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14741

Distr.
LIMITED

UNIDO/IO
FEBRUARY 1985

ENGLISH

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Hong Kong.

IMPROVEMENT OF EMISSIONS FROM MOTOR VEHICLES

DP/HOK/82/003

INTERIM REPORT *

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Background

During 1984, the United Nations Industrial Development Organization (UNIDO) commissioned a study of the motor vehicle emissions problem in Hong Kong. The primary objective of the project is to evaluate the particulate emissions problem from diesel vehicles and to determine the adequacy of the existing inspection and maintenance (I/M) program in addressing it. For those shortcomings identified, it is intended to develop administrative or regulatory changes which would result in a practicable and efficient program. In addition to diesel particulate, other motor vehicle problems, if any, are to be reviewed.

During the first phase of the project, the objective has been to prepare an interim report assessing the shortfall in the existing inspection and maintenance program in Hong Kong, with emphasis on the impact that pollution has on public health. This interim report attempts to analyze the existing problems and to identify potential areas of improvement which will form the basis for phase two of the study. It is based on a review of documents provided by the Government of Hong Kong during the middle of 1984 as well as an extended visit to Hong Kong during November, 1984. The purposes of the trip were two-fold:

1. To meet with the appropriate Hong Kong government officials and private companies to discuss their views on the motor vehicle problem and potential solutions.
2. To gather available data regarding the existing motor vehicle related air pollution problem.

The visit achieved both objectives and was very fruitful overall. (A complete list of individuals interviewed is attached as Appendix A.)

Based on the discussions and the collected data, a series of conclusions have been reached.

Conclusions

1. A significant motor vehicle air pollution problem exists today in Hong Kong.

There is currently a widespread particulate problem across Hong Kong as is evidenced by monitored Total Suspended Particulate (TSP) in excess of accepted healthy levels. Diesel fueled motor vehicles are a significant contributor to this problem. In some ways, the motor vehicle problem is more hazardous than is reflected in the monitored TSP levels, since diesel particles are very small (and therefore able to penetrate to the deepest recesses of the alveolar region of the lung) and are emitted in close proximity to the actual breathing zones of people rather than from tall stacks.

Smoke and particulate emissions from diesel vehicles are the primary concern of government officials. Diesel taxis accumulate very high mileage annually (with many of them in operation 24 hours each day) and they tend to be concentrated in the central business district where congestion of vehicles and people is greatest. Buses and goods vehicles also emit significant quantities of smoke.

Diesel smoke is composed primarily of unburned carbon particles from the fuel and usually results when there is an excess amount of fuel available for combustion. This condition is most likely to occur under high engine load conditions such as acceleration and engine lugging when the engine needs additional fuel for power. Further, a common maintenance error, failure to clean or replace a dirty air cleaner, may produce high smoke emissions because it can choke off available air to the engine resulting in a lower than optimum air-fuel mixture. Vehicle operation can also be important since smoke emissions from diesel engines are minimized by selection of the proper transmission gear to keep the engine operating at the most efficient speeds. Moderate accelerations and lower highway cruising speed changes as well as reduced speed for hill climbing also minimize smoke emissions. Conversely, overloading a diesel engine, forcing it to perform more work than the amount for which it has been designed, can significantly increase smoke emissions.

Hong Kong currently experiences an unacceptibly high coefficient of haze (COH) as indicated in roadside air quality measurements. COH has been associated with the fine particulate matter which diesel vehicles emit. (Environmental concerns associated with diesel particles are summarized in Appendix B.)

Other motor vehicle related pollution problems also exist in Hong Kong - most notably, rising NO_2 levels and excess lead although these are not as severe as the diesel particulate problem. The Economic Commission for Europe (ECE) regulations have been adopted for motor vehicles but so far these only require modest reductions in NOx emissions. (Environmental concerns associated with nitrogen oxides emissions are summarized in Appendix C.)

With regard to lead, significant progress has been made in Hong Kong - gasoline lead content was reduced from 0.84 to 0.6 grams per liter in 1981, and then to 0.4 in 1983, with a planned further reduction to 0.25 in January 1985. Health effects studies around the world, however, continue to lower the threshold for "acceptable" lead exposure in children, making even lower lead levels attractive. (The adverse effects associated with lead are summarized in appendix D.)

In addition, the unavailability of even a single grade of unleaded gasoline prevents the use of catalyst technology to reduce CO, HC and NOx from vehicles. While further lead reductions would be difficult, and the widespread introduction of a grade of unleaded fuel even more difficult, they appear worth further exploration.

2. These environmental problems will likely retard industrial and economic development in the future unless they are addressed.

