Background Report Reference

AP-42 Section Number: 3.3

Background Chapter: 3

Reference Number: 8

Title: Feasibility of Controlling Emissions from Off-Road, Heavy-Duty Construction Equipment

Energy and Environmental Analysis, Inc.

CARB, Arlington, VA

May 1988

626

CA ARB 1988

FEASIBILITY OF CONTROLLING EMISSIONS FROM OFF-ROAD, HEAVY-DUTY CONSTRUCTION EQUIPMENT

FINAL REPORT

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December 1988

ABSTRACT

The feasibility of controlling emissions from off-road heavy-duty construction equipment was assessed. The term "construction equipment" embraces a variety of self propelled machines that span a wide range of engine horsepower ratings. An evaluation of the market suggested that "heavy-duty" be defined as equipment having engines rated at over 50 HP. The market evaluation also showed that the imposition of on-highway emission standards and test procedures would be inappropriate. The assessment of construction equipment operation showed that a steady-state test procedure would be more representative for most types of equipment.

Three levels of emission control were considered. Level I, 10 g/BHP-hr $HC+NO_x$, was found to be achievable by all manufacturers, with additional equipment costs of $14, on average. Level II, 1.07HC/5.7 NO_x/0.6 particulate g/BHP-hr, is more difficult for engines rated between 50 and 120 HP, and would require additional components with a cost of $240, on average, while resulting in a fleetwide fuel economy penalty of 2.7 percent. Level III, 1.07HC/4.5 NO_x/0.25 particulate g/BHP-hr is difficult to achieve without a particulate trap. Concerns regarding particulate trap durability in the off-road environment has led to the suggestion that this area be re-examined when better information on traps is available. A regulatory framework similar to that utilized for heavy-duty trucks is suggested. Modifications to the regulations suggested include deletion of the durability test, a simplified test procedure and exemptions for engine families with very low unit sales in California.

Actual sales of construction equipment in California is estimated to be 8,000-10,000 units per year. The total population is estimated at 127 thousand units of which 89,000 are in the heavy-duty category. The contribution to emissions inventory under no control and different levels of control were tabulated. Economic impacts on both the construction industry and manufacturing industry were investigated, and appear to be small. Air Quality impacts due to control are also small, due to the small size of the fleet relative to the on-highway fleet.

ACKNOWLEDGEMENTS

The report was prepared under the direction of Mr. K.G. Duleep, Director of Engineering at EEA. The contributions of the industry associations, namely the Engine Manufacturers Association, the Construction Industry Manufacturers Association, the Farm and Industrial Equipment Institute, the Associated General Contractors of California, and the Construction Industry Research Board were very valuable in the preparation of this report. In addition, information supplied by Caterpillar, Cummins, John Deere, Komatsu and Deutz was most useful in the individual case study preparation. The guidance provided by ARB technical staff, Mr. Rod Summerfield, Mr. Michael Bogdanoff and Ms. Rose Polido is also gratefully acknowledged.

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EXECUTIVE SUMMARY

E.1 INTRODUCTION

Off-highway construction equipment represents one sources of emissions that is currently not subject to any emission regulations in California or nationwide. In the early 1980's, the California Air Resources Board (ARB) conducted a study which concluded that non-farm equipment constituted a significant percentage of total statewide emissions of HC, CO and NO_x. Concern focused in particular on the heavy-duty construction equipment's contribution to total NO_x emissions statewide. In view of this concern, this report assesses the feasibility of controlling emissions from such equipment.

E.2 INDUSTRY AND MARKET STRUCTURE

The term "construction equipment" is not well defined, nor is the term "heavy-duty" with reference to construction equipment. Although some types of equipment such as asphalt pavers and compactors are very clearly used uniquely in construction, many others are used in agriculture, forestry and mining. Such equipment types include off-highway trucks, backhoe-loaders and skid-steer loaders. In addition, many farm tractors can easily be retrofitted with equipment for use in construction. The term "heavy-duty" is also not defined in any regulatory sense and was left as an open question for resolution in this study. Construction equipment comes in a variety of different types covering a range of uses. In an assessment prepared for the California Air Resources Board in 1980 by ERT, the inventory was classified into 21 types of equipment. This study also classified equipment into 21 types, with some differences in the classification in comparison to the one employed by ERT.

A consideration of the market structure and the manufacturers of construction equipment revealed the following:

- Construction equipment manufactures are not necessarily engine manufacturers for construction equipment. Of the five largest (in sales terms) construction equipment manufactures, three build their own engines, while two purchase engines from a variety of suppliers. Most of the smaller firms purchase engines from other suppliers.
- A study of engine specifications reveals that very few gasoline engines are sold above the 45-50 HP range, and very few diesels are sold below the 40-45 HP range in construction equipment. A definitional cutpoint for "heavy duty equipment" in the range of 40 to 50 HP appears appropriate. This study utilizes 50 HP, although the results and conclusions of the study will be largely unchanged for any cutpoint in the 40 to 50 HP range.
- The engines utilized in heavy-duty off-road construction equipment range from 50 to 1200 HP. Of these, only a segment in the 120 HP - 400 HP range have engines that are physically similar to on-highway truck engines. Even in this range, there are numerous imported engines sold that have no on-highway engine equivalents.
- In the absence of data, EEA estimates that off-road heavy-duty construction equipment sales in California amounted to 9,000 units/year in 1985, 1986 and 1987. Although the top four major manufacturers have sales volumes of about 1,500 units/year, most of the small manufacturers sell a few tens to a few hundred units per year.
- EEA estimates that total sales (for all manufacturers) of equipment over 480 HP in California is approximately 50 units per year. Given the principal application in mining, it is unlikely that these machines will be a significant contributor to emissions in populated areas.

