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Mobile-Source NOx Emissions

Sources and Control Options

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SOURCES AND CONTROL OPTIONS

1.0 OVERVIEW: NOx EMISSIONS FROM MOBILE SOURCES

Motor vehicles and other mobile sources of pollution are among the most important sources of oxides of nitrogen (NOx) emissions. The nitrogen oxides, NO and NO_2 play a key role in the chemistry of the atmosphere, including photochemical ozone formation. For this reason, increased NOx emissions due to human activity contribute to a wide range of environmental problems on the local, regional, and global scales. These include urban ozone and fine particulate concentrations, regional ozone and acid deposition problems, and the projected global warming due to the "greenhouse" effect.

Highway vehicles and other mobile pollution sources such as railway locomotives, ships, and aircraft are responsible for a large fraction of total anthropogenic NOx. Through appropriate emission control measures, these emissions can be reduced by between 60 and 90% from their uncontrolled levels, at a cost which many countries consider acceptable. The purpose of this document is to summarize much of the available knowledge on mobile-source NOx emissions for consideration in formulating emissions-control policy. It discusses the environmental effects of NOx, measurement techniques for mobile-source emissions, and NOx formation and control in gasoline, diesel, and gas-turbine engines. Technological options for NOx control and their costs are also discussed, together with some consideration of non-technological measures such as transportation controls.

Environmental significance of NOx emissions

The photolysis of NO_2 to produce NO plus ozone is a key reaction in chemistry of the atmosphere. In the presence of volatile organic compounds (VOC), NO is subsequently re-oxidized back to NO_2 in a cyclic process. Ozone is itself an important local- and regional-scale pollutant, and a contributor to the projected greenhouse warming. In high concentrations in urban areas, ozone causes or contributes to a variety of respiratory health problems. At the lower concentrations often found over large areas in Europe and North America, ozone retards growth of crops and other plants, and can damage sensitive vegetation. This is now suspected to be a major factor in the widespread forest decline throughout Europe and Eastern North America which had previously been attributed to acid rain.

The reaction of ozone and other photochemical oxidants with NO_2 and SO_2 in the atmosphere results in their being converted to nitrates and sulfates, which form fine particles in the atmosphere. These nitrate and sulfate species are major contributors to the total burden of respirable particulates (PM10) in many heavily polluted cities. High PM10 concentrations in urban air are linked to increased rates of death and illness due to respiratory problems. Due to their acidity, sulfate and nitrate particles are considered especially damaging in this respect. Deposition of these acid particulate materials (either as "acid rain" or in the form of dry deposition) has also been demonstrated to have damaging effects on sensitive ecosystems, as well as many man-made materials, buildings, and monuments.

Because of the complex chemical interactions involved, changes in NOx emissions can seldom be translated linearly into changes in specific atmospheric or other environmental conditions. There is widespread consensus, however, that a substantial reduction in NOx emissions would produce significant environmental benefits.

Sources of NOx Emissions

NOx (primarily NO) is formed by the reaction of atmospheric oxygen and nitrogen under high-temperature conditions, such as in an internal combustion engine or other combustion source. NOx emissions in the U.S. in 1988 were equivalent to about 19.8 million tonnes (metric tons) of NO_2 (U.S. EPA, 1990). Of this, 8.1 million (41%) was due to mobile sources. Highway vehicles (passenger cars, trucks, and buses) accounted for 6.1 million of these 8.1 million tonnes -31% of the total inventory. Around 60% of the total for highway vehicles was due to light-duty gasoline vehicles (passenger cars and light trucks), with heavy-duty diesel trucks responsible for nearly all of the remainder. Among non-road vehicles, railway locomotives contributed 0.6 million tonnes (3% of the total inventory), ships and vessels contributed 0.2 million tonnes, and "other" non-road vehicles (mostly farm, construction, and industrial equipment) contributed 1.1 million tonnes (5.6% of the total). Most of the non-mobile source NOx emissions were due to combustion in electric utilities (7.1 million tonnes) and industrial boilers and furnaces (3.7 million tonnes). The latest Western European NOx inventory (for 1980) shows somewhat smaller emissions (totaling 13.3 million tonnes), with a smaller contribution from electric utilities, and with mobile sources accounting for an even larger share of the total at roughly 44%. (Lübkert and de Tilly, 1989).

Neither the U.S. nor the European NOx inventories fully accounts for the contribution of mobile sources to global NOx emissions. Both inventories omit the NOx emissions produced by ships operating in trans-oceanic trade, and by aircraft in long-distance flight (ships entering and leaving harbor, and aircraft takeoff and landing are included in the U.S. inventory, but not the greater emissions due to travel between airports and harbors).

NOx Control Strategies

NOx emissions from mobile sources can be reduced by about 50-80% from the uncontrolled level through appropriate combustion modifications - primarily reducing flame temperature. Even greater control is possible through the use of NOx reduction catalysts - alone or in combination with combustion modifications. However, such controls add expense and complexity, and often affect fuel consumption and power output - thus, they are unlikely to be incorporated into engine designs unless required by regulation.

The combustion modifications and catalytic systems required for NOx emissions control are most conveniently incorporated in new vehicles during the design stage. In some special cases, retrofit application of NOx controls may also be justified. At present, more-or-less stringent NOx emissions standards for passenger cars and light trucks are in force throughout most of the OECD countries. Technology-forcing emissions standards for engines used in heavy-duty vehicles have been in effect for a decade in California, and in the rest of the U.S. since the 1990 model year, but not in any of the other OECD countries. Technology-forcing NOx emissions standards for non-road vehicles such as railway locomotives, ships and boats, farm and construction machinery, and aircraft have not yet been adopted in any OECD nation.

To be effective, NOx emissions standards for new vehicles (and retrofit requirements, where implemented) must be supplemented by a comprehensive enforcement system to ensure that the NOx controls remain effective in actual use. This should include in-use auditing and recall requirements to encourage durable design of emissions controls, and inspection/maintenance and anti-tampering programs to ensure that they remain in place and operational. Other programs to limit and/or redirect vehicular traffic may also be required to meet air-quality goals in specific cases. For maximum emissions reduction, use of alternative transportation fuels and/or power sources (in particular, electricity) may ultimately be required.

2.0 ENVIRONMENTAL IMPACTS OF NOx EMISSIONS

Because of the important role NOx plays in atmospheric chemistry, NOx emissions contribute to a number of environmental problems. These include localized and regional-scale concentrations of ozone, NO_2, and fine particulate matter; regional acid deposition; and global warming due to the "greenhouse" effect.

Urban and regional air pollution

Tropospheric ozone - Ozone, a powerful oxidant, commonly reaches concentrations damaging both to human health and to many plants and materials in cities around the world. In the lower atmosphere, ozone (O_3) is formed primarily through the photochemical reaction of oxides of nitrogen (NOx) with sunlight. The reaction sequence is as follows:

$$NO_2 + sunlight \rightarrow NO + O^* \tag{1}$$

$$O^* + O_2 \rightarrow O_3 \tag{2}$$

The reverse reaction, in which ozone reacts with NO to form NO_2, is also significant:

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (3)$$

In the presence of sunlight, reactions 1, 2, and 3 all proceed rapidly, with a cycle time of a few minutes. Thus, the ozone concentration is always reasonably close to the equilibrium concentration, which is proportional to the ratio of NO_2 to NO in the starting reactants.

$$[O_3] = k\frac{[NO_2]}{[NO]} \quad (4)$$

The equilibrium constant k has a value of .021 parts per million (PPM) (McDonald, 1987), so that an NO_2/NO ratio of about 5 would be required to generate 0.1 PPM ozone. However, the typical NO_2/NO ratio for NOx emissions from combustion sources (the dominant source of NOx in urban areas) is around 0.1. Thus, if ozone formation were dependent on reactions 1-3 alone, the peak concentration could not exceed about .002 PPM, which is much less than the present U.S. ambient air quality standard for ozone of 0.12 PPM averaged over one hour. In order to generate unhealthy levels of ozone, some alternative path for converting NO to NO_2 is required which does not involve the destruction of ozone. This alternative path is provided by hydrocarbons and other volatile organic compounds, through the following reaction sequence:

$$RH + OH \rightarrow R^{*} + H_2O \quad (5)$$

$$R^{*} + O_2 \rightarrow RO_2 \quad (6)$$

$$RO_2 + NO \rightarrow RO + NO_2 \quad (7)$$

where R may be any VOC compound or CO. Thus, the photochemical oxidation of VOCs results in the conversion of NO to NO_2. Both NOx and VOC or CO emissions are necessary for significant ozone concentrations to form.

The relationship between changes in NOx emissions and changes in ozone concentrations is complex. Freshly-emitted NOx from combustion sources is primarily NO. If ozone is already present, the effect of adding more NO will initially be to increase the rate of Reaction 3 (ozone scavenging), thus reducing the ozone concentration near the source. Further away, the effects will depend on the VOC/NOx ratio. For VOC/NOx ratios of ten or greater, ozone production is primarily NOx limited, and adding more NOx will increase ozone concentrations (Whitten, 1983). For VOC/NOx ratios of around eight or less, ozone formation is primarily VOC limited, and small changes in NOx will have little effect. In practice, most jurisdictions facing severe ozone problems have chosen to try to control both HC and NOx, although the relative emphasis to be given to each has frequently been controversial.

In addition to the high concentrations frequently observed in urban areas, ozone also reaches lower, but still damaging, concentrations over wide regions of Europe and Eastern North America. Because of natural VOC emissions from vegetation, ozone concentrations during these regional ozone episodes are primarily NOx-limited (Sillman and Samson, 1990; NAPAP, 1987). As a result of increased NOx emissions from human activities, ozone concentrations over much of Europe and Eastern North America frequently reach levels high enough to impair plant growth. This is suspected to be a major cause of the widespread forest decline which was previously attributed to acid deposition (NAPAP, 1987).

Nitrogen dioxide - In addition to its role in ozone formation, NO_2 is itself a toxic and irritant gas. The distinctive brownish color of NO_2 is largely responsible for the brownish tinge often associated with severe air pollution. Health-based air quality standards for NO_2 have been established by the U.S. EPA and other jurisdictions. Violations of these standards are relatively rare, however, and tend to be associated with extremely high ozone concentrations as well. Los Angeles, California, is the only U.S. region in violation of the U.S. NO_2 standard, and that violation is only marginal. In contrast, the ozone concentration in Los Angeles is frequently more than double the U.S. standard. Mexico City and Santiago, Chile, two other cities with extremely high ozone levels, also experience occasional ambient NO_2 levels in excess of the U.S. NO_2 standard.

Particulate matter - NO_2 in the atmosphere can be further oxidized by ozone or other photochemical oxidants to form nitrate aerosols. These particulate nitrates are significant contributors to the high concentrations of harmful fine particulate matter (PM10) in many heavily polluted cities. In Los Angeles, California, for instance, (where annual average PM10 levels are more than twice the California standard) particulate nitrates make up roughly 25% of the total fine particulate burden (Witz and MacPhee, 1979).

Acid deposition

NOx emitted to the atmosphere is eventually deposited in downwind areas, in the form of nitrate particles ("dry" deposition) or dissolved in rain or snow. Together with sulfur oxides (SOx), which are similarly deposited, these are responsible for severe damage to vulnerable ecosystems due to acidification. The relative importance of acid sulfates and nitrates in overall acid deposition depends on the relative emissions of the two species. In the northeastern U.S. and much of Europe, sulfates are the major contributor to acid deposition. In California, where SOx emissions have been strictly controlled, most acid deposition is due to nitrates formed from NOx. The formation of acid sulfates and nitrates is driven largely by photochemical ozone, so that NOx plays an important indirect, as well as direct role in the deposition process through its effect on regional ozone concentrations.

Nitrate is an essential plant nutrient, and deposited nitrate is thus quickly incorporated into the ecosystem. For this reason, nitrates are considered less damaging, mole-for-mole, than sulfates, and may even be beneficial in some cases. On the other hand, increased or inappropriately-timed fertilization with nitrates is suspected to impair the winter-hardiness of some trees, and may have other disruptive effects.

Global warming

Tropospheric ozone is a significant greenhouse gas, and there is a trend toward increasing ozone concentrations in the global troposphere. This trend is anticipated to contribute contribute about 4% to anticipated greenhouse warming (Ramanathan et al., 1985). NOx emissions from combustion sources are believed to be a significant factor in this increase. Ramanathan suggests that NOx emissions from aircraft may be especially significant in this regard, since - unlike ground-level emissions - they are not rapidly removed from the atmosphere by surface deposition.

3.0 EMISSIONS MEASUREMENT AND TESTING PROCEDURES

NOx emissions from vehicles and other mobile sources are highly variable. In addition to vehicle-to-vehicle differences, differences in operating conditions can cause emissions to change by more than 100%. In order to establish enforceable regulation of these emissions, a consistent and reproducible test procedure is essential. Such procedures have been established for light-duty vehicles and for engines used in heavy-duty vehicles. Test procedures applicable to other types of mobile sources, such as locomotives, industrial equipment, and boats, are being developed as part of the development of emissions regulations for these sources in California. These may be followed by regulations in the remainder of the U.S.

To ensure that such regulations produce a corresponding improvement in in-use vehicle emissions, the test procedure should be representative of in-use conditions, or else severe enough to ensure effective performance under all conditions likely to be encountered in vehicle use. This is not always the case with current test procedures, as is further discussed below.

Light-Duty Vehicles

Presently, two different sets of emissions test procedures for light-duty vehicles are used in the different ECE countries. One set is established in ECE regulation 15, and will be referred to here as the ECE test procedure. This procedure is used in the countries of the European Economic Community, and in the countries of Eastern Europe. The other set was developed by the United States federal government, and is referred to here as the U.S. federal test procedure or FTP. In addition to the U.S., the FTP has been adopted by Canada, Sweden, Switzerland, Finland, Norway, and Austria in the ECE, and by a number of nations outside the ECE.

Both the ECE procedure and the U.S. FTP include exhaust emissions measurements, taken over a prescribed driving cycle on a chassis dynamometer. The two procedures differ in the specific driving cycle used, however - the U.S. procedure being based on driving patterns in an extended urban area, while the ECE procedure simulates driving in congested European central cities. The U.S. FTP procedure is more demanding of the vehicle, with higher accelerations and frequent transient conditions. Finally, the ECE procedure provides for the sum of hydrocarbon (HC) and NOx emissions to be reported (allowing manufacturers some flexibility to trade off between these two pollutants), while the U.S. procedure requires separate reporting of HC and NOx (in line with U.S. regulatory philosophy, which has established separate standards for HC and NOx emissions).

A new test procedure element, the Extra Urban Driving Cycle (CCMC, 1989) has been developed and tested for inclusion in future EEC and ECE emissions regulations. This procedure accounts for the higher vehicle speeds (120 km/hr maximum) outside congested urban centers, and will be combined with the existing EEC and ECE driving cycle in order to give a procedure for exhaust gas measurements which simulates the overall driving pattern in Europe.

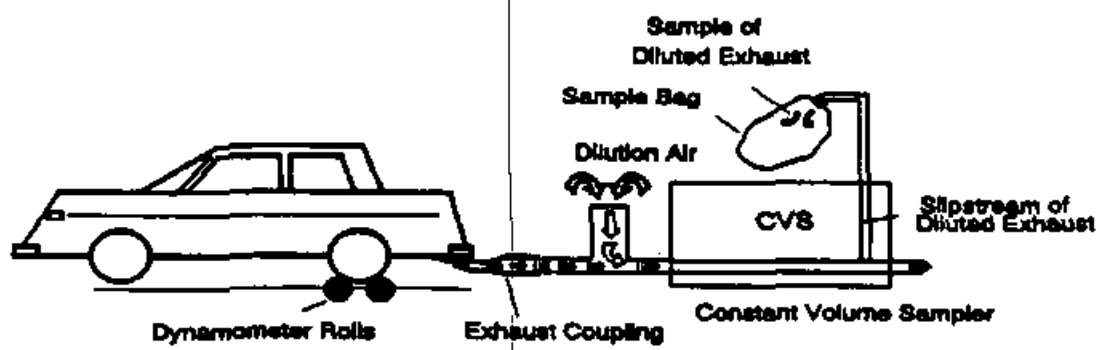

Figure 1: Exhaust Emissions Test Procedure For Light-Duty Vehicles

Because motor vehicle exhaust emissions in urban areas are the principal concern of emission control programs, both the U.S. and ECE test procedures for measuring vehicle emissions are based on vehicle operating patterns in "stop-and-go" driving. For passenger cars and small trucks (<3000 kg gross vehicle weight), the U.S. Federal Test Procedure (FTP) for light-duty vehicles represents urban driving at speeds of 0 to about 90 km/hr with an average speed of about 32 km/hr. The ECE test procedure simulates operation in a more congested urban area, with speeds of 0 to 50 km/hr and an average speed of 19 km/hr. Both procedures are carried out using a chassis dynamometer and constant-volume sampling system, as diagrammed in Figure 1. Speed vs. time traces for both the U.S. and ECE test procedures are illustrated in Figure 2. As the figure shows, the U.S. driving cycle reflects the highly transient nature of actual vehicle operation in an urban environment. The ECE test cycle involves less transient operation, consisting of a set of steady-state conditions linked by uniform changes in speed.