These environmental problems are not just important from the standpoint of public health but have significant potential to retard future economic development. In the first instance, particulate emissions are generated by many sources. Failure to clean up the motor vehicles will necessitate tight restrictions on stationary sources - factories and plants which create jobs. In addition, diesel emissions cause a strong negative public reaction because of the smoke and odor. It seems quite likely that the tourism industry which is such a significant ingredient of the Hong Kong economy will be adversely affected as the public recoils against these noxious fumes.

3. The problem of motor vehicle pollution is likely to get much worse in the future.

The population of Hong Kong has been growing dramatically and is projected to continue to do so in the future. It increased by 26% from 1971 to 1981 with an additional 19% estimated between 1981 and 1991. This growth will inevitably lead to growth in the number of vehicles and in the use of those vehicles. For example, the government projects the car population will grow by about 5% per year over the next decade. Even more importantly, goods vehicles (which are the largest portion of the diesel population at present) have been growing at a faster rate than cars over the last decade, averaging over 8 percent per year.

4. The existing programs are not sufficient to solve the diesel particulate problem.

<u>New vehicle controls</u> are not adequate. For example, there is no requirement that diesel cars and taxis meet U.S. particulate standards, which are the most stringent in the world. In addition, a significant proportion of goods vehicles are imported into Hong Kong, second hand, after having been used extensively in Japan. These vehicles

emit more pollution than new vehicles. (Control technologies for new diesel fueled vehicles are summarized in Appendix E while gasoline engine technologies are summarized in Appendix F.)

More importantly, the controls on in-use vehicles are deficient. Taxis, for example, receive a routine inspection for smoke but only once per year. This is inadequate incentive to encourage good, low emissions maintenance because the vehicles accumulate in excess of 100,000 km. in a year whereas particulate emissions can increase after only 20,000 km. without proper maintenance. Therefore, taxis can spend 75 or 80% of the year in an excessively smoky condition.

In addition, the charge for re-submission of a failed vehicle at the annual inspection is too low ($140.00 HK) to encourage good maintenance. It is cheaper for owners to ignore maintenance costs (including loss of time on the road) and to pay this charge or an occasional fine. In fact, the charge is so low that many taxi operators appear to use the inspection as a diagnostic device i.e., rather than checking and repairing vehicles prior to the scheduled annual inspection, they will subject the vehicle to the inspection and make repairs based only on those faulty items identified.

During the year, taxis are subject to random roadside inspections but even these do not appear to provide sufficient incentive to maintain vehicles because the risk of being caught is low (and getting lower as the police department program devoted to this effort was recently cut back), and the fixed penalty ticket issued for failure is only $200.00 HK. Also, if this roadside test is failed, there is no requirement to repair the problem.

The in use problem is even worse for goods vehicles because they are not subject to an annual inspection until they are 10 years old. While they are subject to the random roadside checks, the risk of being caught is minimal because police avoid the disruption associated with pulling over large bulky vehicles. Further, many trucks have odd shaped tailpipes which preclude testing by the Hartridge smokemeter without an adaptor; therefore, they are effectively exempted from the test. Because competition for business is very intense, goods vehicle operators appear willing to carry loads in excess of their vehicles design capacity; this leads to even more smoke emissions.

Private cars are currently exempted from annual inspections entirely. It is anticipated that this will change next year when a private inspection system will be instituted. Private cars are not, however, major contributors to the smoke problem as only about 3 percent are diesel, and the annual distance travelled is low (about 20,000 km.).

Without inspections to assure proper maintenance, there is very little incentive to reduce smoke emissions for all but large bus fleets or other large companies which have an image to protect. In fact, for many goods vehicles and taxicabs which are run as small businesses, there appears to be a disincentive in that owners attempt to minimize all costs including routine maintenance until repairs are necessary to keep the vehicle running. While fuel costs will tend to rise without good maintenance, this is usually the responsibility of the operator who "rents" the vehicle for the shift or the day.

In order to upgrade the motor vehicle control program, it is necessary to consider certain other fundamental underlying problems:

1. Organization

No agency or element of government at present has both the responsibility and authority to solve the diesel smoke problem. The Transport Department which conducts the annual inspections of vehicles perceives its major responsibility to be safety and allocates its resources toward this end. The Police, who conduct the roadside inspections, are responsible for protecting lives and property with only minimal concern with vehicle emissions. The Environmental Protection Agency, for whom emissions control is a high priority, has no operational responsibility for motor vehicle emissions. The net result is that no single organization is either responsible for or accountible for addressing motor vehicle pollution problems.