Based on these findings, the implications for the analysis are as follows. First, it will be unreasonable to design a test procedure that is specific to each vehicle types' operating characteristics. Even at some level of aggregation, this will result in at least 19 different test procedures. Rather, the broad characteristics of off-road construction equipment duty cycles should be the basis for any test cycle. Second, this analysis considers only <u>diesel equipment with engine ratings over 50 HP</u> as being in the "heavy-duty" category. ARB can, at its discretion, lower the 50 HP criterion to any point in the 40 to 50 HP range, based on manufacturer comments to any rulemaking on emissions the ARB may choose to undertake. Third, the blanket imposition of current on-road heavy-duty diesel emissions standards on the off-road construction equipment industry is not feasible, as only a segment of the market utilizes engines similar to on-road emissions certified engines but featuring different calibration. Separate standards based on a different duty cycle and the technology capability of the different engines should be utilized. Fourth, industry sensitivity on sales data prevents a detailed analysis of the burden of compliance faced by manufacturers. While it is clear that many equipment manufacturers may sell only 10 to 100 units per year in California, commonality of engines used across different equipment types suggests that individual engine model volumes are generally higher. Finally, the relatively low sales volumes of some types of vehicles such as those with engines over 480 HP suggests that exemptions may be appropriate for certain types of engines or equipment depending on sales volume. However, the very diverse nature of the market argues against providing blanket exemptions based on sales volume or else a very large percent of the fleet may be exempted, making regulations ineffective.

E.3 DUTY CYCLES AND TEST PROCEDURES

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. 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 by Deere 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.

The analysis of engine operation provided 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.

EEA believes that 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 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. One possibility is the 13-mode steady state test utilized for on-highway engines until 1984, with some adjustment.

In response to inquiries from EEA, the Engine Manufacturer's Association (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.

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 of 0.65 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, and an eighth mode of rated speed at low load be added to represent machines in the full throttle reverse mode with no load. More recently, EMA has suggested that the eighth mode have a load factor of 10 percent rather than 2 percent (as in the 13-mode) to simulate accessory loads. EEA believes this is appropriate; the composite load factor is then 58.75 percent.

E.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. 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 from diesels are relatively low, any standard, such as 10 g/BHP-hr, can be implemented.

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. 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. 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. 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. 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. 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 diesel engines for on-highway use 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 objected to the use of the on-highway engine smoke test, which was designed to replicate engine operation on a truck. 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, it appears appropriate to retain on-highway smoke opacity standards while altering the test procedure as suggested by EMA.

E.5 TECHNOLOGY ANALYSIS

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. Engines typically 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.

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. 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.

EEA interviewed the major manufacturers, who suggested that several on-highway technologies to meet Level III standards were inappropriate for off-highway use. They include high pressure turbocharging, air-to-air intercooling, electronic timing control, and particulate traps or catalysts.

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.

Case studies indicate that most manufacturers will meet Level I standards by injection timing optimization and the use of low sac injectors. As noted, many engines of higher horsepower are already in compliance with this standard. 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.

To meet Level II standards, it is believed that many naturally aspirated diesels will require significant changes. 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. 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. 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 estimated that 50 percent of all engines will require this change. We have also estimated 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 aftercooled (increasing aftercooler penetration from about 20 percent to 30 percent). The net weighted cost is $240, which represents the incremental price over Level I standards. This does not include the weighted price effects of increased R&D

and certification costs. 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.

Attainment of Level III 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. It will be possible to quantify the costs of meeting Level III standards to a much greater degree of precision in 1991.

One potential method of meeting Level III standards is to change the fuel type used in the engines. Both compressed natural gas (CNG) and methanol have been suggested as possible alternatives. 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.

The use of methanol in diesel engines is difficult due to methanol's low cetane number. 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 or glow plug ignition.

Manufacturers 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.

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, manufacturers have done little with the smaller 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. 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.

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. 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. 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.

E.6 REGULATORY STRATEGIES

Based on the technology analysis, 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. 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. 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.

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 some exceptions, will be able to implement the standard with a four to five year lead time. 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 also suggests that ARB may wish to consider a "split standard" approach, allowing engines less than 120 HP to certify to Level I standards. 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. 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.

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. This exemption, however, should be restricted to <u>no more than 3 or 4 engine families</u> per engine manufacturer to prevent a proliferation of separate engine families.

EEA also does <u>not</u> believe that a separate durability test is necessary. 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 impose very high costs per unit relative to other simple methods, 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, but the ARB may wish to retain a smoke standard to control emissions during transient modes not included in the emissions test cycle. 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.

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.

Since there are no emissions regulations which apply to off-highway diesel engines, new methods of enforcement are required. Three approaches were examined: voluntary compliance, compliance with Air Quality Management District (AQMD) supervision and vehicle registration. Since construction equipment is manufactured by large and reputable firms, and generally sold to large construction firms, the voluntary compliance approach is very cost-effective and results in a compliance rate of at least 70-80%, with a cost under $200,000 per year. Compliance with AQMD supervision may raise the compliance rate to 90 percent, with costs of 3 to 4 million dollars. Some AQMD's suggested that enforcement fairness considerations may require inspection of half of all construction sites, raising costs as high as 30 million dollars. Vehicle registration would cost the state about $2 million per year, which could be covered by a registration fee. This does not include costs of owner time spent on registering the vehicle, and the registration concept is opposed by construction contractors. This method will yield a 98 to 99 percent compliance rate, and also allows the ARB to track the vehicle population in California.

