Based on data supplied by Deere, changes to the injection pump to a high pressure in-line pump from a rotary pump can increase costs by $300-$400. Most heavy-duty engines already feature in-line pumps and the change is required for about 10 percent of the market (mostly Deere 300 Series). However, increasing in-line pump pressure from about 9000-10,000 psi to 14,000-15,000 psi with suitable adjustments to injector lines and injectors can impose costs of $100 per engine. We have assumed that 50 percent of all engines will require this change. We have also assumed that 10 percent of engines will be turbocharged (decreasing naturally aspirated engines from 29 percent to 19 percent), and 10 percent of turbocharged engines will be after-cooled (increasing aftercooler penetration from about 20 percent to 30 percent). Increased use of turbocharging and aftercooling are occurring in the industry even without the instigation of emission regulations, and it is not clear if the price effects of turbocharging and intercooling should be allocated to standards.

The interaction of new technology, cost and fuel economy impact is vividly illustrated by considering the aftercooler, which represents a significant NO_x/particulate control technology. An air-to-air after cooler reduces both NO_x and particulate at any given injection timing. Clearly, manufacturers can choose lower cost technologies to meet NO_x/particulate standards such as injection system improvements, turbocharger improvements and timing retard, and suffer a fuel economy penalty of 4 to 5 percent. However, they can incorporate an air-to-air aftercooler (ATAAC) and balance the fuel economy penalty. At current NO_x certification levels of 7.5 to 8 g/BHP-hr, the ATAAC provides a 2 percent fuel economy gain; at 1988 low mileage target NO_x levels of 4.8 to 5.0 g/BHP-hr, there is little or no fuel economy loss in comparison to water-aftercooled engine at 7.5-8 g/BHP-hr. However, the fuel economy gain associated with the ATAAC at 1988 emission levels is nearly 5 percent, and is the foregone fuel economy associated with the ATAAC.

Fleetwide price increases are as follows:

Technology	Cost ($)	Market (%)	Weighted Price ($)
In-line pump	300	10	30
High pressure pump	100	50	50
Turbocharging	1000	10	100
Aftercooling	600	10	60
Total			240

The net weighted cost is $240, which represents the incremental price over Level I standards. Again, this does not include the weighted price effects of increased R&D and certification costs, discussed in Section 7.

Net fuel economy losses for turbocharged engines is on the order of 4 to 5 percent, while for naturally aspirated engines, it is about 5-6 percent. On those engines which are converted to turbocharging or aftercooling, fuel economy can be expected to increase by 8 percent and 2 percent respectively. The fleetwide fuel economy losses are as follows:

Engine Type	% Fuel Economy Loss	% Market	% Weighted F/E Loss
Naturally Aspirated(NA)	5 to 6	19	1.0
Turbocharged (T)	4 to 5	61	2.7
NA converted to T	(8)	10	(0.8)
Intercooling Added	(2)	10	(0.2)
Total			2.7

Hence, net fleetwide fuel economy loss is estimated at 2.7 percent. This should be treated as a "gain foregone" because other improvements to diesel engines unrelated to emission standards, such as friction reduction, may result in actual fuel economy increasing, even if standards are imposed.

4.3.3 Level III Standards

Attainment of these standards has not been extensively analyzed by the off-highway manufacturers. It is likely that a significant fraction of off-highway engines will require particulate traps or catalysts, as well as advanced timing controls (either electronic or mechanical) to meet these standards. A related issue of concern is the fact that engines are certified separately from equipment, and different engines can be utilized in the same equipment type. In addition, packaging of the trap or catalyst would vary by equipment type.

There is considerable disagreement about the costs of a trap. EPA has projected costs to be U.S. $457 for a LHDDE*, U.S. $553 for a MHDDE* and U.S. $661 for a HHDDE*. Manufacturer estimates are higher by a factor of 2 to 5 <u>times</u> EPA estimates. Such large differences cannot be explained by differences in assumed dealer or profit margins. As an example, Ford, IH and GM estimated trap costs for a MHDDE to be U.S. $2200, $2080, and $2300, respectively. If one assumes that these estimates were arrived at independently, they are remarkably consistent. Costs for the HHDDE's ranged from U.S. $2800 to $7000, with most values lying between $3000 and $4500. GM supplied an estimate of U.S. $575-900 for LHDDE traps. Clearly the M- and H-HDDE categories are the ones with the largest disagreement in cost estimates. Since there are no traps available commercially, an informed judgement about the trap costs is difficult. Some of the variation is undoubtedly due to technology differences, as some traps have separate regeneration devices while others use catalytic action for regeneration. An independent consultant to EPA estimated costs of the ceramic trap with a burner system for regeneration at U.S. $624, $800, $1320 for light, medium and heavy-heavy engines respectively.

EEA believes that costs of the medium and heavy classes are underestimated by EPA. Based on historical relationships between manufacturer estimates and actual price changes, estimate of retail price increases for the 50 to 120 HP segment is about $2000 for the trap alone, and for 240-480 HP segment, is

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* LHDDE, MHDDE and HHDDE stand for light-, medium- and heavy-duty diesel engines respectively, which are approximately comparable to the 50-120 HP, 120-240 HP and 240-480 HP categories, respectively.

about $4000. Costs of meeting the NO_x standard may add another $500 to $1000 due to the inclusion of an aftercooler of the jacket-water or air-to-air type.The costs quoted above are very approximate, but should be much better quantified in the near future.

4.4 RETROFIT

The ARB also instructed EEA to address the issue of retrofitting existing off-highway diesels. Clearly, the best opportunity for retrofitting the diesels comes at the time of rebuild. At this time, no economic penalty in terms of downtime or unnecessary replacement of parts occurs. Industry sources indicated that a typical off-highway diesel is rebuilt after 6000 to 9000 hours of service, which translates to 5 to 8 years after the engine is placed in service.

In a typical rebuild, injectors, piston rings and cylinder liners are replaced, valves changed and the injection pump is cleaned and reset (sometimes it is replaced by a rebuilt unit). However, the camshaft and crankshaft are generally not given any service at the time of rebuild. A second rebuild at 12,000 to 16,000 hours of use may occur, at which time pistons and camshaft may be replaced.

As noted, Level I standards will generally require only changes to injection timing and the use of low sac injectors. Both changes are easily accomplished during rebuild. In our interview with construction firms, we were informed that a large majority of construction firms depend upon the dealerships for all rebuilds. It would be relatively easy for manufacturers to direct dealers to rebuild the engine with the new timing specification, and make only the low sac injectors available. Over the course of a decade or so, manufacturers phase out old engine lines and bring in new engines. For discontinued engine lines, it may be difficult for manufacturers to design retrofit kits to meet Level I standards. In addition, most engines undergo evolutionary changes that may result in incompatibility of part sizes. For this reason, exemptions to the retrofit requirement for older engines (e.g., over 10 years old) or for discontinued engine lines, may be needed. In some cases, it will be necessary to exchange an older injection pump design with a newer type, as with one incorporating timing control.

Retrofit to Level II standards will be much more difficult. As noted, changes to the combustion chamber, valve timing and compression ratio may be required as well as a newer high pressure fuel injection system. Typically, these changes would require a new camshaft, pistons, injection pump, injectors and injection lines. Retrofit of turbochargers and intercoolers may be required in some instances. Such an extensive retrofit is generally not feasible, although it may well be possible for some engines. A regulation requiring all rebuilds to Level II standards is clearly infeasible, but the ARB may wish to pursue the possibility of rebuilding some sub-category of engines to meet Level II standards. This would require an engine by engine analysis of required changes and suitability for retrofit. EEA recommends that the ARB request specific manufacturer comments on the feasibility of this action for some specific high volume engine lines.

4.5 USE OF ALTERNATIVE FUELS

One potential method of reducing emissions is to change the fuel type used in the engines. Both compressed natural gas (CNG) and methanol have been suggested as possible alternatives. In one respect, both fuels are poorly suited for diesel engines - they have low cetane numbers and require that the compression ignition engine use some type of combustion assistance. The potential for both alternative fuels is briefly summarized, although the focus is on methanol for reasons described below. We note that the discussion is not exhaustive, as the ARB is currently sponsoring other work on the use of CNG and methanol that will offer a far more comprehensive analysis. However, this section provides some insight into special factors to be considered for the off-highway market.

4.5.1 CNG Engines

Many existing diesel engines have been converted to CNG use. For example, Caterpillar offers a CNG version of the 3406 for use as a stationary diesel. The conversion to CNG involves the changing of the combustion process to that of a spark ignition engine. Typical large direct-injection diesels have compression ratios of 16:1 to 19:1. CNG in a spark ignition engine cannot use such high compression ratios(CR), so the CR is lowered to 13:1 to 15:1. In addition, the intake manifold must be changed and a spark ignition system added. After conversion, the CNG engine resembles the standard spark ignition engine operating on CNG. It loses some efficiency at part load due to throttling losses absent in the diesel, but full load efficiency is very similar to that of a diesel. Typical of a spark-ignition engine, particulate emissions are very low, and HC emissions are mostly unburned methane, which has low photochemical reactivity. However, NOx emissions of 4 to 6 g/BHP-hr are typical, even with lean operation.

Operationally, the largest difficulty associated with CNG is on-vehicle storage. Large high pressure tanks are the usual method of storage but the tanks become extremely bulky if off-road equipment is required to operate for 8 to 10 hours, as is expected for diesel equipment, without refueling. Tank filling also requires high pressure compression equipment, and is a slow process. Pre-filled tanks can however, provide "fast-fill" of on-board tanks. The use of high pressure on-board tanks in the rough construction environment may pose safety threats that would require careful redesign of equipment to house the tanks in a shielded area on the vehicle. Little research has been done in these areas to date.

The lack of significant NOx emissions benefits, the difficulties associated with on-board storage and the problems of on-site refueling has led to little interest in substituting CNG for diesels in off-highway vehicles. There are obvious benefits for HC and particulate emissions. Should the ARB wish to pursue CNG as a possible emission control strategy, it would have to encourage new research into the area to solve the problems described above. None of the problems appear to be intractable, but the R&D and commercialization phase will result in a lead time of about 10 years for commercialization.

4.5.2 Methanol

Three methods have been utilized to overcome the effect of methanol's low cetane number for use in a diesel (compression-ignition) engine. They are:

- addition of ignition improvers to methanol
- dual-injection or pilot injection
- spark ignition of alcohols.

Methanol (and ethanol) with ignition improvers can provide satisfactory performance in a diesel engine with adequate quantities of ignition improvers. Typical improvers that have been explored are cyclohexyl nitrate, isopropyl nitrate and isoamyl nitrate. These improvers are explosive and some are corrosive as well. A significant quantity of the ignition improver is needed to increase cetane numbers to acceptable levels -- ranging from 10 to 25 percent of the total fuel volume. More recently, ignition improvers based on dimethyl ether have been shown to be effective with methanol at concentrations ranging from 2 to 4 percent by volume. However, costs of such additives are still prohibitive. Researchers have pointed out that rated cetane numbers of alcohols with ignition improvers are not representative of the actual characteristics of the fuel, and the current cetane rating method used for diesel fuel is unsuitable for alcohols. Limited emission testing of ethanol with ignition improvers in Brazil has shown the potential for a 40 to 60 percent reduction in HC as measured by the FID and a 20 to 40 percent reduction in NO_x. However, there is only limited data on emissions from engines calibrated to meet U.S. emission standards using methanol with ignition improvers as a fuel.

Dual injection or pilot injection relies on the introduction of a small quantity of diesel fuel injected separately to initiate the ignition process.

The engine requires two separate injection systems, which adds considerably to cost and complexity. The amount of diesel fuel injected to maintain ignition varies as function of load and ranges from less than 10 percent (by energy) of total fuel required at full load to 40 to 60 percent at low load or idle. Volvo developed an engine (with dual injection) in the late 1970's and it was tested by EPA. HC_{FID} emissions, uncorrected for FID response, increased by 100 percent (as measured on the EPA Transient Cycle) over an equivalent diesel fueled engine and CO emissions increased over 300 percent. Unburned alcohols (which are the overwhelming fraction of total organics) were measured at 4.9 g/kw-hr, and aldehydes at 250 mg/kw-hr. In comparison, aldehyde emissions with diesel fuel was 14 mg/kw-hr. NO_x and particulate emissions declined by about 35 percent, relative to a diesel-fueled engine. In conjunction with an oxidation catalyst, both HC_{FID} and CO emissions were reduced substantially to levels equal to or below that of the diesel engine, but aldehyde emissions were not reduced at all.

The spark-plug and glow-plug assisted ignition method have received more attention recently. A "spark-assisted" compression ignition engine developed by M.A.N. is being extensively tested by California and the U.S. EPA. The engine is based on an existing M.A.N. diesel engine and was specially modified with spark plugs. The engine uses an oxidation catalyst to reduce emissions of unburnt methanol and aldehydes. Detroit Diesel Corporation (DDC) has also developed a modified diesel engine capable of running on pure methanol. At low loads, the DDC engine uses glow plugs to achieve ignition. At higher loads, the intake temperature and pressure are controlled electronically to achieve conditions for autoignition. The DDC engine does not yet utilize a catalyst.

The M.A.N. and DDC engines have been refined over the last two years. Data presented by DDC in 1988 has shown the latest version of the methanol 6V-92 engine to have very low NOx and particulate emissions. DDC reported NOx emissions of about 2 g/BHP-hr and particulate emissions of less than 0.1

g/BHP-hr. M.A.N. has reported somewhat higher values, although further optimization work is in progress. Caterpillar has also converted the 3306 and 3406 diesel engines to glow plug operation with methanol, and has reported NOx emissions of about 3 g/BHP-hr and particulate emissions of 0.15 g/BHP-hr. A wide variety of diesel engine manufacturers have been experimenting with methanol. Table 4-5 provides a listing of manufacturers active in the off-highway markets who are experimenting with methanol. As shown in the table, the vast majority seem to prefer the glow plug or spark plug approach to combustion. Most reports indicate a 50 percent reduction from the equivalent diesel engine's NOx emissions, virtually no smoke emissions and particulate emissions in the 0.1 to 0.15 g/BHP-hr range. The particulate is thought to arise from unburned lubricating oil, and could be further reduced.

While the emissions of methanol engines have been generally good, there are many problem areas. Aldehyde emissions are approximately twice the level of emissions from diesel engines, and their control to low levels may require a catalyst. Serious durability problems remain, and significant progress is required before methanol engines can be commercialized. The DDA engine was tested in San Francisco and experienced a wide variety of component failures, including failures of the glow plug, cylinder head cracking, injector tip fouling and blower control failures. Caterpillar also reported glow plug failures, fuel injector nozzle plugging, and nozzle tip breakage. Japanese manufactures such as Nissan have reported similar failures. In addition, fuel economy on an energy basis has been found to be 5 to 20 percent worse than the equivalent diesel engine of the same power. This is thought to be because of poor part-load combustion, and the power needs of the glow plug/spark plug system.

For off-highway construction equipment, there are two other significant factors to be considered. First, most manufacturers have concentrated on relatively large diesels (of over 240 HP) for conversion to methanol. With the exception of Komatsu, manufactures have done little with the smaller

TABLE 4-5

METHANOL COMPRESSION IGNITION ENGINE RESEARCH

Manufacturer	Engine	Combustion Assist
Detroit Diesel	6V-92TA	Glow plug and intake air temperature control
Caterpillar	3306T	Glow plug
	3406TA	Glow plug
Deutz	F8L413F	Glow plug
Navistar (IH)	DT466	Surface ignition
Nissan	PE6H	2 spark plugs
Isuzu	11-liter/6 cylinder	Spark plug
Cummins	NTC855	Cetane improver
Komatsu	4D95L	Spark plug

diesel engines that account for high sales volume in the off-highway market. Second, off-highway construction equipment is usually fueled only once a day by a fuel truck that arrives at the construction site. The low energy content of methanol and the reduced energy economy requires that methanol fueled equipment have a tank about 2.5 times as large as the diesel. This would necessitate redesign of the equipment to accommodate the large tank. Both Komatsu and Caterpillar have installed methanol compression ignition engines in off-highway equipment. Except for the refueling requirement, the performance of the engines has been satisfactory and operators were generally unable to perceive any differences from the equivalent diesel engine. Of course, all problems associated with methanol use in the on-highway segment, such as engine durability, fuel availability and fire safety are common to the off-highway market as well.

In summary, methanol conversion offers the potential to meet and exceed Level III emission requirements by a significant margin. However, the status of technology development relative to the off-highway market suggests that it is a solution for the post-1995 time frame.

5. REGULATORY STRATEGIES

5.1 EMISSIONS REGULATIONS

While the Districts are responsible for controlling air pollution from all sources other than motor vehicles, California Health and Safety Code Sections 39002 and 39500 provide that the ARB has the responsibility for control of emissions from motor vehicles. The definition of motor vehicles may be found in Health and Safety Code Section 39039, which references the Vehicle Code. "Motor Vehicle" is defined in Vehicle Code Section 415; "vehicle" is defined in the Vehicle Code Section 670. These two definitions provide the criteria to determine whether a source is a motor vehicle and thus under the jurisdiction of the ARB. The definitions are:

- Vehicle Code 670. A "vehicle" is a device by which any person or property may be propelled, moved, or drawn upon a highway, excepting a device moved exclusively by human power or used exclusively upon stationary rails or tracks.
- Vehicle Code 415. A "motor vehicle" is a vehicle which is self-propelled.

From these definitions, it is clear that self-propelled construction equipment such as graders, earth movers, and tractors, falls under the jurisdiction of the ARB. However, equipment such as pile drivers and portable generators fall under the jurisdiction of the Districts, since this equipment is not self-propelled.

Based on the technology analysis in Section 4 of this report, EEA suggests the following sets of standards and the minimum lead time required for implementation. The regulatory framework would be similar to that utilized for heavy-duty trucks in that all standards will be based on the concept of an engine family that would cover several different horsepower ratings of an engine with similar bore, stroke, aspiration and fuel injection system. Standards would apply to all new diesel-powered self-propelled construction equipment sold in California and would cover all of the equipment categories detailed in Table 2-1 of this report. However, the ARB may provide exemptions to log skidders and feller-bunchers, which are predominantly used only in the forestry industry. All standards are based on the 13-mode test, but EEA recommends that the ARB set optional standards of equivalent stringency based on an eight-mode test using data the manufacturers provide comparing results from 13-mode and eight-mode tests. Lead times for the implementation for standards are dictated by manufacturer specific constraints, and the proposed minimum lead times should, in EEA's opinion, allow for a smooth transition on the part of most engine manufacturers competing in this market. Due to the diverse and fragmented nature of this market, the ARB should be prepared to address the possibility of individual low volume manufactures who may face special difficulties not foreseen in this report.

Imposition of the Level I standard of 10 g/BHP-hr HC + NO_x based on the 13-mode test can occur with a minimum two-year lead time after rule promulgation. Most engines from Caterpillar and Cummins are close to compliance or are in compliance with this standard. Based on information supplied by the manufacturers, Deere and Komatsu should have no substantial difficulty in meeting this standard. EEA believes that Deutz and IH also should have no difficulty in meeting this standard. The two year lead time is required to:

- allow enough time to develop new calibrations on all engine lines
- set up additional dynamometer and emissions measurement facilities for select manufacturers
- incorporate modest design changes in injection pumps and injectors in some engines
- complete the certification process
- segregate products for California and set up a system to track product flow to California.

In the calculation of emission inventories, one of the scenarios evaluates the implementation of Level I standards in 1991 as the earliest possible date.

Although the lead time is relatively short by historical standards, most manufacturers have been anticipating the introduction of standards since the early 1980's and are therefore well prepared to embark on this process. However, 1991 is also the year when stringent new standards are in effect for heavy-duty trucks. In order not to strain the development and certification burden for manufacturers ARB may consider imposing standards in 1992 or beyond.

The imposition of Level II standards of 1.07 HC/5.7 NO_x/0.6 particulate standards requires a lead time that varies by both manufacturer and horsepower category. In the horsepower categories of 120 to 480 HP, most major manufacturers with the exception of John Deere, will be able to implement the standard with a four to five year lead time. The lead time is associated with:

- changes to fuel injection system to high pressure systems
- increased use of turbocharged aftercooled engines
- equipment underhood design changes to accommodate the plumbing associated with turbocharging and aftercooling
- changes of engine suppliers among some equipment manufactures.

A significant fraction of equipment using engines rated between 120 and 480 HP already utilize turbocharging and aftercooling, and, therefore, only a small (~10%) fraction of equipment in this category will require significant engine changes. This would imply that the standard could be imposed in 1993 or 1994 model year, at the earliest. Of course, other competing issues such as the 1994 standards for heavy-duty trucks may cause significant difficulties for the manufacturers so that more lead time may be appropriate.

In the 50-120 HP category, EEA believes that many engines will require significant redesign, either to prechamber type design or to incorporate advanced in-line fuel injection pumps and turbocharging to meet the Level II standards. Because of the more extensive design changes involved, we believe an additional one to two year lead time is warranted especially for naturally aspirated engines. The economic impact analysis in Section 7 also suggests that ARB may wish to consider a "split standard" approach, allowing engines less than 120 HP to certify to Level I standards.

In addition, EEA believes that the engines over 480 HP will be automatically exempted by the proposed low sales volume exemption (described in the following pages) and compliance for these engines will not be an issue, if the ARB permits a low sales volume exemption.

The use of "carry over" of certification from 1986-1990 California on-highway engine families can significantly reduce the compliance burden of manufacturers. These on-highway standards are equivalent to proposed Level II standards. Multi-year certification can also provide reductions in compliance costs.

EEA does not believe that Level III standards should be imposed without further study. Many of the technologies planned for use in meeting equivalent standards for on-highway trucks are yet unproven and thought to be unsuitable for use in the rough off-highway operating environment. The use of particulate traps is a significant unknown in heavy-duty use, and the need for such stringent particulate standards for off-highway construction equipment is unclear. EEA recommends that ARB readdress the issue following the 1991 model year, when the status of the technology to meet the standards will be fully understood. However, EEA suggests that engines certified to heavy-duty diesel truck standards be automatically granted certification for use in off-highway equipment.

As noted, EEA suggests a low sales volume exemption be granted for meeting Level II standards. Because of the difficulty in achieving low emissions with naturally aspirated diesels and small diesel engines, as well as the high unit cost of certifying engines which may sell only a few units per year, it is economically efficient to exempt those engine families selling less than 10 or 12 units per year. Since the sales in the construction industry of specific pieces of equipment is very cyclic, EEA recommends that the sales volume exemption be based on average sales for three years rather than any particular year's sales. We anticipate that, at most, ARB will grant exemptions to 30 to 35 families (mostly imports and engines over 480 HP), amounting to an exemption to 5 percent of new vehicles sold. This exemption, however, should be restricted to no more than 3 or 4 engine families per engine manufacturer to prevent a proliferation of separate engine families.