2. Resources

The EPA has no resources devoted solely to the motor vehicle problem. While Transport and Police do expend resources in this area, they are not specifically earmarked for pollution control. As a result, they can be easily shifted to other responsibilites as routine priorities for these Departments shift. For example, about 20 man years were devoted to random road checks by the Police for most of 1984 (Five teams of 4 men each); late in the year these resources were shifted and the total effort declined to about 4 or 5 man years with a dramatically scaled down program.

Preliminary recommendations have been developed which will be researched and refined during the second phase of the project in 1985. These will form the basis of a final report to implement and adopt practicable administrative or regulatory measures in regard to motor vehicle pollution control. The report will carefully consider Hong Kong's economic adaptability, the cost-effectiveness of the recommendation and control legislation in countries with similiar social structure.

Tentative Recommendations

A Implementation of an I/M Program

1. A program element should be set up within EPA with specific full time responsibility for motor vehicle pollution control.

2. A visual check should routinely replace the Hartridge check in the random inspection program.

This test with the Hartridge smokemeter takes from twenty minutes to a half-hour from the time a vehicle is pulled over until it is sent on its way (records checks, instrument calibrations, test operation, etc.) which reduces the number of tests which can be run in any given time period.

3. Vehicles which fail any emissions inspection must be required to be repaired.

4. The penalty for failure of a roadside test, and the charge for re-submission of a vehicle which fails its

routine inspection must be increased sufficiently to provide an incentive to maintain vehicles.

5. Trained EPA smoke examiners should conduct the roadside checks.

6. EPA smoke examiners should periodically conduct silent smoke checks to determine trends and priority problem areas.

7 Routine smoke checks should be done more frequently than annually for high mileage vehicles.

B Other Recommendations

8. As of January 1986, all new vehicles should be designed to operate on unleaded gasoline without valve problems.

9. As of January 1986, all new diesel taxis should be required to meet U.S. particulate standards.

C Recommendations for further study

10. A retrofit demonstration project should be initiated to determine the feasibility of retrofitting diesel trucks and buses with particulate control devices such as trap oxidizers.

11. Further analysis needs to be carried out to detrermine the extent to which goods vehicles are being overloaded in use and whether strategies beyond upgraded I/M will be needed to reduce its incidence.

Appendix A

List of Individuals Interviewed In Hong Kong

Mr. John Blay
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Mr. Tom Bowles
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Hong Kong

Mr. Michael Chan
Principal Environmental Protection Officer
Hong Kong Government
Environmental Protection Agency
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Tsim Sha Tsui East
Hong Kong

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Principal Assistant Secretary
Transport Branch, Government Secretariat
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Director and Company Secretary
Johnson Matthey Hong Kong Limited

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Mr. A.A. E. "Tony" Milford
Senior Assignment Officer

Independent Commission Against Corruption
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8 Cotton Tree Drive
Hong Kong

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Vehicle Examination Centre
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Kowloon, Hong Kong

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Appendix B
Adverse Health and Environmental Concerns Associated with Diesei Particulate Emissions

There is currently a widespread particulate problem across Hong Kong as is evidenced by monitored Total Suspended Particulate (TSP) in excess of accepted healthy levels. Diesel fueled motor vehicles are a significant contributor to this problem. In some ways, the motor vehicle problem is more hazardous than is reflected in the monitored TSP levels, since diesel particles are very small (and therefore able to penetrate to the deepest recesses of the alveolar region of the lung) and are emitted in close proximity to the actual breathing zones of people rather than from tall stacks.

Smoke and particulate emissions from diesel vehicles are a concern because a strong correlation between suspended particulate and variations in infant mortality and total mortality rates has been established. Further, clear evidence emerges from the body of epidemiological literature that implicates particles in aggravating disease among bronchitics, asthmatics, cardiovascular patients and people with influenza.

In addition, with diesel particulate emissions especially, there are concerns about potential carcinogenicity. For example, the National Academy of Science notes that "because of their small size, (diesel particles) remain suspended in the air for a week or more and they can be inhaled and deposited in the narrowest passages of the lungs. Because of their small size, however, they offer a relatively large surface on which toxic, mutagenic, and carcinogenic compounds can be absorbed." A pilot study of U.S. railroad workers, conducted by researchers at Harvard, indicated that the risk ratio for respiratory cancer in diesel exposed subjects relative to unexposed subjects could be as great as 1.42, i.e., the possibility of developing cancer may be 42 percent greater in individuals exposed to diesels than in individuals which are not exposed. A follow up study supports the initial conclusion.

Because of their size and composition, diesel particles can also have a major, negative effect on visibility. A study conducted for the State of California, found that because diesel particles are composed largely of elemental carbon and because this "elemental carbon strongly absorbs light in addition to scattering light, fine soot particles have a light extinction efficiency of 3 to 4 times that of other fine aerosols."