To represent the ambient conditions that exist during periods of high ozone levels, the temperature of the U.S. FTP for light-duty vehicles is controlled to between 20°C and 30°C. At the beginning of the test, the vehicle is started after being parked for a minimum of 12 hours. A sample of exhaust collected in a plastic bag during the first 505 seconds and 5.8 km of the test is used to determine the "cold start" emissions of the vehicle. "Hot stabilized" emissions are collected in a second bag during the next 867 seconds and 6.2 km. The engine is then turned off, and vehicle is allowed to sit for ten minutes with the engine hood closed, and then the engine is restarted. "Hot start" emissions are collected in a third bag during the final 505 seconds and 5.8 km of the test (which is a repeat of the first 505 seconds of the test). At the completion of the test, 17.8 km of driving have been completed. Weighting factors are applied to the emissions contained in each sample bag: 0.43 for bag 1; 1.0 for bag 2; and 0.57 for bag 3. The composite emissions, reported as grams per mile (g/mi), represent urban driving during which 43% of the starts are with a "cold" engine.

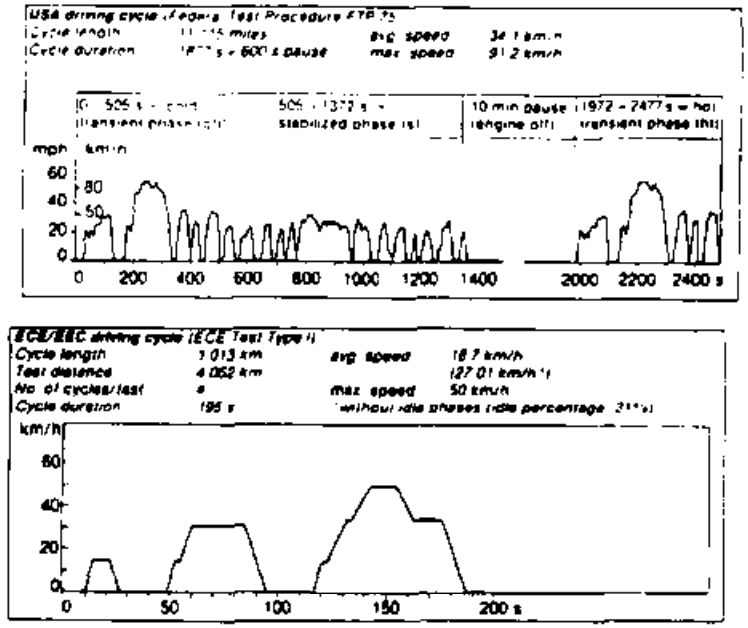

Figure 2: Speed vs. time for U.S. FTP and ECE driving cycles (Source: Robert Bosch AG, 1986).

Neither the U.S. FTP nor the ECE Extra Urban Driving Cycle fully represents operating conditions in high-speed motorway driving, such as may occur on the U.S. interstate highway system or the European Autobahns. This is especially significant for NOx emissions, since these emissions tend to increase markedly under high-speed driving conditions, which are effectively unregulated by these procedures. As a partial answer to this problem, the U.S. also requires vehicles to be tested on a different driving cycle, the Highway Fuel Economy Test (HFET). NOx emissions per mile on the HFET test are required to be less than 150% of the emissions standard based on FTP emissions. However, even this test does not reflect typical speeds on U.S. motorways, which - with the liberalization and widespread non-enforcement of speed limits - frequently exceed 104 km/hr.

There is presently a large body of exhaust emissions data available using the U.S. light-duty test procedure. In order to maintain consistency in the data sources and to take advantage of the large data base using the U.S. test procedure, this report will refer primarily to data based on the U.S. test procedure.

Heavy-duty engines

For engines used in heavy-duty vehicles, there are also two emissions test procedures in use: the U.S. transient test procedure for heavy-duty engines, and the steady-state test procedure established by ECE regulation R 49. Both procedures measure exhaust emissions from the engine alone (removed from the vehicle), operating over a specified cycle on an engine dynamometer. In the case of the U.S. procedure, this operating cycle involves continuous changes in speed and load, in an attempt to mimic the conditions in actual road operation. The ECE procedure consists of emissions measurements in a number of steady-state operating conditions across the engine "map", which are then combined according to a weighting formula. In both cases, emissions are reported in terms of mass of pollutant per unit of work output - thus equalizing between engines of different power ratings.

The official U.S. exhaust emissions test procedure for heavy-duty gasoline and diesel engines involves the use of an engine dynamometer rather than a chassis dynamometer. This allows engines designed for use in a wide variety of vehicles to be tested without using a particular chassis. In this procedure, engine speed and load are continually varied according to a fixed schedule, in order to simulate a typical urban driving pattern. Emissions are measured using a constant volume sampling system. The particular speed-load schedule used is a composite developed from measurement and statistical analysis of actual speed-load histories for a large number of heavy-duty trucks driven in urban areas in the 1970s. The test cycle is repeated twice: once with the engine started cold, and once with it restarted after having been warmed up by the first cycle. Final emissions results are calculated by weighting the cold-start cycle results by 1/7 and the hot-start cycle results by 6/7.

The Transient Test replaced an earlier 13-mode, steady-state emissions test procedure, a variation of which is still used as the basis for European emissions regulations in ECE R 49. The 13-mode test specified in ECE R 49 involves "mapping" the engine emissions by operating at 10, 25, 50, 75, and 100% of maximum torque at two speeds: rated speed for maximum power, and the maximum torque speed. Three periods of idle operation complete the 13 modes. Emissions (in g/hr) and power output (in kw) from each mode are then combined according to a weighting scheme to arrive at a composite value for each. Dividing the composite emission rate by the composite power gives composite emissions in grams per kilowatt-hour.

Non-road vehicles

As mentioned above, emissions test procedures for non-road vehicles have not yet been formally adopted - these are still under development, along with the emissions regulations that will accompany them. Due to the great variety of non-road vehicle types and sizes, it is likely that - when these procedures are adopted - they will be based on pollutant emissions per unit of work output (as in heavy-duty truck engines) rather than emissions per unit of distance travelled (as with light-duty vehicles). Some of the issues involved in establishing emissions test cycles for these applications are discussed in a recent contractor report to the U.S. EPA (Weaver, 1988). Emissions from existing large stationary engines and gas turbines, which are technically similar to engines used in locomotives, boats, ships, and aircraft, are generally measured and regulated either in terms of pollutants per unit of work output, or of pollutant concentration in the exhaust, corrected to a standard oxygen concentration conditions (thus, in effect, limiting pollutant emissions per unit of fuel burned). The latter is less desirable, as it provides no credit for increasing engine efficiency, and therefore reducing the amount of exhaust which must be emitted to perform the same quantity of work.

4.0 NOx EMISSIONS AND CONTROL IN OTTO-CYCLE ENGINES

Emissions, power output, and fuel consumption levels for spark ignition engines are determined by the basic design, level of technology, and calibration of the engine, and by the characteristics of the fuel used. This section reviews the combustion process and pollutant formation mechanisms for Otto-cycle engines, and examines the basic engine-related factors that affect emissions levels and efficiency.

Combustion and NOx Formation in Otto-cycle Engines

Figure 3 diagrams the normal combustion process in an Otto-cycle engine. Following the initial spark, there is an ignition delay while the flame kernel created by the spark grows to significant size. Following that, the flame front spreads through the combustion chamber. The rate of spread is determined by the flame speed, which is a function of the air-fuel ratio, temperature, and turbulence level. The increase in volume of the hot burned gases behind the flame front presses the cooler unburned charge outward. Overall cylinder pressure increases, raising the temperature of the unburned charge through compression heating. Finally, during late combustion the remaining elements of the unburned mixture burn out as the piston descends.

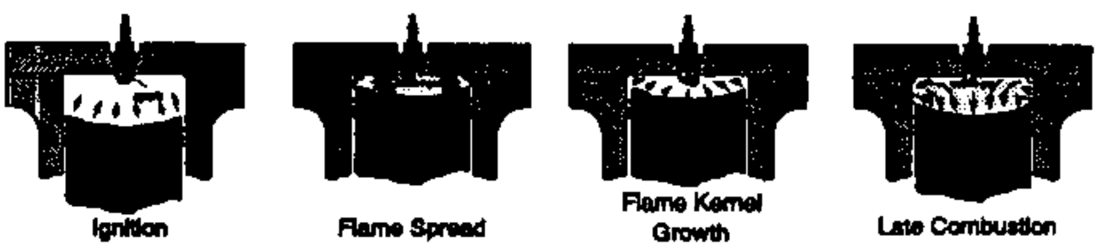

Figure 3: Combustion stages in a spark-ignition engine.

Most NOx from combustion engines is in the form of NO. This gas forms from nitrogen and free oxygen at high temperatures. The rate of NO formation is a function of oxygen availability, and is exponentially dependent on the temperature. Figure 4 shows the experimentally derived relationship between flame temperature, λ, and NO formation rate. Total NO formation is equal to the integral of the NO formation rate over the combustion cycle. Thus, both the flame temperature and the amount of time spent at that temperature are significant in determining NO emissions. Emissions of NO_2 from combustion engines are much less affected by combustion temperature, suggesting that they are formed by another mechanism. However, except at very low NOx levels, NO_2 emissions are generally small compared to those of NO. Thus, overall NOx emissions control is achieved by reducing the flame temperature, and by minimizing the time spent at high temperatures by the burned gases.

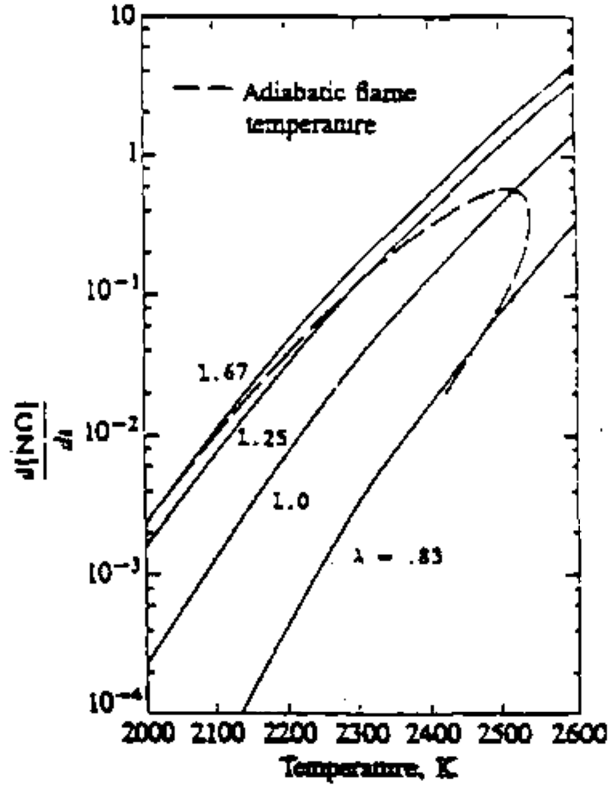

Figure 4: Flame temperature vs. NOx formation rate at various air-fuel ratios (Source: Heywood, 1988).

NOx Control Technology for Otto-Cycle Engines

NOx emissions from Otto-cycle engines can be reduced through changes in the engine design and combustion conditions, and through catalytic aftertreatment. Some of the important engine and combustion variables that affect emissions include the air-fuel ratio λ, ignition timing, the level of turbulence in the combustion chamber, and the amount of exhaust gas recirculation, if any. Through appropriate engine design and control strategies, engine-out NOx emissions can be reduced to relatively low levels, although at some cost in fuel economy and power output. The use of catalytic aftertreatment allows a further reduction in NOx emissions and, by reducing the need for engine-out NOx control, an improvement in power and fuel economy at a given NOx level.

Air-fuel ratio - The ratio of air to fuel in the combustible mixture is a key design parameter for Otto-cycle engines. This ratio is expressed in various ways. In this report, the normalized air-fuel ratio, denoted by λ, is used. An air-fuel mixture in which there is exactly as much air as required to react completely with the fuel is called a stoichiometric mixture, and has a λ of 1.0. Mixtures with a greater amount of air are termed "lean", and have λs greater than 1.0; those with a greater amount of fuel are "rich", and have λs less than 1.0. The equivalence ratio, ε, another commonly used measure, is the inverse of the λ ratio.

The air-fuel ratio has an important effect on engine power output, efficiency, and pollutant emissions. Engines using lean mixtures ($\lambda > 1.0$) tend to have better efficiency than those using stoichiometric mixtures. There are a number of reasons for this, including lower heat losses, the ability to use higher compression ratios (since lean mixtures knock less readily), lower throttling losses at part load, and more favorable thermodynamic properties in the burned gases. Since a lean mixture contains less fuel for the same cylinder volume, however, the maximum work output per stroke is less. This effect can be offset by turbocharging, or by using lean mixtures only under part-load conditions - going to rich or stoichiometric conditions at full throttle.

Figure 5 shows the typical variation of pollutant emissions with λ for a spark-ignition engine. At λs below 1.0, there is too little oxygen to react fully with the fuel, so that CO and HC emissions increase. NOx emissions show a peak in the vicinity of $\lambda = 1.1$, where flame temperatures are high and excess oxygen is available. For leaner mixtures, flame temperature decreases, since the chemical energy from the same amount of fuel must heat a greater mass of gas. Flame speed also decreases as the mixture becomes leaner, and ignition becomes more difficult. As the air-fuel ratio increases, both the average ignition delay and the variability in ignition delay (and thus in combustion timing) increase to unacceptable levels, with an accompanying decrease in fuel efficiency and increase in HC emissions. This is known as the "lean ignition limit". The exact location of the lean ignition limit varies considerably, depending on the ignition system, combustion chamber design and engine rotational speed. However, with ordinary spark ignition systems, this limit is always well below the actual lean flammability limit of the gas.

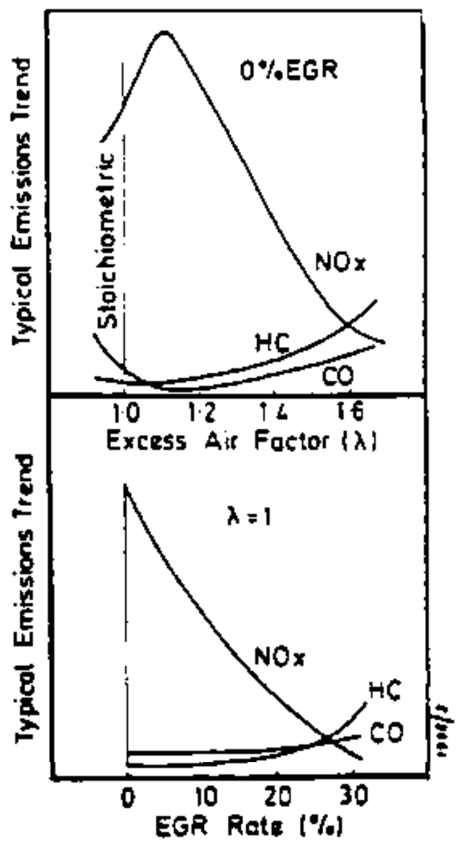

Figure 5: Effect of air-fuel ratio and EGR rate on SI engine emissions (Hundleby, 1989)

Exhaust Gas Recirculation - Dilution of the incoming charge with spent exhaust also affects pollutant formation. In four-stroke engines, this technique is achieved through exhaust gas recirculation (EGR). EGR can also be used in two-strokes, but a more convenient approach is to reduce the scavenging ratio, thus increasing the amount of spent gas retained in the cylinder. The effect of exhaust gas dilution is similar to that of excess combustion air - by diluting the combustion reactants, it reduces flame temperature and flame speed. A given volume of exhaust gas generally has a greater effect on flame speed and NOx emissions than the same quantity of excess air (Heywood, 1988), due to the greater heat capacity of the CO and H_2O contained in the exhaust and the reduced oxygen content of the charge. As with excess combustion air, too much exhaust gas leads to unacceptable variability in combustion and increased HC emissions. The degree of exhaust gas dilution that can be tolerated before this occurs depends on the ignition system, combustion chamber design, and engine speed. In general, ignition systems and combustion chamber designs which improve performance with lean mixtures also improve performance with high levels of exhaust gas dilution.