E.7 POPULATION AND EMISSIONS INVENTORY

The population of off-road heavy-duty construction equipment is a subject of some controversy. Power Systems Research (PSR), a subcontractor, developed a detailed population inventory by equipment type, horsepower category and engine type for Northern and Southern California. PSR maintains detailed sales records of all engines sold in the U.S. and allocates sales to the county level using statistical techniques. Scrappage ratio are based on engine make/model design life specifications, equipment operating hours per year and load factor to compute median life. Life expectancy is completed with a normal distribution curve, given a survival rate at 25+ years. The PSR inventory for California was 127,336 units of diesel equipment, of which 89,766 could be classified as "heavy-duty", i.e., over 50 HP.

The Construction Industry Manufacturers Association (CIMA) derived a much lower population figure of 61,139, less than half the PSR estimate. CIMA estimates that California accounts for only 6.2 percent of all construction equipment in the U.S. EEA's detailed analysis suggests that the PSR estimates are more credible, since California accounts for 13 percent of all construction activity in the U.S. Specifically, we found the CIMA estimate for average life to be too low, and inconsistent with their claim of average use per year, given the design life specifications for the engines. In addition, CIMA may have ignored certain types of equipment included in the PSR inventory. As a result, the PSR population estimate was used to derive the emissions inventory.

The emissions inventory was derived using vintage specific emission rates and scrappage and use rates consistent with PSR estimates. It must be noted that considerable uncertainties surround these factors ($\pm$ 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 largely because of the expectation of no growth in the construction industry. 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

The above figures are derived for the no exemptions case with 100 percent compliance, and are therefore the maximum benefits associated with emission standards.

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* Percent of statewide inventory in parentheses.

E.8 ECONOMIC IMPACTS

Emissions regulations would directly affect two industries: the California construction industry and equipment manufacturing industry, by increasing the cost of doing business and by influencing the competitiveness.

Heavy-duty construction equipment is used primarily in large earthmoving jobs such as residential site preparation, road building, bridges and dams. The Construction Industry Research Board estimates slow or negative growth in these areas because of the completion of most major highway and dam projects in California, slowing population and personal income growth, and the proliferation of building restrictions and moratoriums on growth. It is reasonable to assume a constant population of equipment in California to 2000 under these circumstances.

The cost of equipment and fuel used as a proportion of total construction spending is generally quite small. In residential construction, cost breakdown for a site preparation project shows that equipment costs account for 30 percent of total site preparation costs, which in turn accounts for one-third of total project cost. In road building, equipment costs can account for as much as 80 percent of total costs.

Emissions regulations can increase new equipment costs by about 1 percent (under Level II control) and increase fuel use by 2 to 3 percent. Thus, residential costs will rise by less than 0.3 percent, while road building costs will rise by less than 1 percent due to the imposition of regulations. Such increases are not likely to affect competition with out-of-state contractors with the possible exception of some limited border counties. Due to equipment transportation costs, cost increases are also unlikely to cause California contractors to purchase equipment from other states. In addition, it appears that mining, forestry and agriculture sectors will bear little burden if the ARB provides exemptions for a few specific equipment types such as log skidders and very large off-highway trucks used primarily by these sectors.

Engine manufacturers will face a range of fixed costs associated with the imposition of standards. They include research and development costs to meet standards, certification costs, recall liability and investment in new test facilities. These costs are over and above variable costs associated with addition of specific components for emission control. All of the fixed costs are strongly dependent on how many different engine "families" are certified. This, in turn, is dependent on regulations allowing exemptions for low sales volume families, and the carryover of "on-highway" certification families.

Assuming the adoption of specific policies by the ARB, EEA has estimated that 34 families would be certified to off-highway standards, 28 families carried over from on-highway certification families and 34 exempt families due to sales of less than 10 units per year. (EMA has disagreed with this estimate, but no data was provided to develop another estimate.) To meet Level I standards, EEA estimated a total fixed cost of $2.82 million for the entire industry. To meet Level II standards, a total fixed cost of $8.18 million is estimated for the industry. In addition, industry may invest new test facilities, and the total industry investment is estimated at $12 million.

It is not clear how fixed costs will be charged to the customer. Much depends on the period of time of amortization of fixed costs and tax benefits associated with depreciation. Typically, R&D and depreciation is expensed so that such costs are not charged directly to California sales. If costs are charged to the individual certified families, the burden can exceed over $1000 per engine. In view of the accounting practices followed by U.S. engine manufacturers, such a burden is unlikely. For any given manufacturer, the total fixed cost annualized burden is no larger than 1 percent of current R&D expenses.

E.8 AIR QUALITY ANALYSIS

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 were 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 were simulated to see whether there is a discernable effect on ambient air quality levels in the vicinity of the construction sites. Concentrations of all ambient pollutants were found to be extremely low, with average hourly concentrations of HC, NOx or particulates less than 10^{-4} grams per cubic meter.

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. Control of HC emissions were found to result in emission changes too small to produce measurable changes in ozone. NO_x emission changes could produce an ozone reduction of up to 0.01 ppm, but the results are far from conclusive. At this time, there is considerable uncertainty regarding the reaction mechanisms linking ozone to NO_x emissions.

1. INTRODUCTION

Off-highway construction equipment represents one of the last mobile sources of emissions that is currently not subject to any emission regulations in California or nationwide. In the early 1980's, the California Air Resources Board (ARB) conducted a study which concluded that non-farm equipment constituted a significant percentage of total statewide emissions of HC, CO and NO_x. Concern focused in particular on the heavy-duty construction equipment's contribution to total NO_x emissions statewide. In view of this concern, this report assesses the feasibility of controlling emissions from such equipment.