Soiling is the accumulation of particulate matter on the surface of a material which arises from the impingment of these particles on the surfaces. Soiling due to particles can result in increased cleaning and painting costs for building and other materials and reduction in the useful life of fabrics. Diesel particles may be especially harmful from a soiling standpoint since the soiling of fabrics and vertical surfaces has been ascribed to fine particles, particularly dark carbonaceous materials. In addition, the National Academy of Sciences has determined that "there are grounds for believing that the oiliness of diesel particulates suspended in the atmosphere might cause a more serious soiling problem than an equal weight of particulates from other sources."

Particles affect structural materials principally by promoting and accelerating the corrosion of metals, the degradation of paints, and the deterioration of building materials such as concrete and limestone. It has been demonstrated that moist air polluted with SO_2 and particulate matter results in a more rapid corrosion rate than air polluted with SO_2 alone.

Appendix C
Adverse Health and Environmental Effects Associated With Nitrogen Oxides Emissions

As a class of compounds, the oxides of nitrogen impact adversely on a host of human health and welfare concerns. Nitrogen dioxide (NO_2) has been linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function. Even short term exposures to NO_2 have resulted in a wide ranging group of respiratory problems in school children -- cough, runny nose and sore throat are among the most common. Asthmatics are especially sensitive to even one hour exposures. A small group of asthmatics were initially exposed to carbachol, a bronchoconstrictor representative of urban pollen, and then to NO_2; adverse effects such as increased airway resistence were experienced by some of the individuals at levels as low as 0.1 parts per million (ppm) for 1 hour.

The World Health Organization concluded that a maximum 1 hour exposure of 190-320 micrograms per cubic meter (0.10-0.17 ppm) should be consistent with the protection of public health and that this exposure should not be exceeded more than once per month.

While nitrogen dioxide alone does not significantly reduce visual range, it is responsible for a portion of the brownish coloration observed in polluted air. In addition, nitrogen dioxide and particulate nitrates also contribute to pollutant haze.

Oxides of nitrogen have also been shown to affect vegetation adversely. This effect is even more pronounced when nitrogen dioxide and sulfur dioxide occur simultaneously. Further, nitrogen dioxide has been found to cause deleterious effects on a wide variety of textile dyes and fabrics, plastics and rubber.

The oxides of nitrogen also play a significant role in the formation of that family of compounds known as photochemical oxidants as well as acid deposition. These problems have not been demonstrated to be serious concerns in Hong Kong but a careful review is underway at this time.

Appendix D
Adverse Health and Environmental Effects Associated With Lead in Gasoline

With regard to lead, significant progress has been made in Hong Kong - gasoline lead content was reduced from 0.84 to 0.6 grams per liter in 1981, and then to 0.4 in 1983, with a planned further reduction to 0.25 in January 1985. Health effects studies around the world, however, continue to lower the threshold for "acceptible" lead exposure in children, making even lower lead levels attractive.

The toxic properties of lead at high concentrations have been known since ancient times as lead has been mined and smelted for more than 40 centuries. Precautions in its use have been widespread for centuries, but it has only been recently that its adverse impacts at very low levels have been fully appreciated. There has been an explosion of knowledge during the last decade with regard to the adverse health impact of long term exposure to low levels of ambient lead.

The seminal work in this area is the 1979 report by Dr. Herbert Needleman and his colleagues which concluded that children with high levels of lead accumulated in their baby teeth experienced more behavioral problems, lower IQ's and decreased ability to concentrate.

The latest series of health studies in the U.K tends to confirm the Needleman work. They add further evidence that low levels of lead contributes to behavioral problems, lower IQ's and decreased ability to concentrate. Even after taking up to 15 social factors into account, a 3 IQ number deficit is consistently found. While not necessarily statistically significant in any individual study (a factor which is largely influenced by the size of the sample among other factors), the body of data consistently shows the effects. It is important to note that it is not only the length and severity of exposure to lead which results in the health damage but the age at which exposure occurs. This is especially important because "Of all the persons in the community, the newborn child is the most prone to injury from overexposure to lead for several reasons, and the damage that may be caused then will have the greatest long-term social and economic consequences."

The studies of Dr. Winneke in Germany offer further evidence that "neuropsychological effects are causally related to very low blood lead levels." The effects are not necessarily the dominant ones in any particular instance but they are real, a matter of concern and preventable.