Combustion timing - The time relationship between the motion of the piston and the combustion of the charge has a major effect on both NOx emissions and engine efficiency. For best efficiency, combustion should be timed so that most of the combustible mixture burns near or slightly after top-dead-center (TDC). Mixture that burns late in the expansion stroke does less work on the piston, decreasing fuel efficiency. Mixture that burns before TDC increases the compression work that must be done by the piston, and thus also decreases efficiency. Since the combustion process takes some time to complete, it is necessary to compromise between these two effects. For any given engine speed and load, therefore, there is an optimimum combustion time - advancing or retarding the timing from this point decreases fuel efficiency. In general, optimum timing usually occurs when half the charge is burned at 10° of crankshaft travel after TDC (Heywood, 1988).

The timing of the combustion process is determined by the timing of the initial spark, the length of the ignition delay, and the rate of flame propagation through the mixture. The flame propagation rate, in turn, is controlled by the geometry and turbulence level in the combustion chamber. Of these, only the timing of the initial spark is subject to control without redesigning the engine. The greater the ignition delay and the slower the flame propagation rate, the earlier (or more advanced) the initial spark must be to maintain optimum combustion timing. For typical gasoline engines, the optimum or MBT (for Maximum Brake Torque) spark advance is usually about 20 to 40° crankshaft rotation before TDC. The MBT spark advance is also a function of engine speed--at higher speeds, a greater angular advance is required, since the ignition delay time remains roughly constant.

The portions of the air-fuel mixture that burn at or before TDC account for a disproportionate part of the NOx emissions, since they remain at high temperature for relatively long periods. To reduce NOx emissions, it is common to retard the ignition timing somewhat from MBT in emission-controlled engines. Excessively retarded ignition timing increases

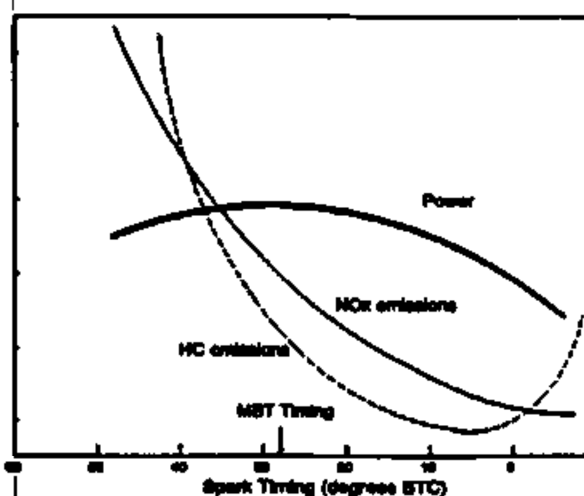

Figure 6: Typical effect of ignition timing on SI engine emissions and power output.

HC emissions, reduces power output, and increases fuel consumption, however. Figure 6 shows the effects of retarding ignition timing on emissions and power output.

With lean mixtures, the ignition delay becomes longer and the flame speed becomes slower, so that the optimal spark timing is further advanced than for a stoichiometric mixture. For this reason, design features to increase flame speeds and reduce combustion time are very important for lean-burn engines. Several combustion systems to achieve these goals have been developed.

<u>"Fast-burn" techniques</u> - To reduce knock and improve efficiency, it is desirable to minimize the time required for combustion. This can be done by designing the combustion chamber to maximize flame speed and burning rate and/or minimize the distance the flame has to travel.

Figure 7 compares typical graphs of the fraction of fuel burned and its derivative, the combustion rate, for conventional and "fast-burn" combustion chambers. In the conventional chamber, the flame spreads radially outward at a relatively slow rate, giving a relatively long combustion time. To avoid having too much fuel burning late in the expansion stroke, it is necessary to advance the timing so that a significant part of the fuel burns before TDC. With the "fast-burn" chamber, the flame spreads rapidly due to turbulent effects, giving a higher combustion rate and shorter combustion duration.

With the shorter combustion time, MBT combustion timing is more retarded than for conventional engine. Since significant combustion does not take place until after TDC, the compression work is reduced, efficiency is increased, and NOx emissions are lower. There is also less fuel burned during the later stages of the expansion stroke, which also contributes to better efficiency. Finally, reducing the combustion time reduces the time available for the remaining unburned mixture to undergo preflame reactions and self-ignite, causing knock. Reducing the tendency to knock allows an increase in compression ratio, further increasing efficiency.

Fast-burn techniques are especially important for engines using lean mixtures. Faster combustion and higher compression ratio allow leaner mixtures to be burned, reducing emissions and further improving efficiency. This is the basis for the so-called "lean-burn/fast-burn" engine. Such engines commonly achieve a 15-20% advantage in fuel consumption compared to stoichiometric en-

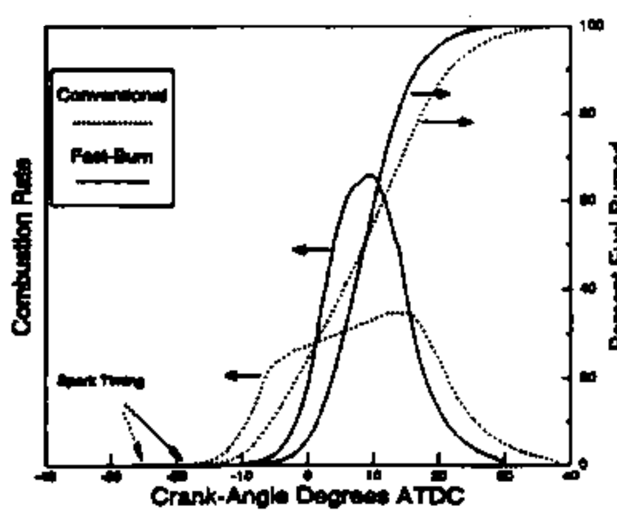

Figure 7: Combustion rate vs. crank angle for conventional and "fast-burn" combustion chambers.

gines. Pre-catalyst emissions of CO and NOx are also substantially lower, but HC emissions from these engines may be increased compared to a conventional stoichiometric engine.

Ignition systems - The type of ignition system used, and especially the amount of energy delivered, have an important effect on the ignition delay and subsequent combustion. For any given flammable mixture, there is a minimum spark energy required for ignition. Both the minimum ignition energy and the ignition delay are lowest for stoichiometric mixtures, and increase greatly as the mixture becomes leaner or more diluted with exhaust gas. The minimum ignition energy also increases with increasing gas velocity past the spark plug. Increasing the spark energy beyond the minimum required for ignition helps to reduce both the average length and the variability of the ignition delay. For good results, lean-burn engines and engines using high EGR rates require much higher-energy ignition systems than are required for conventional stoichiometric engines.

High ignition energies are attained by increasing the spark gap (and thus the breakdown voltage) and by increasing the stored energy available to supply the arc. The former approach is the more effective of the two. To supply the necessary voltages, transistorized coil and distributorless electronic ignition systems are increasingly used. Driven by an electronic computer, these can also provide very flexible control of ignition timing.

For very lean or dilute mixtures, the ignition energies required are extremely high. Two approaches that have been developed for ignition in these cases are plasma jet ignitors and stratified charge combustion systems. In the plasma jet system (Kupe et al., 1987), a very high-energy discharge is created in a small chamber, ionizing the gas within and causing it to shoot out into the combustion chamber as a turbulent jet of plasma. The high electrode wear rates with this system have prevented its practical application, however. In a stratified charge engine, the mixture in the immediate vicinity of the spark is made richer than the rest of the charge, so that ignition and early flame growth occur more quickly and reliably. The flame can then spread quickly to the leaner remainder of the charge. An extreme form of the stratified-charge engine is one having a separate prechamber where ignition occurs. The expansion due to combustion in the prechamber causes the burning gases to shoot into the main chamber through the prechamber orifices in one or more turbulent jets, providing excellent mixing and rapid combustion throughout the main chamber. This gives a substantial improvement in the fuel-economy/NOx tradeoff at a given air-fuel ratio, and allows efficient combustion at very lean air-fuel ratios.

Electronic control systems - Electronic control technology for stoichiometric engines using three-way catalysts has been extensively developed. Nearly all engine emission control systems used in the U.S. since 1981 (and an increasing number used in Europe) incorporate computer control of the air-fuel ratio. These systems rely on feedback of measurements of the actual air-fuel ratio in the exhaust to adjust the air-fuel ratio going into the engine.

The main function of the computer in a feedback emissions control system is to adjust the air-fuel ratio to keep it in the narrow range needed by the three-way catalyst. In addition to the air/fuel ratio, modern computer control systems are also used to control many features that were controlled by vacuum switches or other devices on earlier emission control systems. These include spark timing, exhaust gas recirculation, idle speed, air injection systems, and evaporative canister purging.

The stringent air-fuel ratio requirements for three-way catalyst operation made these systems necessary. However, the increased precision and flexibility of air-fuel ratio control made possible by the electronic system has the potential to reduce emissions even in the absence of a catalytic converter. Many computer control systems also have the ability to "self-diagnose" problems with the engine and control system to some extent. The capability to warn the driver of a malfunction and assist the mechanic in its diagnosis may help to improve the quality of maintenance. Such self-diagnostic capabilities are becoming more sophisticated (and also more important) as the complexity of engine control systems increases. Computer-controlled engine systems are also more resistant to tampering than the older mechanical controls.

Catalytic converters - A useful alternative to controlling emissions within the engine cylinder is to reduce them instead by subsequent treatment of the exhaust gas using a catalytic converter. This allows the combustion process within the cylinder to be optimized (within some limits) for best power and fuel economy, rather than for lowest emissions. The catalytic converter is among the most effective exhaust emissions control devices available. By chemically processing the exhaust to remove pollutants, the catalytic converter makes it possible to achieve much lower emissions levels than are possible with in-cylinder techniques alone. At the same time, by separating the main pollution control process from the engine, it makes it possible to optimize the engine itself for power and/or fuel economy, rather than for minimum emissions. Catalytic converters require lead-free fuel, since lead from the antiknock compounds often used in gasoline forms deposits on the catalytic converter. These deposits "poison" the catalytic converter by blocking the exhaust gases' access to the catalyst. As little as a single tank of leaded gasoline will significantly degrade catalyst efficiency.

Two types of catalytic aftertreatment are commonly used for automotive engines: oxidation or "two-way" catalysts and oxidation/reduction or "three-way" catalysts. Only the latter type is effective for NOx control. Three-way catalyst formulations use a combination of platinum and/or palladium and rhodium. In addition to promoting the oxidation of hydrocarbons and CO, these metals also promote the reduction of NO to nitrogen and oxygen. For the NO reduction to proceed efficiently, an overall rich or stoichiometric air-fuel ratio is required. The efficiency of NOx control drops rapidly as the air-fuel ratio becomes leaner than stoichiometric. If the air-fuel ratio is maintained precisely at or just rich of stoichiometric, a three-way catalyst can simultaneously oxidize HC and CO while reducing NOx. The "window" of air-fuel ratios within which this is possible is very narrow, however, and there is a tradeoff between NOx and HC/CO control even within this window. Figure 8 shows how the efficiency of a typical three-way catalyst varies as a function of air-fuel ratio. To maintain the precise air-fuel ratio required, modern gasoline cars use exhaust λ sensors (also known as oxygen sensors) with computer electronic control systems for feedback control of the air-fuel ratio.

In order to perform their function, the precious metals in the catalytic converter must be supported in intimate contact with the exhaust gas. The most common type of catalyst support is a single piece of ceramic (ceramic monolith) which is extruded to form numerous small parallel channels and then fired. The exhaust gases flow lengthwise through the parallel channels, which provide a very high surface area. Other types of supports include ceramic bead beds and cellular structures of high-temperature metal alloy. The latter are used primarily in situations where mechanical or thermal shock would be likely to damage the relatively brittle ceramics.

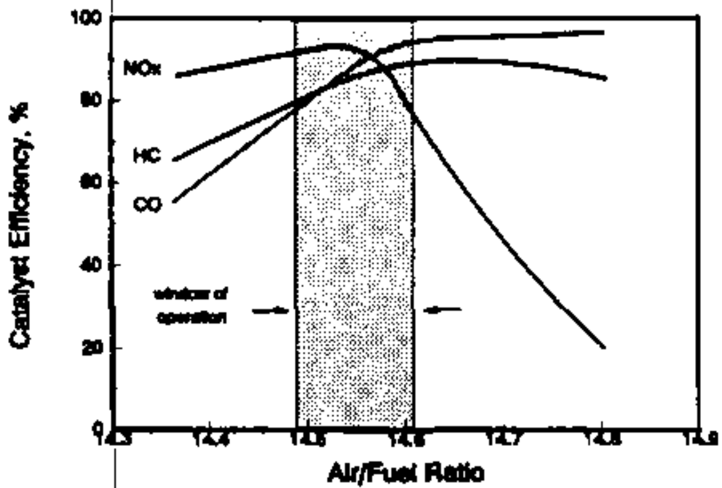

Figure 8: Effect of air-fuel ratio on three-way catalyst efficiency.

The chemical reactions promoted by the catalytic converter take place at the catalyst surface. For economic reasons, a typical catalytic converter contains only a fraction of a gram of the catalytic metals. In order to make efficient use of this expensive material, it is necessary to give it a very high surface area, and to ensure good access by the exhaust gases to the catalyst surface. The most common and damaging maintenance problems with catalytic converters are those which reduce the surface area of catalyst exposed. For example, lead from the fuel and phosphorus from fuel or the engine oil will form deposits in the catalytic converter, blocking the pores and destroying its efficiency. Excessive temperatures can cause the metal crystals to sinder together, losing surface area, or even partially melt the ceramic. This causes a loss of porosity and a drop in conversion efficiency. Such high temperatures are most commonly due to excessive combustible materials and oxygen in the exhaust (due to a misfiring cylinder, for instance). These materials will react in the catalytic converter, and can easily raise its temperature enough to cause permanent damage. Correcting the cause of the misfire will not restore emissions performance unless the catalyst is replaced. This highlights the importance of reliable fuel and ignition systems with catalyst systems.

5.0 NOx EMISSIONS AND CONTROL IN DIESEL ENGINES

In order to discuss the means available for reducing diesel NOx emissions, it is necessary to examine their sources and the engine-related factors that can affect their formation and emission. This section presents background information on diesel combustion and NOx formation, and the effects of different engine technologies on NOx emissions.

Diesel Combustion and NOx Formation

Diesel engine emissions are determined by the combustion process. This process is central to the operation of the diesel engine. As opposed to Otto-cycle engines (which use a more-or-less homogeneous charge) all diesel engines rely on heterogeneous combustion. During the compression stroke, a diesel engine compresses only air. The process of compression heats the air to about 700 to 900°C, which is well above the self-ignition temperature of diesel fuel. Near the top of the compression stroke, liquid fuel is injected into the combustion chamber under tremendous pressure, through a number of small orifices in the tip of the injection nozzle. Figure 9 diagrams the stages of the diesel injection and subsequent combustion process.

As fuel is injected into the combustion chamber just before TDC, the periphery of each jet mixes with the hot compressed air already present. After a brief period known as the ignition delay, this fuel-air mixture ignites. In the *premixed burning* phase, the fuel/air mixture formed during the ignition delay period burns very rapidly, causing a rapid rise in cylinder pressure. The subsequent rate of burning is controlled by the rate of mixing between the remaining fuel and air, with combustion always occurring at the interface between the two. Most of the fuel injected is burned in this *mixing controlled combustion* phase, except under very light loads.

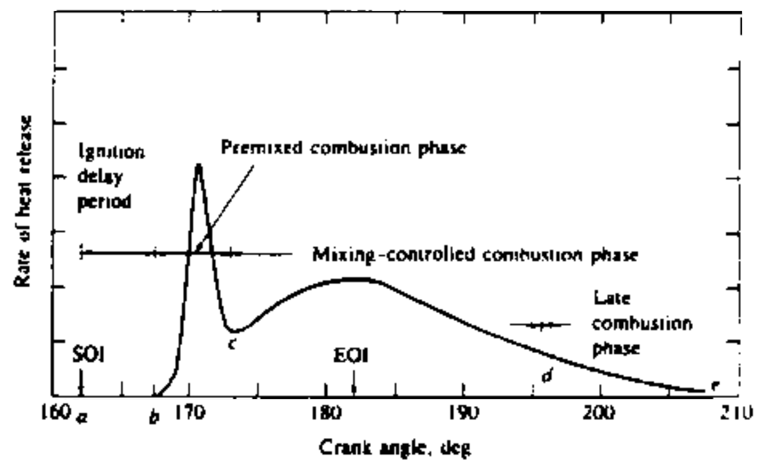

Figure 9: Diesel combustion stages (Heywood, 1988).