EEA also does not believe that a separate durability test is necessary. Available data from EPA certification suggests that the diesel engine's deterioration factors are generally quite low. The ARB may choose to take the following actions:

- accept on-highway deterioration factors for engines that are substantially similar to off-highway engines
- provide assigned deterioration factors similar to those available for on-highway certification
- increase the stringency of the standard by an amount equal to the average deterioration factor for on-highway engines at equivalent standards, and delete all requirements for a durability test.

The durability test is one of the most time consuming and expensive activities of certification, and, in the context of heavy-duty diesel engines, of limited value. Due to the relatively low sales volumes for off-highway equipment, EEA believes that the durability tests imposes very high costs per unit relative to the options listed above, which largely accomplish the objective sought by the ARB.

EEA believes that the need for a separate smoke test is unclear if a Level II type particulate standard is enacted. The ARB may wish to retain only the peak smoke requirement and deleting requirements for the acceleration and lug modes, as manufacturers and the EMA have raised objection to applying the on-road smoke standards to off-highway engines. In addition, manufacturers must be in compliance with California Health and Safety Code 41701, which sets a 40 percent limit to opacity. The South Coast Air Quality Management District apparently requires a 20 percent opacity limit, but these are based on approximate visual enforcement requirements.

EEA suggests that the ARB work with manufacturers in setting a recommended measurement procedure for particulates with the steady-state test. The procedure is currently defined only for the transient test. Although the measurement of steady-state test particulate has been performed, some specific areas of concern regarding test protocol, e.g., dilution ratio and filter temperatures, require ARB's attention. Deere staff have noted some specific concerns and their comments are provided in Appendix A.

Separately, EEA also suggests the ARB require manufacturers to uprate their rebuild kits so that rebuilt engines will meet Level I standards. EEA believes that the regulation can be broadly implemented for engines built since 1980, except in some cases where engine lines have been discontinued (as with Case diesels). Due to continuous evolutionary improvements to most engines, engines older than 1980 vintage may have enough design differences to cause problems in upgrading to a newer specification. For this requirement, ARB should be prepared to examine requests for an exemption on a case-by-case basis.

5.2 ENFORCEMENT OF REGULATIONS

There are currently no regulations which apply to off-highway diesel engines in the State of California. Therefore, any regulations of this type would require new and innovative methods of enforcement. This section of the report examines the current state of regulation in California in terms of mechanisms already in place that may be adapted for the purposes of regulating off-highway construction vehicles, and discusses possible regulatory scenarios with varying levels of cost, effort, and expected compliance.

Three conditions are necessary for any regulatory approach to be effective: Certified equipment must be differentiable from non-certified equipment by means of a tag or sticker, the equipment model year must be easily observable, and penalties must be assessed for non-compliance. Several alternate approaches have been developed which represent the range of enforcement options from a simple, low cost approach with fairly high levels of compliance, to a maximum amount of enforcement with nearly 100% compliance.

5.2.1 Voluntary Compliance

The least cost, simplest approach to regulation would require that manufacturers certify that all new equipment and rebuilt engines sold by California dealers meet the standards set by the Air Resources Board (ARB), and that all contractors certify via construction permits that all new equipment is certified for use in California. The only method of enforcement suggested is to institute random spot checks by ARB or Air Quality Management District (AQMD) inspectors of construction equipment dealers and rental agencies. Violators would be subject to fines, and repeat violators could be subject to loss of license. The advantages to this method are its low cost and probable high levels of compliance as most dealers would not risk the chance of being caught. However, this method does not allow for assessment of compliance rates, and would require additional inspection staff.

The total number of establishments which sell or rent construction vehicles has been estimated by California dealers to be 250. Quarterly inspections would require 1000 inspections per year. If inspectors could inspect two dealerships per day, an additional 2-3 inspectors would be needed to perform this task. Assuming the average burdened salary of each employee is $40,000, multiplied by 1.5 to factor in office space and overhead costs, the additional staff would require an additional $180,000 per year.

Compliance is expected to be at least 70-80%, based on the expectation that the larger construction firms (which represent most of the construction industry) will not risk non-compliance by buying non-certified equipment.

5.2.2 Compliance with AQMD Supervision

The intermediate approach would require that all new equipment sold in California display prominent stickers showing emissions compliance, with routine site inspections by Air Quality Management District (AQMD) inspectors to determine compliance. Precise enforcement policies could vary locally to represent the various needs of each AQMD. For example, more frequent inspections could be required in areas such as the SCAQMD areas where emission control needs are critical. However, increased costs of enforcement may be greater than the marginal increase in compliance rates gained from using the intermediate approach over voluntary compliance. There are several obstacles to the intermediate approach:

- Locating compliance stickers on dirty or dust-covered vehicles may be difficult
- It may be difficult to distinguish between model years which fall under regulations and those that do not as equipment model year is not easily identifiable
- Vehicles which fall in the 50-75 HP range may not be easily distinguishable from those under 50 HP
- Many short-term heavy construction projects (i.e., site preparation for small structures, laying underground tanks or pipelines, or digging swimming pools) may be missed if inspections are not done on a weekly basis. Hence, some portion of the fleet may remain uninspected.

The first three obstacles may be largely avoided with proper regulatory specification regarding the placement of the stickers. For example, equipment owners may be required to place compliance stickers in covered places and the model year and horsepower rating can be listed on the sticker itself. However, stickers placed on some of the smaller vehicles without cabs or other enclosed spaces will still be subject to the above concerns.

Several points must be made regarding the capabilities of AQMDs in enforcing these standards. At this time, the individual Air Quality Management Districts are responsible for management of air quality in their jurisdictions. The AQMDs have the authority over implementation of permit programs and enforcement.

Within these areas, the AQMDs strive to attain and maintain state and federal standards for air quality, and respond to and abate nuisances that have been identified by citizen complaints and inform the public about current air quality conditions.

Several other organizations have some jurisdiction over construction sites, primarily the Federal Occupational Safety and Health administration (Fed-OSHA), the California Occupational Safety and Health Administration (Cal-OSHA), local building inspection agencies, and, for public works, the sponsoring government agency. Some research was conducted into the feasibility of ARB interaction with these agencies. As most jurisdictions inspect buildings for safety and for compliance with local building codes after the work is completed and the equipment is no longer on the work site, these local agencies do not appear to be an avenue for local inspection of construction equipment.

Cal-OSHA currently regulates the safety of the public sector with Fed-OSHA having jurisdiction over the private sector. Cal-OSHA is in the process of regaining its private sector jurisdiction and should be restructured by the end of 1989. Currently both agencies inspect buildings or construction sites under the following conditions:

- an accident has occurred
- an employee or employer has requested an inspection
- an unsafe situation is spotted by an inspector while driving by a work site, or while inspecting a nearby safety hazard

Thus, current inspection practices are more "reactive" than "proactive". The current level of inspections being conducted is enough to keep the staffs of these agencies busy. An possible hook-ups with these agencies for inspections of individual pieces of equipment would require extra staffing. As Cal-OSHA is now in a state of transition, this does not appear to be a feasible solution at this time, but could be pursued in the future.

The intermediate approach would necessitate the monitoring of construction sites to ensure compliance with equipment emissions statutes at the AQMD level. Currently there are state and local regulations that specify limits to dust and noise produced by any person or operation, which would include construction sites, such as State Health and Safety Code 41701, which sets a limit of 40% opacity in excess of three minutes of visible emissions of smoke, dust, and dirt. However, the AQMDs contacted reported that construction sites are not inspected on a frequent or regular basis, and that public complaints of nuisance caused by construction activities are rare. In fact, the monitoring efforts of AQMDs vary considerably throughout the state, due to such factors as staff availability and funding. Additional monitoring activities necessitated by regulation on construction vehicles (i.e. regular site visits to construction operations) would require sufficient funding to the AQMDs for increased staff.

In order to estimate the additional staff needed to conduct regular site inspections, EEA contacted two of the largest Air Quality Management Districts, the South Coast (SCAQMD) and the Bay Area (BAAQMD). The BAAQMD currently employs approximately 46 inspectors. A BAAQMD representative estimated that regulations requiring thorough inspections of construction sites by AQMDs would require a 30-50% increase in staff time. The SCAQMD has 170 inspectors, and estimated that need for an additional 5 inspectors in order to inspect construction sites on a regular basis. Due to the inconsistency of these estimates, EEA estimated the number of additional inspectors and other AQMD personnel which would be needed under this regulatory scenario based on the number of construction sites issued permits in California each year. In 1987, approximately 535,000 construction permits were issued for residential and nonresidential construction activities, including building, remodeling, and demolishing. This number overestimates the number of actual sites, as each house in a development may carry a separate permit, and so forth. Based on a conversation with a staff member from the SCAQMD, random inspections of 10-15% of the population should be enough to pose a threat to all contractors. If the AQMDs are able to randomly inspect 10-15% of the total number of construction sites at three sites per day, an additional 100 inspectors would be needed. As several of the jurisdictions currently conduct drive-by inspections of job sites, this number may be reduced by 30-40%, to a total of 60-70, or 1-3 additional inspectors per District, on average. Multiplying this number by an average burdened salary of $40,000, and multiplying by a factor of 1.5 for administrative and overhead costs yields 3 to 4 million dollars needed to fund additional staff.

The estimated compliance for this strategy is 85-90%. In addition to the expected compliance of equipment dealers, the additional threat to the small contractors themselves should increase compliance by another 10% over a scenario of only equipment dealer inspections. It should be noted, however, that a representative from the BAAQMD stated that, while the most effective policy would be inspections of 100% of the population, that inspections of at least 50% of all sites would be necessary to maintain a threat to all contractors. He also felt that random inspections would result in complaints of unfairness from contractors. He suggested that all contractors give 10 days notice prior to beginning a project, which would allow for thorough inspections of all construction activities. This strategy would raise the manpower needed for inspections and the total costs of inspections by 8-10 times the previously estimated amount. Due to the large discrepancy between these estimates, this matter should be studied in a more extensive manner before policies are made.

Vehicle Registration

A maximum level of enforcement would require registration of all vehicles by the Division of Motor Vehicles. A registration sticker similar to those on passenger vehicles would be provided with certification of emission compliance for all vehicle model years covered by regulation. All vehicles at construction sites would need to be inspected regularly by AQMD inspectors for registration plates. This approach would ensure up to 98% compliance state-wide, and would provide detailed statistics on the equipment population in California which could be used in creating an accurate emissions inventory. The 2% non-compliance rate is associated with border areas of the state, where there are no severe air quality problems.

The disadvantages to this approach are as follows:

- High costs compared to marginal benefits of registration over compliance with AQMD supervision or voluntary compliance
- Uncertain cooperation from the DMV, as these offices may already be overburdened
- Significant opposition from equipment owners as this will create an avenue for taxation of vehicles. The AGC stated its members would oppose such a move on ARB's part.

The processing of each vehicle would require mailing out information, obtaining payment, providing plates, and data processing. From the local (Washington) DMV, we were provided an estimate of 1/3 man-hour per vehicle for all activities listed. Thus, an additional 20-22 people are required to process the fleet of 120,000 vehicles, plus an additional 8-10 people for administrative, technical and clerical duties. A total of 30 additional staff members, with an average burdened salary of $40,000, multiplied by a factor of 1.5 to cover office and overhead costs, would require $1.8 million per year. These costs would be incremental to the costs of AQMD inspectors required to inspect and ticket unregistered machines.

The DMV would be able to recover these costs by requiring a $15 registration fee plus $3 for the cost of the tags. This would amount to $2.2 million per year revenue, which should cover the costs incurred. The cost of $18 per vehicle is not inconsistent with the procedures of many jurisdictions in the registration of cars and trucks.

6. EQUIPMENT AND EMISSIONS INVENTORY

6.1 INTRODUCTION

In order to assess the impacts of regulation in terms of emissions reduction, it is first necessary to estimate the current population of vehicles which would fall under emissions regulations, as well as to forecast the future population of the vehicles. Emissions factors can then be applied to the estimated inventory of construction vehicles in order to derive an emissions inventory from that sector.

This section of the report discusses the baseline inventory and the forecast to 2000 of off-highway construction vehicles in California. Using this information, total emissions from this sector are estimated. The methodology used to determine a reasonable inventory of equipment is discussed in Section 6.2. Section 6.3 examines three different estimates and their methodologies: the 1979 ERT baseline, the 1987 Construction Equipment magazine survey estimates of the U.S. population of common construction equipment which have been modified by CIMA to represent the California population, and the recently developed inventory determined by Power Systems Research, Inc. (PSR) under contract to EEA. The differences between these estimates are explored in Section 6.4. This section attempts to validate the results which were chosen to be the most reasonable estimates. It also addresses the updated ERT inventory. Section 6.5 discusses the projected inventory of equipment to 2000. The emissions inventory is discussed in Section 6.6.

6.2. METHODOLOGY

Several difficulties arise in compiling a state-specific inventory of construction equipment. These difficulties result from the lack of precise data on sales and shipments of construction equipment in the U.S. and differing opinions regarding equipment life and California's share of the U.S. market. This study attempts to reconcile several estimates of the baseline construction equipment population in California by examining the differences between them and outlining the strengths and deficiencies of each. The critique of these inventories consists of comparing them with other sources of available data, such as Bureau of the Census data, and by using anecdotal information gained from interviews and surveys of contractors, equipment dealers, and industry groups. The ERT Emissions Inventory Report performed in 1979, the CIMA adaptation of Construction Equipment Magazine's "Universe of Construction Equipment", and Power Systems Research's "California Off-Highway Application Engine Population Profile" are the studies used in this analysis.

6.3 THE EQUIPMENT INVENTORIES

This section discusses the goals, methodologies and results of the CIMA/ERT, Construction Equipment Magazine, and PSR studies. Each inventory is first discussed separately, and the inventories are compared in Section 6.4.

Environmental Research and Technology, Inc.

In late 1980, the Construction Industry Manufacturers Association (CIMA) contracted Environmental Research and Technology, Inc. (ERT) to study the impact of off-highway equipment upon air quality in California. One goal of this study was to gather more reliable and up-to-date industry data to be used by the ARB when developing emission inventories. This study has been the basis for the ARB equipment inventory since 1980. ERT developed equipment population and emissions from several equipment-using sectors, including those classified as MS-1 (New Off-Road Heavy-duty Non-farm Equipment). The MS-1 database was derived from information submitted by manufacturers, their associations (the Association Liaison Group, FIEI, EMA and CIMA) past inventory reports, and the ERT study. Construction machinery data collected on a yearly basis by the Bureau of the Census were used to verify the manufacturers' data. The California MS-1 inventory was derived by summing up the portion of U.S. equipment shipments sold in California for ten years. Ten years was chosen because manufacturers determined that it is a reasonable estimate for the average life of construction equipment. The proportion of total U.S. sales to California was derived from data submitted by the Association Liaison Group (ALG), based on prior sales data for California. Some of this data was estimated based on past trends, some received from Power Systems Research, Inc., while some was extracted from the internal records of manufacturing firms. The study did not attempt to account for the interstate movement of equipment, as no data on this subject was available.

The ERT 1979 baseline estimates of the California Domestic population by 24 equipment types are shown in Table 6-1. The sum of equipment sold to California buyers totals 65,267. Forty-one percent of the total population falls into a single category, industrial tractors, which includes backhoe/loaders and rough terrain forklifts. The ERT report supplied the number of each equipment type estimated to be owned in California, and the percentage of the U.S. population assigned to each type. From this information, the U.S. population was calculated. Across all of the equipment types for which the ERT report supplied estimates of the percentage distributed to California (all types except industrial tractors and pipe layers), California represents approximately 5% percent of the nation's total of construction equipment.

CIMA Revision of Construction Magazine's "Universe of Construction Equipment"

In 1988, CIMA created a revised population estimate based on a study done by MacKay & Company which was commissioned by Construction Equipment Magazine and The Associates Commercial Corporation. The purpose of Construction Equipment's study was to aid manufacturers and dealers in their marketing efforts, and was not necessarily created to be used as a precise measurement of the equipment inventory. The estimates are generally rounded up or down to the nearest hundred. The data was obtained by adding sales and shipments data for the U.S. for each type of equipment in the survey by for a number of years, depending on expected equipment life. The survey included the major types of

Table 6-1

CAL/ERT Estimates of 1979 MS-1 Population in California and U.S.

Equipment Type	% to California	California Domestic ** Population (1979)	U.S. Domestic ** Population (1979)
BITUMINOUS PAVER	6.0 *	497	8283
COMPACTOR (static)	6.0 *	2623	43717
COMPACTOR (Vibratory)	6.0 *	1267	21117
CONCRETE PAVER	6.0 *	730	12167
CRAWLER CRANE	1.8	186	10333
CRAWLER EXCAVATOR	4.0	1080	27000
DITCHER & TRENCHER	3.8	3992	105053
HYDRAULIC EXCAVATOR	3.7	226	5649
HYDRAULIC WHEEL CRANE (one-stat)	3.6	785	21806
HYDRAULIC WHEEL CRANE (mult-stat)	6.8	278	4088
INDUSTRIAL TRACTOR	--	26729	--
LOG SKIDDER	1.1	1161	25455
MOTOR GRADER	6.2	2787	44968
OFF-HIGHWAY TRUCK	2.4	392	15500
PIPE LAYERS	--	45	--
SKID STEER LOADERS	3.1	2490	160677
SCRAPERS	6.1	1480	28885
TRACK LOADER 20-89 hp	7.7	2607	33156
TRACK LOADER +90 hp	8.2	1808	20902
TRACK TRACTOR 20-89 hp	5.3	2949	62208
TRACK TRACTOR +90 hp	7.9	3976	69937
WHEEL CRANE	7.5	530	7067
WHEEL LOADERS < 2 1/2 cu. yd.	6.2	3509	60935
WHEEL LOADERS > 2 1/2 cu. yd.	5.2	3160	59923
TOTAL	--	65267	848824
TOTAL (w/o Industrial Tractors and Pipe Layers)	[4.5%]	[38493]	[848824]

* Manufactuers' Estimate

** Includes some MS-2 Equipment

equipment used by contractors, but did not necessarily include all of the equipment which would be used by specialty contractors, the sum of which could be a considerable amount of equipment. Equipment life expectancy data was gathered by surveying manufacturers and equipment users.

The Construction Equipment survey listed total U.S. equipment population by equipment type and use. CIMA then used these numbers and applied market share percentages for sales to California, and subtracted out the equipment believed to be used for purposes such as agriculture, mining and forestry. Overall, CIMA's numbers would indicate that California holds 5-6% of the U.S. total equipment inventory. These estimates are shown in Table 6-2, and are discussed further in Section 6.4.

Power Systems Research, Inc.

PSR's tabulation of population data begins with a compilation of an accurate sales record. PSR maintains an engine sales record for every engine make and model installed in original equipment in North America. In addition, PSR has a compilation of each engine driven product delivered to North America, including records of the engine make and model installed in each product. This data was compiled over an extended number of years. The resulting data provides an insight into the total number of engine-driven products originally placed into service in North America. The data is adjusted by the number of engine driven products produced in or imported to North America which are later exported. This information is derived from U.S. Department of Commerce export records.

PSR then establishes a scrappage or attrition rate, by establishing for each engine make and model a design life specification, which is the mean time before scrap for each of the over 1,300 engine models being tracked. These numbers were developed through PSR field research and have been compared to manufacturers specifications where possible. The life is expressed in horsepower hours for greater accuracy in estimating engine life. For each

Table 6-2

CIMA Estimates of 1987 California Equipment Population (Based on MacKay Study)

Equipment Type	U.S. Population MacKay	CA Population CIMA	CA % of US Total
CRAWLER TRACTORS	115000	5670	5.3%
(CIMA estimated total)	(106663)		4.9%
CRAWLER LOADERS	64000	2484	3.9%
(CIMA estimated total)	(52387)		4.7%
WHEEL LOADERS	130000	7215	5.6%
CONVENTIONAL & ELEVATING SCRAPERS	16400	1148	7.0%
MOTOR GRADERS	74000	3700	5.0%
RIGID FRAME OFF-HIGHWAY HAULERS	19400	543	2.8%
LATTICE CRAWLER CRANES	14300	300	2.1%
LATTICE BOOM WHEEL CRANES	10500	819	7.8%
HYDRAULIC WHEEL CRANE (one-stat)	27500	1485	5.4%
HYDRAULIC WHEEL CRANE (multi-stat)	40800	3713	9.1%
HYDRAULIC WHEEL EXCAVATORS	16800	208	1.2%
(CIMA estimated total)	(6295)		3.3%
HYDRAULIC CRAWLER EXCAVATORS	46000	1472	3.2%
SKID/STEER LOADERS	140000	6300	4.5%
INDUSTRIAL WHEEL TRACTORS	212300	20699	9.7%
COMPACTION EQUIPMENT	42800	4049	9.5%
COLD PLANERS/MILLING MACHINES	1800	137	7.6%
ASPHALT PAVERS	12000	780	6.5%
CONCRETE PAVERS	8400	437	5.2%
TOTAL	992000	61139	6.2%
Total with CIMA Adjustments	(961545)		[6.4%]

application and horsepower range, PSR established a normal number of operating hours per year and an expected load factor of percentage of full rates load which is normally experienced in that application. For example, PSR has found that 50-120 HP gasoline engines used in Northern California for agricultural purposes are normally operated 221 hours per year, with a load factor of 52%. Thus, an engine rated at 100 HP would actually output 11,500 horsepower hours per year. If this engine has a design life at full output of 2,000 hours, then this engine in this application can be expected to have a median life of 17.3 years. Given this expectation, PSR distributes life expectancy around a normal distribution curve, expecting that, for example, 20% of the engines will have failed within 8 years or at half the expected life, while 20% of the engines will still be in service after 23 years. This normal distribution of life expectancy is applied for every engine make, model, and application combination.

This information allows PSR to calculate the number of engines in service at any specific time for which shipments records exist. The aggregation of these numbers through the year being reviewed (in this case 1987) allows PSR to compile expected units to be remaining in service at this date. Geographic distribution of units was accomplished by utilizing the U.S. Bureau of the Census County Business Patterns Database, which includes number of establishments by SIC Code, employees, revenue, and employment.

The PSR aggregate estimates of construction equipment in use in California by equipment types are shown in Table 6-3. The sum of equipment used in construction for 1987 is 127,336. A detailed PSR breakdown of equipment by year, type, region, and fuel type is provided as an attachment to this report.