Other health concerns with lead are receiving increasing attention. For example, in the United States, the National Cancer Institute has just completed a review of metals for the selection of candidates for further study; based on this review and the potential for considerable human exposure as well as "the high suspicion of potential carcinogenic activity", it has ranked lead as a high candidate for more careful analysis.

When lead additives were first discovered to improve gasoline octane quality, they were also found to cause many problems with vehicles. Notable among these was a very significant build up of deposits in the combustion chamber and on spark plugs, which caused durability problems. To relieve these problems, lead scavengers were added to gasoline at the same time as the lead to encourage greater volatility in the lead combustion by-products so they would be exhausted from the vehicle. These scavengers continue to be used today with leaded gasoline.

Ultimately, a significant portion of these additives are emitted from vehicles. These lead scavengers, most notably ethylene dibromide, have been found to be carcinogenic in animals and have been identified as potential human carcinogens by the National Cancer Institute. In October of 1983, the U.S. EPA concluded that the harmful effects were so serious that it banned the use of this material in pesticides.

Gasoline lead affects human health through several media. First, of course is air and it is generally recognized that over 90 percent of atmospheric lead concentrations in most urban areas are associated with gasoline lead emissions. Beyond this, however, gasoline lead increases the amount of lead ingested through the digestive system. This is especially true with children who not only receive this lead through the normal food chain, but through their playing in streets and yards which are contaminated with lead. When viewed in this context it is not surprising that "both average blood lead levels and cases of lead poisoning in children correlate more strongly to gasoline lead than to lead in the air alone." Because of this close relationship, reducing the lead content of gasoline has been demonstrated to significantly reduce the health risks in urban areas in the United States. For example, based on data collected in more than 60 United States cities by the Center for Disease Control (CDC), the decline in mean blood lead levels computed by six month intervals almost parallels the amount of lead used in the production of gasoline from 1976 to 1980. This study is generally referred to as the NHANES II study.

In addition, the unavailability of even a single grade of unleaded gasoline prevents the use of catalyst technology to reduce CO, HC and NOx from vehicles. While further lead reductions would be difficult, and the widespread introduction of a grade of unleaded fuel even more difficult, they appear worth further exploration.

Appendix E
Emission Control Technologies: Diesel Fueled Vehicles

The greater use of diesel equipped vehicles for private cars and all categories of commercial vehicles is the major trend observed worldwide over the last decade in the motor vehicle field. While the energy advantages of the diesel are unquestioned, concerns began to grow during the 1970's over the environmental consequences of increased dieselization. Although inherently cleaner than gasoline engines from the standpoint of carbon monoxide (CO) and evaporative hydrocarbons (HC), diesels produce more aldehydes, sulfur oxides (because of the higher sulfur content in diesel fuel than in gasoline) and nitrogen oxides. Offensive smoke and odor emissions are also a problem. Most importantly, however, uncontrolled diesels emit approximately 30 to 70 times more particulate than current gasoline-fueled engines equipped with catalytic converters.

Smoke and Particulate

Smoke is composed primarily of unburned carbon particles from the fuel and usually results when there is an excess amount of fuel available for combustion. This condition is most likely to occur under high engine load conditions such as acceleration and engine lugging when the engine needs additional fuel for power. Further, a common maintenance error, failure to clean or replace a dirty air cleaner, may produce high smoke emissions because it can choke off available air to the engine resulting in a lower than optimum air-fuel mixture. Vehicle operation can also be important since smoke emissions from diesel engines are minimized by selection of the proper transmission gear to keep the engine operating at the most efficient speeds. Moderate accelerations and lower highway cruising speed changes as well as reduced speed for hill climbing also minimize smoke emissions.

Two major approaches exist for meeting tight diesel particulate standards: engine modifications to lower engine out emission levels, and trap-oxidizers and their associated regeneration systems. Engine modifications include changes in combustion chamber design, fuel injection timing and spray pattern, turbocharging, and the use of exhaust gas recirculation. Using these techniques, average particulate emissions from light duty vehicles in the United States have been reduced from a mean of approximately 0.6 grams per mile in 1980 to about 0.3 grams per mile (based on U.S. certification data). These reductions are even more remarkable in that they occurred simultaneously with a lowering of NOx emissions levels from 2.0 grams per mile to under 1.5 grams per mile. This is significant because there is a trade off between certain NOx control techniques and particulate controls. Further particulate controls appear possible through greater use of electronically controlled fuel injection which is currently under rapid development. Using such a system, signals proportional to fuel rate and piston advance position are measured by sensors and are electronically processed by the electronic control system to determine the optimum fuel rate and timing.