Analysis of the off-highway segment is made particularly difficult due to serious data constraints. The manufacturers of construction equipment are reluctant to disclose any information on product sales or scrappage. The industry itself is very fragmented, with literally dozens of companies of various sizes competing in the equipment market. The engines in such equipment span the range from 25 HP to 1500 HP. Certain specialized kinds of equipment, especially in the high horsepower categories sell only a few units per year in California. As a result, information on the sales of equipment, types, engine models, and horsepower ratings are available only in limited cases. Little information is known about the emissions characteristics of the engines used in construction equipment.

This report is a "broad-brush" attempt at characterizing the equipment and the feasibility of control of emissions from such equipment. It covers the span of activities associated with a comprehensive regulatory analysis, namely:

- Industry Characterization
- Equipment Use Patterns
- Emissions and Control Technology
- Contribution to Total California Emissions Inventory

- Regulatory Strategies for Emission Control
- Economic Impact Analysis
- Effect of Regulation on Air Quality.

It must be noted that, given the state of data on this industry, an in-depth evaluation of each of these factors would constitute a large undertaking. The time and resource constraints of this project has necessitated analysis that provides only qualitative, but no quantitative, insights into some aspects of the problem.

Data on off-road construction equipment were obtained by EEA from a wide variety of sources, and this report combines actual data with EEA estimates based on statistical and engineering analysis. On some specific topics where no data is available, EEA obtained anecdotal estimates from conversations with construction equipment users and field personnel. EEA also interviewed the major off-highway engine manufacturers, and worked with the Construction Equipment Manufacturers Association (CIMA), the Farm and Industrial Equipment Institute (FIEI) and the Engine Manufacturers Association (EMA) to obtain the best possible information.

Accordingly, Section 2 provides an overview of the types of equipment that are covered in this analysis and some of the characteristics of the market and the competition. Section 3 analyzes the use patterns of the equipment and the duty cycles encountered by the engines to derive an emissions testing procedure suitable for off-highway engines. Section 4 addresses the technological feasibility of attaining different sets of potential emission standards that could be imposed. Using a case study method, an in-depth analysis of four manufacturers' capabilities is provided in Section 4. Section 5 provides the ARB with a range of regulatory strategies and enforcement procedures. Section 6 is a detailed assessment of equipment and emissions inventory in California. This section incorporates the equipment inventory developed by a subcontractor, Power Systems Research. Section 7 describes our economic impact analysis on both California contractors and the equipment manufacturers as a result of imposing emissions standards in California. Section 8 provides an assessment of the impact of emission control on air quality.

2. INDUSTRY OVERVIEW AND ANALYTICAL IMPLICATIONS

2.1 OVERVIEW OF CONSTRUCTION EQUIPMENT

The term "construction equipment" is not well defined, nor is the term "heavy-duty" with reference to construction equipment. Although some types of equipment such as asphalt pavers and compactors are very clearly used uniquely in construction, many others are used in agriculture, forestry and mining. Such equipment types include off-highway trucks, backhoe-loaders and skid-steer loaders. In addition, many farm tractors can easily be retrofitted with equipment for use in construction. The term "heavy-duty" is also not defined in any regulatory sense and was left as an open question for resolution in this study.

Construction equipment comes in a variety of different types covering a range of uses. In an assessment prepared for the California Air Resources Board in 1980 by ERT (referred to as the CAL/ERT Study) and sponsored by the Construction Industry Manufacturers Association (CIMA), the Engine Manufactures Association (EMA) and the Farm and Industrial Equipment Institute, the inventory was classified into 21 types of equipment listed in Table 2-1. However, 41% of the total inventory was listed under the heading "industrial tractor," an equipment type not frequently used in construction, at least in the commonly understood meaning of this term. Moreover, the inventory did not list separately the popular backhoe-loader, leading EEA to suspect that the terminology utilized may be different from common parlance.

The lack of standardized terminology for equipment types is but one of the difficulties in characterizing off-highway construction equipment. There are also numerous types of equipment that are very specialized and used in small numbers. These may include asphalt reclaimers, small on-site dumpers, self-

TABLE 2-1
TYPES OF OFF-HIGHWAY CONSTRUCTION EQUIPMENT CONSIDERED

CAL/ERT Study	EEA
Bituminous Paver	Bituminous Paver
Concrete Paver	Concrete Paver
(?)	Other Paving
Compactor (static)	Roller/Compactor
Compactor (vibrating)	Roller/Compactor
Crawler Crane	Crane
Wheel Crane	Crane
Hydraulic Wheel (one-stat) Crane	Crane
Hydraulic Wheel (multi-stat) Crane	Crane
Crawler Excavator	Excavator
Hydraulic Excavator	Excavator
Trencher/Ditcher	Trencher/Ditcher
Industrial Tractor	Industrial Tractor
(Included in Industrial Tractor)	Backhoe Loader
(Included in Industrial Tractor)	Rough Terrain Fork Lift
Log Skidder	Log Skidder
Motor Grader	Motor Grader
Off-Highway Truck	Off-Highway Truck
Pipe Layer	Included in Excavator
Skid Steer Loader	Skid Steer Loader
Scraper	Scraper
Track Type Loader (2 categories)*	Track Loader
Track Type Tractor (2 categories)*	Crawler Tractor
Wheel Loader (2 categories)*	Wheel Loader
	Wheel Dozer
	Dumper
	Feller/Buncher

* Subdivided by horsepower category.

propelled road breakers, etc. that are manufactured by small firms and not typically reported in any systematic study or inventory. Finally, the construction equipment manufacturing industry is very sensitive about sales and provides little public information on unit sales by equipment type, either nationwide or in California. In spite of several requests from EEA to CIMA and FIEI, no sales data was provided by these organizations, and EEA had to rely on public data sources to estimate the population and sales profile. The CAL/ERT study provided estimates of population, but no sales data was disclosed.