6.4 COMPARISONS OF THE INVENTORIES

The most striking difference between the three inventories discussed above is that the PSR estimate of the construction population in California is roughly twice as large as the ERT and CIMA estimates. There are also large discrep-

Table 6-3

PSR Estimates of 1988 California Diesel Equipment Population

Equipment Type	H.P. < 50	H.P. 50-120	H.P. 120-240	H.P. 240-480	H.P. > 480	Total
BITUMINOUS PAVER	0	2313	1185	31	0	3529
CONCRETE PAVER	1892	1828	2296	0	0	6016
OTHER PAVING	0	462	753	379	41	1635
ROLLER/COMPACTOR	5846	3308	3881	27	0	13062
CRANE	0	2225	2407	312	197	5141
EXCAVATOR	1975	2370	3242	1170	72	8829
TRENCHER/DITCHER	8850	340	280	0	0	9470
INDUST. TRACTOR	4386	1431	202	40	0	6059
LOG SKIDDER	0	2237	1777	0	0	4014
GRADER	0	1456	1137	51	0	2644
OFF-HWY TRUCK	0	0	646	983	853	2482
SKID-STEER LOADER	10838	1872	0	0	0	12710
SCRAPER	0	1237	2313	581	55	4186
TRACK LOADER	NA	NA	NA	NA	NA	NA
CRAWLER TRACTOR	2491	4266	5408	2219	409	14793
WHEEL LOADER	0	7412	7583	1848	123	16966
WHEEL DOZER	0	424	664	218	79	1385
BACKHOE LOADER	0	10942	185	0	0	11127
DUMPER	1496	0	0	0	0	1496
FELLER/BUNCHER	0	0	1486	306	0	1792
TOTAL	37774	44123	35445	8165	1829	127336

ancies in population estimates for each type of equipment. For example, PSR estimates the population of excavators to be 8829, whereas the MS-1 baseline estimate is 1680. Some of the discrepancies may be due to definitional problems; for example, backhoe/loaders are placed in the industrial tractor category in the ERT report. However, most of the differences appear to be caused by other reasons. EEA has attempted to validate the estimates provided, and has determined two primary reasons for the differences between the studies.

EEA believes that the ERT and 1988 CIMA estimates understate the actual population of construction equipment in California, because:

- Using 10 years as an average life appears to be low
- The estimates of California's share of the U.S. market which CIMA applied to the MacKay study appear to be low.

Average Life

EEA considers CIMA's choice of ten years average life for construction equipment to be low. This assumption is based on information gained from contractors and equipment dealers, and from a survey distributed by EEA to contractors, rental agencies, and state and local agencies.

The MacKay study presents the average life for each piece of equipment studied. When the average life across all types is calculated by weighting life by the percentage of the inventory represented by each type of equipment, the calculations would show that the average life of construction equipment is approximately ten years. However, in the MacKay study, several of the most numerous pieces of equipment, i.e. backhoe/loaders, skid steer loaders, and drum rollers/compactors, are given useful lives of 7-8, 7-8, and 7 years, respectively. These equipment types are a significant portion of the equipment inventory, and thus bring down the average significantly.

Conversations with several equipment dealers contacted revealed that the estimates of average life for backhoe/loaders, skid/steer loader, and rollers/compactors are very low, and that these pieces of equipment can last in the 12-20 year range. In many cases, equipment is traded in and sold as used equipment after 7-8 years, as the equipment is most useful during the first five years. Equipment is also often sold after five years because it can no longer be depreciated in an accounting sense.

There is a large market for used equipment. This equipment is purchased by small companies, companies just starting out, and by owner/operators (refer to Section 7). According to one equipment dealer who deals only in used equipment, his company's fleet consists of equipment built from 1965 to the early 1980's.

A survey of contractors, state and local agencies, and equipment rental agencies was conducted in the Spring of 1988 by EEA, Inc. A copy of the survey is shown in Figure 6-1. Preliminary results show that according to those owners of backhoe/loaders and rollers/compactors who responded to the average life section of the survey, the average life of a backhoe/loader is 10 years, and the average life of a roller/compactor is 9 years. While many reported the average life of equipment to be 15-20 years, other contractors reported average equipment lives of 5, 7, or 10 years across the board. In these cases, the estimates appear to be the number of years contractors own equipment before resale, and not necessarily the entire useful life of the equipment. County and city governments tend to own equipment for much longer periods of time than private contractors, as these agencies do not use equipment as frequently and as intensively as their private counterparts. Private contractors tend to replace equipment more frequently than government agencies, possibly due to different accounting procedures and/or greater financial ability. For example, many companies replace all equipment types once it reaches a certain age in order to maintain a new, modern fleet, a luxury not always afforded by a city or county agency. The point of resale is

Figure 6-1

Population Of Off-highway Diesel Construction Equipment

TYPE OF CONTRACTING: ____________________
(e.g. road building, site preparation, underground work, bridges, etc)
LOCATION (COUNTY): ____________________
ANNUAL SALES: $ ____________________

	NUMBER OF VEHICLES HP*						AVERAGE ANNUAL USAGE	TYPICAL AVERAGE LIFE
EQUIPMENT TYPE	<50	50-120	120-240	240-480	> 480	TOTAL	(hrs/yr)	(yrs)
BITUMINOUS PAVER								
CONCRETE PAVER								
OTHER PAVING								
ROLLER/COMPACTOR								
CRANE								
EXCAVATOR								
TRENCHER/DITCHER								
INDUST. TRACTOR								
LOG SKIDDER								
GRADER								
OFF-HWY TRUCK								
SKID-STEER LOADER								
SCRAPER								
TRACK LOADER								
CRAWLER TRACTOR								
WHEEL LOADER								
WHEEL DOZER								
BACKHOE LOADER								
DUMPER								
FELLER/BUNCHER								
OTHER								
TOTAL								

* IF YOU ARE UNABLE TO LIST EQUIPMENT BY HP, PLEASE LIST TOTAL PIECES OF EQUIPMENT

generally when the equipment has been depreciated fully in an accounting sense. However, this equipment is not necessarily scrapped, especially if the corporate policy is to replace equipment every seven or eight years, and is resold to smaller contractors or owner operators.

As backhoe/loaders and roller/compactors make up a large percentage of the construction equipment owned in California, increasing the average life from 6-7 years to 10-12 years increases the calculated overall average life of construction equipment by several years.

Based on the above information, EEA believes that the average life of construction equipment as an aggregate is approximately 13-15 years, and this number is used in EEA's calculations.

California Share of the Total U.S. Market

The MacKay study provided a construction equipment population for the U.S. as a whole. CIMA then derived California's share of the total by multiplying these numbers by estimates of California's share of the U.S. construction machinery market. Overall, CIMA's equipment population amounts to 4% of the U.S. total. This compares to earlier CIMA/ERT estimates of 5%. These percentages appear to be quite low, as discussed below.

Table 6-4 displays California's shares of U.S. construction employment and business receipts for the 1977 and 1982 U.S. Census of Construction Activities. In the 1977 survey, California construction firms amount to 9.8% of all U.S. construction firms, with 9.9% of all construction employees, and 13.7% of all construction receipts. The figures for 1982 vary slightly, with 9.8%, 10.3% and 13% of the number of U.S. construction firms, construction employees and total business receipts, respectively. In the heavy construction industry, where much of this equipment is used, contractors often work during the nine or ten dry months of the year (March - November) and close down during the rainy months. Consequently, much of the equipment used is

Table 6-4

1982 U.S. Census Of Construction Industries

	All Establishments			Establishments w/o Payroll		Establishments w/ Payroll		
	Number	All Employees	All Business Receipts	Number	All Business Receipts	Number	All Employees	All Business Receipts
U.S.	1,369,309	4,275,070	365,420,747	932,608	40,908,315	456,701	4,275,070	324,512,432
California	136,972	443,349	48,739,078	90,279	5,462,742	46,693	443,349	43,276,336
(% of U.S.)	9.9%	10.4%	13.3%	9.7%	13.4%	10.2%	10.4%	13.3%

1977 U.S. Census Of Construction Industries

	All Establishments			Establishments w/o Payroll		Establishments w/ Payroll		
	Number	All Employees	All Business Receipts	Number	All Business Receipts	Number	All Employees	All Business Receipts
U.S.	1,200,407	4,272,659	244,815,908	720,393	20,150,970	480,014	4,272,659	224,664,938
California	104,032	424,397	33,412,414	59,341	2,897,536	44,691	424,397	30,514,878
(% of U.S.)	8.7%	9.9%	13.6%	8.2%	14.4%	9.3%	9.9%	13.6%

only utilized during nine months of the year, during which time the California industry is producing roughly ten percent of the nation's construction activity. Based on this information, it is difficult to explain how California could account for only 4% of total U.S. construction equipment ownership. When it is assumed that California holds 10% of the U.S. market share for construction vehicles, the MacKay study's U.S. totals translate into 120,000 machines owned in California. This number compares well to PSR's estimate of 127,000.

The above information enabled EEA to make a final check of the PSR estimate by using manufacturer's estimates of U.S. sales per year. Based on Department of Census records, manufacturers sell approximately 90,000 pieces of construction equipment domestically each year. When this number is multiplied by 13-15 as an average life, and divided by 10 to calculate California's market share, the inventory amounts to approximately 117-135 thousand machines.

6.5 THE EQUIPMENT INVENTORY FORECAST TO 2000

The creation of the equipment inventory and subsequent emissions inventory consisted of several stages. The first step was to develop a forecast of construction activity to 2000. Based on expected construction activity it was possible to create a population growth rate for construction vehicles to 2000. The final step was to apply emissions factors to expected construction equipment population through 2000.

Table 6-5 shows EEA's projection of total construction activity to 2000. The historical data for residential, non-residential, and heavy construction was provided by the Construction Industry Research Board. Forecast data for residential and non-residential construction permit values was available from the UCLA Business Forecast for California. The data was adjusted for inflation and changed into 1982 dollars, so that the permit valuation may be used as a proxy for construction activity. The residential building category includes new construction of and renovations to single and multifamily

Table 6-5

California Construction Trends to 2000
Permit Valuation
($1982)

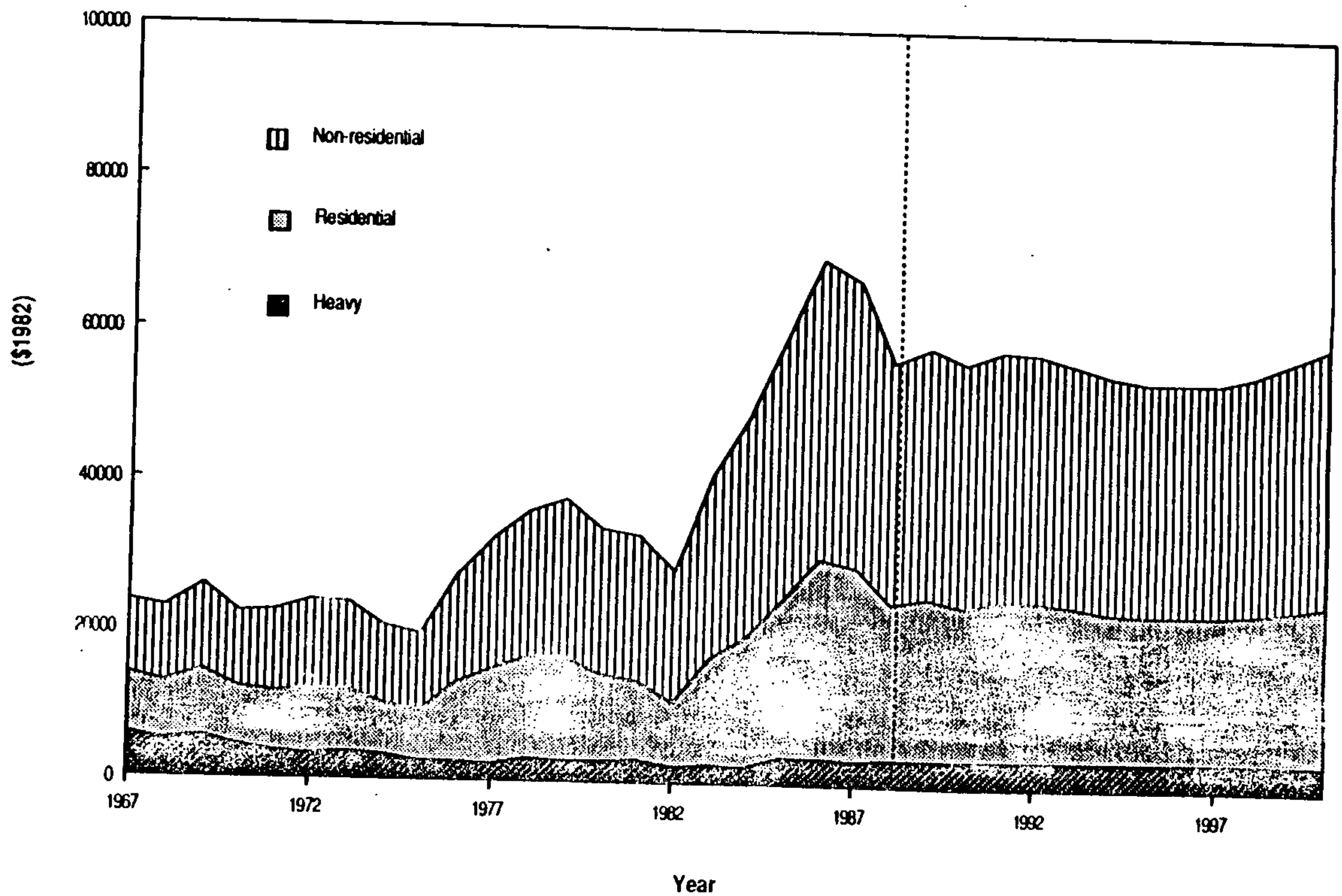
YEAR	HEAVY	RESIDENTIAL	NON-RESIDENTIAL
1967	5830	2091	1877
1968	4883	2840	2193
1969	5662	3148	2531
1970	4437	3178	2544
1971	3476	4526	2977
1972	3277	5407	3049
1973	3485	4892	3233
1974	3289	3691	3251
1975	2351	4525	3106
1976	2560	7987	3477
1977	2249	10494	4714
1978	2903	10661	5954
1979	2861	10789	7291
1980	2646	9088	7458
1981	2994	7486	8822
1982	2268	6273	8698
1983	2534	11828	9911
1984	2279	15068	12007
1985	3544	17807	13532
1986	3590	22839	13488
1987	3385	22107	12875
1988	3500	17366	11036
1989	3500	18183	11430
1990	3500	17150	11542
1991	3500	17827	11769
1992	3500	17784	11739
1993	3500	17179	11537
1994	3500	16514	11507
1995	3500	16090	11551
1996	3500	16073	11553
1997	3500	16080	11616
1998	3500	16374	11922
1999	3500	17110	12443
2000	3500	17775	13001

structures. Non-residential buildings are defined as commercial buildings such as offices, stores, hotels, amusement and recreation facilities, parking garages and service stations, industrial buildings and hospitals. Non-building or heavy construction includes the building of: streets and highways, bridges, sewerage and waste systems, electric power and heating systems, river and harbor flood control, water supply systems, and dams and reservoirs.

No forecast data was available for heavy construction; however, the general trend of the last ten years was extended to 2000, under the assumption that heavy construction growth will remain fairly stable throughout this period. The underlying assumptions are as follows. First, the magnitude of heavy construction activity is generally a function of public expenditures on roads, dams, bridges, and utility projects, and of large private enterprise projects such as refineries or manufacturing facilities. It is impossible to forecast the amount of this type of activity, since public expenditures are subject tax legislation and public referendums, and it is difficult to forecast how the public may vote on these issues. Private sector heavy building is as equally difficult to forecast, as private corporations do not usually disclose their long-range building plans. Second, heavy construction activity has remained fairly stable throughout the last ten years, as displayed in Figure 6-2. The large amount of building activity in the late sixties and early seventies declined greatly in the mid-seventies, and, except for an increase in the level of activity in 1983-1984, has remained stable for the last ten years. The rise in the early eighties may be attributed to two political developments in 1983. First, a $0.02 state tax per gallon and a $0.05 Federal tax per gallon was placed on gasoline which was ear-marked for road construction and maintenance. Second, the new administration headed by Governor Deukmejian has placed more emphasis on transportation matters than the previous administration. For these reasons, the forecast for heavy construction activity is that it will be constant at current levels through 2000.

Figure 6-2

California Construction Trends - Permit Valuation 1967-2000



Based on this information and the UCLA forecasts of residential and non-residential construction permit values, the permit valuation of total construction has been calculated to 2000. This information appears in Table 6-5. From 1988 to 2000, construction activity, as assessed by permit valuations, remains stable at approximately $34 billion per year.

6.6 THE EMISSIONS FORECAST TO 2000

The emissions inventory was calculated by assuming the following:

- sales
- scrappage rate as a function of vintage
- usage as function of vintage
- load factor
- emission factors
- average horsepower

Sales were assumed to be constant (non-cyclic) between the years 1985 to 2005. The assumption is based on the fact that construction activity and, hence, construction equipment fleet size are projected to be constant for the next 15 years. Sales were projected at 5900 units/year for equipment over 50 HP (i.e., heavy-duty equipment).

Scrappage Rate was constructed from anecdotal information, indicating there was little scrappage initially (2 percent per year) to 10 years, with most of the scrappage occurring between 10 and 20 years (5 percent per year). Our surveys have shown that there are significant quantities of equipment in California older than 20 years, and, therefore, we have the final element of scrappage between 20 and 30 years. Survival rates as a function of vintage are shown in Table 6-6. The scrappage curve provides a mean life of 15 years consistent with other estimates cited in this section.

Table 6-6 California Heavy Construction Equipment Survival and Use Rates by Vintage

Equipment Vintage	Equipment Survival Rate	Equipment Use Hours/year
1	1.00	1400
2	0.98	1400
3	0.96	1400
4	0.94	1400
5	0.92	1400
6	0.90	1400
7	0.88	1400
8	0.86	1300
9	0.84	1200
10	0.80	1100
11	0.75	1000
12	0.70	1000
13	0.65	1000
14	0.60	1000
15	0.55	1000
16	0.50	1000
17	0.45	950
18	0.40	900
19	0.35	850
20	0.30	800
21	0.27	750
22	0.24	700
23	0.21	700
24	0.18	700
25	0.15	700
26	0.12	700
27	0.09	700
28	0.06	700
29	0.04	700
30	0.02	700

Usage Rates were also derived from anecdotal information. Construction companies interviewed said that new equipment was intensively used in the eight to ten years of its life. At that point it was traded to a second owner who typically used it less intensively. The second owner could also use it for eight to ten years before scrapping it or reselling it after rebuild. Based on some preliminary information from the EEA survey, equipment older than 20 years appear to be used 700-800 hrs/year about one-half the new equipment usage of 1400-hrs per year. Average use rate is about 1050 hours per year, consistent with PSR estimates for equipment above 50 HP. Usage rates as a function of vintage are also shown in Table 6-6.

Load Factor was assumed constant as it represents an operational element not correlated with age. The load factor assumed is 0.55, consistent with EEA's recommendation for the load factor on a modified test procedure for emissions certification.

Emissions Factors are a subject of much contention. The original MS-1 baseline used emission factors derived from the CAL/ERT study. The study was based on manufacturer inputs which we understand varied widely. The CAL/ERT estimates seem unreasonably low in many cases - 9 out of 24 categories of equipment reported NO_x emissions well below 10 g/BHP-hr, some as low 6.6 g/BHP-hr, for example. Yet, none of the major manufacturers we interviewed provided information suggesting that any of their off-highway engine lines were currently calibrated to achieve 6.0 g/BHP-hr. (The baseline dated to 1979, when manufacturers claimed 6.0 g/BHP-hr was virtually unachievable.) Our estimates, based on information detailed in Section 4 for the major manufacturers also accounts for the improvements that have occurred due to increased penetration of turbocharging, low sac injectors, etc. in the construction equipment engine market. Assumed emission factors are shown in Table 6-7. We have also derived emission factors for Level I and Level II control efforts, based on certification levels of on-highway engines meeting equivalent standards. The details are also shown in Table 6-7. CO emission

TABLE 6-7

EMISSION FACTORS BY MODEL YEAR
(g/BHP-hr)

Model Year	HC	NOx	Particulate
Pre-1970	1.8	14.0	0.7
1970-1974	1.5	13.0	0.6
1975-1979	1.4	12.0	0.5
1980-1984	1.3	11.0	0.5
1985-1990	1.2	11.0	0.5
(no control) 1991+	1.1	11.0	0.5
(Level I) 1991+	0.8	8.2	0.6
(Level II) 1994+	0.6	5.2	0.5

levels are not shown, but a CO emission factor of 4 to 5 g/BHP-hr appears reasonable. It must be noted that considerable uncertainties surround these factors (± 15 percent). Total California inventories were obtained from ARB officials in Sacramento.

Based on our analysis, the base emissions inventory* for 1987 are as follows:

- HC 35.91 tons/day (0.56%)
- NO_x 301.03 tons/day (10.53%)
- Particulate 13.61 tons/day (0.23%)

While the contribution of off-road construction equipment to total HC and particulate inventory is low, it is relatively large for total NOx. Under a no control scenario, by the year 2000, emissions decline to:

- HC 27.42 tons/day (0.41%)
- NO_x 262.96 tons/day (8.90%)
- Particulate 11.91 tons/day (0.15%)

Contrary to expectations, the contribution of off-road construction equipment to total emissions inventory does not increase over the next decade even under a no control scenario. Under a scenario where only Level I standards are imposed in 1991, the benefits in 2000 over a no control scenario are:

- HC reduced by 4.72 tons/day
- NO_x reduced by 47.22 tons/day
- Particulate increased by 1.57 tons/day

Under a scenario where Level I standards are introduced in 1991 and Level II in 1994, benefits in 2000 over a no control scenario are:

- HC reduced by 7.10 tons/day
- NO_x reduced by 82.83 tons/day
- Particulate increased by 0.39 tons/day

---

* Percent of statewide inventory in parentheses.

In effect, Level II controls allow particulate to remain constant or unchanged from the base scenario, and illustrates the NO_x/particulate tradeoffs. Figures 6-3 to 6-5 show the influence of no control, Level I and Level II control on HC, NO_x and particulate emissions respectively. More detailed output is presented on emissions in tons/year in Appendix B.

All of the above figures are derived for 100 percent compliance and no exemptions. Reductions of emissions with exemptions and at less than 100 percent compliance rate can be calculated by:

$$\text{Actual reduction} = \text{Theoretical Reduction} \times \frac{\text{Exempt (BHP-hr)}}{\text{Total (BHP-hr)}} \times \text{Compliance Rate}$$

Table 6-8 shows the BHP-hr distribution by equipment and HP category. The table can be used as a guide to estimate the effect of exempting any specific category of engines or equipment from emission regulations.