In diesel engines, the fact that fuel and air must mix before burning means that a substantial amount of excess air is needed to ensure complete combustion of the fuel within the limited time allowed by the power stroke. Diesel engines, therefore, always operate with overall air-fuel ratios which are considerably lean of stoichiometric (λ greater than one).

The air-fuel ratio in the cylinder during a given combustion cycle is determined by the engine power requirements, which govern the amount of fuel injected. Diesels operate without throttling, so that the amount of air present in the cylinder is essentially independent of power output, (except in turbocharged engines, where the energy in the exhaust gas determines the boost pressure). The minimum air-fuel ratio for complete combustion is about $\lambda = 1.5$. This ratio is known as the smoke limit, since smoke increases dramatically at air-fuel ratios lower than this. The smoke limit establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine.

As with other combustion engines, NOx from diesels consists primarily of NO. This gas forms from nitrogen and free oxygen at high temperatures close to the flame front. The rate of NO formation is a function of oxygen availability, and is exponentially dependent on the flame temperature. In the diffusion burning phase, flame temperature depends only on the heating value of the fuel, the heat capacity of the reaction products and any inert gases present, and the starting temperature of the initial mixture. Flame temperature can be altered by changing the composition of the charge. As Figure 10 shows, this has a direct effect on NOx emissions. In the premixed burning stage, the local fuel-air ratio also affects the flame temperature, but this ratio varies from place to place in the cylinder and is very hard to control.

In diesel engines, most of the NOx emitted is formed early in the combustion process, when the piston is still near top-dead-center (TDC). This is when the temperature and pressure of the charge are greatest. Recent work by several researchers (Wade et al., 1987; Cartellieri and Wachter, 1987) indicates that most NOx is actually formed during the premixed burning phase. It has been found that reducing the amount of fuel burned in this phase can significantly reduce NOx emissions.

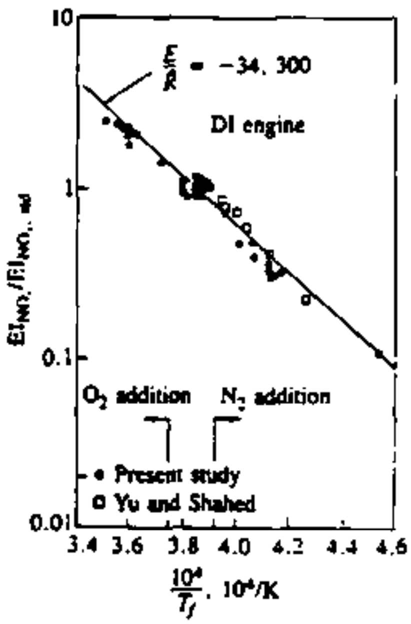

Figure 10: Correlation of NOx emissions with flame temperature (Plee et al, 1983).

NOx can also be reduced by actions which reduce the flame temperature during combustion. These actions include delaying combustion past TDC, cooling the air charge going into the cylinder, reducing the air-fuel mixing rate near TDC, and exhaust gas recirculation (EGR). Since combustion always occurs under locally near-stoichiometric conditions, reducing the flame temperature by "lean-burn" techniques, as in spark-ignition engines, is impractical.

Influence of Engine Variables on Emissions

The engine variables having the greatest effects on diesel NOx emission rates are the rate of air-fuel mixing, fuel injection timing, compression ratio, and the temperature and composition of the charge in the cylinder. Most techniques for in-cylinder NOx emission control involve manipulating one or more of these variables.

Air-fuel mixing - The rate of mixing between the compressed charge in the cylinder and the injected fuel is among the most important factors in determining diesel performance and emissions. During the ignition delay period, the mixing rate determines the amount of fuel that mixes with the air, and is thus available for combustion during the premixed burning phase. The higher the mixing rate, the greater the amount of fuel burning in premixed mode, and the higher the noise and NOx emissions will tend to be.

In the diffusion burning phase, the rate of combustion is limited by the rate at which air and fuel can mix. The more rapid and complete this mixing, the greater the amount of fuel that burns near TDC, the higher the fuel efficiency, and the lower the particulate emissions.

In engine design practice, it is necessary to strike a balance between the rapid and complete mixing required for low soot emissions and best fuel economy, and too-rapid mixing leading to high NOx emissions. The primary factors affecting the mixing rate are the fuel injection pressure, the number and size of injection orifices, any swirling motion imparted to the air as it enters the cylinder during the intake stroke, and air motions generated by combustion chamber geometry during compression. Much of the progress in in-cylinder emissions control over the last decade has come through improved understanding of the interactions between these different variables and emissions, leading to improved designs.

Air-fuel mixing rates in present emission-controlled engines are the product of extensive optimization to assure rapid and complete mixing under nearly all operating conditions. Poor mixing may still occur during "lug-down"--high-torque operation at low engine speeds. Turbocharger boost, air swirl level, and fuel injection pressure are typically poorer in these "off-design" conditions. Maintenance problems such as injector tip deposits can also degrade air-fuel mixing, and result in greatly increased emissions.

Injection timing - The timing relationship between the beginning of fuel injection and the top of the compression stroke has an important effect on diesel engine emissions and fuel economy. For best fuel economy, it is preferable that combustion begin at or somewhat before TDC. Since there is a finite delay between the beginning of injection and the start of combustion, it is necessary to inject the fuel somewhat before this point (generally 5 to 15 degrees of crankshaft rotation before).

Since fuel is injected before the piston reaches TDC, the charge temperature is still increasing as the charge is compressed. The earlier fuel is injected, the cooler the charge will be, and the longer the ignition delay. The longer ignition delay provides more time for air and fuel to mix, increasing the amount of fuel that burns in the premixed combustion phase. In addition, more fuel burning at or just before TDC increases the maximum temperature and pressure attained in the cylinder. Both of these effects tend to increase NOx emissions.

On the other hand, earlier injection timing tends to reduce particulate and light-load HC emissions. Fuel burning in premixed combustion forms little soot, while the soot formed in diffusion combustion near TDC experiences a relatively long period of high temperatures and intense mixing, and is thus mostly oxidized. The end-of-injection timing also has a major effect upon soot emissions - fuel injected more than a few degrees after TDC burns more slowly, and at a lower temperature, so that less of the resulting soot has time to oxidize during the power stroke. For a fixed injection pressure, orifice size, and fuel quantity, the end-of-injection timing is determined by the timing of the beginning of injection.

The result of these effects is that injection timing must compromise between PM emissions and fuel economy on the one hand and noise, NOx emissions, and maximum cylinder pressure on the other. The terms of the compromise can be improved to a considerable extent by increasing injection pressure, which increases mixing and advances the end-of-injection timing. **Another approach under development is split injection, in which a small amount of fuel is injected early in order to ignite the main fuel quantity which is injected near TDC.**

Compared to uncontrolled engines, modern emission-controlled engines generally exhibit moderately retarded timing to reduce NOx, in conjunction with high injection pressures to limit the effects of retarded timing of PM emissions and fuel economy. The response of fuel economy and PM emissions to retarded timing is not linear - up to a point, the effects are relatively small, but beyond that point deterioration is rapid. Great precision in injection timing is necessary - a change of one degree crank angle can have a significant impact on emissions. The optimal injection timing is a complex function of engine design, engine speed and load, and the relative stringency of emissions standards for the different pollutants. To attain the required flexibility and precision of injection timing has posed a major challenge to fuel injection manufacturers.

Initial injection rate and premixed burning - Reducing the amount of fuel burned in the premixed combustion phase can significantly reduce total NOx emissions. This can be achieved by reducing the initial rate of injection, while keeping the subequent rate of injection high to avoid high PM emissions due to late burning. This requires varying the rate of injection during the injection stroke. This represents a difficult design problem for mechanical injections systems, but is possible using electro-hydraulic injectors. Another approach to the same end is split injection, in which a small amount of fuel is injected in a separate event ahead of the main fuel injection period.

Data published by a U.S. manufacturer (Gill, 1988) show a marked beneficial effect from reducing the initial rate of injection. Based on these data, it appears likely that a 30 to 40 percent reduction in NOx emissions could be achieved through this technique, without significant adverse impacts on fuel consumption, HC, or PM emissions. As a side benefit, engine noise and maximum cylinder pressures (for a given power output) are also reduced.

Compression ratio - Diesel engines rely on compression heating to ignite the fuel, so the engine's compression ratio has an important effect on combustion. A higher compression ratio results in a higher temperature for the compressed charge, and thus in a shorter ignition delay and higher flame temperature. The effect of a shorter ignition delay is to reduce NOx emissions, while the higher flame temperature would be expected to increase them. In practice, these two effects nearly cancel, so that changes in compression ratio have little effect on NOx.

Engine fuel economy, cold starting, and maximum cylinder pressures are also affected by the compression ratio. For an idealized diesel cycle, the thermodynamic efficiency is an increasing function of compression ratio. In a real engine, however, the increased thermodynamic efficiency is offset after some point by increasing friction, so that a point of maximum efficiency is reached. With most heavy-duty diesel engine designs, this optimal compression ratio is about 12 to 15. To ensure adequate starting ability under cold conditions, however, most diesel engine designs require a somewhat higher compression ratio--in the range of 15 to 20 or more. Generally, higher-speed engines with smaller cylinders require higher compression ratios for adequate cold starting.

Charge temperature - Reducing the temperature of the air charge going into the cylinder has benefits for both PM and NOx emissions. Reducing the charge temperature directly reduces the flame temperature during combustion, and thus helps to reduce NOx emissions. In addition, the colder air is denser, so that (at the same pressure) a greater mass of air can be contained in the same fixed cylinder volume. This increases the air-fuel ratio in the cylinder and thus helps to reduce soot emissions. By increasing the air available while decreasing piston temperatures, charge-air cooling can also make possible a significant increase in power output. However, excessively cold charge air can reduce the burnout of hydrocarbons, and thus increase light-load HC emission. This can be counteracted by advancing injection timing, or by reducing charge air cooling at light loads.

Charge composition - NOx emissions are heavily dependent on flame temperature. By altering the composition of the air charge to increase its specific heat and the concentration of inert gases, it is possible to decrease the flame temperature significantly. The most common way of accomplishing this is through exhaust gas recirculation (EGR). At moderate loads, EGR has been shown to be capable of reducing NOx emissions by a factor of two or more, with little effect on particulate emissions. Although soot emissions are increased by the reduced oxygen concentration, the soluble organic portion of the particulate and gaseous HC emissions are reduced, due to the higher in-cylinder temperature caused by the hot exhaust gas. EGR cannot be used at high loads, since the displacement of air by exhaust gas would result in an air-fuel ratio below the smoke limit--and thus very high soot and PM emissions.

Emissions Tradeoffs - It is apparent from the foregoing discussion that there is an inherent conflict between some of the most powerful diesel NOx control techniques and particulate emissions. This is the basis for the much-discussed "tradeoff" relationship between diesel NOx and particulate emissions. Figure 11 diagrams this tradeoff for two different levels of diesel technology. As that figure shows, the "tradeoff" is not absolute--a combination of technical advances can lead to reductions in both NOx and particulate emissions. These tradeoffs do place limits on the extent to which any one pollutant can be reduced, however. To minimize emissions of all pollutants simultaneously requires careful optimization of the fuel injection, fuel-air mixing, and combustion processes over the full range of engine operating conditions.

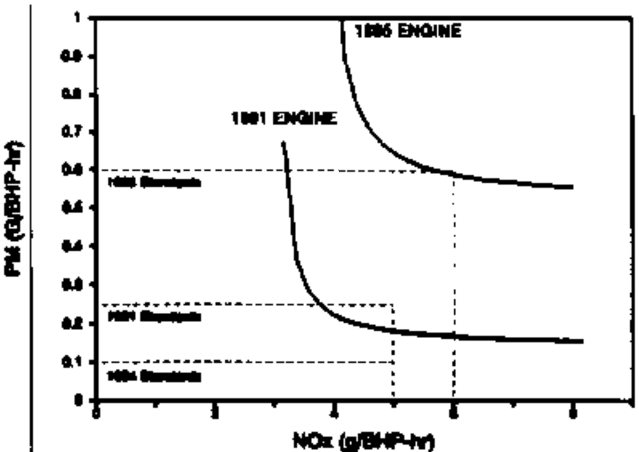

Figure 11: NOx/particulate tradeoff for conventional and advanced diesel engine technologies.

Selective Catalytic Converters - Because they operate with an overall lean air-fuel ratio, diesel engines cannot use three-way catalytic converters for NOx control. An alternative approach for reducing NOx emissions is *selective catalytic reduction* (SCR). Unlike the non-selective catalytic reduction of the three-way catalyst, SCR does not require an overall rich or stoichiometric air-fuel ratio, making it suitable for use with diesel and other lean-burn engines. In this approach, the required chemical reduction potential is supplied by a separate reductant material, such as ammonia or urea. Selective catalytic converter systems based on precious metals, on non-precious metal-oxide catalysts, and on zeolite catalysts are now being offered commercially for stationary diesel engines, although relatively few have been installed to date. The need for a separate reductant supply makes SCR impractical for highway vehicle use, but it could be used on larger mobile sources such as ships and locomotives. At least one SCR system has already been installed on a diesel motorship in California.

6.0 NOx EMISSIONS AND CONTROL IN GAS-TURBINE ENGINES

Gas-turbine engines are used in vehicle applications which require high power-to-weight ratios, and in which the lower fuel-efficiency of the gas-turbine can be tolerated. These include aircraft, some high-speed trains, warships, and some other ships (such as fast ferries) with very high power requirements. Although gas-turbine engines for highway vehicles have been under development for more than 30 years, this effort has not produced a commercially acceptable result - due mostly to the relatively poor efficiency and part-load performance of present gas turbines. Even under optimum operating conditions, the best simple-cycle gas turbines seldom exceed 35% thermal efficiency, whereas slow- and medium-speed diesel engines frequently exceed 50% efficiency in comparable applications. While combined-cycle (gas turbine/steam turbine) systems can reach thermal efficiencies of 70%, their size and complexity would rule them out in mobile applications other than, perhaps, ships; while their lesser tolerance for poor-quality (and thus inexpensive) fuels would rule them out in most marine applications.

From an emissions standpoint, the limited applicability of gas-turbine engines in mobile applications is unfortunate, since these engines are capable of achieving very low emissions levels. Uncontrolled NOx emissions from gas-turbine engines are generally considerably lower than those from uncontrolled diesel or spark-ignition engines, and they can be reduced still further through combustion modifications. The steady-state nature of gas-turbine combustion also helps to minimize emissions of unburned hydrocarbons, carbon monoxide, and particulate matter.

Combustion and NOx Formation

In a gas-turbine (Brayton cycle) engine, combustion occurs continously, rather than intermittently as in diesel and spark-ignition engines. Air is taken in and compressed by a rotary compressor, then a portion of the compressed air is mixed with fuel and burned in a *combustor*. The hot gases from the combustor are then mixed with the remaining compressed air to reduce their temperature before they are expanded through the turbine to produce work. For thermodynamic reasons, it would be desirable to have the temperature of the gases entering the turbine be as high as possible, in order to maximize efficiency. The permissible turbine-entry temperature is limited, however, by temperature capability of the turbine materials.

As in the case of diesel combustion, combustion in the gas-turbine engine requires the mixing of air and fuel which are initially separate, and the combustion rate is normally limited by the rate at which air and fuel can diffuse and mix. For this reasons, the local air-fuel ratio at the flame front is near the stoichiometric ratio, even though the overall air-fuel ratio in the gas-turbine is extremely lean. Under these circumstances, the temperature of the flame and the burned gases is determined by the specific chemical energy of the fuel and the initial temperatures and heat capacities of the reactants. The NOx concentration in the exhaust gases increases exponentially with the temperature of the burned gases, and linearly with the length of time that they remain at that temperature. For typical industrial gas-turbines, full-load NOx concentrations when burning distillate fuel are about 160 PPM in the exhaust gas (corrected to 15% oxygen). This is equivalent to about 12 grams of NOx per kilogram of fuel burned.

NOx Control Technology

NOx emissions from gas-turbine engines can be reduced by changes in the combustion process which reduce the burned-gas temperature and residence time, or by selective catalytic reduction (SCR). NOx control technology for gas-turbine engines has been developing rapidly over the last decade, due to ever-increasing requirements for NOx control in stationary applications. NOx concentrations below 25 PPM in the exhaust gas (corrected to 15% oxygen) have been demonstrated in stationary applications, using combustion modifications such as water injection, steam injection, and dry low-NOx combustion. With the use of combustion modifications plus SCR, NOx concentrations below 9 PPM can be achieved (Schorr, 1989). Catalytic combustion, presently the subject of engineering development, would allow combustion to occur at a temperature only slightly greater than the allowable turbine inlet temperature, thus resulting in very low NOx emissions. Levels as low as 1-5 PPM NOx have been measured in the laboratory (Angello and Lowe, 1989). Because of the cost and complexity of the SCR technique, combustion modifications are by far the preferred approach for stationary engines, with SCR being added only for compliance with the most stringent NOx regulations, such as those in California and Japan. This would be even more the case in mobile applications, where the bulk and weight of the catalytic converter, and the cost and safety hazards of the ammonia supply for the SCR unit would be major drawbacks.