The equipment types chosen for inclusion in the study are also listed in Table 2-1, and some types of equipment in the ERT/CIMA inventory have been combined into one group, while others have been added. The lack of exact correspondence in nomenclature may make comparisons inexact, but the equipment types are so varied that this is a persistent problem. Separate categories have been created by EEA for wheel type dozers, backhoe-loaders, dumpers, feller-bunchers and rough-terrain forklifts. On the other hand, different categories of cranes, excavators and compactors have been combined in this study.

The term "heavy-duty" is also not defined by regulatory statute, as no regulations apply to off-highway emissions currently. The study by ERT suggested that an engine rating of 50 HP be selected as a cutpoint, and all equipment with engines rated above that level by treated as "heavy-duty." EEA examined available equipment specifications in detail and found:

- Most gasoline-engine powered construction equipment is rated at below 50 HP
- A few types of construction equipment below 50 HP are diesel powered, typically by one or two-cylinder air cooled diesels
- The lowest rating for some diesel powered types that utilize industry defined "heavy-duty" diesels are in the 40-50 HP range. For example, Deere and Cummins each offer one engine rated in that range.

EEA believes that setting <u>any</u> cutpoint in the 40 to 50HP range should be adequate to define the term "heavy-duty." To maintain consistency with the CAL/ERT analysis, this analysis utilizes 50 HP as the cutpoint. Given the inherent uncertainties in our inventory and emission estimate, the choice of another cutpoint in the 40 to 50 HP range will not materially affect the results or conclusions of the analysis.

The principal reasons for selecting a cutpoint are (1) to eliminate the need to consider small hand-held or self-propelled pieces of equipment that use gasoline engines. Such equipment has very different use patterns, duty cycles and useful lives than heavy-duty equipment, and are not included in this analysis (2) to minimize the impact of any potential regulations on agriculture, which utilizes many similar types of equipment as the construction industry, but typically only in the low horsepower range. In addition, this analysis considers only <u>self-propelled</u> construction equipment, as per ARB staff directive. Hence, stationary cranes, pile-drivers, concrete mixers, etc. are not included in this analysis.

2.2 <u>EQUIPMENT AND ENGINE MANUFACTURERS</u>

As with the on-highway heavy-duty truck industry, off-highway construction equipment manufacturers are not necessarily vertically integrated with engine manufactures. There are a very large number of manufacturers of equipment, and many of the manufactures buy engines from a variety of suppliers. The picture has been made more complex recently by joint ventures between American and Japanese manufacturers.

From the equipment side, Caterpillar is probably the best known name in the construction equipment manufacturing business, and offers a near complete product range in all machine categories. Caterpillar builds its own engines and virtually all of its equipment rated over 100 HP use Caterpillar built engines. However, on some of the smaller equipment, Caterpillar uses Perkins diesels. Caterpillar has dominant market share in large equipment (over 240

HP) but does not dominate the market in smaller equipment. Another full-line manufacturer is Komatsu, which competes world-wide with Caterpillar. Like Caterpillar, Komatsu manufactures its own engines, some under license from Cummins. A third "full-line" manufacturer is Dresser, but Dresser buys engines from a wide variety of sources. In its crawler tractor, crawler loader and wheel loader products, Dresser utilizes International Harvester (IH) engines for application ratings up to 200 HP and Cummins engines over 200 HP in its larger models. In its excavator line, Dresser uses the Mercedes OM-421 engine and Deutz BF6-L913 engine in its larger models and IH engines in its smaller models. In vibratory compactors, Dresser uses the Detroit Diesel 4-53 and 3-53 sizes of engines. Dresser also manufactures large off-highway trucks with Detroit Diesel or Cummins engines rated from 450 to 1200 HP.

In the smaller equipment types (50-200 HP), the firms with dominant market shares are John Deere and JI Case. Deere manufactures its own engines and most of its product line sales are in applications below 120 HP. JI Case (and Dresser) sell a significant fraction of their total in the 100-200 HP range. The five companies discussed above - Caterpillar, Komatsu, Case, Dresser, and Deere - probably account for 75 percent of unit sales in the U.S. However, there are numerous smaller firms that are being rapidly consolidated in the industry. Northwest Engineering is one example. A relatively small manufacturer of lattice-boom crawler cranes (1985 sales of $26 million), it recently bought Koering cranes and Terex, a major manufacturer of very large earth-moving equipment. Its 1987 consolidated sales are about $300 million. Foreign manufacturers have moved aggressively - Volvo has acquired Michigan and Euclid, two major construction equipment machinery manufacturers, and is incorporated as VME. Fiat bought Allis Chalmers and sells equipment under the Fiatallis name. More recently, Komatsu and Dresser have formed a joint venture to market and manufacture equipment in North America; Hitachi and Deere have combined to form a joint venture for manufacturing excavators.

In spite of the industry consolidation, numerous small companies and importers continue to operate in individual niches. Isuzu, Mitsubishi and Kobelco sell a variety of equipment as do Liebherr-America and Hanomag from Europe. In addition, numerous U.S. firms such as Bomag, Ingersoll-Rand, Ford and Melroe offer unique pieces of equipment. For example, Melroe offers small excavators and skid-steer loaders, powered by Kubota, Deutz and Perkins diesels.