FIGURE 6-3

Heavy Duty Equipment HC Emissions
California, 1985 - 2005

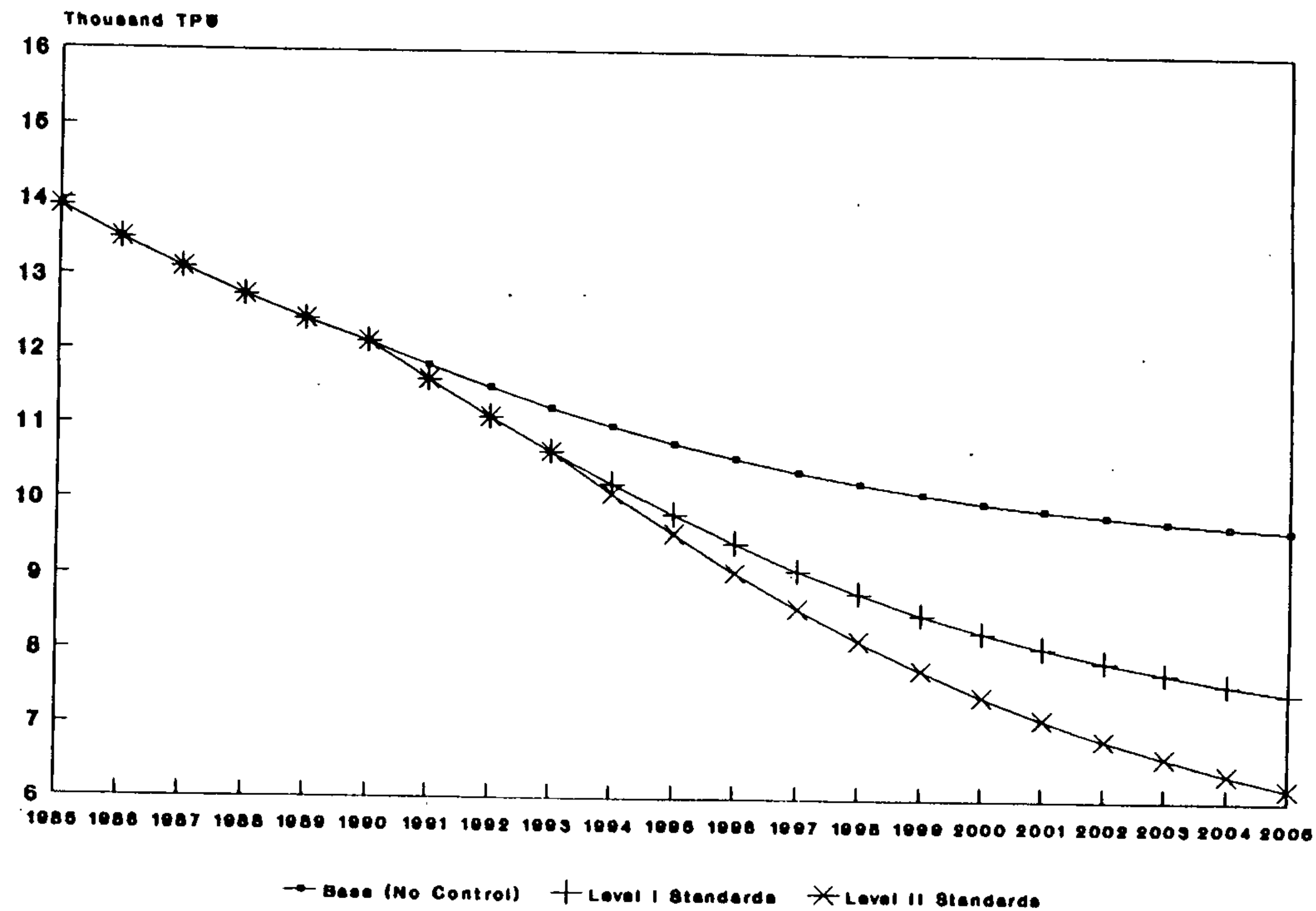


FIGURE 6-4

Heavy Duty Equipment NOx Emissions
California, 1985 - 2005

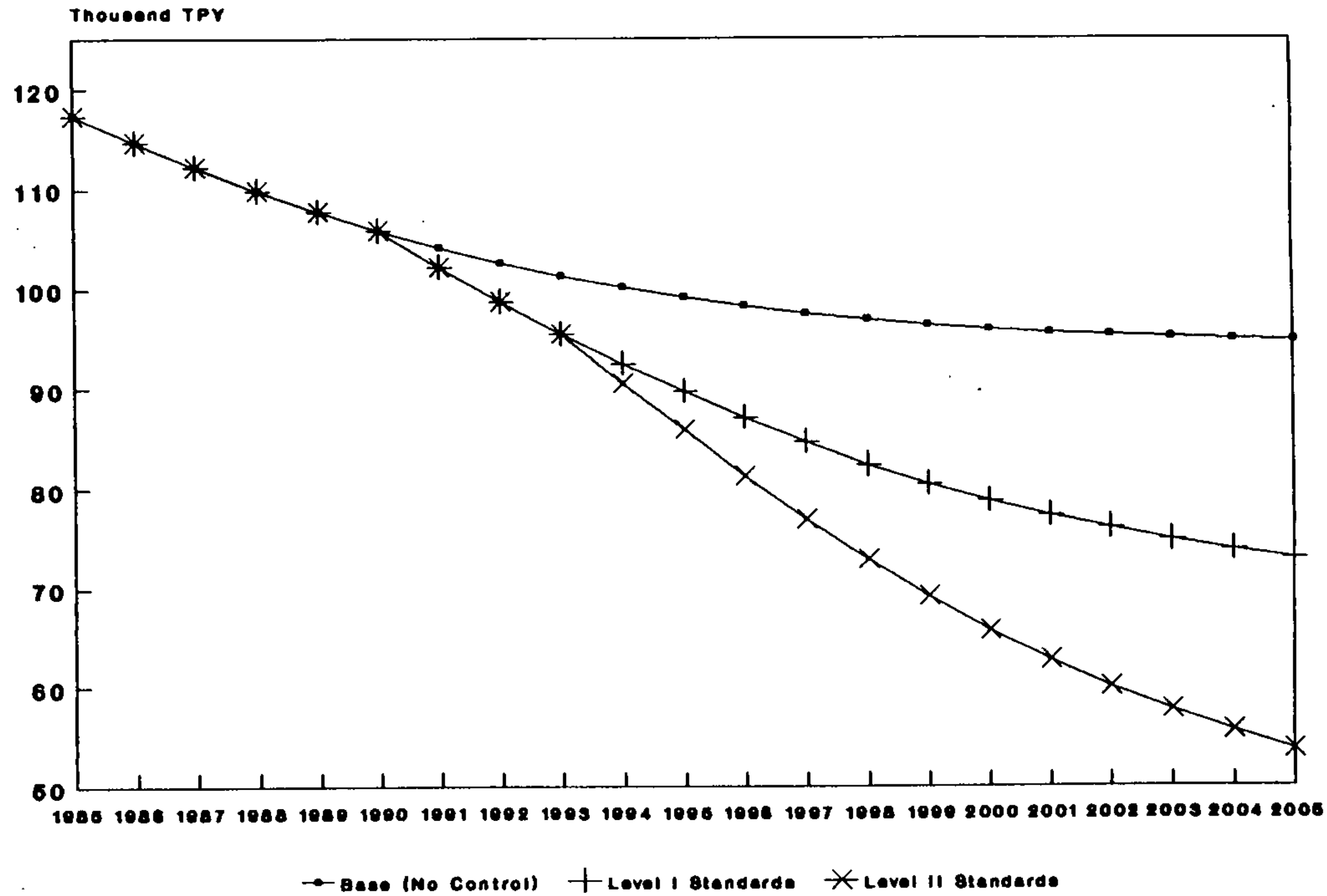


FIGURE 6-5

Heavy Duty Equipment PM Emissions
California, 1985 - 2005

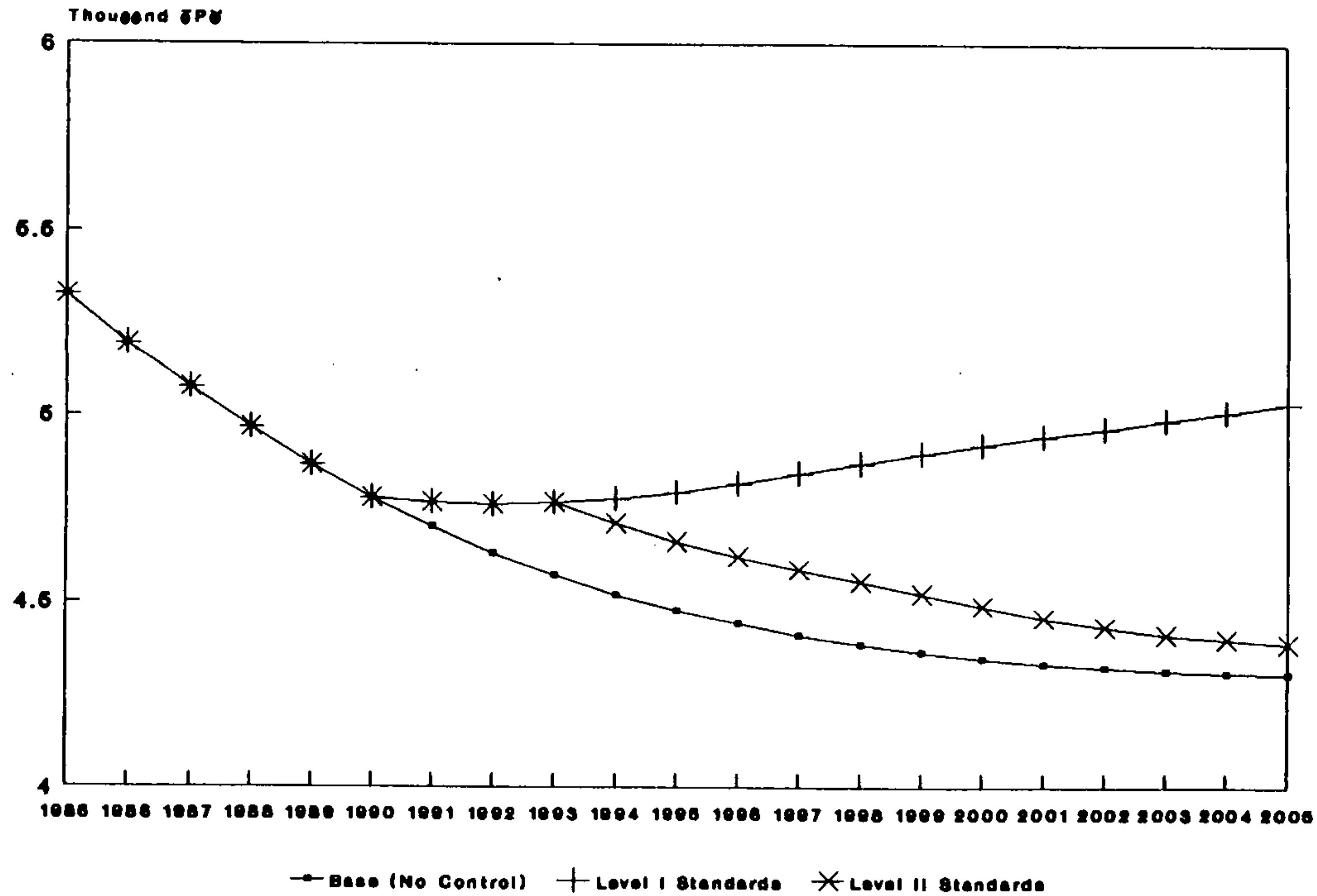


Table 6-8

Total BHP-HR Inventory For Off-Highway Diesel

(Billions of BHP-HRS)

Equipment Type (Average HP)	H.P. < 50 (40)	H.P. 50-120 (85)	H.P. 120-240 (180)	H.P. 240-480 (360)	H.P. > 480 (600)	Total
BITUMINOUS PAVER	0	106	165	11	0	282
CONCRETE PAVER	13	44	166	0	0	223
OTHER PAVING	0	11	52	65	11	139
ROLLER/COMPACTOR	24	94	330	6	0	453
CRANE	0	29	97	31	29	186
EXCAVATOR	30	120	499	450	41	1141
TRENCHER/DITCHER	50	6	16	0	0	73
INDUST. TRACTOR	53	58	25	12	0	148
LOG SKIDDER	0	180	434	0	0	614
GRADER	0	34	79	9	0	121
OFF-HWY TRUCK	0	0	92	358	440	891
SKID-STEER LOADER	65	36	0	0	0	101
SCRAPER	0	24	137	85	12	258
TRACK LOADER	NA	NA	NA	NA	NA	0
CRAWLER TRACTOR	38	217	839	854	236	2183
WHEEL LOADER	0	294	899	546	55	1793
WHEEL DOZER	0	24	113	92	50	279
BACKHOE LOADER	0	602	32	0	0	634
DUMPER	19	0	0	0	0	19
FELLER/BUNCHER	0	0	344	176	0	519
TOTAL	293	1879	4317	2694	874	10057

7. ECONOMIC IMPACTS

7.1 OVERVIEW

Potential regulations would most directly affect two industries: the equipment manufacturing industry, which consists of both domestic and international firms, and the California construction industry itself. The economic impact analysis focuses on these industries, but also considers (in less detail) the mining, agriculture, and forestry industries which utilize some types of equipment used by the construction industry. Two sets of effects caused by regulation are examined: the impact on costs and the impact on competitiveness.

The imposition of emissions standards on construction equipment will lead to increased costs of doing business for both the construction industry and equipment manufacturers. The construction industry may experience increases in equipment purchase costs and fuel costs (due to reduced fuel economy), both of which lead to increased total project costs. The manufacturing industry may experience increases in R&D expenses, expenses associated with certification and will require investment in additional facilities needed to certify engines. Engine unit costs can increase due to the addition of emission control components. These costs are determined and allocated between firms, consumers, and taxpayers. Certain non-pecuniary costs which are difficult to quantify are also discussed: for example, manufacturing firms with smaller market shares in California might decide to limit their equipment offerings rather than redesign every equipment type, resulting in limited choices for consumers. The diverse nature of the industries being discussed prevents universally applicable conclusions, but the discussion provides the ARB with an understanding of the range of economic impacts likely under regulation.

The impact of potential regulations on the competitive atmosphere in the construction and manufacturing industries is also examined. Several examples of how regulation might effect competitiveness are as follows. If regulations are imposed on all equipment sold in California (i.e. regulations are imposed on manufacturers who sell equipment in California), large national or international construction firms who could easily purchase or ship equipment from out of the state may have a cost advantage over locally based firms. Regulations may force some manufacturers who sell only a few pieces of equipment to California buyers per year, such as the manufacturers of specialty equipment, to withdraw from the California market entirely. Conversely, if regulations require California contractors to use equipment which meets emission standards (i.e., the regulations are placed on contractors), out-of-state contractors may choose to withdraw from that market rather than purchase new equipment or retrofit existing equipment to meet California standards.

Section 7.2 presents the objectives of the economic analysis and the methodology used to achieve them. Section 7.3 focuses on the practices, cost structures, and competitive behavior of the California construction industry. California mining, forestry, and agricultural operations are discussed in Section 7.4. Section 7.5 discusses the structure of the equipment manufacturing industry, and competitiveness issues.

7.2 METHODOLOGY

In order to determine the effects of regulation on the construction industry, the analysis was divided into several phases. First, it was necessary to develop a general understanding of the economic structure of the industry as a whole. Second, specific cost data was gathered from individual firms. These two areas were then integrated to formulate an understanding of how increased costs might affect not only the industry as a whole, but also individual firms, consumers and taxpayers.

The economic analysis of the manufacturing industry also consisted of two phases. First, it was necessary to determine the manufacturers selling in California and the share of their business represented by California buyers. This information was used to gain an understanding of how manufacturers might react to regulations, in terms of continuing sales to the California market. Second, economic data was gathered on the structure of the industry, as well as information on economic trends in annual sales volumes and R&D expenses. Estimated cost increases to manufacturers were used in calculating the increase in costs to the manufacturing industry. The following section discusses these procedures in greater detail.

7.2.1 California Construction Industry

In studying potential effects on the construction industry, it is important to understand the past economic trends of the industry as a whole and within different types of construction activities. This information provides insight into whether construction activity is likely to grow or decline in the future, which segments of the construction industry are growing or declining, etc. All of these factors are important in terms of the impacts a regulation might have and timing and scope considerations for imposing emission regulations. Several specific types of projects were investigated: commercial building, residential development, utility projects, civic projects such as roads, dams and bridges, and the emergency preparedness activities of state and local governments. These types of projects were selected because they were either numerous, equipment-intensive, or are politically important. The original intent was to select several projects within these categories, and to gather data on projects cost structures (i.e., the relative importance of labor, materials, equipment and fuel costs to total project costs) plus information on types of equipment used, annual usage and average life, and fuel use. However, early research revealed that the majority of equipment-intensive work is done in earth-moving operations such as site preparation and paving, grading and excavating for roads, dams, and bridges. Most of this work is done by firms which specialize in such projects.

For these reasons, interviews were conducted with three California contractors who are involved primarily in site preparation, road building, and other paving, grading, and excavating activities: Teichert Construction of Sacramento, Sully-Miller Contracting/Blue Diamond Materials of Long Beach, and Oliver de Silva Company of Hayward. These contractors are members of the Associated General Contractors of California (AGCC), an industry group which represents over 900 contractors who are responsible for nearly 70% of all nonresidential construction sales (dollars) in California. These interviews provided us with data on construction project cost structures and equipment inventory, as well as anecdotal information on the characteristics of the industry. Low, medium and high cost increase scenarios were developed and applied to a number of equipment types to determine the range of regulatory impacts. If cost increases were less than 2%, then the effects of regulation are considered to be negligible. Cost increases in the 2-10% are of concern, and regulations which would create cost increases in this range should be modified to minimize negative impacts. The impact of regulation were determined to be of significant concern if equipment costs rise by ten percent or more.

7.2.2 Equipment and Engine Manufacturing Industry

To conduct an analysis of the impacts of the regulation of California equipment on the equipment industry, it was necessary to understand how the equipment industry is structured, and to what extent California is involved in the equipment-buying market. Because California is only part of a worldwide market for construction equipment, the impacts on the industry as a whole are somewhat limited. As described in Section 2, it was determined that 5 or 6 engine manufacturers account for a majority of the sales but dozens of smaller ones have very low sales volumes in California.

Increases in R&D costs and costs associated with the need for new or improved dynamometer facilities and certification were estimated, and calculated as a percentage of typical R&D costs and net revenues of the major manufacturing firms, to determine quantitatively the increased costs to the manufacturing industry. Data on annual sales and operating expenses were taken from annual reports supplied by the manufacturers. Again, cost increases were evaluated by the criterion set forth above: less than two percent increases were seen to be negligible, two to ten percent increases raised cautionary flags, and increases greater than ten percent were seen as significant.

7.2.3 Data Sources

The information needed to undertake this study was gathered both anecdotally and quantitatively. Because of time constraints and the lack of precise, publicly available data on both the U.S. and California construction industries, it was necessary to combine existing data, in the form of value of shipments, permit values, and annual revenues with anecdotal information on areas where no data or published information existed, such as the general structure and practices of the industry. This combination provided a basis on which to make judgments as to the behavior of equipment-using industries. As the scope of this project is very broad, in that regulations would potentially affect all industries which use off-highway construction equipment, anecdotal information about a broad range of topics gathered from conversations with contractors and industry representatives made it possible to determine which areas should be studied extensively, and which areas did not need as much emphasis. Most of the economic data was gathered from the 1982 U.S. Census of Construction Industries and monthly issues of the California Construction Review, while anecdotal information was gained from conversations with the Construction Industry Research Board (CIRB), Associated General Contractors of California (AGCC) and individual contractors.

7.3 THE CALIFORNIA CONSTRUCTION INDUSTRY

An examination of the construction industry in California is of critical importance to understanding several key issues relating to cost and competitive impacts of regulations on construction equipment which are used throughout this study. This examination was used to:

- Identify firms which will be affected by regulations, i.e., which sectors of the construction economy will be directly affected, and who is likely to absorb the costs
- Analyze equipment buying patterns and usage, such as the sale and resale of construction equipment, which are important to the creation and analysis of an accurate construction equipment and emissions inventory
- Analyze cost structures in order to understand the cost impacts of regulation
- Develop an understanding of potential regulatory and competitive problems resulting from interstate/border county trade
- Determine enforcement needs and methods

Section 7.3.1 discusses the expected future trends in the California construction economy. Section 7.3.2 discusses several construction project categories examined for cost impacts. Project cost structures and competitiveness issues are discussed in 7.3.3 and 7.3.4.

7.3.1 Trends in the Construction Economy

In analyzing the potential impacts of regulations on the construction industry, it is important to understand the direction trends for California construction activity. Currently, total construction permit values amount to only 1.15% of the Gross State Product. The forecast dollar value of residential, nonresidential and heavy construction activity in California is shown in Table 6-5. This table shows a near constant level of total construction activity through 2000. These forecasts are based on data from the UCLA Business Forecast for California and from historical figures received from the Construction Industry Research Board, which are discussed further in Section 6. The number of residential and non-residential building permits are expected to decline slightly throughout the 1990s but recover slightly by 2000. Some of the reasons for slow or negative growth in these construction activities are:

- slower income growth
- higher mortgage rates
- slower population growth
- movement away from a goods-producing economy towards a services-oriented economy
- current excess capacity of non-residential structures,
- the proliferation of building restrictions and moratoriums on growth.

It is reasonable to assume that nearly stable construction activity will result in a constant level of equipment usage and fleet size in the future.

Since this study focuses on heavy construction activities, it is appropriate to discuss the role of heavy construction in the California construction economy. The most recent Census of Construction Industries reported that heavy construction and general contracting firms amount to 4% of the total number of California construction firms. Non-building/heavy construction firms employ 13% of the construction employees in California. The contract awards won by these firms constitute 10% of total permit valuation in California during 1986 and 1987, and 9% of the U.S. total for non-building construction in 1987. Heavy construction activity is expected to remain at its current level through 2000, as discussed in Section 6.

This data is useful in understanding the role of heavy equipment in the construction industry and can be used in calculating the cost impacts of regulations on the construction industry. While heavy equipment is used in areas other than heavy construction, heavy equipment usage is found primarily in these activities, and heavy construction contractors may be the most affected if equipment prices increase. Since most of the heavy equipment use is found primarily in the building of roads, dams, and bridges, and in site preparation and development, these industries are examined and a "worst case scenario" for cost impacts is developed for equipment-intensive sectors of the industry.

7.3.2 Selected Construction Categories

In designing this study, five construction categories were designated as areas where cost impacts would be analyzed: Commercial building, residential development, public works projects, utilities, and the activities of state and local governments. These categories were chosen either because they were seen as heavy equipment-intensive or because they constitute a large part of the California construction economy. The following is a discussion of each of these categories.

Residential/Commercial Building

While there is a great deal of commercial building in California, amounting to $5,718,634,000, or 15% of total California construction permit value in 1987, commercial building is not typically equipment-intensive. Most of the actual building is more labor-intensive, uses small equipment, or equipment such as stationary cranes or hand-held equipment which do not fall into the categories addressed in this study. However, since any new building requires site development to some extent, either in grading and excavating the site or putting in sewer and utility lines, heavy equipment is used during the initial phases of the project.

Residential buildings accounted for 56% of the total dollar value of building permits and contract awards in California in 1987. As with commercial building, much of the equipment used in the activities involved in building would not fall under proposed regulations. However, the site development itself, either residential, commercial or industrial, is heavy-equipment intensive. Again, this work is often done by specialty firms, who are expected to pass costs increases on to developers. Large, earth moving land development projects, such as the hillside developments in the Los Angeles area, use heavy equipment extensively.