Steam and water injection - These techniques reduce the temperature of the flame and burned gases in the combustor by adding an inert diluent to the reacting mixture. With a water injection flow rate equal to that of the fuel, NOx emissions on distillate can be reduced from about 160 PPM to about 40 PPM (Wilkes, 1989). Water injection also increases the maximum power output of the engine somewhat, since the water vapor adds to the mass of working fluid available to expand through the turbine. Fuel efficiency is reduced, however, due to the loss of the heat of vaporization in the water vapor exhausted from the engine. In stationary applications, this drawback is often overcome by injecting steam (produced by a heat-recovery boiler in the exhaust) rather than liquid water. A greater mass flowrate of steam is required to achieve the same NOx effect.

Because of the large amounts of water required, water injection is probably not a feasible emissions control option for gas turbines used in mobile applications such as aircraft. Since the weight of fuel on board is already a significant penalty to aircraft performance, adding an equivalent weight of water would be impossible. Water injection could conceivably be used during takeoff, however, when NOx emissions tend to be highest, and when the extra power output provided by the water injection would be useful.

Dry low-NOx combustion - Dry low-NOx combustors have recently been developed as an alternative to steam or water injection in stationary gas turbines. By premixing some of the dilution air with the fuel to achieve lean mixture, these combustors are able to achieve a lower flame temperature and lower NOx emissions, just as in the lean-burn Otto cycle engines discussed in Section 3. Unlike diffusion flames, however, they resulting premixed lean flames are relatively sensitive to operating conditions and air-fuel ratio - easily "blowing out" if the air-fuel ratio becomes too lean, or "flashing back" into the mixer if it becomes too rich. Preventing this and achieving stable, efficient combustion under all load conditions has required significant advances in combustor design.

Dry low-NOx combustion chambers used with distillate fuel generally employ a staged combustion approach. The initial combustion stage is extremely rich, so that flame temperatures are low and little oxygen is available for NOx formation. This combustion serves to vaporize and partly react the fuel. The partly-reacted gases are then quenched by injecting large amounts of cold dilution air, which is allowed to mix with the partly reacted fuel. The resulting very lean air-fuel mixture is then reignited in the second combustion stage, where it completes reacting. Since all combustion occurs under either very rich or very lean conditions, overall NOx emissions are considerably reduced. NOx concentrations of 25 PPM or less in the exhaust gas (2 g/kg fuel) have been achieved by this means in stationary industrial gas turbines (Davis, 1989).

7.0 NOx EMISSION FACTORS AND INVENTORIES

Planning for improvements in air quality depends on accurate knowledge of the sources and amounts of pollutant emissions, both now and in the future. For this reason, air-quality planning agencies devote considerable time and resources to the development of accurate *emissions inventories*. These inventories are developed by combining estimates of activity levels (e.g. vehicle-kilometers travelled, liters of fuel consumed) with *emission factors* (expressed e.g. as grams of pollution per vehicle-kilometer travelled or liter of fuel burned). This section summarizes available data on NOx emission factors for different categories of mobile sources, and the role of mobile-source NOx emissions in the overall NOx inventories for the U.S.A. and Europe.

Emission Factors

Estimates of mobile-source pollutant emission factors vary considerably in sophistication and reliability. In the case of light-duty vehicles, extensive testing has been carried out, and sophisticated models have been developed. Despite this effort and sophistication, however, studies using other techniques, such as pollutant concentration measurements in tunnels and at roadsides, continue to suggest that the emission factor models contain significant errors (Gorse, 1990; Pierson et al., 1990). This area remains controversial, and the subject of further investigation. Although the available data suggest that these errors may be much more significant for HC and CO than for NOx, there is nonetheless some question as to the accuracy and reliability even of NOx emission models.

Much less effort has been expended on testing and modeling of heavy-duty vehicle emissions than those from light-duty vehicles, and still less has been expended on non-road vehicles. Thus, emission factor estimates for these vehicles are subject to even greater uncertainty, and should be treated with appropriate caution.

Light-duty vehicles - Emission factors for light-duty vehicles are traditionally expressed as grams of pollutant per vehicle-kilometer travelled, as data on the process rate variable (vehicle-km travelled) are usually available fairly readily. Since vehicle emissions per unit of travel vary considerably depending on speed, temperature, vehicle mix, emission control technologies, and other variables, emission factor models have been developed to deal with these variations in a consistent way. MOBILE4 (U.S. EPA, 1989), the most widely used emission factor model in the U.S., reflects more than a decade of development, and incorporates the results of emissions tests on more than 10,000 vehicles in customer use performed over the last 20 years. In addition to testing under standard conditions, many of these tests have included emissions measurements at other temperatures, with different grades of fuel, and under different driving cycles. Emissions measurements have also been made before and after restorative maintenance on hundreds of vehicles. Based on these tests, EPA analysts have defined relationships between vehicle emissions and average speed, ambient temperature, and other variables. The effects of inadequate maintenance and tampering with emissions controls have also been quantified, and estimates the impact of different inspection/maintenance and anti-tampering programs have been developed.

Table 1 summarizes the MOBILE4 emission factor estimates for light-duty gasoline and diesel passenger cars and light-duty trucks, operating under urban conditions at an average speed of 31.4 km/hr and 24°C (the conditions of the U.S. Federal Test Procedure). Figures 12 and 13 show how the estimated emission factors vary as functions of temperature and of average speed. Estimates for four levels of gasoline-vehicle control technology and two levels of diesel control technology are given (in each case at the midpoint of the vehicle's estimated useful life). The estimated combined NOx emission factors for each vehicle class in the U.S. fleet are also shown for the years 1990 and 2000.

Table 1: NOx emission factors from MOBILE4 for U.S. light-duty vehicles under FTP conditions (24°C and 31.4 km/hr average speed).

	NOx Emissions (g/km)			
	Gasoline Car	Gasoline Lt. Truck	Diesel Car	Diesel Lt. Truck
Uncontrolled	2.14	2.63	1.02	1.45
Timing/EGR	1.59	1.62	0.65	0.76
3-way Catalyst	0.52	1.00	-	-
Advanced 3-Way Catalyst	0.50	0.67	-	-
U.S. Avg. 1990	0.95	1.16	0.90	0.96
U.S. Avg. 2000	0.58	0.74	0.66	0.75

As Figure 12 indicates, the MOBILE4 model projects NOx emissions from gasoline vehicles to increase substantially with decreasing temperature. Since NOx generally increases strongly with charge temperature, this is counter-intuitive. The explanation may lie in the effect of temperature on emission controls, such as EGR, retarded spark ignition timing, and the three-way catalyst. To improve cold drivability, EGR and spark timing controls are normally disabled until the engine reaches operating temperature; and the catalyst is ineffective until it reaches its light-off temperature. Both of these would take longer under cold conditions.

Figure 13 shows the MOBILE4 projections for the effect of changes in average driving cycle speed on NOx emissions. NOx emissions tend to be highest under congested

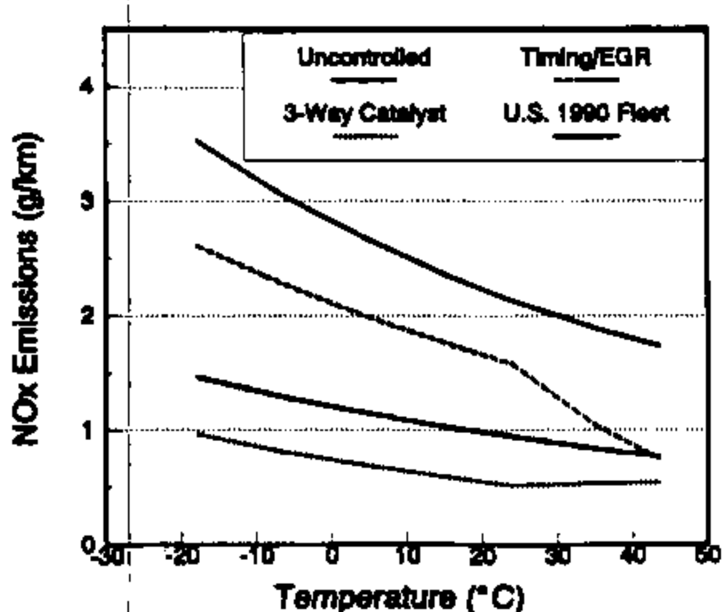

Figure 12: Effect of Temperature on NOx emission from light-duty vehicles.

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For vehicles without NOx controls (those of the 1960s in the U.S.), NOx emissions are estimated at 2.14 g/km on average, at the mid-point of their useful lives. For vehicles equipped with ignition timing adjustments and EGR (those of the 1970s in the U.S), NOx emissions at the midpoint of useful life are estimated at 1.59 g/km. For three-way catalyst equipped vehicles (those of the 1980s in the U.S., NOx emissions at the midpoint of useful life are estimated at 0.5 g/km. NOx emissions for light-duty trucks are somewhat higher, due to their greater average weight and laxer emissions standards. NOx emissions from diesel vehicles are lower than those for gasoline vehicles without three-way catalysts, but not as low as can be achieved with catalytic control.

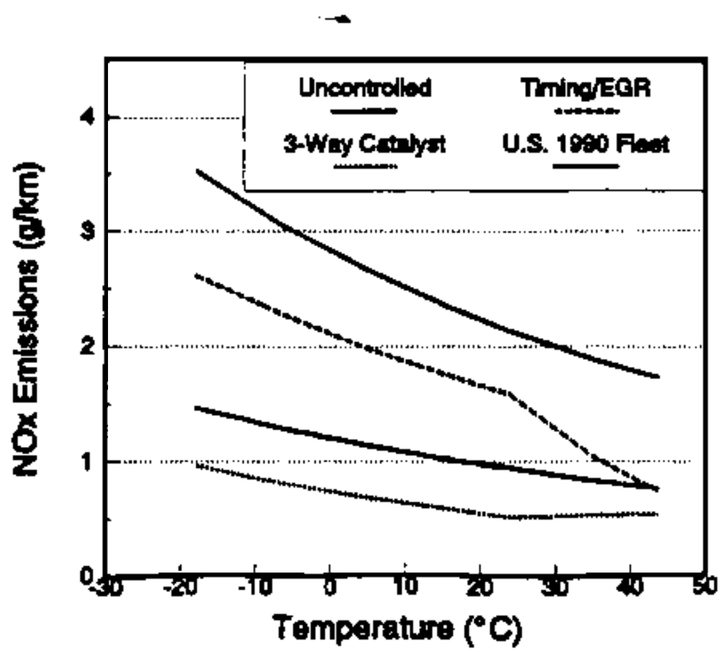

Figure 12: Effect of Temperature on NOx emission from light-duty vehicles.

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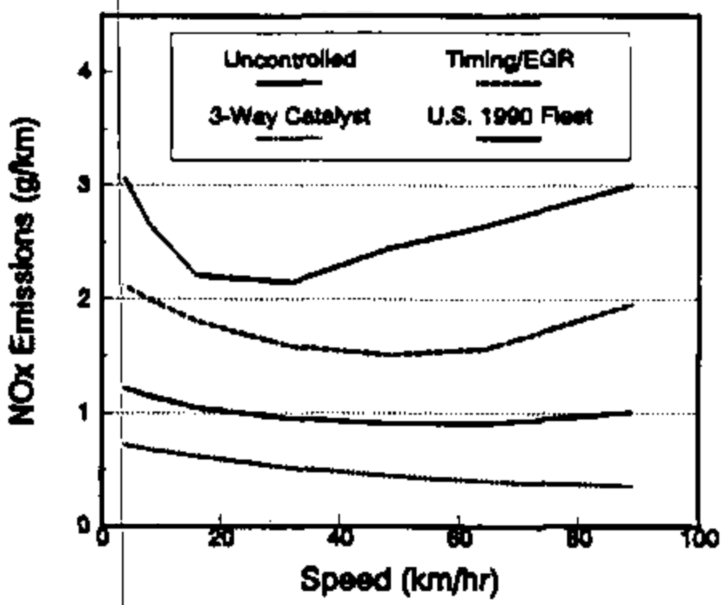


Figure 13: Effect of average speed on NOx emissions from light-duty vehicles.

Figure 13 shows the MOBILE4 projections for the effect of changes in average driving cycle speed on NOx emissions. NOx emissions tend to be highest under congested conditions, when there is much stop-and-go driving and average speeds are low. They also increase under high-speed driving conditions, when load on the engine is greater, and the pressure and temperature in the combustion chamber are correspondingly high. Although the MOBILE4 projections do not extend beyond 90 km/hr, other data show that - under high-speed motorway driving conditions, NOx emissions increase substantially with all emission control technologies (Derwent, 1988).

Figure 14, taken from Derwent's study, shows projected NOx emissions as a function of speed for European vehicles without emission controls, and with lean-burn, open-loop three-way catalyst, and closed-loop three-way catalyst controls, respectively. In comparing the closed-loop, three way catalyst line from this figure with the corresponding line in Figure 13 for

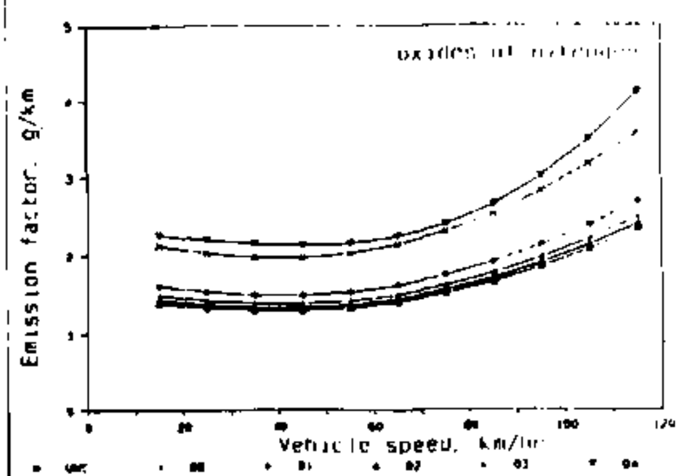


Figure 14: Variation of NOx emissions with speed for European vehicles (Derwent, 1988).

U.S. vehicles, it is apparent that both the NOx emissions at any given speed and the projected rate of increase with speed are considerably higher for the European than the U.S. vehicles. This may be due to the differences in test cycle - as discussed in Section 2, the U.S. test requires effective NOx control in both the urban FTP cycle and the Highway Fuel Economy Test. The European test procedure does not yet include a simulation of motorway operation, so that emissions under high-speed conditions may be effectively uncontrolled.

Table 2: MOBILE4 Emission Factors for heavy-duty vehicles.

	grams/kilometer		grams/kWH		grams/kg fuel	
	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
Uncontrolled	6.2	18.7	9.2	12.6	22	44
Minimal controls	3.5	12.8	8.5	11.3	22	43
3-way Catalyst	2.7	-	6.4	-	17	-
Advanced diesel controls	-	5.0	-	5.3	-	20
U.S. Avg. 1990	3.6	11.6	8.6	10.3	22	40
U.S. Avg. 2000	2.8	5.5	6.6	5.7	17	22

Heavy-duty vehicles - Table 2 shows MOBILE4 projections of NOx emission factors for U.S. heavy-duty gasoline and diesel vehicles with various levels of control technology. These projections are based on the results of engine dynamometer tests (expressed in grams of pollutant per unit of work produced), which are then converted to grams of pollutant per kilometer based on fuel consumption. This conversion is a source of considerable uncertainty, since both fuel consumption and pollutant emissions per kilometer vary considerably (and not necessarily in parallel), depending on vehicle size and weight, and on the driving cycle. Also shown in Table 2 are the approximate equivalents to the MOBILE4 emission factors in grams/kWH and gram/kg fuel. These are frequently more convenient to use than the gram/km values, as heavy-duty emission regulations are expressed in g/kWH, and emission inventories for these vehicles are often based on fuel consumption.

As Table 2 shows, average NOx emissions from heavy-duty vehicles have been reduced significantly, and are projected to decline still further as vehicles meeting the strict NOx standards recently introduced make up an increasing fraction of the fleet. Until very recently, the reduction in NOx emissions per kilometer has been due primarily to a reduction in work required to travel one kilometer, rather than in brake-specific NOx emissions. This is attributable primarily to improvements in fuel economy through aerodynamic and other improvements, and to the use of smaller trucks for many urban applications. With the advent of strict NOx emissions standards in model year 1991, brake-specific NOx and fuel-specific NOx emissions are also projected to be reduced substantially.