The discussion above illustrates the widely splintered nature of the market. Although five or six manufacturers may have sizeable market share, there are dozens of other manufacturers that sell relatively few pieces of equipment. Of greater concern to this study is the variety of engines sold in this market. The range of horsepower ratings, engine sizes and models available in the off-highway equipment market is significantly larger than in the on-highway market. For example, horsepower ranges are from 50 to 1200 HP in comparison to the 150-400 HP for on-highway truck engines. In the lower end of the horsepower range - 50 to 120 HP - engines are typically naturally aspirated 3 to 6 cylinder engines that have no on-highway equivalent engines. The 120-400 HP market typically consists of versions of on-highway engines that have identical displacement but are more similar to the on-highway engines sold prior to 1980. Over 400 HP, the market consists of very specialized diesels built in small volumes, although the 400 to 500 HP category includes some variants of on-highway diesels. Even in the 120-400 HP category, however, there are numerous diesel engine models sold in small volumes (typically imports), that have no equivalent U.S. certified "on-highway" diesels. In our analysis we have divided engines into four categories: 50-120 HP, 120-240 HP, 240-480 HP and 480+ HP. Although the distinctions are somewhat arbitrary, there is significant technological homogeneity with each category, aiding our technical analysis.

Another point of importance is the likely range of sales volumes by engine type. Because of the secrecy surrounding sales figures, EEA was forced to estimate sales in California and the probable range of sales by engine family.

Obviously, it becomes very expensive to certify engines if sales in California amount to no more than a few units per year. The most comprehensive data on sales available publicly is from the Census. Based on data in the 1987 Industrial Outlook, 1985 sales of construction equipment nationwide is around 90,000 units as shown in Table 2-2. The Construction Industry Manufacturers Association has estimated that sales have stayed relatively flat for 1986 and 1987, although imports have lost market share.

California is estimated to account for approximately 10 percent of the market, or 9,000 units per annum. (This 10 percent figure is more adequately documented in Section 6). If one assumes that Caterpillar, Deere, JI Case and Dresser have 2/3 of the total market or 6,000 units, each company would probably have sales of about 1,500 units. EEA has obtained unofficial confirmation of the appropriateness of this number from Caterpillar and Deere. Of course, the remaining 2,000 units are spread over dozens of manufacturers, indicating that a large number of manufacturers sell in the range of about 100 to 200 units a year.

A detailed analysis of the inventory (see Section 6) reveals that only 1.5 percent of units are in the over 480 HP category. Typically these units last much longer than the small units and their market share has been declining in recent years due to an end to the large earthmoving contracts in California. The likely range of sales is about 1/2 to one percent of the total, i.e., 45 to 90 units per year, in California. With only 4 manufacturers competing in this segment of the engine market, each manufacturer is likely to sell only 10 to 20 units of <u>all</u> engine models above 480 HP. The imposition of emission standards on this group of engines can have a significant impact on their price as compliance and certification costs must be recovered from a very small sales base.

TABLE 2-2
SALES BY EQUIPMENT TYPE

Product Type	Total Manufacturer's Shipments - Export Shipments 1985	1984
Bituminous Pavers	1,042	768
Compactors (static)	2,882	2,558
Compactors (vibratory)	4,734	2,255
Concrete Pavers	91	316
Crawler and Wheel Cranes	3,434	2,763
Ditchers and Trenchers	6,111	6,122
Hydraulic Excavators	2,815	3,157
Industrial Tractors	5,009	2,928
Log Skidders	1,371	2,075
Motor Graders	3,022	2,877
Off-Highway Trucks	4,917	2,511
Skid Steer Loaders	13,957	14,047
Scrapers	3,047	2,039
Track-Type Loaders	1,780	2,479
Track-Type Tractors	5,442	6,628
Wheel-Type Loaders (less than 2.5 cu.yd.)	1,391	3,768
Wheel-Type Loaders (greater than 2.5 cu.yd.)	633	397
TOTAL	**61,678**	**57,688**
Total Shipments	81,650	77,738
Total Imports	27,971	20,129
Total Exports	19,972	20,050
Total Domestic	**89,649**	**77,817**

Sources: Bureau of Census, "Current Industrial Reports-Construction Machinery," MA 35D (85)-1, 1985. "1987 U.S. Industrial Outlook," p.22-2.

2.3 IMPLICATIONS FOR THIS ANALYSIS

A consideration of the market structure and the manufacturers of construction equipment reveals the following:

- The market for construction equipment is very diverse, incorporating a wide variety of equipment types. Some types of equipment are very specialized, while others have more general application, including application in agriculture, forestry and mining.
- Construction equipment manufactures are not necessarily engine manufacturers for construction equipment. Of the five largest (in sales terms) construction equipment manufactures, three build their own engines, while two purchase engines from a variety of suppliers. Most of the smaller firms purchase engines from other suppliers.
- There is currently no fixed definition of the term "heavy-duty" as applied to construction equipment. A study of engine specifications reveals that very few gasoline engines are sold above the 45-50 HP range, and very few diesels are sold below the 40-45 HP range in construction equipment. A definitional cutpoint in the range of 40 to 50 HP appears appropriate. This study utilizes 50 HP, although the results and conclusions of the study will be largely unchanged for any cutpoint in the 40 to 50 HP range.
- The engines utilized in heavy-duty off-road construction equipment range from 50 to 1200 HP. Of these, only a segment in the 120 HP - 400 HP range have engines that are physically similar to on-highway truck engines. Even in this range, there are numerous imported engines sold that have no on-highway engine equivalents.
- In the absence of data, EEA estimates that off-road heavy-duty construction equipment sales in California amounted to 9,000 units/year in 1985, 1986 and 1987. Although the top four major manufacturers have sales volumes of about 1,500 units/year, most of the small manufacturers sell a few tens to a few hundred units per year.
- EEA estimates that total sales (for all manufacturers) of equipment over 480 HP in California is approximately 50 units per year. Given the principal application in mining, it is unlikely that these machines will be a significant contributor to emissions in populated areas.