Public Works Projects

This study defines public works projects as highways, dams, bridges, or other large-scale projects undertaken by local, State or Federal governments. These projects are financed through taxation, and significant increases in the costs of these projects would require additional sources of tax revenue.

The building of roads, bridges and dams requires extensive use of heavy earth-moving vehicles. This sector is perhaps the most equipment intensive of all construction activities which have been examined for potential regulatory impacts. In 1987, building permits and contract awards for this category was valued at $1,503,940,000 or 4% of total construction permit value in California. However, the Associated General Contractors of California indicated that the number of very large road building projects nationally as well as in California is declining. This is primarily because the Federal Interstate Program will come to an end in 1990, and the amount of space available to build new highways going into and out of the major cities is declining. Rather than constructing new highways, in many cases median strips are being removed and replaced with road. Double-decker freeways are being considered in some parts of the state. As road building decreases, it seems likely that bridge construction, which uses heavy equipment extensively, will also decrease.

The congested traffic in most of the state's major cities has led to the planning and building of rapid transit systems, such as the Sacramento Light Rail System and the Long Beach Rail. This was seen as a possible area where heavy equipment use may be growing. In some cases these projects require heavy earth moving, such as tunneling underground rail systems; however, the Sacramento Light Rail system was built in existing railroad tracks, and did not require the use of heavy earth moving equipment.

Public works projects require extensive use of large construction equipment. Although industry sources indicate that heavy construction projects are expected to decline as a percentage of total construction in California in the coming years, these projects will remain extensive users of heavy equipment. Therefore, the road, dam and bridge building contractors will be among the most affected by regulations.

Utilities

The building of gas, electric and nuclear utilities requires the use of heavy construction equipment. This work is generally subcontracted out to specialized contracting firms. However, these facilities have ongoing use for equipment in their daily operations, such as digging trenches and laying cable. The types of equipment-using activities vary across types of utilities; telephone companies and electric utilities erect poles for transmission wires while gas companies must dig trenches to put in pipelines. Much of the equipment required for these activities is smaller than 50 HP, and would not fall under proposed CARB regulations. For example, Pacific Gas and Electric in San Francisco indicated that of over one hundred pieces of self-propelled, diesel vehicles in its fleet not already licensed for street use (which comprise less than one percent of the utility's total vehicles and equipment), none were greater than fifty horsepower. Therefore, it does not appear that regulations would significantly affect this sector.

State and Local Governments

Each of the 58 counties and 445 cities in California own off-road equipment for road maintenance and for emergency situations such as flood control and snow removal. In addition to equipment owned by local governments, CALTRANS owns over nine hundred pieces of diesel off-highway equipment which are over 50 HP. The total number of vehicles owned by these agencies has not yet been assessed, but could amount to several thousands. EEA is conducting a mail-in survey of all county and city Public Works Departments in California, and results have not been tabulated. However, preliminary results indicate that the total amount of equipment owned by county and city governments is large, and that this sector could be impacted by proposed regulations.

A study conducted by EEA of State and Local public works departments and private contractors indicates that government agencies on average own their equipment longer than private contractors as they have low annual usage rates. Because of this, any regulatory impacts would occur over a longer time span in this sector than the private sector.

7.3.3 Project Cost Structures

Construction project costs consist of those charges resulting from parts, equipment, labor, material, and fuel. The proposed legislation would increase equipment costs and possibly fuel costs to equipment users; therefore, equipment costs as well as the usage patterns and buying decisions of equipment users must be understood in order to determine the total impact on projects costs and on the industry, consumers and taxpayers as a whole.

Some of the information used here is anecdotal in nature, gathered from conversations with contractors and industry groups. Project cost figures for typical construction projects were supplied by contractors. Equipment costs were furnished by contractors, equipment dealers, and rental agencies. The analysis of project cost structures is divided into several parts. First, the equipment usage and buying patterns of contractors are examined. Second, equipment cost increases under three regulatory scenarios (low, medium, and high stringency) are applied to the current prices of a variety of commonly used construction machines in order to determine percentage costs impacts. Finally, the cost breakdown of typical construction projects is analyzed to quantify the effect of increases in equipment costs on overall project cost.

Equipment Buying Patterns/Usage

The importance of investigating the equipment buying patterns and usage of contractors is twofold. Understanding what motivates contractors to buy particular brands of equipment, or to rent rather than purchase certain pieces of equipment, gives insight into how increased costs of equipment or reduced fuel economy might affect future buying decisions. Understanding the equipment usage patterns of contractors aids in compiling an inventory of construction equipment, as discussed in Section 6.

Contractors both rent and own equipment, and it is not unusual for a firm to own 75-85% of its off-highway construction equipment while renting the remaining 15-25% of the equipment used in its projects. As a rule, larger firms tend to buy more of their equipment than smaller firms, primarily because heavy equipment is costly, and smaller firms may not have the resources to maintain a large fleet. The decision to rent or own equipment is a matter of equipment utilization; it is not cost-effective to purchase equipment which is not used on a regular basis.

Several factors influence a contractor's choice of equipment brands. Service is foremost; the contractors contacted agreed unanimously that availability of parts and good dealer support are the most important factors in the buying decision. Price enters the decision-making process only if there is at least a 10% price differential between the buyers preferred brand and another brand of equipment. Service is more important than price because "down time" in the construction industry is extremely expensive. Equipment fuel economy was <u>not</u> cited as a factor in purchasing decisions, because contractors did not feel that there are significant differences between equipment brands in terms of fuel economy. In addition, the fuel costs are tracked only at an aggregate level, and contractors cannot typically distinguish between small fuel economy differences of less than 5 percent. These facts are important in a regulatory sense since price increases and decreased fuel efficiency may occur when engines are upgraded to meet emissions requirements.

To fill gaps in their equipment fleets, firms rent equipment either from rental companies or from owner/operators. There is little data available regarding equipment rental agencies. According to Associated Equipment

Distributors, who represent firms which rent, sell, service and supply parts for heavy construction equipment (but not firms that only rent, sell or service) there may be as many as 250 equipment dealers in California who sell or rent new or used equipment. The precise number of rental dealers is not known, nor is the total amount of equipment in the rental fleet.

Owner operators are individuals, often without contractors licenses, who move from site to site offering their equipment services. These businessmen own backhoes, graders, skip loaders and other small to medium sized pieces of equipment, and fill voids in larger companies' fleets. It is unknown how many owner/operators are working in California, but is has been estimated that there are at least several thousand. These owner operators generally purchase used equipment, either locally or from out-of-state auctions, and therefore would not be affected immediately by regulations on new vehicles.

Equipment Costs

The costs of off-road construction equipment vary greatly across equipment types and sizes. Table 7-1 lists purchasing costs for a range of off-highway construction vehicles. The table also shows maximum first cost increases under the three regulatory scenarios considered. For vehicles under 120 HP, the maximum costs are $100, $1000, and $2500. The costs applied to equipment in the 120-240 horse power range are $100, $1000, and $3750. For the largest category, engines over 240 HP, the costs increases are $100, $1000, and $5000. Note even that under the highest cost (Level III) scenario when costs were imposed on the smallest pieces of equipment (the "worst case scenario"), the increase in price for any piece of equipment is less than five percent. Since EEA is recommending that the Level III regulations be reconsidered in 1991/1992, the economic impact provides further justification for reconsideration before imposition of these standards. In all cases, cost increases amount to less than under Level I and Level II regulatory scenarios.

Table 7-1

Estimated Maximum Cost Increases for Selected Pieces of Construction Equipment

Model	Horse Power	Average Cost	Level I	Level II	Level III		
			$100.00	$1,000.00	$2,500.00	$3,750.00	$5,000.00
Cat 623 E Scraper	330	$300,000.00	0.03%	0.33%	–	–	1.67%
Cat 14G Motor Grader	200	$180,000.00	0.06%	0.56%	–	2.08%	–
Cat 225 Excavator	145	$170,000.00	0.06%	0.59%	–	2.21%	–
Cat AP12000 Asphalt Paver	150	$180,000.00	0.06%	0.56%	–	2.08%	–
Cat CB514 Roller/Compactor	91	$91,000.00	0.11%	1.10%	2.75%	–	–
JD410C Backhoe	75	$55,000.00	0.18%	1.82%	4.55%	–	–
JD 670B Grader	135	$125,000.00	0.08%	0.80%	–	3.00%	–
JD 544D Front End Loader	115	$88,000.00	0.11%	1.14%	2.84%	–	–
P&H T400 Crane	225	$275,000.00	0.04%	0.36%	–	1.36%	–
Asphalt Roller	50	$60,000.00	0.17%	1.67%	4.17%	–	–

If all equipment owners face the same changes in price, then no firm has a competitive advantage over others. It is only when the possibility of local or out-of-state firms buying equipment from outside California the state at a cheaper cost is introduced that the competitive balance is disturbed. This possibility is discussed in more detail in Section 7.5.

Project Cost Breakdowns

Table 7-2 shows the labor, material and equipment breakdown for an example of an earth moving project. This data was contributed by one of the contractors interviewed, and is a "typical" cost breakdown for that type of project. The contractors contacted generally agreed that equipment costs as a percentage of total project costs vary according to the nature of the job; however, thirty percent is a reasonable estimate for the average earth moving job. It should be remembered that the site preparation, etc., is only one stage in the total building process, thereby reducing the role of heavy equipment in actual total project costs. It is likely that if equipment costs increase, the largest impact on total costs will be a 3% increase in an area which constitutes only 1/3 of total project costs (i.e., a 1% increase in total project costs).

As noted previously, fuel economy is not considered a factor in equipment purchasing decisions. Typical fuel costs, shown in Table 7-2, in the example project amount to 6% of total project costs. Fuel cost increases due to engine recalibration are expected to be in the 2-3% range, or less than 0.2% of total project costs. Even in the cases where engines are converted to pre-chamber type systems, the impact on total project costs is less than 1 percent.

In heavy construction projects such as road building, where the projects consist primarily of paving, grading, and/or excavating activities, the role of equipment costs is more predominant. For this reason, road building has been chosen to be used as an example of the highest possible cost increase. Table 7-3 shows labor, equipment, and material breakdowns for several heavy

Table 7-2

Cost Breakdown Of A Typical Site Preparation Project

	Costs	% of Total Costs
Labor	$190,800.00	26%
Equipment	$213,600.00	29%
Material	$294,100.00	40%
Misc	$28,100.00	4%
Total	$726,600.00	100%

	Costs	% of Equipment	% of Total Costs
Equipment			
Fuel, Oil and Grease	$40,500.00	19%	6%
Maintenance	$84,300.00	39%	12%
Other	$88,800.00	42%	12%
Total	$213,600.00	100%	29%

Source: Teichert Construction

construction activities. These figures are taken from Means Heavy Construction Cost Data 1988, which is used by estimators in the construction industry when bidding for jobs. The percentages displayed in Table 7-3 are in many cases greater than fifty percent of the total costs. If the highest cost increase scenario as shown in Table 7-1 is applied to a project whose total costs consist of 80% equipment costs, such as a large road building project using high horse power equipment, the 2-3% expected increase in equipment costs will result in a 1.6 to 2.4% increase in total project costs. Across all construction activities, costs increases due to regulation will be less than this "worst case scenario," especially in building activities, where site preparation accounts for less than 10% of total project costs, and equipment cost increases of 2% will result in a 0.2% increase in total project costs. In addition, road building is generally undertaken by state, county or city governments and the worst-case burden falls on the taxpayer.

7.3.4 Competitiveness Issues

The potential impacts on the competitive environment in construction must be explored in order to fully understand the total economic impact on an industry. In some cases, due to the lack of quantitative information on this subject, it was necessary to rely on the opinions and impressions of contractors, dealers, and other industry personnel.

Anecdotal information gathered from industry contacts and contractors provided information on various competitiveness issues. There were two major concerns. First, out-of-state contractors or contractors that buy equipment from outside California might have a competitive advantage over California contractors as a result of the proposed regulations. Second, that the existence of these contractors, if widespread, may lessen the effectiveness of emissions restrictions on off-highway vehicles. The discussion of these issues divides into two topics: the scope of construction work done in border counties, and the transportation of equipment across state lines.

Table 7-3

Labor, Material And Equipment CostsAs A Percentage Of Total Costs For Selected Construction Activities

	Mat'l	Labor	Equipment
Excavating, bulk dozer, open site - 50' haul common earth	-	51%	48%
Excavating, trench or continuous footing hydraulic backhoe - 1' to 4' deep - 3/4 c.y. common earth	-	38%	62%
Grading, site excavation and fill - 300 HP dozer, 300' haul 70 c.y./hr	90%	5%	5%
Paving, prepare and roll sub-base small areas to 2500 s.y.	-	20%	80%
Paving, base course for roadways, large paved areas - 3/4" stone compacted to 6" deep	-	47%	53%

Source: Means Heavy Construction Cost Data 1988

Regulations placed on construction equipment may cause some contractors to have a competitive advantage over others. In border counties, contractors might face competition from out-of-state contractors, who could easily bring equipment across the border. Conversely, out-of-state competitors may be driven from or choose to exit the market rather than buy equipment that meets California emissions standards. The following is a discussion of three issues which effect these issues: the amount of construction activity in border counties, the extent to which out-of-state contractors work in California, and the amount of equipment movement across the California border.

Border Counties

Industry contacts reported that there is very little heavy construction work being done in the border counties of California. To support these claims, data was gathered from the January 1988 California Construction Review, published by the CIRB. In 1987, the total building valuation in border counties amounted to 27% of total California building valuation, based on building permits issued. The fifteen counties considered border counties are shown in Figure 7-1 and are as follows: Del Norte, Siskiyou, Alpine, El Dorado, Imperial, Inyo, Lassen, Modoc, Mono, Nevada, Placer, Riverside, San Bernardino, Sierra and San Diego. When the values for San Bernardino County, Riverside County and San Diego County, all of which contain large Metropolitan areas, are removed from the calculations, total construction permit values in the remaining 12 border counties drops to 3% of state totals for total building valuation.

As there is little construction activity in the border areas of California, it is difficult to estimate how those contractors doing business in these regions may be impacted, if at all. Moreover, concerns regarding the widespread transportation of equipment from other states into border counties regions would appear to be unfounded.

Figure 7-1

California Border Counties

Out-of-State Contractors

According to industry sources, out-of-state contractors account for only 2-5 percent of the total dollar value of construction work done in California. Generally, out-of-state firms enter the California market for large, specialized, and/or long-term projects such as off-shore oil projects or dams. In the heavy construction industry, it appears that the competition is primarily from local firms, and therefore few firms are transporting equipment in order to work across state lines. This situation is influenced by licensing restrictions placed on contractors in California. To operate as a construction contractor in California a firm must first obtain a California license, which requires passing a test on the legal and trade aspects of the construction industry.

Because of moving costs, legal requirements, and the corporate taxes that must be filed in California, out-of-state contractors find it economical to bid on several jobs within the state rather than just one. Firms such as large nationals or internationals who wish to enter the California market find it easier to set up offices in California, and therefore do not operate permanently as out-of-state contractors. It should be noted, also, that these large firms are often the owners, developers, or general contractors for projects, and usually subcontract the site work to local earth-moving firms.

Equipment Movement

Most contractors buy new equipment from California dealers, but some buy equipment from out-of-state dealers if there is a significant price differential. The contractors contacted agreed unanimously that dealer support and parts supply were the most important factor in purchasing equipment, rather than purchasing costs or fuel economy. Contractors reported that buying from out-of-state dealers would require a price differential of at least 10-15%, to compensate for the loss of local dealer support and the costs of transporting the equipment. Thus, if regulations increased the price of California equipment by only 2-3%, then there would be no price advantage to buying equipment from other states.

When discussing equipment transportation with contractors, responses varied. Generally, if a contractor is working on an out-of-state job but rental equipment is available nearby, it is probably more cost-effective to rent rather than to transport equipment. If equipment is purchased from non-local dealers, the cost of transporting adds to the total cost of the equipment. Transporting equipment can be very costly; for example, to move a Caterpillar D9 Dozer can cost $2,500-$3,000. To relocate all the equipment needed for a job could be extremely expensive. However, some contractors and rental agencies contacted stated that if a firm owns their fleet, it may be more sensible to utilize equipment in which they have already invested their money rather than to spend resources on rental equipment.

The duration of a project and the extent to which specialized equipment is used are factors in the decision to rent versus transport equipment. If a job requires specialized equipment which may be difficult to rent locally, it may be necessary for a large national firm to transport that equipment if it is in the company's stock. For long-term projects, the cost of renting locally may be greater than the cost of transporting a company's fleet to the site.

In summary, it is not necessarily clear what decisions an out-of-state firm will make regarding the movement of its fleet. Costs, types of equipment used, the availability of locally rented equipment, and the duration of a project all factor into the decision. However, as these firms constitute only 2-5% of California construction values, it is not likely that their presence will result in significant anti-competitive effects due to emissions regulations on California construction equipment.

7.4 MINING, FORESTRY AND AGRICULTURE IN CALIFORNIA

The purpose of this section is to briefly describe the amount of mining, forestry, and agriculture activity in California, and the types of equipment used in these activities. Although proposed regulation are not directed towards these sectors, each may be affected due to the use of certain types of equipment. Some of the equipment used in construction activities, such as backhoes, loaders, tractors, and haulers, are used extensively in these non-construction activities. An equipment inventory representing agriculture/forestry has been developed by Power Systems Research, and is discussed in Section 6. Mining equipment is part of the inventory developed by Construction Equipment Magazine's Universe of Construction Equipment, also discussed in Section 6.

Mining

The California mining industry accounts for approximately 5% of the total U.S. mining value of shipments. Seventy-eight percent of this is contributed by the oil and gas extraction industry. Heavy equipment is used in the industry preparing well sites, laying pipelines, and building roads to new sites. Most of the other activity is in gravel pits, but a few gold mines have opened in Northern California recently.

The equipment types used most predominately in the mining industry are large off-highway trucks, as shown in Table 7-4. Data used in this table is from Construction Equipment Magazine's Universe of Construction Equipment survey, and shows the distribution of selected types of construction equipment across construction, mining, materials handling, government, utilities, and other categories. The "other" category includes agriculture, logging, and manufacturing. The purpose of and methodology used in this survey are discussed in Section 6 of this report. Since most of the equipment used in gravel pits and mining are large, high horsepower machinery, an exemption for such machines is suggested under the regulatory scenarios.

Table 7-4

Ownership Distribution Of Selected Equipment Types By End-User Category

Equipment Type	Construction	Mining	Materials	Government	Utilities	Other
Crawler Dozer	62.1	7.0	10.8	4.2	9.6	6.3
Crawler Loader	84.7	2.1	3.0	4.3	3.4	2.5
Crawler-Mounted Hydraulic Excavator	82.0	3.1	4.3	1.9	6.7	2.0
Wheel-Mounted Hydraulic Excavator	63.6	3.2	0.0	24.1	4.4	4.7
Truck-Mounted Telescopic Hydraulic Excavator	71.9	4.0	0.0	15.1	2.0	7.0
Articulated Motor Grader	74.1	3.3	4.8	13.0	3.7	1.1
Rigid Frame Motor Grader	66.8	7.0	7.4	8.5	6.2	4.1
Off-Highway Rear Dump Truck	21.1	60.3	14.2	1.6	1.6	1.2
Off-Highway Articulated Rear Dump Truck	51.8	32.7	11.3	1.0	2.7	1.0
Off-Highway Tractor-Trailor Rear/Side Dump	28.1	46.5	24.4	1.3	0.0	0.0
Open Bowl Conventional Scraper	72.3	7.4	6.8	7.0	4.5	1.9
Elavating Scraper	81.0	3.3	5.6	4.1	4.5	1.4
Skid/Steer Loaders	76.3	2.9	7.6	2.6	8.2	2.4
Tractor Backhoe Loaders	69.6	6.7	6.7	4.2	6.2	6.5
Chain-Type Trenchers	47.6	4.0	7.0	2.4	32.4	6.6
Wheel-Type Trenchers	56.1	3.0	7.1	4.6	24.3	4.9
Wheel Loaders	56.2	8.4	14.2	5.7	9.8	5.7
Lattice Boom Crawler Cranes	64.9	6.0	12.2	2.5	5.0	9.4
Lattice Boom Truck Cranes	75.1	6.7	6.1	2.6	3.8	5.7
Rough Terrain Cranes	68.0	11.8	2.5	2.0	7.8	7.9
Hydraulic Truck Cranes	83.4	3.6	2.2	2.8	4.8	3.2
Rough Terrain Telescopic Forklifts	87.8	2.9	5.0	1.0	1.0	2.3
Rough Terrain Verticle Mast forklifts	80.0	4.6	6.5	3.2	3.4	2.3
Asphalt Pavers	81.0	1.7	0.5	11.9	3.0	1.9
Concrete Pavers - Slab	93.0	0.0	0.5	4.4	0.5	1.6
Concrete Pavers - Slipform	94.9	0.0	0.0	4.4	0.7	0.0
Concrete Pavers - Combination	99.0	0.0	0.0	1.0	0.0	0.0
Wheel-Mounted Planers/Profilers	75.0	0.0	4.3	9.3	11.4	0.0
Crawler Mounted Planers/Profilers	80.9	2.3	7.3	3.6	2.3	3.6
Drum Rollers & Compactors	74.7	2.1	8.6	5.2	1.2	8.2
Rubber Tired Rollers	69.1	1.7	8.1	11.2	7.5	2.4

Source: Construction Equipment Magazine, "Universe of Construction Equipment"

Agriculture/Forestry

California represents less than 4% of the total number of farms in the U.S. From 1950 to the present, the number of farms has been declining both nationally and in California. The construction equipment used most frequently in agricultural activities are backhoes and skid/steer loaders. Although they are numerous, eighty-five percent of all skid-steer loaders sold in the U.S. are under 50 HP, and would not fall under proposed regulations. However, backhoes, which are used a great deal in agricultural activities, would fall under regulations. Anecdotal information suggests that backhoes used in farming are usually purchased used, and any increase in first cost (price) would not be felt by farmers for several years. In addition, any initial cost increases may or may not affect resale prices 6 to 9 years down the road. This information suggests that the impact of emission regulations on farming will be very small. Of course, for that small fraction of farmers that do buy new equipment such as skid-steer loaders, or backhoes, with engines over 50 HP output, there will be a cost increase. EEA does not believe that there are any simple methods available to segregate units used in agriculture to exempt them from emission standards. One possibility would be to provide a "refund" or tax-abatement to such consumers at the time of income-tax filing.

The equipment used in forestry operations generally overlaps those used in construction. Therefore, it will be difficult to insulate the forestry industry from the effects of regulation. EEA suggests that certain pieces of equipment, such as feller bunchers and log skidders,* might be exempted from emissions regulations in order to prevent undue hardship on the forestry industry.

* Used primarily in logging operation.