NOx emission factors for European vehicles are generally higher than those in the U.S., reflecting the less-stringent NOx standards applicable there. Larssen (1989) has estimated fuel-specific NOx emissions from heavy-duty diesel vehicles at 50 g/kg fuel in urban driving, 55-60 g/kg in rural driving, and 60-70 g/kg in high-speed motorway driving. For heavy-duty gasoline trucks, Larssen estimates 36 g/kg fuel average over all types of driving. In terms of grams of pollutant per kilometer, Derwent (1989) cites studies by Veldt (1986) and Hassel (1983), estimating NOx emissions at 6.27 to 21.33 g/km, depending on vehicle size, with a weighted average of 12.7 g/km. These estimates may be somewhat too high - emissions test data for Chilean buses using European-type diesel engines show average NOx emissions of 5.38 g/km in urban driving (Steiner, 1989), compared to 10.8 g/km projected by Derwent.

Non-road mobile sources - Although mobile sources other than road vehicles account for a significant fraction of total mobile-source NOx emissions, they have received relatively little study compared to passenger cars and heavy-duty trucks. Major sources of NOx emissions among non-road vehicles include farm and construction equipment, railway locomotives, boats, and ships (all primarily equipped with diesel engines) and jet aircraft. Two studies which have examined the available data on emissions from diesel non-road vehicles are those of Weaver (1988) for the U.S. EPA, and Larssen (1989). Table 3 summarizes the results of these studies.

Table 3: Estimated emission factors for diesel engines used in U.S. and European non-road vehicles.

	Weaver (U.S.)		Larssen (Europe)
	g/kWH	g/kg fuel	g/kg fuel
Locomotives	18	74	20
Construction Equipment	12	50	-
Farm Equipment	15	63	50
Boats	16	67	70

The study by Weaver estimated emission factors for diesel engines used in non-road vehicles in the U.S., while Larssen's study estimated those for Europe. However, since emissions from these vehicles are not presently subject to control either in Europe or the U.S., the technology is basically the same, and some U.S. manufacturers build European-designed engines under licence, it is reasonable to expect the emissions from U.S. and European engines to be similar. As Table 3 shows, the estimates agree fairly well for engines used in boats and farm equipment. In the case of locomotives, however, Larssen's number is considerably lower than Weaver's estimate for the U.S., and is also much lower than most other types of uncontrolled diesel engines. Since locomotive engine technology is generally similar on both sides of the Atlantic, and is also very similar to that used in medium-speed marine engines, the lower estimates cited by Larssen appear highly questionable.

Neither the Weaver nor the Larssen studies estimated emission levels for ocean-going ships, as opposed to coastal and inland traffic. Commercial cargo ships are driven primarily by large, slow-speed and medium-speed diesel engines. Other power sources which are occasionally found include steam turbines, and gas turbines (the latter in high power-weight ratio vessels such as fast ferries and warships). The number of vessels equipped with steam or gas-turbine propulsion is small, however, and their NOx emissions are insignificant, since these power sources produce much less NOx per unit of fuel burned than diesels. A number of emissions measurements have recently become available for such engines. Hadler (1990) reports data from which it can be calculated that a 9800 kW engine in a containership, operating at 85% power, produced 87 grams of NOx per kilogram of fuel burned. Melhus (1990), studying engines used in Norwegian coastal vessels, found NOx emissions ranging from 43 to 75 g/kg fuel in four-stroke medium-speed engines, and from 50 to 83 g/kg fuel in (presumably slow-speed) two-stroke engines. Bremnes (1990) used an average value of 70 g/kg fuel, based on earlier measurements by Marintek. Alexandersson (1990) used NOx emission factors of 17.7 g/kWH (94 g/kg fuel) for two-stroke and 14.0 g/kWH (72 g/kg fuel) for four-stroke marine diesel engines (both at 80%) load. Although these measurements vary considerably among themselves, it is apparent that brake-specific and fuel-specific NOx emissions from marine diesel engines are at least comparable to those from other non-road diesels, and much higher than the NOx levels achieved by heavy-duty truck engines in the U.S.

NOx emissions from aircraft are another area which has received relatively little attention. As with other non-road engines, this is doubtless due in part to the absence of applicable emissions regulations. While emission factors have been developed for most commercial aircraft types, these are expressed in terms of emissions per landing and take-off cycle (LTO) - an inconvenient unit for cross comparison. From data in the U.S. EPA's publication AP-42 (U.S. EPA, 1985), it is possible to calculate emissions per kg of fuel burned for a number of engines in use in the early 1980s. These calculations are shown in Table 4 for three engines and several operating modes. As this table shows, fuel-specific NOx emissions from turbofan engines vary considerably, both engine-to-engine and mode-to-mode for the same engine. Under idling and part-load approach conditions, NOx emissions are low, both per kg of fuel burned and in absolute terms.

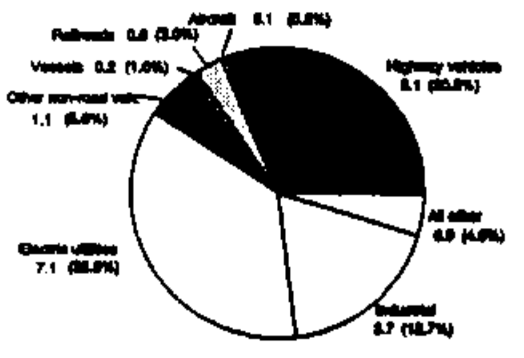
Table 4: NOx emission factors for some common aircraft engines (source: U.S. EPA, 1985).

Engine/ Aircraft	Operating Mode	Fuel (kg/hr)	NOx (kg/hr)	NOx (g/kg fuel)
Pratt & Whitney JT8D-17	Idle	1150	1.77	1.54
	Takeoff	9980	91.90	9.21
	Climbout	7910	55.97	7.08
B-737 DC-9	Approach	2810	8.80	3.13
General Electric CF6-50C2F	Idle	1206	1.37	1.14
	Takeoff	18900	304.3	16.1
	Climbout	15622	209.6	13.4
DC-10	Approach	5280	23.95	4.54
Rolls-Royce RB211-524	Idle	802	2.15	2.68
	Takeoff	8096	299.6	37.0
	Climbout	6662	213.2	32.0
B-747 L-1011	Approach	2472	28.53	11.54

Under high-power takeoff and climbout conditions, however, fuel-specific NOx emissions can reach diesel levels in some engines. Since fuel consumption rates are also very high under these conditions, the absolute NOx emissions can be very large. It should be noted that - due to their age and the large variations in engine emissions levels, the data shown in Table 4 may not be representative of the current generation of engines, much less those which may be used in the future. The widespread use of higher pressure ratios in new engines would be expected to increase NOx emissions per unit of fuel burned, while the increased use of staged combustion and improved engine fuel-efficiency would tend to reduce them.

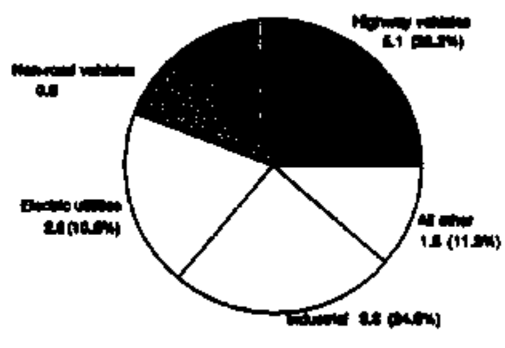
NOx Emissions Inventories

Mobile sources account for a large fraction of total NOx emissions both in the U.S. and in Europe. Figure 15 shows the U.S. NOx emissions inventory (U.S. EPA, 1990), broken down by source type. Mobile sources account for 40.9% of the inventory, with on-road vehicles alone accounting for 30.8%. Figure 16 shows the comparable breakdown of the OECD/MAP inventory for Europe in 1980 (Lübkert and de Tilly, 1989). Mobile sources account for 44% of the European NOx inventory, with on-road vehicles alone accounting for 38.8%. The major differences between the European and U.S. NOx inventories are in the much greater NOx emissions from electric utilities in the U.S., and in the lesser role played by non-road vehicles in Europe. This, in turn, is largely due to smaller NOx emissions from railroads, due to the extensive electrification of the European railway network.



U.S. 1988 NOx Inventory
Total 19.8 million tonnes

Figure 15: Role of mobile sources in the U.S. NOx inventory.



OECD/MAP European Inventory
Total 13.3 million tonnes

Figure 16: Role of mobile sources in the European NOx inventory.

8.0 NOx CONTROL STRATEGIES - METHODS, COSTS, AND BENEFITS

NOx emission control requirements for light-duty vehicles have grown increasingly stringent over the last 25 years, and are likely to continue to do so for at least the next decade. Stringent NOx regulations for heavy-duty vehicle engines have also been in force in California for some time, and came into effect throughout the U.S. in the 1990 model year. Engine emissions control technology, in consequence, has grown ever more sophisticated and expensive, and emissions requirements have come to play a dominant role in overall engine design for highway vehicles. This will likely become the case for engines in non-road vehicles as well, since new regulatory initiatives under way in California are establishing emission regulations for a number of non-road vehicular sources. In addition, the 1990 Clean Air Act amendments adopted at the U.S. federal level require EPA to establish regulations for railroad locomotives within five years, and give it discretion to regulate other non-road vehicles.

The experience of the last decades has also shown the importance of emissions control measures for vehicles in use, as complements to the emissions standards established for new vehicles. An effective *inspection and maintenance* (I/M) program can significantly reduce emissions even from uncontrolled vehicles, and is required to ensure that the anticipated emissions benefits of new-vehicle control technologies are not lost through poor maintenance and/or tampering with emission controls. *Recall programs* are also necessary to obtain the correction of manufacturing and design defects that are discovered on vehicles in customer service. *Retrofit* programs for existing vehicles may be practical in some cases, and may contribute to reduced in-use emissions.

Other, more far-reaching measures for mobile-source emission control may also be required to achieve air-quality targets in some areas. *Transportation control measures* (TCMs) may contribute to improved air quality in specific areas, and some organizations consider them an important element of the emissions control strategy. Changes to vehicle fuel characteristics and/or use of *alternative fuels* may also constitute cost-effective emissions control strategies in some cases.

Light-Duty Vehicles

Because of the large number of vehicles and vehicle-kilometers travelled that they represent, passenger cars and light-duty trucks are responsible for a larger share of total mobile-source NOx emissions than any other vehicle category. For this reason, many jurisdictions have adopted strict limits on NOx emissions from new light-duty vehicles. Efforts to control emissions in customer use are equally important, however, and have been somewhat slower to get under way.

Emissions control strategies for new vehicles - As a result of the continual tightening of emissions regulations, several different levels of emissions control technology have been developed. These can be arranged in ascending order of effectiveness, complexity, and cost. The possible levels of emissions control range from those achievable through simple air-fuel ratio and timing adjustments through standards requiring sophisticated feedback-controlled fuel injection systems with exhaust gas recirculation and three-way catalysts.

It is important to note that the benefits of stringent vehicle emissions standards will be greatly reduced unless they are accompanied by a vigorous and well-planned system of enforcement to ensure that vehicles actually comply with such standards, first when they are manufactured, and second in consumer use. Compliance at the point of manufacture can be confirmed by government enforcement auditing. Compliance in consumer use can be determined only through an in-use emissions surveillance program, as discussed in the section on in-use emissions controls below.

Table 5: NOx emissions control levels for light-duty vehicles.

Control Level	NOx Limit (g/km @ 80,000 km)	Controls Required	Estimated Cost/Veh.
Minimal control	1.9	Ignition timing Air-fuel ratio	$20
First-level control	1.3	Ignition timing EGR	$100
U.S. 1981 standard	.63	3-way catalyst or Advancd lean-burn	$450
California 1990	.25	3-way catalyst Elect. Fuel Inj. EGR	$650
California LEV Std.	.13	Adv. 3-way catalyst Elect. Fuel Inj. EGR (Other technologies?)	>$700

Table 5 summarizes five possible levels of NOx emissions control for light-duty vehicles. These control levels would require emission control technologies ranging from the simple controls used in the U.S. from the early 1970s up to the most sophisticated systems now available. The first level, *minimal controls*, could be achieved by retarding ignition timing and adjusting air-fuel ratios in gasoline vehicles, and would require no change for light-duty diesels. The costs of the resulting modifications would be minimal as well. This control level corresponds to the initial NOx standards established in the U.S. More-stringent *first-level* controls would require a combination of ignition timing, air-fuel ratio, and exhaust-gas recirculation (with an oxidation catalyst probably added to control HC emissions). The cost of the EGR system, electronic timing control unit, and high-energy ignition would be about $100 (U.S. 1990 dollars). These levels could also be met by lean-burn technology, at a similar cost. The next level, corresponding to *U.S. 1981 standards*, is generally met with the use of three-way catalyst technology. In addition to the U.S. itself, many other countries have adopted these emissions standards, and current ECE and EEC regulations require a similar level of control, at least in some vehicles. An open-loop catalytic converter system, with ignition timing and other controls, would cost about $450 (note that some of this cost should be ascribed to HC and CO control, since the catalytic converter would control all three pollutants. Advanced lean-burn engines have also demonstrated the ability to meet these standards in a laboratory environment (Quissek et al., 1988). Diesel passenger cars can meet these standards with the use of exhaust gas recirculation and careful optimization of injection timing.

The fourth level of NOx control, corresponding to the *California 1990* standards, reflects approximately the present state-of-the-art in emissions control for light-duty vehicles. These standards will be phased in for the rest of the U.S. in the mid-1990s. To meet these emission standards while also complying with similarly strict HC and CO regulations requires an effective three-way catalyst, with precise control of the air-fuel ratio through electronic fuel injection with λ feedback. The cost of this system is about $650 (again, some of this cost is ascribable to HC and CO control). The last level, corresponding to the new *California low-emission vehicle (LEV)* requirements, will require still more precise control of air-fuel ratio, heavier catalyst loadings, and better engine-out NOx control, and possibly new technologies or alternative fuels. This standard level, which is to be phased in during the late '90s in California, will pose a significant development challenge for motor vehicle manufacturers. The cost is presently unknown, but likely to be significantly more than $700.

<u>Emissions surveillance and recall</u> - U.S. emissions certification procedures require that emissions control system durability be demonstrated through 80,000 km. of operation in an accelerated test cycle (current California requirements and the new Federal Clean Air Act Amendments extend this period to 160,000 km. for passenger cars and 192,000 for light-duty trucks). Despite this requirement, it is not unusual to find that emission controls have significantly poorer durability in actual customer service. While there is no substitute for actual in-service testing to determine compliance, improvements in in-use emissions control performance could be achieved by improving the durability driving cycle used in vehicle certification to more accurately affect in-use conditions.

To guard against emissions increases due to defective emission controls in customer use, both the U.S. EPA and California Air Resources Board have instituted extensive testing programs for vehicles in consumer use. Several hundred vehicles per year are temporarily procured from consumers for testing. A questionaire and physical examination of the vehicle are also used to determine whether the vehicle has been properly maintained. The vehicles are then adjusted to specifications and tested for emissions.

Average emissions from all properly maintained vehicles of a given make and model tested must comply with the applicable emissions standard within an allowance for statistical uncertainty, otherwise the manufacturer may be ordered to recall the vehicles for repairs or modifications to bring them within the standard. The number of vehicles so recalled in the U.S. varies from year to year but averages about 20 percent of a manufacturers' current production. This means that several million vehicles are recalled each year for emissions reasons.

To avoid the heavy expense and consumer dissatisfaction generated by emissions recalls, manufacturers have been forced to develop far more durable and effective emissions control systems, and to establish internal emissions targets for new vehicles which are well below the legal standards. Although the present U.S. NOx exhaust standard is 0.63

g/km for passenger cars, most manufacturers have calibrated their emission control systems to produce less than half that level during certification testing, to allow sufficient cushion for in-use deterioration. The result has been a significant improvement in vehicle emissions performance in use.

Inspection/maintenance and anti-tampering programs - In order to help assure a reasonable level of emissions-related maintenance and proper functioning of emissions controls, many jurisdictions in the U.S., Japan, many European nations, and an increasing number of developing countries have found it necessary to establish inspection and maintenance (I/M) programs for light-duty cars and trucks. A few jurisdictions have extended these programs to include heavy-duty trucks and/or motorcycles as well. The "inspection" element of the I/M program typically includes a measurement of tailpipe HC and CO concentrations. In some jurisdictions, a visual check of the emission control systems is performed, and some areas conduct a functional check of certain systems, such as the EGR system and ignition timing. Vehicles with malfunctioning or disabled emission controls and/or excessive levels of exhaust pollution must be repaired and retested. (Often, but not always, there is provision for a "cost waiver" - a limit on the amount that the vehicle owner can be required to spend for repairs, except in the case of deliberate tampering.)