Exhaust aftertreatment methods include traps, trap oxidizers, and catalysts. Trap oxidizer prototype systems have shown themselves capable of 70 to 90 percent reductions from engine out particulate emissions rates and with proper regeneration the ability to achieve these rates for high mileage. A very recent and comprehensive review concluded that three types of trap oxidizer systems show promise for commercial development:

* ceramic monolith trap/burner regeneration system

* catalyzed wire mesh trap/regeneration by HC and CO enrichment of exhaust, and
* ceramic monolith trap/self regeneration by means of fuel additives.

Prototypes of these systems have been successfully tested for extended periods on light duty vehicles and the first commercial system has now been introduced in the U.S..

NOx Control Techniques

Exhaust gas recirculation (EGR) is the principal technology used at present to reduce NOx emissions. EGR reduces combustion temperatures and thereby NOx emissions. In the short term, use of first generation systems which employ constant EGR, can also lead to increased particulate emissions. Concerns have also been raised regarding increased engine wear. However, in the longer term, electronically modulated EGR systems combined with careful control of fuel injection timing should minimize or even eliminate any trade-offs.

NOx control techniques likely to be available in the near future include variable injection timing and pressure, charge cooling, and possibly exhaust gas recirculation. Retarding injection timing, while a well known method of reducing NOx formation, can lead to increases in fuel consumption, particulate and hydrocarbon emissions. These problems can be mitigated by varying the injection timing with engine load or speed. Also, high pressure injection can reduce these problems. If coupled with electronic controls, it appears that NOx emissions could be reduced significantly with a simultaneous improvement in fuel economy.

Appendix F
Emission Control Technologies - Gasoline Fueled Vehicles

Before controls were required, engine crankcases were vented directly to the athmosphere. Crankcase emissions controls which basically consist of closing the crankcase vent port were introduced on new cars in the early 1960's with the result that today, control of these emissions is no longer considered a serious technical concern.

The hydrocarbon evaporative emissions result from distillation of fuel in the carburetor float bowl and evaporation of fuel in the gas tank. To control these emissions, manufacturers generally feed these emissions back into the engine to be burned along with the other fuel. When the engine is not in operation, vapors are stored, either in the engine crankcase or in charcoal cannisters which have a strong affinity for these emissions and then burned off when the engine is started.

By far the most difficult emission problems are those related to vehicle exhaust. Fortunately, great progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the exhaust pollutants. The following section reviews briefly the combustion factors which most influence emissions rates, the critical design variables which can be modified to reduce emissions and, finally, the technologies available for addressing the above problems.

Combustion and Emissions

Emissions of hydrocarbons, thousands of different chemical compounds, are largely the result of incomplete combustion of the fuel. The amounts emitted are related to the air/fuel mixture inducted, the peak temperatures and pressures in each cylinder, whether lead is added to the gasoline, and such hard to define factors as combustion chamber geometry.

The oxides of nitrogen are generally formed during conditions of high temperature and pressure and excess air (to supply oxygen). Peak temperatures and pressures are affected by a number of engine design and operating variables and, accordingly, so are the concentrations of nitrogen oxides in the exhaust.

Carbon monoxide results from incomplete combustion of the carbon contained in the fuel and its concentration is generally governed by complex stoichiometry and equilibrium considerations. The only major engine design or operating variable which seems to affect its concentration is the air/fuel mixture; the leaner the mixture or the more air per quantity of fuel, the lower the carbon monoxide emission rate.

Finally, lead compounds (and their associated scavengers) are exhausted by an automobile almost directly in proportion to the amounts which are fed into the vehicle.

Engine Modifications

Certain key engine design variables are capable of causing significant increases or decreases in emissions. Most notable among these are air/fuel ratio and mixture preparation, ignition timing, and combustion chamber design and compression ratio,.

Air/Fuel Ratio and Mixture Preparation

Air/fuel ratio has a major effect on all three pollutants from gasoline engines. In fact, CO emissions are almost totally dependent on air/fuel ratio whereas HC and NOx emissions rates can be strongly influenced depending on other engine design parameters. CO emissions can be dramatically reduced by increasing air/fuel ratio to the lean side of stoichiometric. HC emissions can also be reduced significantly until flame speed becomes so slow that pockets of unburned fuel are exhausted before full combustion occurs or in the extreme misfire occurs. Conversely, NOx emissions increase as air/fuel mixtures are enleaned up to the point of maximum or peak thermal efficiency; beyond this point, further enleanment can result in lower NOx emission rates.