7.5 ENGINE AND EQUIPMENT MANUFACTURING INDUSTRY

Our analysis of technology in Section 4 showed that under Level I and Level II emissions scenarios, it is the engine manufacturer who is principally affected. In some instances, as in conversion from a naturally aspirated engine to a turbocharged one, due to the imposition of Level II standards, the equipment manufacturer is also affected, but such cases are likely to occur in only 10 percent of the new equipment fleet. The lead time recommendation for level II standards is 5 years, which also is typical of the design life cycle for equipment. Hence, it provides adequate time for equipment manufacturers to react to changes in engines.

In the technology analysis section, it was indicated that Caterpillar, Cummins and Deere accounted for a large (~50%) fraction of the total heavy-duty construction type engines sold in California. The next set of manufacturers such as Deutz, Komatsu, IH and Perkins probably account for 25 to 30 percent of the engines sold. The remaining 20 percent is divided among another 14 or 15 manufacturers each with market shares in the 0.5 percent to 2 percent range. In absolute terms, each percent of the market is 50 to 70 unit sales.

Engine manufacturers face the following costs to bring the engines into compliance:

- component costs for emission control
- development costs to bring each engine family into compliance
- certification costs
- liability associated with recall
- investment in new test facilities.

Of these costs, all except component costs (discussed in Section 4) are fixed costs dependent on the number of engine families being certified, but not on sales volume. Moreover, research and development costs are typically expensed by all manufacturers, and, therefore, not associated with costs applied to a specific engine line.

The economic impact analysis is very sensitive to the regulations employed in California. Three specific suggestions were provided to ARB in Section 5. They are:

- a "carry over" of certification of engines certified to equivalent on-highway standards
- the deletion of the requirement for a durability test
- a low sales volume exemption for up to three engine families of a specific manufacturer whose sales are less than 10 units/year.

Our economic impact analysis assumes that ARB will implement these or similar suggestions to estimate the total compliance burdens.

In order to develop an estimate of engine families, we used the information on the types of engines sold (shown in Section 4) by engine manufacturer. As an example, Caterpillar offers five different series of engines, 3110, 3200,3300, 3400 and 3500. We assumed that each engine could be offered in naturally aspirated (NA) turbocharged (T) and turbocharged/aftercooled (TA) versions except for the 3400/3500 series where no naturally aspirated versions would be offered. Of these, only the following engine families would not be certified to on-highway equivalent standards for Level II: the 3110 NA, 3300 NA, 3300 T, 3400 T, 3500 T and 3500 TA. The 3500 series is used on relatively low sales volume applications, and would probably qualify for the low volume exemption as two engine families 3500 T and 3500 TA. This would leave only 4 engine families for certification to California off-highway standards. The carry over of 1986-1990 HDT certification would mean that many off-highway engines will meet Level II standards even in 1991/1992 to reduce certification costs.*

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* Manufacturer comments on the draft report were not in agreement as they believed that number of cylinders would also be a distinguishing factor, leading to more "families" than anticipated by EEA.

Table 7-5 shows the possible certification strategy under California regulations which allows 3 exempted engine families per manufacturer with sales less than 10 units per year, and carry-over certification of on-highway engines certified to Federal 1990 heavy-duty diesel standards. The total number of "families" is estimated at 96. In contrast, the CAL/ERT study presented data that (on the basis of EEA analysis) indicates a total of 280 "families." It is believed that the CAL/ERT study classified each HP rating as a different "family" whereas the EEA family covers several HP ratings. Typically, each engine family covers 2 to 4 different ratings of horsepower and RPM (this is also true for on-highway engine families). At 3 ratings per EEA "family," the EEA estimate (96x3) is closely comparable to the CAL/ERT study estimate of 280 families. In their comments, the engine manufacturers did not agree with this analysis. Their response stated that the CAL/ERT study used EPA-designated classifications, but the response provided no documentation of the 280 families estimate.

Certification costs are directly proportional to the number of engine families. As can be seen from Table 7-5, EEA anticipates that only 34 engine families will be certified for the off-highway market uniquely. These, however, will be the high sales volume units. Based on the distribution of sales of engines, EEA estimates the sales volume breakout as follows:

• families certified to off-highway standards	4,000
• families certified to on-highway standards	1,500
• exempt families	300
Total Sales	5,800

Thus, each certified family will sell 120 units per year on average. There is likely to be considerable variance from the average. However, manufacturers selling 20 to 50 units per year may attempt to consolidate their engine families or leave the California market altogether. Of the 90 to 100 families, EEA anticipates that 10 families may be in this position, and

TABLE 7-5

POTENTIAL OFF-HIGHWAY FAMILIES
CERTIFICATION STRATEGY

Manufactuer	Total Families	On-Highway Certified	Exempt	Off-Highway Certified
Domestic				
Caterpillar	13	7	2	4
Cummins	13	6	3	4
DDA	8	3	3	2
Deere	8	1	3	4
IH	4	4	0	0
Foreign				
Komatsu	13	0	3	10
Deutz	7	2	3	2
Perkins	4	1	3	0
All Others	26	4	14	8
TOTAL	96	28	34	34

manufacturers will decide to delete these engines or consolidate them with other engine lines.

Certification costs were based upon a "free market" cost of having South-West Research provide certification type tests and data. They have quoted a certification cost of $22,000 per family, covering two HP ratings (the highest and lowest). The South-West Research figure was cited by Deere for the transient test and it is possible that a steady-state test will be cheaper.

Paperwork costs were estimated at $2,500 per family by the CAL/ERT study. EEA has allocated $3000 per family to adjust for effects of inflation. Total certification costs are:

- Paperwork 96 x 3,000 = $288,000
- Certification test 34 x 22,000 = $748,000

Total = $1,036,000

Development costs were estimated as follows by the CAL/ERT study. To meet Level I standards, the study estimated a team of one engineer and two technicians would require six months to bring the engine into compliance. EEA's study of the manufacturers reveals that most manufacturers are already capable of certifying to Level I standards, and we have reduced the average time required to three months to check and optimize fuel injection pump timing. The cost per year of the team, adjusted for inflation is $210,000/year based on the CAL/ERT study. Thus, the cost per certified family is $52,000, for a total cost $1,785,000 for the 34 certified families. If the CAL/ERT estimates on the total number of families is more appropriate, costs will be three times as high, i.e., about $6 million.

The R&D to meet Level II standards will vary greatly by manufacturer. Cummins and Caterpillar already have extensive knowledge of technology to attain this standard, while Deere may require substantial R&D efforts to meet these standards. The CAL/ERT study estimated that it would require the team of one engineer and two technicians a year to meet a 6.0 HC + NO_x standard (no particulate standard). In the absence of any alternative data, EEA has utilized the same estimate to cost the R&D effort for Level II standards, i.e., $210,000 per engine family. The total cost is:

34 x 210,000 or $7,140,000 million.

Given the uncertainties facing attainment of Level III standards it is difficult to estimate the cost of an R&D effort to meet these standards. Much will depend on the transferability of trap technology to off-highway equipment.

Manufacturers may also need to install new dynamometer equipment to handle the additional testing and certification burden. Our conversations with manufacturers indicated that a steady-state test facility with particulate measurement capability costs about $1 million. It is not clear, however, that a significant number of new facilities will be needed. Cummins and Caterpillar may need to add one or two facilities each to certify four engine families (as shown in Table 7-5) as they already face a large certification and development burden for their on-highway engine families. Deere and Komatsu, on the other hand, may not need to add any facilities since they do not face the same burden for on-highway emissions certification. Each facility is capable of supporting certification and development of one engine family according to the CAL/ERT study. Given excess capacity, EEA believes that approximately 12 facilities will be added worldwide to certify the 34 additional families, requiring a worldwide investment of $12 million. The average cost of capital is about 12 percent, and if these facilities are depreciated over 10 years, a total annual cost of $2.64 million is associated with facility costs.

At the individual manufacturer level, an example of a manufacturer certifying 4 families for the off-highway California market is as follows, assuming one new dynamometer facility is added.

- Certification cost: $ 100,000
- Development cost (Level II): $ 840,000
- Annual cost of one dyno-facility: $ 220,000
- Paperwork (13 families): $ 39,000

Total Cost: $1,199,000

Thus, the annual increased burden in any one year is on the order of $1.2 million. In contrast, the total 1986 R&D budget for Cummins was $125 million, Komatsu was $184 million, Deere was $224 million and Caterpillar was $308 million. These expenses therefore amount to no more than 1 percent of the R&D budget for the major companies. The size of the R&D budget for other manufacturers such as IH, Deutz, DDA and Perkins is also very large relative to the annual expenses incurred in meeting California standards. Again, if the number of families is much larger as suggested by the Engine Manufacturers Association, three dyno facilities would be needed, and the manufacturer would certify 12 families in this example, so that total costs will be approximately $3.6 million.

Assuming that a given set of standards are in place for three years at least and the certification and R&D expenses can be associated with three years worth of sales volume, the total annual expenses for all manufacturers are as follows:

- Certification costs $ 345,000/yr
- R&D Costs (Level II) $ 2,380,000/yr
- Facility Costs $ 2,640,000/yr

Total Costs $ 5,365,000/yr

The volume of certified engines is estimated to be 4000 units per year. Hence, the net burden of R&D and certification to meet Level II standards is $1,350, a very significant sum. If the number of families is much larger, as claimed by EMA, the net burden would be about $4,000 per engine. In contrast, the variable cost of $240 per engine is a much smaller amount.

It is not clear that California customers will be paying the fixed cost burden of $1,350, as R&D costs, facility costs and certification costs are expenses from an overhead pool. Moreover, if EPA enacts standards for off-highway engines, the unit cost burden associated with fixed costs will fall by a factor of 10. Although fixed costs are presented here, its use in a cost benefit analysis for California is not clear, if California customers are not paying for such costs. The EMA's suggestion that there would be three times as many families does not appear realistic, and no documentation was provided to support such an estimate. The issue of separate certification families for engines that vary only by number of cylinders, but are otherwise equivalent in displacement/cylinder, aspiration, and fuel injection is important for transient cycle emissions, but much less for steady-state cycles. ARB permission to merge across engines differing only in number of cylinders into one family would reduce costs to levels indicated by EEA's analysis. Even if this is not the case, we expect the total number of families to increase to about 125 (from 96) with "off-highway certified" to about 45, "exempt" to about 45 and "on-highway certified" to 35. The costs would therefore be significantly less than those estimated by EMA. ARB can request manufacturers to provide details on the number of families and sales volume to obtain a more accurate cost estimate.

8. AIR QUALITY ANALYSIS

8.1 OVERVIEW

The effects of off-highway construction equipment on air quality can be considered at the regional level or at a more microscale level where impacts could be greater. Given that there are only about 125,000 construction machines in comparison to a total on-highway fleet of 15,000,000 vehicles in California, it can be anticipated that the impact on air quality is relatively small. The emphasis in this air quality analysis was on microscale modeling around simulated construction sites where high concentrations of heavy-duty construction equipment would be found. Thus, the Point, Area, and Line (PAL) source model has been applied to examine short-term concentrations downwind of construction sites where emission impacts of construction machinery are likely to be the highest. Two different construction site situations are modeled. One is a new residential subdivision with about 10 pieces of equipment. The other is a construction project adding a lane to an existing highway. Uncontrolled and controlled emission cases are simulated to see whether there is a discernable effect on ambient air quality levels in the vicinity of the construction sites.

The complexities of modeling the effects of NOx and HC control on regional air quality and ozone prevented an extensive or rigorous analysis. Rather, the concepts embodied in the Empirical Kinetic Modeling Approach for an urban area like Los Angeles were utilized to provide an approximate estimate of regional air quality effects.

8.2 MICROSCALE MODELING

PAL is a method of estimating short-term dispersion using Gaussian-plume steady-state assumptions. The algorithm can be used for estimating concentrations of non-reactive pollutants at 30 receptors for averaging times of from 1 to 24 hours, and for a limited number of point, area, and line sources (30 of each type). Calculations are performed for each hour. The hourly meteorological data required are wind direction, wind speed, stability class, and mixing height. Single values of each of these four parameters are assumed representative for the area modeled. The sensitivity of model results to changes in these parameters is presented in the analysis, though. Appendix B provides some modeling details on PAL.

The PAL algorithm is not intended for application to entire urban areas, but is intended, rather, to assess the impact on air quality, on scales of tens to hundreds of meters, of portions of urban areas such as shopping centers, large parking areas, and airports. Level terrain is assumed. Subroutines are included that estimate concentrations for multiple-lane line and curved path sources, special line source (line sources with endpoints at different heights above ground), and special curved path sources.

PAL is an EPA guideline model. While not on the preferred list, it is approved for use by EPA. It has been chosen for application in this study because it is believed to be more appropriate for modeling both residential construction sites and highways than any of the preferred air quality models.

The air quality impacts of hydrocarbons (HC), NO_x, and particulates from heavy duty construction equipment were evaluated using the PAL dispersion model. The attributes that make this a desirable model to use for evaluating the air quality impacts of this type source were described earlier. Two different construction situations were modeled. First, development of a thirty lot subdivision was modeled as an area source using two different configurations. Second, the addition of a 0.5 mile long extra lane to a median strip of an existing highway was modeled as a line source.

8.2.1 Area Source Modeling

The two different physical configurations for the subdivision modeling are shown in Figures 8-1 and 8-2. These figures show that the area source in configuration number 1 (Figure 8-1) was oriented along the southern boundary of the subdivision and was confined to the southernmost six lots. In configuration number 2 (Figure 8-2) the area source encompassed 5 lots oriented north-south and located approximately in the center of the total subdivision.

Source strengths for each area were determined by summing the HC, NO_x, and particulate emissions from each piece of heavy duty construction equipment and dividing the total by the total area over which the equipment was operated (6 and 5 lots for area source configurations 1 and 2 respectively). It is assumed that all equipment was operating and was within the shaded areas in Figures 8-1 and 8-2.

Receptors were located at the corners and mid-points of each side of a rectangle 0.5 km larger in all directions than the subdivision. This was done to simulate "fenceline" conditions. Receptor heights were 1.5 meters.

8.2.2 Line Source Modeling

The addition of the extra lane to an existing median strip was modeled by establishing an east-west line source 0.5 miles long and 40 yds. wide.

The source strengths for the line source modeling were also determined by summing the total HC, NO_x, and particulate emissions from each piece of heavy duty construction equipment and dividing by the area over which the equipment was operated.

Receptors were located at the corners and mid-points of each side of a rectangle 0.5 km larger in all directions than the extra lane. Again, this

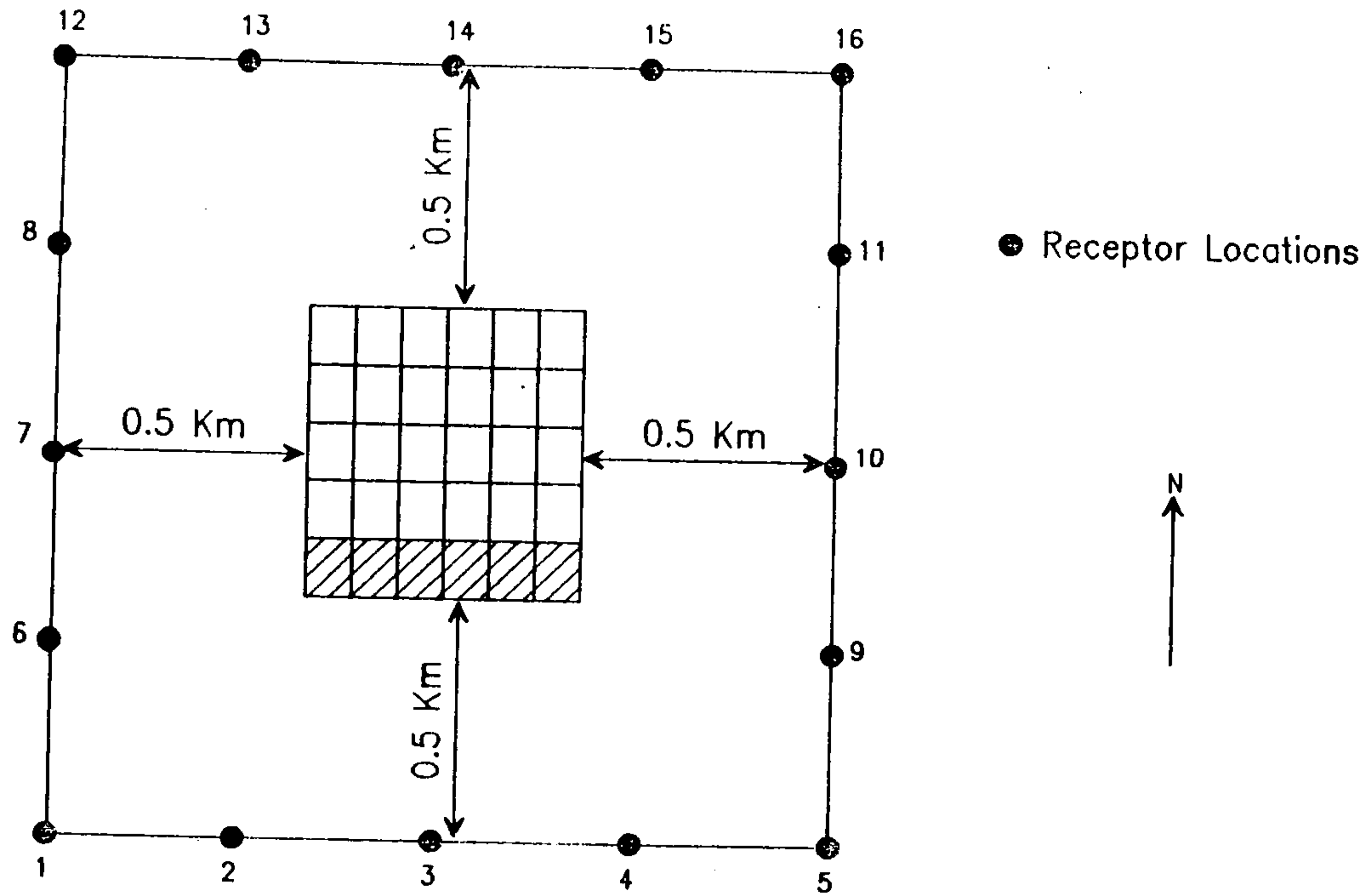


FIGURE 8-1

Subdivision area source modeling configuration #1. All equipment was assumed to operate in the shaded area.

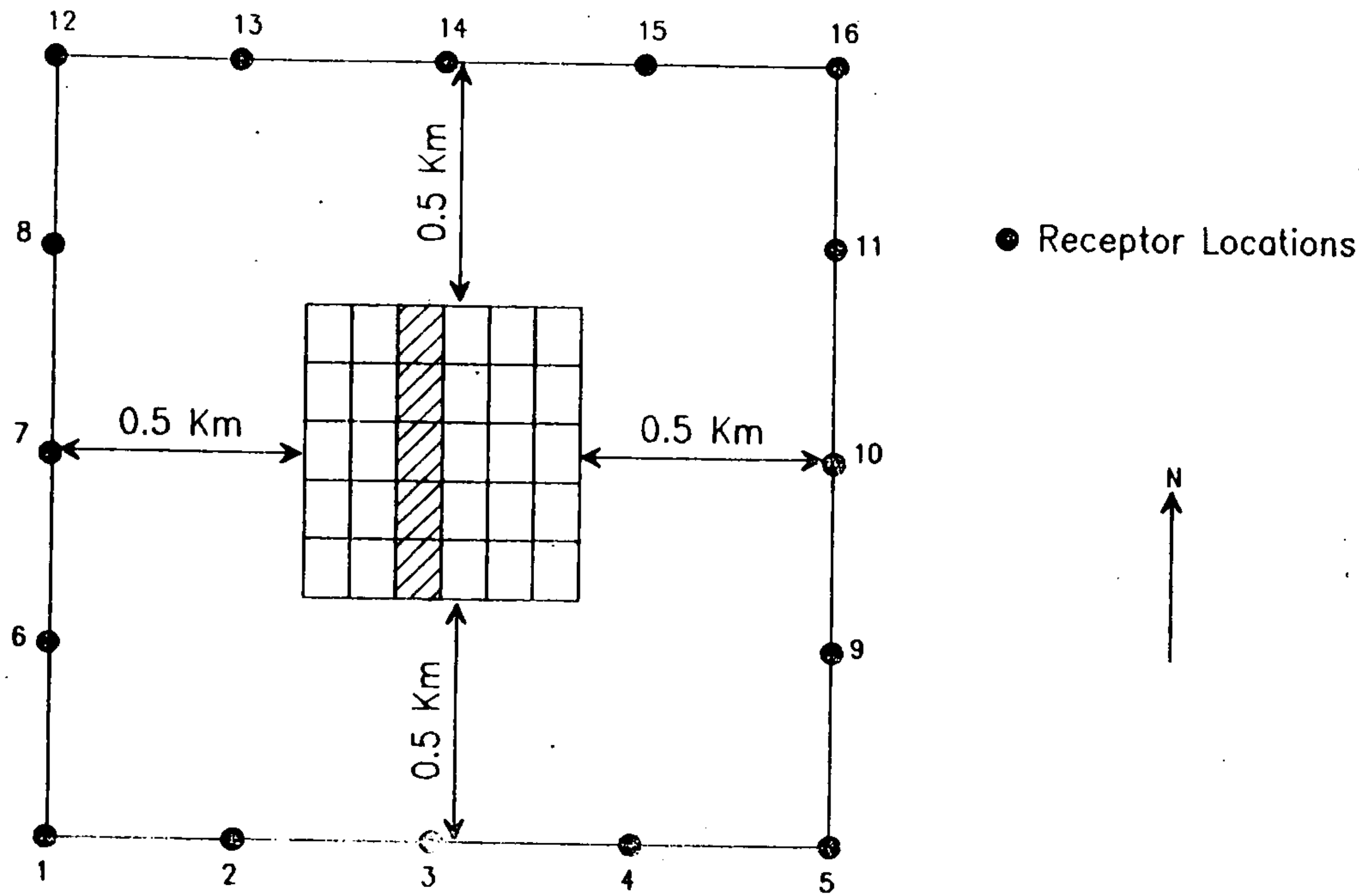


FIGURE 8-2

Subdivision area source modeling configuration #2. All equipment was assumed to operate in the shaded area.

was to simulate what could be considered "fenceline" conditions. The location of the line source and receptors are shown in Figure 8-3.

8.2.3 Meteorological Data

Meteorological information from airports located in Ontario, CA and Fresno, CA was used as model input to evaluate the source contributors to the various receptors. Hourly observations of wind speed, wind direction, and temperature for the first day of January, April, July, and October of 1972 (for Ontario) and 1986 (for Fresno) were evaluated and data for the hours 0700 to 1700 were extracted. These hours were thought to constitute a "normal" length construction day. The first day of each of the above months was chosen as a random seasonal observation to simulate the potential conditions likely to be observed at construction sites in California. No information on mixing height and stability was included with the data available, so estimates of these parameters were made. Stability was estimated using wind speed information and mixing height was allowed to vary from 500 meters at 0700 hours to 1200 meters at 1700 hours. Stability classes considered ranged between neutral and unstable. The mixing heights used at 0700 and 1700 are typical morning and afternoon values for California. Intermediate hour values were interpolated.