The measurement of HC and CO levels as part of the I/M program does little to reduce NOx emissions (indeed, calibration changes to reduce HC and CO can increase NOx with some technologies). However, the functional check and anti-tampering elements of the I/M program can help to reduce excess NOx emissions due to malfunctioning or disabled emission controls. The major problem areas for NOx emissions include EGR valves, ignition timing, three-way catalysts, and air-fuel ratio control. Direct measurement of NOx emissions in the exhaust could give effective control of NOx emissions, but requires that the vehicle be tested under load, since idle NOx emissions are not representative of emissions in other normal operating modes. This I/M program area is currently under active investigation in the U.S.

Inspection and maintenance programs can be classified as either centralized or decentralized. In centralized programs, vehicles are required to be presented at one of a small number of high-volume inspection facilities for inspection. These facilities are government-controlled, and may be run either by government employees or by an independent contractor (the latter arrangement is more common, due to its generally lower costs). In a decentralized program, vehicles may be inspected at any of a large number of private service stations and garages. These inspection stations are generally licensed and authorized by the regional or local government, but are not under its direct control. Because of the greater efficiency and uniformity of inspection, centralized I/M programs are generally considered more effective. They are also better suited for handling retests after repair, and for determining elibibility for cost waivers. Inspection costs also tend to be lower at these facilities, due to economies of scale. These programs are sometimes opposed by the private automotive repair industry, however, which stands to gain customers and revenues from decentralized programs (in the U.S., increasingly complex testing procedures and equipment requirements have blunted some of this opposition, however). Nonetheless, for political reasons, the majority of I/M programs established in the United States have used decentralized inspection. In other nations, centralized inspection programs have been more the norm.

An effective inspection/maintenance program requires each of the following:

- a suitable test procedure, supplemented by inspection of emission control systems where necessary;
- effective enforcement of vehicle compliance (e.g., through the vehicle registration process);
- adequate attention to repair procedures and mechanic training (so that the mechanics are able to diagnose and fix the vehicle after it fails the inspection);
- routine quality control;
- enforcement of program requirements for inspectors and mechanics - especially in decentralized programs - through means such as undercover vehicles containing known defects;
- periodic evaluation and review, to identify problem areas and develop solutions;
- vehicle model year coverage that includes older vehicles; and
- minimization of repair cost waivers and other waivers and exemptions.

To meet these requirements calls for a very well designed program that is well-funded, politically supported, and staffed with technically competent personnel. In some jurisdictions, especially in decentralized programs, it has proven difficult to maintain these elements over the long term, and this has resulted in less effective programs.

On-board diagnostic systems - As vehicle engine and emission control systems have grown more complicated, diagnosis and repair of malfunctioning systems has become more difficult. With present I/M program designs, many emissions-related malfunctions can go undetected in modern vehicles. This is especially true for NOx-related malfunctions, since present I/M programs do not test for NOx emissions. To improve the effectiveness of emissions control diagnosis, California recently adopted second-generation requirements for on-board diagnosis of emissions-related malfunctions (a similar requirement is included in the U.S. Clean Air Act Amendments of 1990, but has not yet been implemented). Under this requirement, the vehicle's computer system is required to detect failures or loss of efficiency in the major emissions-related components and systems, including the catalytic converter, λ sensor, EGR system, evaporative purge system, and all emissions-related sensors and actuators connected to the computer. The system is also required to detect engine misfire (a common cause of catalytic converter failure). When a failure is detected, the system sets internal malfunction codes and lights a special warning light, prompting the driver to have the vehicle repaired. A check of the codes and this warning light is also included in the California I/M program, and the vehicle will not pass if the light is illuminated.

Retrofit programs - Under some circumstances, retrofitting emission controls to existing vehicles may be a practical and cost-effective means of reducing emissions. This approach is most practical where the control measure in question can be implemented without changing the basic engine calibration, as in the case of a catalytic converter. A catalytic converter retrofit program has been underway in the Federal Republic of Germany for several years. This program, driven by tax incentives for vehicle modification, has been characterized as a modest success. A similar program is underway in Sweden, and programs are being considered in Mexico City and Taiwan. On the other hand, a program of engine control retrofits in California in the 1960's, intended to reduce NOx emissions, suffered implementation difficulties, and was abandoned after a few years.

Transportation control measures - Measures to reduce (or, more realistically, limit the growth of) vehicle traffic are considered an important part of vehicle emissions control programs by many agencies in Europe and the U.S. However, the attitude towards these programs can be quite different between countries. Because of these differences, it is useful to present information on both the U.S. and European approach to traffic management.

In the U.S., regulatory agencies have felt that transportation control measures are difficult to justify if undertaken solely for emissions control purposes. In addition, when undertaken solely for emission control purposes, such measures have proven very unpopular politically, and have generally been unsuccessful. U.S. regulatory agencies have calculated that in order to reduce vehicle travel by as much as 20% in any major city would involve a massive program, hundreds of millions of dollars in investment, and probably enormous economic disruption. In contrast, a 20% reduction in emissions per vehicle-kilometer, which would have the same effect on total emissions as a 20% reduction in travel, could be achieved fairly readily and at much lower cost through technical changes and improved maintenance. Thus, while reductions in vehicle emissions may be an important secondary benefit of transportation measures undertaken for other reasons (such as reducing traffic congestion, travel time, and/or travel costs), such measures are generally not considered cost-effective (except perhaps on an emergency basis) on the basis of vehicle emissions alone.

Measures to reduce vehicle traffic have been divided into four groups: coercive measures such as no-drive days, parking prohibitions, etc.; incentives to use other forms of transportation such as mass transit; measures to improve traffic flow; and land-use planning to reduce the amount of travel required by establishing commercial and industrial employment sources closer to residential areas. Coercive measures directed toward the general public are usually very unpopular in the U.S., and difficult to sustain in the face of the resulting political pressure. They also have very poor cost-effectiveness if the full social costs (in wasted time, inconvenience, etc.) are counted in.

Incentives to use mass transit and other forms of collective locomotion (such as car-pooling) do not carry the same high social cost, but they have generally proven to have limited effectiveness in the U.S. Persons who can afford to do so have demonstrated their willingness to pay substantial prices for the convenience of driving their own cars, and no economically feasible subsidy level is likely to overcome this. The enormous costs of (e.g.) fixed-rail transit systems are very difficult to justify on the basis of air pollution control alone.

Measures to improve traffic flow, by reducing congestion (thus increasing average speed), can also reduce vehicle emission factors. These measures tend to be self-limiting, however -- by reducing congestion, they make travel by private vehicles more attractive, and thus tend to increase the number of vehicle trips at the expense of mass transit ridership.

Land-use planning, so that residential areas are closer to areas of significant employment generation, has some potential for limiting growth in transportation requirements in the long run. This potential is limited, however, by the tendency of workers to change employment, the number of multi-worker households, the tendency to choose residence locations based on other criteria, and the fact that heavy industry, in particular, is an unattractive neighbor.

In Europe, measures to limit the growth of vehicle traffic or to reduce it are considered an important part of emissions control programs. For example, if the government were to force NOx control technology on vehicles to attain a reduction of VOC emissions of about 20% in ten years, the government must also assure that this emission reduction is not offset by traffic growth. Traffic management measures in Europe are usually not taken for emission reduction purposes alone, but cover a wide field of achievable aims, such as noise reduction, improving traffic safety, and quality of life, especially in residential areas. Some measures toward achieving these goals are listed below.

i) On an urban/metropolitan level

- Improving the use of metropolitan public transport, such as building new transit lines, improving travel frequencies, establishing lower prices, setting traffic priorities for trams and buses and providing good access to the stations for foot passengers and cyclists. Suburban stations should be equipped with park and ride, as well as bike and ride facilities as appropriate for their particular locations.

- Improving footpaths and cycling paths in metropolitan areas in order to increase the proportion of foot passengers and cyclists in metropolitan transport. Considering that in many European countries about one third of the vehicle trips are shorter than three kilometers, it is obvious that this measure has considerable potential for reducing emissions.

- Car pooling and car sharing may considerably reduce the number of commuter trips.

- Road pricing for urban areas, where taxes can be fixed according to the level of pollution. An existing method is the raising of access taxes to town centers, which tends to be simplified by the improvement of electronic vehicle location devices.

- Motor vehicle bans for certain areas and/or for special times. This is a possibility to reduce the number of vehicle trips. This quite stringent control measure should be used very carefully, and is used mainly for urban areas.

- Lowering the capacity of the street network in urban areas, either by cutting off or narrowing lanes for vehicle traffic or replacing them by bus or cycling lanes or foot passenger zones. This measure should generally be an integral part of a traffic management plan.

- Improving the traffic flow by either coordinating the traffic signals or turning them off in hours with lower traffic or transforming signal controlled intersections into roundabouts. These measures tend to be self-limiting, because they might make travelling by private car more attractive and therefore increase the number of vehicle trips at the expense of foot passengers, cyclists or mass transit ridership.

- Speed limits on main urban streets and in residential areas (e.g. speed limit 30 km/h) may also reduce emissions, as experiences in FRG towns shows.

- Parking control measures or parking restrictions have a direct influence on the number of road trips and therefore also on emissions. This kind of measure should also be part of a transportation management plan.

- Promotion of electrical vehicles, which are acceptable alternatives for metropolitan gasoline powered vehicle traffic.

<u>Heavy-duty vehicles</u>

Although they constitute only a small fraction of the total vehicle fleet in numbers, heavy-duty trucks and buses (primarily diesels) account for roughly 32% of total mobile-source NOx emissions in the U.S. (U.S. EPA, 1990), and 33% in Europe (Larssen, 1989) - the second largest category after light-duty vehicles. Despite their importance, heavy-duty vehicles have only recently been subjected to stringent NOx regulations, and only in few jurisdictions - notably the U.S. and Canada. Under current emissions regulations in the ECE and most other OECD members, NOx emissions standards for heavy-duty engines are high relative to the potentially low levels to which heavy-duty engines could be controlled.

The most effective measure to reduce NOx emissions from heavy-duty vehicles would be the adoption of stricter emissions standards for new vehicle engines. Emission reductions of 50-70% from uncontrolled levels are possible through with existing diesel engine technology. Still greater reductions have been shown to be achieveable with a switch to alternative fuels such as methanol, natural gas, or gasoline. Improvements in diesel fuel cetane quality have also been demonstrated to give NOx reductions. In addition to emission standards for engines used in new vehicles, modifications to existing engines may also be appropriate under some circumstances. These should be complemented by by in-use measures such as in-use emissions auditing and recall, inspection/maintenance, and control of engine rebuilding practices to ensure that emission controls are not lost when the engine is rebuilt. Transportation control measures, such as shifting road freight to rail or ship transport, may also contribute to reducing overall NOx emissions.

New-engine emissions standards - NOx emissions standards for heavy-duty vehicle engines are concerned primarily with diesel engines, since these are responsible for the bulk of the NOx emissions. These are also where NOx control is most difficult - gasoline engines equipped with three-way catalysts can readily meet any feasible diesel NOx standard. A recent study (Weaver, 1990) prepared for the OECD examined the levels of diesel emissions control achievable from heavy-duty diesel engines, as well as the costs of achieving these levels. Table 6 lists a number of potential diesel emissions control levels, based on that study and on recent technical and legislative developments in the U.S.

Uncontrolled NOx emissions from heavy-duty diesel engines are typically in the range of 12-21 g/kWH, when measured using either the U.S. transient or European 13-mode cycle. By moderately retarding fuel injection timing from the optimal point, this can be reduced to less than 11 g/kWH (in some inexpensive engines, this may require an upgrade in fuel-injection equipment). This *minimal control* level is comparable to that required of California engines in the 1970s, and European engines under current ECE regulations. The next, *moderate control* level at about 8 g/kWH requires further optimization of injection timing, and additional work to optimize the overall combustion system. This is the level of California emissions standards from 1977 to 1990, and of U.S. Federal emissions standards beginning in 1990. The next level of control corresponds to the *U.S. 1991* emissions standards, which have also been adopted in California and in Canada. To achieve this level of NOx control, while simultaneously meeting strict particulate emissions standards, most manufacturers have had to carry out introduce major modifications in engine design. These have included extensive use of variable fuel injection timing, increased fuel injection pressure, low-temperature charge-air cooling, and extensive combustion optimization. Engines meeting these emissions standards are only just beginning to come into widespread use.

Further reductions beyond the 1991 emissions standards are also being contemplated. California has adopted a "low emission vehicle" requirement for diesel engines used in "light-heavy" diesel vehicles of 4.7 g/kWH (3.5 g/BHP-hr) *combined* NOx plus non-methane hydrocarbons, effective in 1998. A corresponding requirement for "ultra-low emission vehicles" (ULEVs) of 3.35 g/kWH (2.5 g/BHP-hr) NOx plus NMHC has also

Table 6: NOx emissions control levels for heavy-duty vehicle engines.

Control Level	NOx Limit (g/kWH)	Controls Required	Estimated Cost/Engine
Uncontrolled	12-21	None	$0
Minimal control	11.0	Injection timing	$0-200
Moderate control	8.0	Injection timing Combustion opt.	$0-1500
U.S. 1991 standard	6.7	Variable inj. timing High-pressure FI Combustion opt. Charge-air cooling	$600-2000
Lowest diesel standards under consideration	4.5.-5.5	Elect. fuel inj. Charge-air cooling Combustion opt. EGR	$1000-2500
Alternative fuel forcing	2.7	Gasoline/3-way cat. Natural gas lean-burn Natural gas/3-way cat. Methanol-diesel	$0-5,000

been adopted, and the State is preparing to undertake a major rulemaking with respect to heavier vehicle engines in 1991. The Clean Air Act Amendments adopted in 1990 by the U.S. require a further reduction in Federal NOx emissions standards for all heavy-duty truck and bus engines to 5.4 g/kWH (4.0 g/BHP-hr) in 1998, and establish special standards for heavy-duty engines used in "clean fuel" vehicles of 4.22 g/kWH (3.15 g/BHP-hr) combined NOx plus NMHC. The latter standard is waivable up to 5.9 g/kWH if EPA determines that the stricter standard cannot be met using "clean" diesel fuel.

The ultra-low NOx standards recently adopted by California and the U.S. would have been out of the question for diesel engines until very recently. With recent developments in fuel injection rate-shaping, however, and the potential use of exhaust gas recirculation (EGR), achievement of NOx emission levels in the vicinity of 4.5-5.0 g/kWH - while at the same time limiting particulate emissions to very low levels - may now be feasible, given sufficient development time. At least one diesel manufacturer has expressed optimism about the potential for meeting California's LEV standard by these means, and recent test data (Needham et al., 1990) using injection rate shaping without EGR show emissions of 4.45 g/kWH NOx and 0.25 g/kWH particulate matter on the U.S. transient test. In addition, no dependence of particulate emissions on NOx was found in this engine at that NOx level. With the use of selective EGR (Narusawa et al.; 1990) and further optimization, even lower NOx levels may be possible in the future. While translating these research results into marketable engines will take time, it may be feasible to do so by the end of the 1990s.

Still further reductions in NOx are possible by changing to alternative fuels. Pre-production methanol direct-injection engines using glow-plug assisted compression-ignition have demonstrated NOx emission levels below 2.9 g/kWH, with efficiency comparable to that of a regulated diesel engine. Heavy-duty lean-burn natural gas engines have also achieved NOx levels below 2.5 g/kWH, with energy efficiencies about 10% worse than the diesel. Spark-ignition engines using natural gas, LPG, and gasoline with three-way catalysts, stoichiometric air-fuel ratios, and closed-loop control have achieved NOx emission levels below 1.5 g/kWH at low mileage, and acceptable catalyst durability has been demonstrated in a few cases (Weaver, 1989).

Emissions surveillance and recall - As with light-duty vehicles, surveillance of in-use emissions performance in use, with the threat of recall for engine models found not be meeting the standards, is an important adjunct to new-vehicle emissions control. This surveillance is much more expensive and difficult for heavy-duty vehicles, however, due to the high cost of the vehicles and engines, and the fact that the engine must be removed from the vehicle for emissions testing. To date, only a few limited studies of in-use emissions performance have been carried out using this approach, and no effective in-use surveillance program is presently in operation. Plans to address this problem are presently under way in California and at the U.S. federal level, however.

Inspection/maintenance - Unlike gasoline engines, NOx control in heavy-duty diesel engines is primarily a matter of basic combustion system design, which does not deteriorate with mileage, and does not lend itself easily to tampering. Thus, inspection/maintenance of heavy-duty vehicles would not be indicated for NOx control purposes alone at the present time. This may change with the advent of ultra-low NOx standards, which will likely lead to the widespread use of exhaust-gas recirculation in diesel engines. Inspection/maintenance of heavy-duty gasoline and alternative fuel engines would also be indicated, as NOx emissions from these engines are much more sensitive to maintenance and tampering than those from diesels.