Ignition Timing

Ignition timing is the second most important engine control variable affecting "engine out" HC and NOx from modern engines. When timing is optimized for fuel economy and performance, HC and NOx emissions are also relatively high (actual values depending of course on other engine design variables). As ignition timing is delayed (retarded), peak combustion temperatures tend to be reduced thereby lowering NOx and peak thermal efficiency. By encouraging combustion to continue after the exhaust port is opened, thereby resulting in higher exhaust temperatures, oxidation of unburned hydrocarbons is greater and overall hydrocarbon emissions reduced.

Compression Ratio and Combustion Chamber Design

According to the fundamental laws of thermodynamics increases in compression ratio lead to improved thermal efficiency and concomitantly increased specific power and reduced specific fuel consumption. In actual applications, compression ratio increases tend to be limited by available fuel octane quality; over time, a balance has been struck between increased fuel octane values (through refining modifications and fuel modifications such as the addition of tetraethyl lead to gasoline) and higher vehicle compression ratios.

Compression ratios can be linked to combustion chamber shapes and in combination can have a significant impact on emissions. Higher surface to volume ratios will increase the available quench zone and lead to higher hydrocarbon emissions; conversely, more compact shapes such as the hemispherical or bent roof types reduce heat loss thus increasing maximum temperatures which tends to increase the formation of NOx while reducing HC. Further, combustion chamber material and size and spark plug location can impact emissions. In general, because of its higher thermal conductivity, aluminum engine heads lead to lower combustion temperatures and therefore lower NOx rates but at the expense of increased HC emissions. Since the length of the flame path has a strong influence on engine detonation and therefore fuel octane requirement, larger combustion chambers which can lower HC emissions tend to be used only with lower compression ratios.

Intake Charge Dilution by Exhaust Gas Recirculation

Dilution of the incoming charge has been shown to reduce peak cycle temperature by slowing flame speed and absorbing some heat of combustion. Recirculating a portion of the exhaust gas back into the incoming air/fuel mixture (EGR) thereby lowering peak cycle temperature has therefore become frequently used as a technique for lowering NOx.

Charge dilution of homogeneous charge engines by excess air and by exhaust gas recirculation has been used for many years. They have been used separately and together. The use of excess air alone seems limited to relatively small NOx reductions, on the order of 35-40%; when EGR is incorporated, substantially higher NOx reductions have been demonstrated. Excessive dilution can result in increased HC emissions, driveability problems or fuel economy losses.

Fuel consumption can be decreased, maintained, or improved when EGR is utilized. Brake specific fuel consumption and exhaust temperature decrease with increasing EGR because dilution with EGR decreases pumping work and heat transfer, and increases the ratio of specific heats of the burned gases.

Improvements in mixture preparation, induction systems, and ignition systems can increase dilution tolerance. The latest technique for improving dilution tolerance is to increase the burn rate or flame speed of the air-fuel charge. Dilution can then be increased until the burn rate again becomes limiting. Several techniques have been used to increase burn rate including increased swirl and squish, shorter flame paths, and multiple ignition sources.

Electronics

With so many interrelated engine design and operating variables playing an increasingly important role in the modern engine, the control system has taken on increased importance. Modifications in spark timing must be closely coordinated with air-fuel ratio changes and degrees of EGR lest significant fuel economy or performance penalties result from emissions reductions, or NOx emissions increase as CO goes down. In addition, controls which can be much more selective depending on engine load or speed have been found beneficial in preventing widespread adverse impacts.

To address these problems, electronics have begun to replace more traditional mechanical controls. For example, electronic control of ignition timing has demonstrated an ability to optimize timing under all engine conditions and has the added advantage of reduced maintenance and improved durability compared with mechanical systems. When coupled with electronic control of EGR, it has been demonstrated that NOx emissions can be reduced with no fuel economy penalty and in some cases with an improvement.

Over the last several years, automotive engineers have worked diligently on the development of engine "maps"; these define optimal adjustments or calibrations of critical engine parameters such as air/fuel mixture, spark timing, EGR rate, etc. to minimize emissions and fuel consumption while maximizing performance over a wide range of engine operating conditions. With electronic controls, it is possible to make much greater use of this information than in the past resulting in much lower "engine out" emissions levels prior to any exhaust aftertreatment.

Exhaust Aftertreatment Devices

Two alternative approaches which receive close scrutiny when tighter exhaust emissions standards (especially hydrocarbons or nitrogen oxides) are considered are: a) exhaust aftertreatment devices such as catalytic converters and thermal reactors or b) advanced combustion techniques such as high compression, lean burn engines.

Oxidation Catalysts

Quite simply, an oxidation catalyst is a device which is placed on the tailpipe of a car and which, if the chemistry and thermodynamics are properly maintained, will oxidize almost all the HC and CO in the exhaust stream. In general, monolith systems lend themselves to smaller size and weight whereas pelleted systems tend to be slightly less expensive.