Output from PAL can be generated for each receptor both on an hourly basis and as an average concentration for the total numbers of hours considered. Average concentration information is presented here, but hourly information is available. Additionally, the meteorology data and source strengths are summarized in the output generated by the model.

8.2.4 Results

Concentrations of all pollutants considered were extremely low. This is partly due to the manner in which the sources were modeled. No piece of heavy duty construction equipment will remain in the same position for one hour, much less over the time period involved in a normal working day. This means

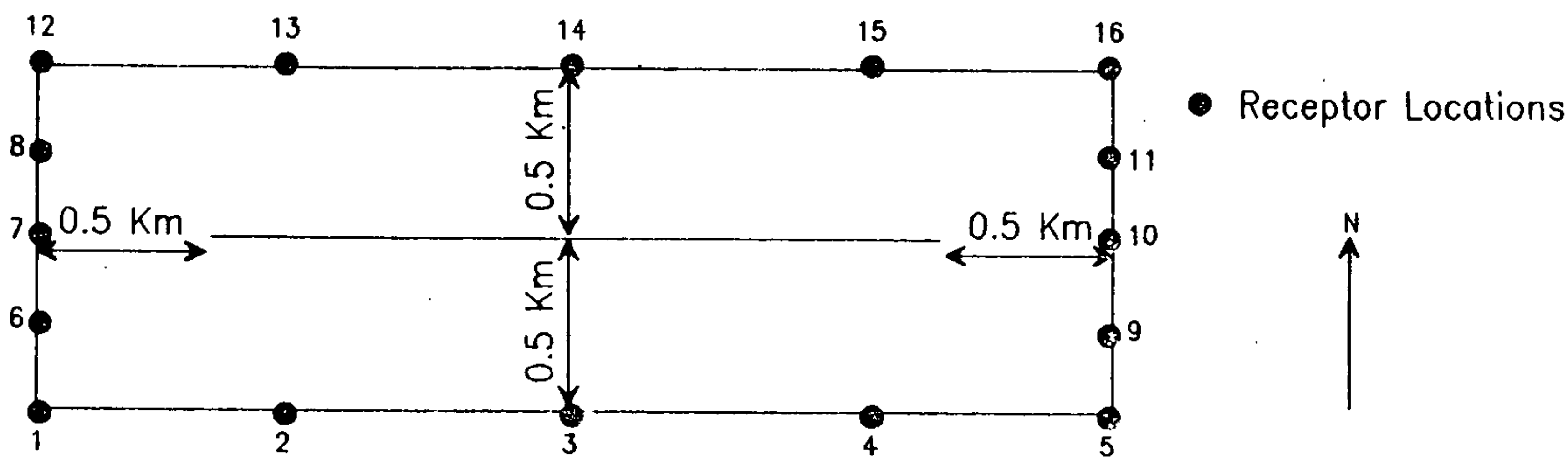


FIGURE 8-3

Median strip/extra lane development line source modeling configuration.

that the individual pieces of equipment cannot be modeled as point sources, but rather must be modeled as area or line sources. As a consequence, the model input requires information on source strengths in units of grams/sec-m^2 for area sources and grams/sec-m for line sources. When the emission rates provided for the heavy duty equipment are spread out over the areas involved in the construction activities considered here, they tend to be relatively small. Thus, their air quality impacts also tend to be relatively small. Some effort was made to maximize these impacts by limiting all of the pieces of equipment to only a portion of the potential work area (see Figures 8-1 and 8-2). There is no reason that each individual piece of equipment couldn't be utilized in a separate subdivision lot.

The information below shows that the average hourly concentration of NO_x, HC or particulates is always less than 10^{-4} grams per cubic meter. The values presented below show the maximum concentration at any receptor, the receptor where the maximum concentration was found and the meteorological data month resulting in the maximum concentration. A value of 1 for the meteorological data month represents January data, 2 represents April data, 3 represents July data and 4 represents October data. Receptors are numbered 1 through 8. Receptor number 1 is located in the southwest corner of the receptor grid. Receptor 2 is located at the midpoint of the southern boundary line of the grid, receptor 3 the southeast corner, receptor 4 at the midpoint of the western north-south boundary line, receptor 5 at the midpoint of the eastern north-south boundary line, receptor 6 at the northwest corner, receptor 7 at the midpoint of the northern boundary line and receptor 8 at the northeast corner of the grid. For the Base Case, and all three control scenarios, the minimum concentration of at least one of the receptors was zero. For this reason, minimum values are not presented here. This meant that the wind direction did not cause transport of the pollutant considered to that receptor for the meteorological conditions modeled.

Modeling results are summarized in Table 8-1 for NO_x and in Table 8-2 for particulates, and Table 8-3 for HC.

Concentration values are given in micrograms/cubic meter for particulates and HC and in ppm for NOx. The Delta column in the tables represents the concentration difference between the Base Case and the different control scenarios. Units are the same as the concentration units. A positive value represents a net air quality improvement over the Base Case. A negative value represents a degradation in the overall air quality relative to the Base Case. It should be noted that the receptors that showed the maximum average concentration levels also showed the maximum delta values.

The data presented in Table 8-1 for NOx show that for all modeling results, the maximum average hourly concentration is well below the one hour California standard of 0.25 ppm. These results also show that all maximum average hourly NOx levels are at least a factor of 3 lower than the national annual standard of 0.053 ppm.

Particulate levels are considerably lower than either the national 24 hour standard of 150 micrograms/cubic meter or the national annual standard of 50 micrograms/cubic meter. It should be pointed out that the particulate concentrations developed with the model and presented in Table 8-2 represent only particulates generated by the vehicle engines. Fugitive dust emissions generated as the result of operating the equipment would certainly result in higher particulate levels than those reported here.

There are currently no national hydrocarbons standards to compare the modeling results with; however, the values presented below are extremely low.

8.3 EFFECTS OF EMISSION CONTROL ON REGIONAL AIR QUALITY

The likely effectiveness of VOC and NO_x controls within a region depends on their relative concentrations in the atmosphere. The higher the ratio of

Table 8-1

NO_x Modeling Results

Area Source Configuration #1 Ontario Met. Data

	Max. Conc.*	Delta	Receptor	Met. Month
Base Case	0.012713		9	1
Scenario 1	0.009761	0.002952	9	1
Scenario 2	0.006473	0.006239	9	1
Scenario 3	0.005904	0.006809	9	1

Area Source Configuration #1 Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.016798		3	1
Scenario 1	0.012899	0.003899	3	1
Scenario 2	0.008559	0.008239	3	1
Scenario 3	0.007803	0.008995	3	1

Area Source Configuration #2 Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.013505		10	4
Scenario 1	0.010351	0.003154	10	4
Scenario 2	0.006856	0.006649	10	4
Scenario 3	0.006229	0.007277	10	4

Area Source Configuration #2 Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.015303		3	2
Scenario 1	0.011729	0.003574	3	2
Scenario 2	0.007771	0.007532	3	2
Scenario 3	0.007053	0.00825	3	2

Line Source Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.013351		10	4
Scenario 1	0.010234	0.003117	10	4
Scenario 2	0.006782	0.006569	10	4
Scenario 3	0.00617	0.007181	10	4

Line Source Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.006569		4	2
Scenario 1	0.005034	0.001536	4	2
Scenario 2	0.003335	0.003234	4	2
Scenario 3	0.003037	0.003532	4	2

* Concentration and Delta values in ppm

Table 8-2

Particulate Modeling Results

Area Source Configuration #1   Ontario Met. Data

	Max. Conc.*	Delta	Receptor	Met. Month
Base Case	1.074		9	1
Scenario 1	1.343	-0.269	9	1
Scenario 2	1.253	-0.179	9	1
Scenario 3	0.6266	0.4474	9	1

Area Source Configuration #1   Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	1.419		3	1
Scenario 1	1.774	-0.355	3	1
Scenario 2	1.656	-0.237	3	1
Scenario 3	0.828	0.591	3	1

Area Source Configuration #2   Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	1.108		10	4
Scenario 1	1.424	-0.316	10	4
Scenario 2	1.345	-0.237	10	4
Scenario 3	0.6329	0.4751	10	4

Area Source Configuration #2   Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	1.255		3	2
Scenario 1	1.613	-0.358	3	2
Scenario 2	1.524	-0.269	3	2
Scenario 3	0.717	0.538	3	2

Line Source   Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	1.129		10	4
Scenario 1	1.389	-0.26	10	4
Scenario 2	1.31	-0.181	10	4
Scenario 3	0.6543	0.4742	10	4

Line Source   Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	0.5553		4	2
Scenario 1	0.6831	-0.1278	4	2
Scenario 2	0.6442	-0.0889	4	2
Scenario 3	0.3221	0.2332	4	2

* Concentration and Delta values in micrograms/cubic meter

TABLE 8-3

Hydrocarbon Modeling Results

Area Source Configuration #1 Ontario Met. Data

	Max. Conc.*	Delta	Receptor	Met. Month
Base Case	2.148		9	1
Scenario 1	1.79	0.358	9	1
Scenario 2	1.432	0.716	9	1
Scenario 3	1.432	0.716	9	1

Area Source Configuration #1 Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	2.839		3	1
Scenario 1	2.366	0.473	3	1
Scenario 2	1.892	0.947	3	1
Scenario 3	1.892	0.947	3	1

Area Source Configuration #2 Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	2.215		10	4
Scenario 1	1.978	0.237	10	4
Scenario 2	1.503	0.712	10	4
Scenario 3	1.503	0.712	10	4

Area Source Configuration #2 Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	2.509		3	2
Scenario 1	2.241	0.268	3	2
Scenario 2	1.703	0.806	3	2
Scenario 3	1.703	0.806	3	2

Line Source Ontario Met. Data

	Max. Conc.	Delta	Receptor	Met. Month
Base Case	2.224		10	4
Scenario 1	1.919	0.305	10	4
Scenario 2	1.501	0.723	10	4
Scenario 3	1.501	0.723	10	4

Line Source Fresno Met. Data

	Max. Conc.	Delta	Receptor	Met Month
Base Case	1.094		4	2
Scenario 1	0.9441	0.1499	4	2
Scenario 2	0.7386	0.3554	4	2
Scenario 3	0.7386	0.3554	4	2

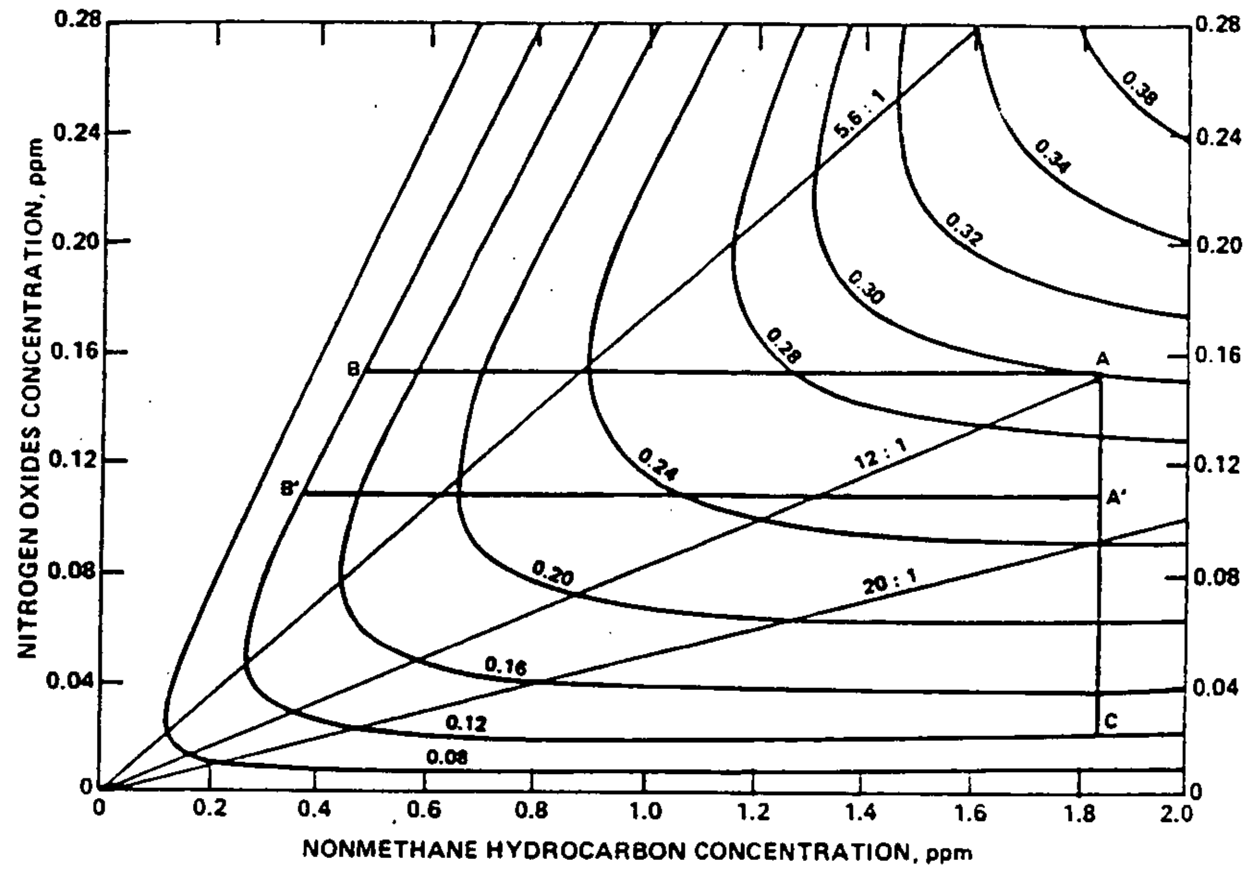
* Concentration and Delta values in micrograms/cubic meter

organics to NO_x, the more likely NO_x controls are to be beneficial. Evidence suggests that each city can be characterized in terms of a critical NMOC/NO_x ratio above which control of NO_x may be beneficial in reducing ozone. Based on currently available information, EPA believes a critical ratio may be about 10:1. Recognizing this potential for NO_x controls to contribute in an ozone attainment strategy, EPA proposes in their post-1987 policy to require ozone SIPs to evaluate the effectiveness of locally implemented NO_x control where the median ambient NMOC/NO_x ratio is equal to or above 10:1. Below this ratio, benefits of reducing NO_x in addition to VOC are less likely.

Considering Figure 8-4 as an example Empirical Kinetic Modeling Approach (EKMA) diagram for a high-oxidant urban area, the proportions of total HC and NO_x for heavy construction equipment under different scenarios along with ARB estimates of total state-level HC and NO_x emissions can be used to provide rough estimates of how O_3 levels might change in an area like Los Angeles. Table 8-4 shows ARB estimates of total statewide emissions along with heavy construction equipment emission estimates for scenarios 1 through 3. Heavy construction equipment emission estimates were converted from Kg/year to tons/day assuming 6 days per week, 52 weeks per year operation.

As Table 8-4 shows, HC emissions are expected to change very little, even under the most stringent control scenario. The difference between scenario 1 and scenario 3 emissions of HC for heavy construction equipment are only 0.14 percent of 1995 and 0.3 percent of 2000 reactive HC emissions. These emission changes are too small to produce any measurable change in O_3 levels.

Of more interest is the estimated change in O_3 that might be observed through controlling NO_x emissions. EPA's proposed post-1987 ozone policy recommends using one of two modeling approaches to determine the effect of VOC and NO_x emission changes on future year O_3 values. Photochemical grid modeling is one of the recommended modeling approaches, with the preferred model being the



Example of EKMA diagram for high-oxidant urban area.

TABLE 8-4

CALIFORNIA STATEWIDE HC AND NOx EMISSION ESTIMATES
(tons per day)
ALL CATEGORIES VS. HEAVY CONSTRUCTION EQUIPMENT

Year	All Categories HC Total	All Categories HC Reactive	Hvy. Const. Scen. 1	Hvy. Const. Scen. 2	Hvy. Const. Scen. 3
1987	6425	3200	46.3	46.3	46.3
1990	6712	3175	42.9	42.9	42.9
1995	6619	3066	38.1	34.7	33.8
2000	6639	3118	35.4	29.3	26.2

Year	All Categories NOx	Hvy. Const. Scen. 1	Hvy. Const. Scen. 2	Hvy. Const. Scen. 3
1987	2857	396.4	396.4	396.4
1990	2824	374.2	374.2	374.2
1995	2804	350.3	316.8	303
2000	2953	339.2	278.3	232.3

Scenario 1 - No control

Scenario 2 - Level I control implemented in 1991

Scenario 3 - As per Scenario 2, with Level II control implemented in 1994.

Urban Airshed Model (UAM). The second acceptable modeling approach is use of the EKMA.

Unfortunately, there are practical problems associated with using either of these approaches to examine the likely effect of NO_x reductions on ambient O_3 in the South Coast Air Basin. UAM is an extremely complex model, and its application to the South Coast, even assuming that all applicable input data were available, would be cost prohibitive. Also, UAM with the carbon bond 4 (CB 4) mechanism is not yet available in the public domain. While the current version of EKMA with CB 4 is available for use, the ambient measurements of NMOC and NO_x needed as input to that model are not available for the South Coast because EKMA is not used by the SCAQMD for SIP demonstration modeling.

In light of the above, rather than attempt to provide a definitive answer to the question of how NO_x reductions might affect future year O_3 levels in the South Coast, an example EKMA diagram for a high O_3 urban area is used to provide a reasonable bound on what the NO_x effects might be.

On Figure 8-4, point A can be used as a starting point for examining control effects for an area with an O_3 design value of 0.30 ppm and a NMOC/NO_x ratio of 12:1. Based on the ARB statewide emission projections shown in Table 1, neither NO_x nor reactive HC emissions are expected to change much between 1987 and 2000. NO_x emissions are estimated to increase by 3.4 percent and reactive HC emissions are projected to decrease by 2.6 percent over this time period. Therefore, it seems reasonable to assume that the current situation could be used as one approximation of how heavy construction equipment emission changes might affect O_3 levels.

Point A on Figure 8-4 has coordinates of NMOC = 1.85 ppm and NO_x = 0.154 ppm. In the year 2000, the reduction in NO_x emissions from Scenario 1 to Scenario 3 is 107 tons per day, which is 3.6 percent of the statewide NO_x emission total. Reducing NO_x emissions by 3.6 percent in the EKMA diagram would be expected to reduce NO_x to 0.148 ppm. Thus, as a rough approximation, O_3 levels would be unlikely to change by more than 0.01 ppm.

The above results are far from conclusive, as the effects of controlling NO_x emissions on O_3 formation are a matter of continuing discussion and research. The inhibition of O_3 formation by NO_x under some circumstances, as demonstrated by the EKMA diagram in Figure 8-4, has been shown in smog chamber studies (Glasson and Tuesday, 1970; Dimitriades, 1972). More recently, Kelly (1985) showed that the addition of NO_x to Detroit ambient air samples suppressed O_3 formation. Kelly also compared EKMA predictions with the results of his smog chamber study and concluded that EKMA correctly describes the respective effects of NO_x and reactive HC on ozone maxima. Conversely, though, a recent application of the UAM to the South Coast Air Basin showed that NO_x control is not useful in reducing peak O_3 levels (study results were not publicly available at the time of this writing). Therefore, there is considerable uncertainty in estimating the effect of NO_x emission reductions on ambient O_3 for any particular area.

8.4 SUMMARY

In general the air quality impacts from heavy duty construction equipment are small. For the microscale modeling analysis presented here, the general conclusions are:

- Configuration #1 tended to produce the highest maximum concentration found at any receptor for any pollutant
- Pollutant levels developed using the Fresno meteorological data produced higher maximum pollutant concentration levels than those found using the data for Ontario for Configuration #1. Ontario meteorological data produced the highest maximum concentration levels for Configuration #2 and for the line source modeling.
- Control scenario 3 produced the lowest maximum concentration levels at any receptor. This control scenario represented the most stringent controls simulated. However, even with this level of control, air quality benefits were very small, primarily because the air quality impacts themselves were so small.

- As the negative delta values in Table 2 show, control scenarios 1 and 2 produced higher maximum concentration levels for particulates at the receptors than the Base Case. This was due to the fact that emissions were summed for all pieces of equipment. Since control scenario 1 had lower control for most equipment and since scenario 2 only stringently controlled two pieces of equipment, the overall control resulted in higher concentration than those found for the Base Case.

Concentrations found for the line source modeling showed that the Ontario meteorological data produced values roughly twice as high as the values found when the Fresno meteorological data was used.

Regional effects on ozone are subject to considerable uncertainty, but a rough approximation suggests a 0.01 ppm reduction in ozone levels. It should be noted that the effects of controlling NOx on ozone is under discussion and different studies have yielded different results.

REFERENCES

Dimitriades, Basil, "Effects of Hydrocarbon and Nitrogen Oxides on Photochemical Smog Formation," Environ. Sci. Tech., 6:253-260, 1972.

Glasson, W.A. and Tuesday, C.S., "Inhibition of Atmospheric Photooxidation of Hydrocarbons by Nitric Oxide," Environ. Sci. Tech., 4:37-44, 1970.

Holzworth, George C., "Mixing Heights, Wind Speeds and Potential for Urban Air Pollution Throughout the Contiguous United States," U. S. EPA Publication #AP-101, January, 1972.

Kelly, N.A., "Ozone/Precursor Relationships in the Detroit Metropolitan Area Derived from Captive-Air Irradiations and an Empirical Photochemical Model," JAPCA, 35: 27-34, 1985.

Peterson, William B., and Rumsey, E.D., "User's Guide for PAL 2.0 - A Gaussian-Plume Algorithm for Point, Area, and Line Sources," U.S. EPA Publication #EPA/600/8-87/009, March, 1987.

APPENDIX A

DEERE'S COMMENTS ON MEASUREMENT OF PARTICULATE EMISSIONS

Several different options exist for measuring particulates. The current EPA double dilution system needs further refinement for measuring particulates under the steady state conditions typical of construction equipment. The alternate, simpler, methods of measuring particulates need similar development for steady state tests. With any system, filter temperature, sampling conditions, and probe design needs to be specified to obtain consistent results.

The EPA currently specifies a full double dilution system for measuring particulates. In this system all of the exhaust gas is mixed with dilution air in the primary tunnel. A sample is drawn from the primary tunnel, further diluted in a secondary tunnel, and then filtered to collect particulates. The primary tunnel is a constant volume system (CVS) where the sum of dilution plus exhaust flow is kept constant. This is done through the use of either a positive displacement pump (PDP) or a critical flow venturi (CFV). A heat exchanger is used at the inlet of the PDP or CFV to hold the temperature constant within ± 11°C; or a flow compensator is used with the CFV. The primary dilution ratio level is set by the requirement that the sampling zone (where the gaseous emissions and secondary dilution sample are obtained) be less than 191°C. The secondary sample is diluted further to obtain a temperature at the primary filter of less than 52°C. A system such as this would cost approximately $250,000 per test cell.