Based on these findings, the implications for the analysis are as follows.

First, it will be unreasonable to design a test procedure that is specific to each vehicle types' operating characteristics. Even at some level of aggregation, this will result in 19 different test procedures. Rather, the broad characteristics of off-road construction equipment duty cycles should be the basis for any test cycle.

Second, the regulatory analysis will consider only diesel equipment with engine ratings over 50 HP as being in the "heavy-duty" category. ARB can, at its discretion, lower the 50 HP criterion to any point in the 40 to 50 HP range, based on manufacturer comments to any rulemaking on emissions the ARB may choose to undertake.

Third, the blanket imposition of current on-road heavy-duty diesel emissions standards on the off-road construction equipment industry is not feasible, as only a segment of the market utilizes engines similar to on-road emissions certified engines but featuring different calibration. Separate standards based on a different duty cycle and the technology capability of the different engines should be utilized.

Fourth, the very large number of engine models and horsepower ratings make a broad scale technology analysis meaningless as there will be a large number of exceptions to every conclusion. Rather, the approach chosen is to examine all products for a few representative manufacturers, and assess compliance feasibility.

Fifth, industry sensitivity on sales data prevents a detailed analysis of the burden of compliance faced by manufacturers. While it is clear that many equipment manufacturers may sell only 10 to 100 units per year in California, commonality of engines used across different equipment types suggests that individual engine model volumes are generally higher. The ARB should direct the construction equipment manufacturers to submit detailed data on sales by vehicle type and engine model.

Finally, the relatively low sales volumes of some types of vehicles such as those with engines over 480 HP suggests that exemptions may be appropriate for certain types of engines or equipment depending on sales volume. However, the very diverse nature of the market argues against providing blanket exemptions based on sales volume or else a very large percent of the fleet may be exempted, making regulations ineffective.

These issues are examined in more detail in the following section of this report.

3. TEST CYCLES AND POTENTIAL STANDARDS

3.1 ENGINE/MANUFACTURER CLASSIFICATION

Based on the engine categorization scheme developed in Section 2, EEA examined in detail available engines used in construction equipment, and determined their specifications and modifications. In brief, specifications of interest were type of diesel (DI, IDI), aspiration (natural, turbo charged, inter-cooled), displacement, horsepower ratings and existence of "similar" on-highway diesel, with the similarity based on specifications of interest. EEA utilized this 1987 Construction Equipment magazine's annual specifications guide as the source of equipment and engine data, supplemented by data from the five largest construction manufacturers - Caterpillar, Komatsu, Deere, JI Case and Dresser. As noted previously, JI Case and Dresser utilize engines from several manufacturers, although JI Case uses primarily Cummins engines manufactured by the joint venture called Cummins-Case diesels.

Examination of the engines used by manufacturers of equipment showed that Caterpillar, Cummins and Deere engines were the three engine manufacturers that had the highest market share. Deutz, Komatsu, IH, DDA and Perkins were the next most significant set manufacturers based on the number of models of equipment offering each type of engine and the equipment manufacturers estimated market share. Engines are also sold by the major Japanese manufacturers such as Mitsubishi and Isuzu, German manufacturers such as MAN and Daimler Benz, and English manufacturers such as Perkins and Lister-Petter. One point to be noted is that most of the manufacturers listed certify at least one engine family for on-highway use, and have familiarity with emissions testing and calibration development in-house.

However, the degree of familiarity, experience in emissions and the number of engine models vary greatly. Of the eight manufacturers who have (as believed from anecdotal information) the largest market shares, only Komatsu does not certify any engines for on-highway use. Deere has certified two engine lines for the first time in 1987, although its sales in the on-highway market are probably negligible. Deutz and Perkins have traditionally certified one or two engine lines in the U.S. for the past decade. At the other end of the spectrum, Caterpillar and Cummins certify (or have certified in the past) virtually every engine type offered for sale in the off-highway market (Caterpillar's new 3110 series is not yet certified, but will be certified for 1989).

There is also some concern over a range of small diesel engines, some versions of which may be rated above the 50HP "heavy-duty" mark. Such small diesels are provided by Hatz, Yanmar, Kubota and Onan, to name a few popular manufacturers. Typically, there has been little testing of these one- or two-cylinder diesels for emissions. It is quite possible that these engines may have considerable difficulty meeting stringent emission standards. One possible option for such manufacturers is to slightly derate engine versions currently rated between 50 and 60 HP to just below 50 HP; another option would be upgrade technology on engines that are important to manufacturers because of sales volume, or else withdraw from the market if sales are very low.

Table 3-1 shows the distribution of engine models by manufacturer for the eight manufacturers with the largest market share. Four of these manufacturers were selected for more detailed technology evaluation to represent a broad range of capabilities. They are:

- Caterpillar - a vertically integrated engine and equipment builder with extensive emissions certification experience
- Cummins - an engine builder that simply supplies engines to equipment manufacturers and has extensive emissions certification experience
- Komatsu - a company like Caterpillar, but without certification experience