Retrofit programs - Since strict NOx standards for new heavy-duty engines have been adopted only recently - and not at all in most OECD nations - the great majority of engines already in service are effectively uncontrolled. To improve air-quality in the short term, it may be desirable in some cases to retrofit these engines for lower NOx emissions. By retarding fuel injection timing - a simple procedure with most engine designes - NOx emissions can be reduced by 20-30% from uncontrolled levels without markedly increasing particulate emissions. Further reductions in both NOx and particulate could be achieved by upgrading engine technology at the time of major overhauls. Given that the overhaul is required in any event, the incremental cost of upgrading technology is relatively small, and the emission reductions could be significant.

A successful retrofit requires considerable care and engineering development work. Proper design, prototype testing (including emissions testing), and manufacturing are required. Due to the expense involved in development, retrofits will generally be cost-effective only where a large number of vehicles of similar type and design are available for retrofit. Examples include transit bus fleets, garbage collection fleets, urban delivery fleets, etc. The highest priority for retrofit programs should probably go to transit buses and to other vehicles operating in congested urban areas, especially those with high-emission stop-and-go driving cycles. Such programs could best be undertaken, at least initially, on a voluntary or quasi-voluntary basis. Because of this, government-owned vehicle fleets are especially suitable.

Diesel fuel modifications - A number of recent research programs have addressed the effects of changes in diesel fuel properties and composition on pollutant emissions. One conclusion reached by these studies has been that diesel fuel cetane number and aromatic content (which is closely linked to cetane number) affect both NOx and particulate emissions (Ullman, 1989; Ullman et al., 1990; Wachter, 1990; Kraus, 1990). Increasing cetane number (whether by reducing aromatics or by use of cetane-improving additives) reduces NOx emissions, but the effect is greater when the increase comes from changes in aromatic content than from additives. Emissions of particulate matter, hydrocarbons, and noise are also reduced. The changes in NOx emissions are small (of the order of 5% for feasible changes in fuel properties), but may still be worth pursuing in some cases.

Transportation control measures - The scope for limiting heavy-duty vehicles emissions through transportation control measures is limited. Trucks are an essential component of urban commerce, and there is no obvious transportation mode available to replace them. The high costs of truck operation have already prodded most truck operators to eliminate unnecessary trips, and to use the smallest vehicle that can do the job effectively. The situation for buses is much the same--indeed, many programs to control light-duty vehicle traffic are likely to increase, not decrease, the use of transit buses. Replacement of buses with electric rail vehicles or trolley buses is seldom cost-effective. Where emission reductions beyond those achievable with diesel engines are required, alternative fuel vehicles using compressed natural gas or methanol are likely to prove a more economic alternative than electric traction.

Changes in traffic patterns to improve the flow of traffic, and reduce time and fuel-consuming stop-and-go operation have some potential for heavy-duty diesel emission reductions. For buses, establishment of special priority bus lanes, limitations on private car access to congested areas, and other traffic improvements have often proven very effective in reducing traffic congestion and delays (World Bank, 1986). By reducing stop-and-start operations as well as congestion, these measures can help considerably in reducing emissions as well.

In the case of heavy-duty trucks, regulations prohibiting operation during peak traffic hours could possibly be justified. Such regulations are now under consideration in Los Angeles. A requirement that truck deliveries to the most congested city areas be made only at night could also prove effective. A similar requirement has been in effect in New York for some time.

Changes in transportation patterns that reduce diesel fuel consumption are also likely to reduce emissions.. Since one large truck uses less fuel (and emits less) than two small ones, governments may wish to review truck size and weight regulations to assure that they are actually justified. Changing to alternative transport modes (such as piggyback rail service instead of long-distance trucking) may help to reduce the regional impacts of diesel emissions. By concentrating trucking activity around one central point, however, such measures may significantly increase the local emissions impact.

Mobile equipment

Mobile equipment such as farm tractors, other agricultural machinery, construction and earthmoving machinery, and industrial forklifts contributes significantly to urban and regional-level NOx inventories. These vehicles are powered almost exclusively by heavy-duty diesel engines, and (except for some machines used indoors or in underground mines) are not presently subject to emission control regulations. By imposing emission controls on these engines, it would be possible to reduce NOx emissions significantly. Since diesel NOx controls tend to exhibit diminishing returns, the cost of a given reduction in NOx emissions from these vehicles should be much less than for further controls on NOx emissions from on-highway vehicles.

Most of the engines used in mobile farm, construction, and industrial equipment are similar to engines used in heavy-duty diesel trucks. In many cases, on- and off- highway engines use the same block, pistons, fuel injection system, and other components - differing only in calibration and turbocharger matching. Even where this is not the case, the basic engine technology used is closely similar, so that many elements of the emissions control technology is readily transferable. The off-highway environment does pose certain constraints, however - due to the adverse environmental conditions experienced by many of these vehicles, air-to-air charge cooling (an important NOx control technique) may not be feasible in some cases. Off-highway environmental conditions and the constraints these pose will have to be further studied to determine whether off-highway engines used in mobile equipment can attain NOx levels as low those achieved by highway trucks.

In a study for the U.S. EPA (Weaver, 1988), it was estimated that NOx emissions from farm and construction equipment could be reduced from present levels of around 12-14 g/kWH to a maximum of 11 g/kWH through the the application of emissions control technology comparable to the "moderate" level discussed above for highway trucks. The application of advanced technology comparable to that required for U.S. 1991 emission regulations) could further reduce NOx emissions to approximately 8 g/kWH. Still further reductions may be possible through the use of advanced diesel control techniques, or with alternative fuels. In a workshop last year, California Air Resources Board staff proposed interim 1995 NOx emissions standards of 6.7 g/kWH for farm and construction equipment engines, with an ultimate 1999 level of 2.7 g/kWH. (The latter proposal was based on the use of alternative fuels).

Before emissions standards for farm, construction, and industrial equipment can go into effect, it will be necessary to resolve many regulatory and testing issues, such as the appropriate test cycle, durability requirements, in-use surveillance, and so forth. These issues are now being addressed in California, and will probably be taken up by the U.S. EPA as well in the near future. The issue of how emissions standards should be phased in also needs to be addressed. In most mobile equipment, the engine is an integral part of the design, and any major changes in configuration would require redesign of the machine. Thus, it may be best to phase in stringent standards gradually, to allow this redesign to take place as part of normal design updating.

<u>Controlling emissions from existing equipment</u> - In addition to setting emissions standards for engines in new mobile equipment, efforts to control emissions from existing equipment may also be worthwhile. Such efforts could include inspection/maintenance programs to assure proper emissions control in-use, retrofit programs (either simple injection timing retardation or more extensive retrofits undertaken during engine overhaul). Retrofits may be especially appropriate for mobile equipment, due to the high cost of replacement units and the relatively slow turnover. Operational changes to minimize the use of equipment (e.g. through reduced-tillage farming) could also provide NOx benefits, as well as savings in fuel consumption.

Railway locomotives

Railway locomotives are presently the largest category of uncontrolled NOx sources in the United States, accounting for about 3% of the total NOx inventory. A number of studies (Weaver, 1988; Storment et al., 1974; SBAPCD, 1987) have shown that NOx emissions from locomotive engines can be reduced substantially, through the same basic emissions control technology used for heavy-duty truck engines. In addition to new locomotives, emission controls could also be applied to the existing locomotive stock, due to the manufacturer's practice of providing upgrade kits to bring even very old locomotive engines up to current technology. Operational changes such as shutting locomotives down when not in use and optimization of inter-modal transfers could also yield significant emissions benefits. Electrification of heavily-used mainlines (as already extensively practiced in Europe) could substantially reduce total railway emissions, as could a switch to alternative fuels such as natural gas.

<u>New-engine emissions standards</u> - Weaver (1988), in a study for the U.S. EPA, estimated that locomotive NOx emissions could be reduced from the current 14-20 g/kWH to 8 g/kWH with the use of technology similar to the "moderate" technology discussed above for on-highway diesel engines. A further reduction to 6.7 g/kWH or lower would be possible with the use of technology like that used in truck engines to meet U.S. 1991 emissions standards. Much of the technology required to meet such standards has already been developed by the engine manufacturers, in order to comply with strict emissions limits placed on the same engines in stationary generating applications. Since a locomotive is essentially an electric generator on wheels, the same technology could be applied.

Further reductions in diesel locomotive NOx emissions could become feasible with the application of the advanced emission control techniques now being developed for on-highway diesel engines. Selective catalytic reduction (already applied to some stationary diesels and at least one ship engine) is also a possibility for achieving very low levels of NOx emissions.

Retrofit and in-use emission controls - Locomotives have extremely long useful lives, and the rate of turnover in the locomotive fleet is slow. To achieve reasonable emissions control in other than the very long term, therefore, it would be necessary to apply emissions regulations to existing locomotives, as well as new production. This would be facilitated by the locomotive manufacturer's existing practice of making available retrofit kits incorporating the latest technology, so that old engines can be brought up to current performance. To minimize the resulting costs, these regulations could be structured to require incorporation of emissions control technology at the time of engine overhaul, when many elements of the combustion system are replaced in any event.

Continuing emissions compliance by locomotive engines should be ensured through occasional emissions testing, as part of an audit procedure. The techniques used for this testing could be adapted from those used in source testing of stationary sources. Because of the diesel-electric drive system, each locomotive comes very conveniently equipped with its own dynamometer, and it is only necessary to channel the generator output to a resistor bank rather than the drive motors to test the engine under any loading condition achieved in service.

Alternative fuels and power sources - In highly polluted areas, the use of alternative fuels could also yield major emissions benefits. Lean-burn natural gas engines based on diesel locomotive engine designs (and sharing the same structure and dimensions) are used extensively for pumping and electric generation in stationary applications. These engines now routinely achieve NOx emission levels below 2.0 g/kWH (many are less than 1 g/kWH), and (having originally been derived from locomotive diesels) could readily be substituted for them. At least one U.S. railroad is already experimenting with liquified natural gas fuel for reasons of economy and security of supply; incorporation of emission-optimized natural gas engines could lead to significant environmental benefits as well.

Locomotive emissions can be completely eliminated through electrification of rail lines, where traffic density is high enough to make this economically feasible. Substituting electric locomotives supplied by overhead wires for diesel-electrics also helps to reduce operating costs and improve efficiency, and this approach has been extensively implemented throughout much of Europe. To date, however, the high capital costs of electrification prevented its use in most North American railways. The cost-effectiveness of this approach depends heavily on the traffic level of the line involved, and complete electrification of all railway lines may never be economically feasible.

Ships and boats

Except for small pleasure craft, ships and boats are powered mostly by diesel engines. Craft such as fishing boats and those of similar size generally use small high-speed diesel engines derived from on-highway truck engines. Larger vessels such as tugboats, offshore-oil supply boats, and icebreakers are propelled by medium-speed diesel engines similar to those used in locomotives. Engines used in ocean-going ships may also be medium-speed types, but the majority are very large, slow-speed, two-stroke diesels which can be directly coupled to the propeller shaft. These engines (which may have a cylinder bores more than a meter in diameter, with a 5-meter stroke) are among the most efficient heat-engines known, with typical thermal efficiencies around 55%, and are capable of burning extremely low-quality (and thus low-cost) fuels. Because of their high efficiency, they have largely displaced the older steam-turbine and steam-reciprocating engines from the world's trade.

In addition to main propulsion engines, most ships and boats also carry smaller diesel engines for electric generation. These engines may also contribute significantly to total NOx emissions, especially in urban areas, since - unlike the main engines - they usually continue to run while the vessel is in port.

A variety of measures are available to help reduce NOx and other emissions from ships and other vessels. Appropriate emissions standards for new engines would eventually result in significant emission reductions as new vessels are phased into the fleet. Retrofit requirements for existing engines (retarding injection timing, or more extensive modifications performed at engine overhaul) could help to accelerate this emissions reduction. Operational changes such as reduction in cruising speeds and use of shore power rather than internal generation when in port could also reduce emissions in heavily-impacted areas such as major ports. In the long run, use of selective catalytic reduction, alternative fuels, or alternative propulsion systems could dramatically reduce NOx emissions, but the practicality of such systems would need to be investigated further.

New-engine emissions standards - High-speed diesel engines used in small and medium-sized boats are similar to those used in highway trucks and mobile equipment, and similar emissions standards could be applied (taking into account the differences in duty-cycle characteristics). In the same way, medium-speed engines used in larger boats and some ships are similar to those used in locomotives, and could use similar emissions control technology and emissions standards. These do not require further discussion. However, the large slow-speed two-stroke engines used in most oceangoing ships are unique to that application. Ship emissions have only recently become a topic of concern, and relatively little is known about the levels of emission control possible with these large engines. Melhus (1990) reports some measurements showing significant NOx reductions due to retarded injection timing and reduced charge-air temperature, but no conclusions can yet be reached as to the emissions standard levels that may be achieveable with diesel technology. A study currently under way for the California Air Resources Board may shed additional light on this question.

Control of in-use emissions - Control of in-use emissions from ships and boats would involve two primary areas: inspection and enforcement of technical emissions control requirements (i.e. presence and proper functioning of emission control systems); and enforcement of operational requirements such as cruising speed limitations and shutdown of generators in port. The former requirement could readily be combined with existing procedures for safety inspection; the latter with existing regulation of traffic patterns and operating practices in harbors and waterways.

Alternative fuels and engine systems - Boat and ship NOx emissions could be reduced to very low levels through the use of alternative fuels and/or engines. For example, steamships exhibit very low NOx emissions compared to diesel motorships. Unfortunately, the poor fuel efficiency of steamships compared to diesels renders them uncompetitive in the world market. An alternative which might be competitive, at least in some applications, would be a gas-turbine/steam-turbine combined cycle propulsion system. Such combined-cycle systems have demonstrated thermal efficiencies in excess of 70% in electric generation service. To be feasible, however, the gas-turbine system would need to be able to tolerate relatively poor-quality marine bunker fuel, which would require advances in gas-turbine technology or extensive gas cleanup.

Another alternative for marine propulsion would be the use of natural gas as fuel. This is already done in liquified natural gas tankers, which burn the boil-off vapors from their cargo as fuel. LNG would also be especially appropriate for refrigerated carriers, fishing vessels, and other vessels using refrigerated storage, since the heat of vaporization of the fuel could be used productively to cool the refrigerated space.

Aircraft

Although aircraft NOx emissions are relatively small compared to other mobile sources, they may have a significant impact in areas with heavy concentrations of air traffic. In addition, the fact that a large fraction of NOx from aircraft is emitted at high altitudes, where it is likely to remain in the atmosphere for some time, could increase the significance of aircraft NOx emissions for global warming. Recent progress with dry, low-NOx combustion in stationary gas turbines suggests that the application of similar technology in aircraft engines could reduce their NOx emissions substantially - possibly by a factor of 10. This would need to be balanced against the added complexity of these systems, with its potential impact on reliability.

At present, too little information on NOx emissions capabilities of aircraft engines is available for any specific numerical standards to be defined. Further research and regulatory development in this area would be required before any standards were set. Once set, such standards should be applied to new engine installations and (where feasible) to retrofits of existing engines during major overhaul. Enforcement of such regulations could best be carried out in conjunction with existing regulatory enforcement of safety and noise regulations.

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Another alternative for marine propulsion would be the use of natural gas as fuel. This is already done in liquified natural gas tankers, which burn the boil-off vapors from their cargo as fuel. LNG would also be especially appropriate for refrigerated carriers, fishing vessels, and other vessels using refrigerated storage, since the heat of vaporization of the fuel could be used productively to cool the refrigerated space.

Aircraft

Although aircraft NOx emissions are relatively small compared to other mobile sources, they may have a significant impact in areas with heavy concentrations of air traffic. In addition, the fact that a large fraction of NOx from aircraft is emitted at high altitudes, where it is likely to remain in the atmosphere for some time, could increase the significance of aircraft NOx emissions for global warming. Recent progress with dry, low-NOx combustion in stationary gas turbines suggests that the application of similar technology in aircraft engines could reduce their NOx emissions substantially - possibly by a factor of 10. This would need to be balanced against the added complexity of these systems, with its potential impact on reliability.

At present, too little information on NOx emissions capabilities of aircraft engines is available for any specific numerical standards to be defined. Further research and regulatory development in this area would be required before any standards were set. Once set, such standards should be applied to new engine installations and (where feasible) to retrofits of existing engines during major overhaul. Enforcement of such regulations could best be carried out in conjunction with existing regulatory enforcement of safety and noise regulations.

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