The primary dilution ratio varies widely during the transient test. Changes in engine rated power without changes to the CVS system results in a shift in the dilution ratio. These effects are ignored in the current system, perhaps under the premise that the transient cycle averages out the effects. The range of dilution ratio also likely changes from lab to lab and cell to cell. These concerns need to be addressed before the current system can be used for steady state tests.

In the state state tests that represent construction equipment, several alternate types of particulate sampling systems should be considered. Sampling of raw particulates is one possible method. The cost to equip a test cell for measuring steady state raw particulates is estimated at $20,000. Raw sampling will minimize the length of time required to obtain a suitable filter mass.

If a dilution method is used to measure steady state particulates, the dilution ratio and sampling temperature needs to be specified. Control to a constant total flow (CVS) should not be required. Several methods of measuring and controlling dilution ratio are available. A split then dilute system could be implemented for approximately $40,000 per test cell. In this system a portion of the raw exhaust is withdrawn and mixed with a known dilution flow. Flows are measured with dry gas meters. The dilution flow temperature is used to control filter temperature. This single dilution type of system is shown in Figure 1.

A simplified double dilution system was investigated at Volvo (Ref. 1). This system can be retrofitted to existing test cells. Under transient conditions the primary tunnel is variable flow and the secondary tunnel is constant flow. Primary flow is determined using an Annubar flow sensor. Secondary flow is measured with Fluidstor flow meters.

Under steady state conditions, a similar system could use a tracer gas (NOx or CO2) to determine the primary flow and the dry gas meters to determine secondary flow. An example of this system is shown in Figure 2. Estimated cost is $60,000 per test cell.

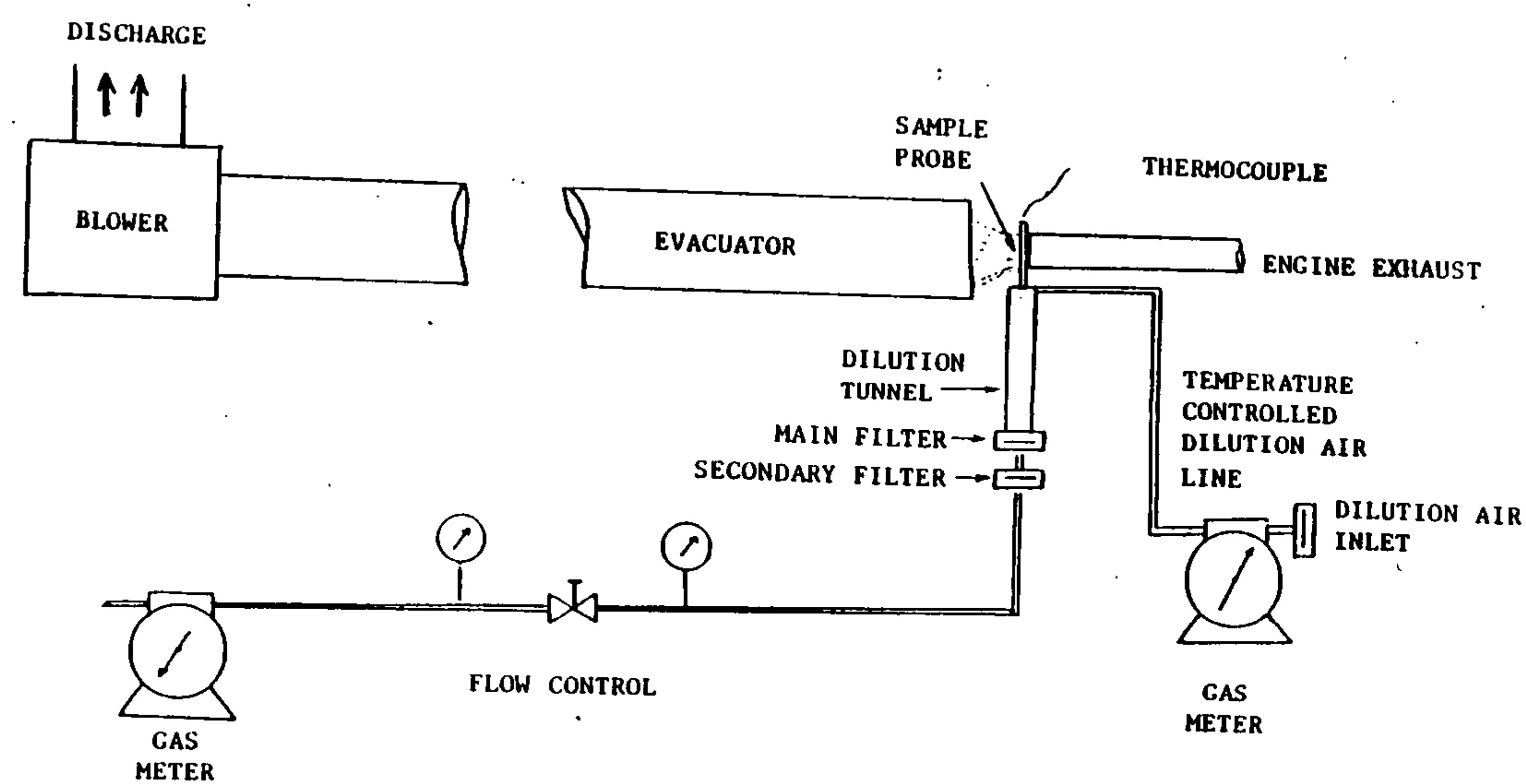


FIGURE 1 SINGLE DILUTION SYSTEM

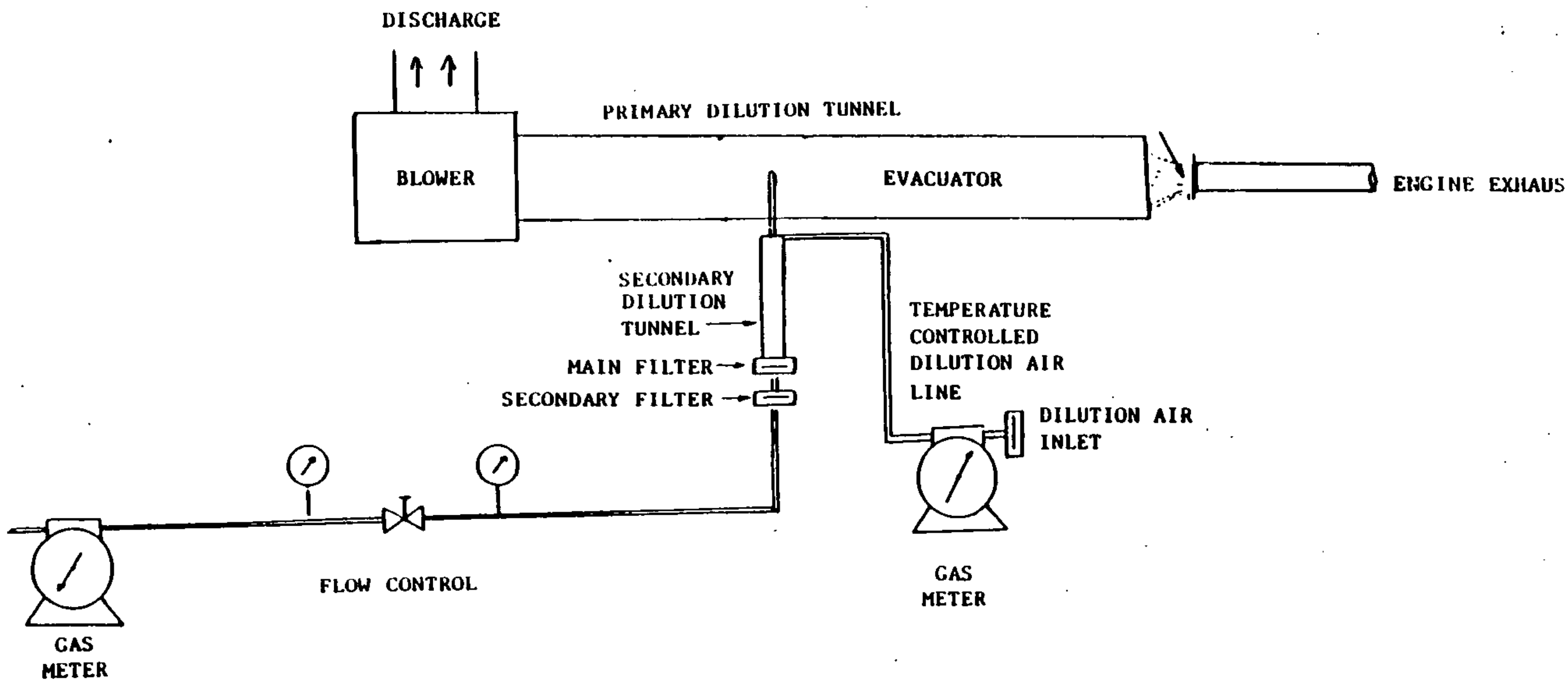


FIGURE 2 DOUBLE DILUTION SYSTEM

APPENDIX B

CALIFORNIA EMISSIONS INVENTORY FROM OFF-HIGHWAY HEAVY-DUTY CONSTRUCTION EQUIPMENT

EXAMPLE CALCULATION OF 1987 EMISSIONS INVENTORY

VINTAGE	SALES	IN_USE	POP	USE_HRS	AVG_HP	LOAD_FCTR	BHp-hr	HC_HP_HR	HC	NOx_HP_HR	NOx	PM_HP_HR	PM
(1987) 1	5700	1.00	5700	1400	152	0.55	6.671E+08	1.2	8.006E+08	11	7.338E+09	0.5	3.336E+08
2	5700	0.98	5586	1400	153	0.55	6.581E+08	1.2	7.897E+08	11	7.239E+09	0.5	3.290E+08
3	5700	0.96	5472	1400	154	0.55	6.489E+08	1.2	7.786E+08	11	7.138E+09	0.5	3.244E+08
4	5700	0.94	5358	1400	155	0.55	6.395E+08	1.3	8.313E+08	11	7.034E+09	0.5	3.197E+08
5	5700	0.92	5244	1400	156	0.55	6.299E+08	1.3	8.189E+08	11	6.929E+09	0.5	3.150E+08
6	5700	0.90	5130	1400	157	0.55	6.202E+08	1.3	8.062E+08	11	6.822E+09	0.5	3.101E+08
7	5700	0.88	5016	1400	158	0.55	6.102E+08	1.3	7.933E+08	11	6.713E+09	0.5	3.051E+08
8	5700	0.86	4902	1300	159	0.55	5.573E+08	1.3	7.245E+08	11	6.130E+09	0.5	2.786E+08
9	5700	0.84	4788	1200	160	0.55	5.056E+08	1.4	7.079E+08	12	6.067E+09	0.5	2.528E+08
10	5700	0.80	4560	1100	164	0.55	4.524E+08	1.4	6.334E+08	12	5.429E+09	0.5	2.262E+08
11	5700	0.75	4275	1000	168	0.55	3.950E+08	1.4	5.530E+08	12	4.740E+09	0.5	1.975E+08
12	5700	0.70	3990	1000	172	0.55	3.775E+08	1.4	5.284E+08	12	4.529E+09	0.5	1.887E+08
13	5700	0.65	3705	1000	176	0.55	3.586E+08	1.4	5.021E+08	12	4.304E+09	0.5	1.793E+08
14	5700	0.60	3420	1000	180	0.55	3.386E+08	1.5	5.079E+08	13	4.402E+09	0.6	2.031E+08
15	5700	0.55	3135	1000	184	0.55	3.173E+08	1.5	4.759E+08	13	4.124E+09	0.6	1.904E+08
16	5700	0.50	2850	1000	188	0.55	2.947E+08	1.5	4.420E+08	13	3.831E+09	0.6	1.768E+08
17	5700	0.45	2565	950	192	0.55	2.573E+08	1.5	3.860E+08	13	3.345E+09	0.6	1.544E+08
18	5700	0.40	2280	900	196	0.55	2.212E+08	1.5	3.318E+08	13	2.876E+09	0.6	1.327E+08
19	5700	0.35	1995	850	200	0.55	1.865E+08	1.8	3.358E+08	14	2.611E+09	0.7	1.306E+08
20	5700	0.30	1710	800	200	0.55	1.505E+08	1.8	2.709E+08	14	2.107E+09	0.7	1.053E+08
21	5700	0.27	1539	750	200	0.55	1.270E+08	1.8	2.285E+08	14	1.778E+09	0.7	8.888E+07
22	5700	0.24	1368	700	200	0.55	1.053E+08	1.8	1.896E+08	14	1.475E+09	0.7	7.374E+07
23	5700	0.21	1197	700	200	0.55	9.217E+07	1.8	1.659E+08	14	1.290E+09	0.7	6.452E+07
24	5700	0.18	1026	700	200	0.55	7.900E+07	1.8	1.422E+08	14	1.106E+09	0.7	5.530E+07
25	5700	0.15	855	700	200	0.55	6.584E+07	1.8	1.185E+08	14	9.217E+08	0.7	4.608E+07
26	5700	0.12	684	700	200	0.55	5.267E+07	1.8	9.480E+07	14	7.374E+08	0.7	3.687E+07
27	5700	0.09	513	650	200	0.55	3.668E+07	1.8	6.602E+07	14	5.135E+08	0.7	2.568E+07
28	5700	0.06	342	650	200	0.55	2.445E+07	1.8	4.402E+07	14	3.423E+08	0.7	1.712E+07
29	5700	0.04	228	650	200	0.55	1.630E+07	1.8	2.934E+07	14	2.282E+08	0.7	1.141E+07
(1958) 30	5700	0.02	114	650	200	0.55	8.151E+06	1.8	1.467E+07	14	1.141E+08	0.7	5.706E+06
			Population				BHp-hr		HC		NOx		PM
Totals, 1987			8.955E+04				9.494E+09		1.311E+10		1.122E+11		5.079E+09

HEAVY CONSTRUCTION EQUIPMENT EMISSIONS ESTIMATES, 1985 - 2005

Year	Total HC Scenario 1 (Kg)	Total HC Scenario 2 (Kg)	Total HC Scenario 3 (Kg)	Total NOx Scenario 1 (Kg)	Total NOx Scenario 2 (Kg)	Total NOx Scenario 3 (Kg)	Total PM Scenario 1 (Kg)	Total PM Scenario 2 (Kg)	Total PM Scenario 3 (Kg)
1985	13,904,855	13,904,855	13,904,855	117,404,784	117,404,784	117,404,784	5,325,261	5,325,261	5,325,261
1986	13,490,267	13,490,267	13,490,267	114,690,909	114,690,909	114,690,909	5,196,056	5,196,056	5,196,056
1987	13,107,812	13,107,812	13,107,812	112,183,900	112,183,900	112,183,900	5,077,267	5,077,267	5,077,267
1988	12,755,970	12,755,970	12,755,970	109,875,417	109,875,417	109,875,417	4,968,473	4,968,473	4,968,473
1989	12,433,989	12,433,989	12,433,989	107,765,255	107,765,255	107,765,255	4,869,128	4,869,128	4,869,128
1990	12,142,354	12,142,354	12,142,354	105,880,562	105,880,562	105,880,562	4,779,781	4,779,781	4,779,781
1991	11,811,694	11,614,189	11,614,189	104,189,976	102,214,926	102,214,926	4,701,402	4,767,237	4,767,237
1992	11,510,012	11,118,952	11,118,952	102,678,022	98,767,423	98,767,423	4,632,658	4,763,011	4,763,011
1993	11,236,335	10,655,671	10,655,671	101,337,753	95,531,106	95,531,106	4,573,067	4,766,621	4,766,621
1994	10,990,759	10,224,440	10,092,770	100,162,284	92,499,090	90,524,040	4,522,153	4,777,593	4,711,758
1995	10,771,781	9,823,757	9,563,050	99,136,519	89,656,279	85,745,680	4,478,620	4,794,628	4,664,275
1996	10,575,725	9,449,947	9,062,837	98,263,664	87,005,879	81,199,232	4,442,029	4,817,289	4,623,734
1997	10,400,594	9,101,011	8,590,131	97,524,994	84,529,165	76,865,971	4,411,254	4,844,448	4,589,008
1998	10,247,828	8,790,523	8,158,507	96,904,587	82,331,539	72,851,299	4,385,467	4,871,236	4,555,228
1999	10,118,850	8,519,342	7,768,823	96,401,930	80,406,847	69,149,062	4,365,261	4,898,431	4,523,171
2000	10,007,201	8,283,547	7,417,158	95,980,340	78,743,797	65,747,968	4,348,474	4,923,025	4,489,831
2001	9,913,215	8,083,755	7,112,218	95,632,322	77,337,716	62,764,669	4,334,837	4,944,657	4,458,889
2002	9,831,691	7,903,478	6,837,139	95,346,681	76,064,550	60,069,467	4,324,149	4,966,886	4,433,717
2003	9,761,483	7,741,571	6,592,468	95,115,132	74,916,013	57,679,470	4,315,818	4,989,122	4,414,571
2004	9,702,613	7,598,056	6,378,416	94,941,063	73,895,494	55,600,888	4,310,424	5,011,943	4,402,122
2005	9,652,047	7,469,899	6,184,423	94,804,513	72,983,032	53,700,901	4,306,208	5,033,590	4,390,853

Scenario 1 - no control

Scenario 2 - Level I control imposed in 1991

Scenario 3 - As per Scenario 2 and Level II control imposed in 1994

APPENDIX C

DESCRIPTION OF PAL ALGORITHM

B.20 POINT, AREA, LINE SOURCE ALGORITHM (PAL-DS)

Reference: Petersen, W. B, 1978. User's Guide for PAL - A Gaussian-Plume Algorithm for Point, Area, and Line Sources. EPA Publication No. EPA-600/4-78-013. Office of Research and Development, Research Triangle Park, NC. (NTIS PB 281306).

Rao, K. S. and H. F. Snodgrass, 1982. PAL-DS Model: The PAL Model Including Deposition and Sedimentation. EPA Publication No. EPA 600/8-82-023. Office of Research and Development, Research Triangle Park, NC. (NTIS PB 83-117739).

Availability: This model is available as part of UNAMAP (Version 6). The computer code is available on magnetic tape from:

Computer Products
National Technical Information Service
U.S. Department of Commerce
Springfield, Virginia 22161

Phone (703) 487-4650

Abstract: PAL-DS is an acronym for this point, area, and line source algorithm and is a method of estimating short-term dispersion using Gaussian-plume steady-state assumptions. The algoritnm can be used for estimating concentrations of non-reactive pollutants at 99 receptors for averaging times of 1 to 24 hours, and for a limited number of point, area, and line sources (99 of each type). This algorithm is not intended for application to entire urban areas but is intended, rather, to assess the impact on air quality, on scales of tens to hundreds of meters, of portions of urban areas such as shopping centers, large parking areas, and airports. Level terrain is assumed. The Gaussian point source equation estimates concentrations from point sources after determining the effective height of emission and the upwind and crosswind distance of the source from the receptor. Numerical integration of the Gaussian point source equation is used to determine concentrations from the four types of line sources. Subroutines are included that estimate concentrations for multiple lane line and curved path sources, special line sources (line sources with endpoints at different heights above ground), and special curved path sources. Integration over the area source, which includes edge effects from the source region, is done by considering finite line sources perpendicular to the wind at intervals upwind from the receptor. The crosswind integration is done analytically; integration upwind is done numerically by successive approximations.

d. <u>Type of Model</u>

PAL-DS is a Gaussian plume model.

e. <u>Pollutant Types</u>

PAL-DS may be used to model non-reactive pollutants.

f. <u>Source-Receptor Relationships</u>

Up to 99 sources of each of 6 source types: point, area, and 4 types of line sources.

Source and receptor coordinates are uniquely defined.

Unique stack height for each source.

Coordinates of receptor locations are user defined.

g. <u>Plume Behavior</u>

Briggs final plume rise equations are used.

Fumigation and downwash are not treated.

If plume height exceeds mixing height, concentrations are assumed equal to zero.

Surface concentrations are set to zero when the plume centerline exceeds mixing height.

h. <u>Horizontal Winds</u>

User-supplied hourly wind data are used.

Constant, uniform (steady-state) wind is assumed within each hour.

Wind is assumed to increase with height.

i. <u>Vertical Wind Speeds</u>

Assumed equal to zero.

j. <u>Horizontal Dispersion</u>

Rural dispersion coefficients from Turner (1969) are used with no adjustments made for surface roughness.

Six stability classes are used.

Dispersion coefficients (Pasquill-Gifford) are assumed based on a 3 cm roughness height.

k. Vertical Dispersion

Six stability classes are used.

Rural dispersion coefficients from Turner (1969) are used; no further ajustments are made for variation in surface roughness, transport or averaging time.

Multiple reflection is handled by summation of series until the vertical standard deviation equals 1.6 times mixing height. Uniform vertical mixing is assumed thereafter.

l. Chemical Transformation

Not treated.

m. Physical Removal

PAL-DS can treat deposition of both gaseous and suspended particulates in the plume since gravitational settling and dry deposition of the particles are explicitly accounted for.

n. Evaluation Studies

None.

The PAL-DS model utilizes Gaussian plume-type diffusion-deposition algorithms based on analytical solutions of a gradient-transfer model. The PAL-DS model can treat deposition of both gaseous and suspended particulate pollutants in the plume since gravitational settling and dry deposition of the particles are explicitly accounted for. The analytical diffusion-deposition expressions listed in this report in the limit when pollutant settling and deposition velocities are zero, they reduce to the usual Gaussian plume diffusion algorithms in the PAL model.

a. Recommendations for Regulatory Use

PAL-DS can be used if it can be demonstrated to estimate concentrations equivalent to those provided by the preferred model for a given application. PAL-DS must be executed in the equivalent mode.

PAL-DS can be used on a case-by-case basis in lieu of a preferred model if it can be demonstrated, using the criteria in Section 3.2, that PAL-DS is more appropriate for the specific application. In this case the model options/modes which are most appropriate for the application should be used.

b. Input Requirements

Source data: point-sources--emission rate, physical stack height, stack gas temperature, stack gas velocity, stack diameter, stack gas volume flow, coordinates of stack, initial σ_y and σ_z; area sources--source strength, size of area source, coordinates of S.W. corner, and height of area source; and line sources--source strength, number of lanes, height of source, coordinates of end points, initial σ_y and σ_z, width of line source, and width of median. Diurnal variations in emissions are permitted. When applicable, the settling velocity and deposition velocity are also permitted.

Meteorological data: wind profile exponents, anemometer height, wind direction and speed, stability class, mixing height, air temperature, and hourly variations in emission rate.

Receptor data: receptor coordinates.

c. Output

Printed output includes:

Hourly concentration and deposition flux for each source type at each receptor; and

Average concentration for up to 24 hrs for each source type at each receptor.