TABLE 3-1
DISTRIBUTION OF ENGINE MODELS BY HORSEPOWER CATEGORY

Manufacturer	50-120	120-240	240-480	480+
Caterpillar	3114T	3116T	3406T/TA	3412TA
	3204NA/T	3208NA/T	3408T	3508T/3512TA
	3304NA/T	3306NA/T	3306T/TA	3516TA
	3306NA	3204T	3412T	3408TA
Cummins	4B3.9	6B5.9	L-10	KT-19
	4A2.3	6C8.3	NT-855	VT-28
	6A3.4			KV-38
DDA		6-71N/T/TA	6-53T	All 149 series
	3-53N/T	3-53T	6-71T/TA	12-71TA/16-71TA
	4-53N	4-53T	8-71T/TA	12-92TA/16-92TA
	2-71N	8.2N/T	6-92N/T/TA	8-92T/TA
Deere	3-179	6-414T	6-619	
	4-239D/T	6-466T/A	8-955	
	6-359D/T	6-359T		
	4-276D/T	6-619A		
IH	D-239	D-466		
	D-360	DT/DTI-466		
Komatsu	4D-94	6D-95	6D-125	6D-170
	4D-95	4D-130	6D-140	8V170
	4D-105	6D-105	6D-155	12V170
		6D-110		
Deutz	FL912	FL913	FL413	
	FL913	FL413	FL513	
Perkins	3-153	6-354	6-734	
	4-203	8-540	8-1062	
	4-236			

• NA - naturally aspirated, T - turbocharged and TA - turbocharged/aftercooled.

- Deere - A vertically integrated engine and equipment builder that specializes in smaller machines, and has little emissions certification experience.

Although EEA had originally intended to also focus on a small manufacturer, the lack of suitable local candidate that had enough sales volume in California to be above any point that could not be handled by a low sales volume exemption led us to drop this option. Moreover, given the considerable industry consolidation taking place, we anticipate a shake-out in the industry of very low volume engine manufacturers. This trend has already begun - Case no longer manufactures it's own engines, while Onan is in a joint venture with Cummins to promote its engines.

Any consideration of the emissions capability of various engines must define both a test cycle and specific emissions levels that all engines will be required to obtain. The consideration of test cycle is necessary because existing test cycles for on-highway truck applications are designed to replicate the typical loads, speeds and accelerations experienced by diesel engines during city driving. Off-highway equipment, in which the engine generally transmits power to the wheels/tracks and accessories through hydraulics, have completely different duty cycles than on-highway trucks. Accordingly, the typical working cycles and cycle times were examined for a wide range of off-highway equipment, and implications for an emissions test procedure drawn for the analysis.

3.2 DUTY-CYCLES FOR OFF-HIGHWAY EQUIPMENT

There is a wide variety of construction machinery available in the United States. The techniques employed by users are widely variable as well. The nature of the job, the configuration of the machine and the individual operator's work habits contribute to the wide range of work cycles to which machines are applied. Any effort to examine or analyze this broad spectrum of work cycles soon becomes fairly complicated. A few examples may be examined to illustrate the problem:

TRACK TYPE TRACTORS are available in a range of sizes from approximately 50 to 575 horsepower. These machines can be fitted with a variety of implements such as bulldozers, rippers, land clearing blades, root rakes, cable laying plows, push plates, drills and many others. They can be used on drawbar work to pull such items as scrapers, wagons, land planes, discs, disc plows, subsoilers, chisels and to skid logs, just to mention a few. Each of these configurations can be applied to a wide variety of work cycles.

Throttle control normally consists of a single hand control lever and frequently, a foot-operated accelerator/decelerator pedal. Specific operating techniques depend on machine configuration, the implement attached and the nature of the work being done.

As an example, the dozer-equipped tractor can be used to do a variety of tasks, each requiring a somewhat different approach. A production dozing operation will usually require the engine to operate at or near rated speed and load for most of the work shift. Changes of direction (reversal) can be affected by the type of transmission employed. Power shift machines can be reversed at full throttle while clutch-equipped machines are usually throttled down for direction changes. The distance material is being pushed and the disposition of the material at the end of the dozing cycle, whether spread or merely dumped, will affect the way the operator changes engine speed. If the machine is pioneering, the cycle will be relatively short and direction changes fairly frequent. Conversely, a dozer can be used, for example in "trapping" sand and gravel and may travel several hundred feet in each direction during the cycle. an operator would normally open the throttle to full speed and leave it there for most of the shift, except for the occasional need to maneuver in close quarters, when the foot decelerator will be used.

A dozer-equipped tractor is often used in intermittent type service, like cleaning up and backfilling, in which the frequency and duration of full-load operation varies directly with the nature of the work and the degree of precision required. Where structures and buried pipe or cables are present, lower throttle settings are used to avoid work cycle for these machines.

MOTOR GRADERS perform a wide variety of functions and can be equipped with a range of attachments. Examples are; (1) Finish grading of roads, streets and airports, canals, earthen dams and industrial sites. This is the most precise work, with the possible exception of grade preparation for paving, that these machines perform, generally because the quantity of material being moved is small and loads are light, making it possible to operate at slow engine speeds. The size or length of the area being graded will determine the duration of the loaded portion of the cycle and the number of direction changes. In finishing, the skill of the operator and the work tolerance will influence the choice of engine speed. The more skilled operator will tend to run at higher speeds and less skilled will operate slower for greater precision of control. (2) Rough grading and spreading fill material are usually done at higher speeds and loads. This is less precise work and can be done with less care. Again, the geometry of the job will determine the length and duration of each cycle and the amount of reduced throttle operation while maneuvering. (3) Graders equipped with attachments like rippers and scarifiers often operate for long periods at rated speed and load, depending on the length of roadway or area being worked (4) Graders equipped with bituminous spreaders will operate at lower speeds and loads because of the fairly precise nature of this work. Such machines are subject to varying waiting periods, depending on the number of hauling trucks supplying spreader.

Throttles used on motor graders usually consist of a hand lever with a foot-operated accelerator/decelerator. On longer runs, the hand throttle is fully opened while on shorter runs the foot controls will be used, The decelerator