Starting with 1975 model year cars, catalysts have been placed on upwards of 80 per cent of all new cars sold in the United States. In 1981, they were placed on 100 per cent of the new cars. In Japan and Canada, oxidation catalysts are also widely used to meet emission standards. Starting in 1986, they will be required on most new cars in Australia.

A major impediment to the use of catalysts is lead in gasoline. Existing, proven catalyst systems are poisoned by the lead in vehicle exhaust. A substantial effort to develop "lead tolerant" catalysts has been underway over the last several years with the result that significant progress has occurred. However, these systems appear to still be in the development stage and remain unproven in any actual vehicle applications.

One of the unique advantages of catalysts is their ability to selectively eliminate some of the more harmful compounds in vehicle exhaust such as aldehydes (which are especially high in alcohol fueled vehicles) , reactive hydrocarbons and polynuclear hydrocarbons.

Three-way Catalysts

Three-way catalysts (so called because of their ability to lower HC, CO and NOx levels simultaneously) were first introduced in the United States in 1977 by Volvo and subsequently became widely used when the U.S. NOx standard was made more stringent (1.0 grams per mile). To work effectively, it is necessary to control air/fuel mixtures much more precisely than is needed for oxidation catalyst systems. As a result, three way systems have indirectly fostered improved air/fuel management systems such as advanced carburetors and throttle body fuel injection systems as well as electronic controls.

Three-way catalyst systems also are sensitive to the use of leaded gasoline. An occassional tankful of leaded gasoline will have a small but lasting effect on the level of emitted pollutants.

Thermal Reactors

Thermal reactors are well insulated vessels with internal baffling to ensure several passes of the exhaust gas to maintain the temperature and extend the residence time thus promoting oxidation of CO and HC emitted from the engine. To maintain the sufficient high temperatures, they are often used in conjunction with exhaust port liners which reduce heat losses. In spite of this, a major problem with these systems is the difficulty in maintaining exhaust temperatures sufficiently high to promote combustion. Measures to increase exhaust temperatures such as retarded ignition, richer air/fuel ratios or valve timing delays result in increased fuel consumption. Ethyl Corporation has developed a hybrid reactor concept which they report to be capable of lowering HC and CO emissions to extremely low levels. Experiments on V-8 engines were reported with results below 0.41 HC and 3.4 CO. In combination with the use of EGR, this system has reportedly also achieved 1.0 NOx.

Advanced Combustion Techniques

Modification of the basic combustion process is proceeding along several fronts by a number of different engine manufacturers or research organizations. Summarized below are the major approaches receiving serious consideration.

High Compression Lean Burn Engines

An alternative to the catalyst which could achieve lower emission levels with leaded gasoline and with potentially good fuel economy is the high compression, lean burn engine. By designing combustion chambers with great turbulence to promote mixing, compression ratios as high as 13:1 and air/fuel ratios in the range of 20:1 have been demonstrated without detonation. Such systems have also demonstrated very good fuel economy; about 20 percent better than from more conventional engines. In addition, CO emissions are very low and NOx emissions are lower than from conventional engines without catalysts. However, because exhaust temperatures are low and a high amount of quench occurs, HC emissions tend to be quite high and have so far proved resistent to control. Further, high compression lean burn engines require very precise carburetion and mixture control as well as high energy ignition systems.

Stratified Charge Engines

In general, a stratified charge engine provides a controlled variation of air/fuel ratios within the combustion chamber - rich mixtures near the spark plug to initiate combustion, with the remainder, the largest portion of the charge, very lean. Such a system has several advantages compared to more conventional systems, lower emissions of all three regulated pollutants and low fuel consumption being the most notable. In addition, stratified charge engines can be designed to use a wide variety of fuels.

The only production stratified charge engine is the Honda CVCC which contains a prechamber where ignition of a fuel rich mixture takes place. The resulting combustion continues into the main chamber where a weak mixture is ignited. This engine produces substantially lower CO and NOx emissions than more conventional engines, without the need for exhaust aftertreatment; however, HC emissions are similiar to normal systems. Therefore, if tight control of HC is needed, catalysts or thermal reactors may be needed.

Fast Burn Systems

The Fast Burn uses a single combustion chamber and a homogeneous mixture. More rapid combustion of the air/fuel mixture is promoted by reducing the flame travel distance. Thus end gas reaction time is lowered; concommitantly, engine octane requirements are reduced. Reliable ignition has to be provided by a sufficiently powerful ignition and rapid combustion by strong turbulence of the charge and/or dual ignition.

Increasing the burn rate of the air/fuel charge substantially increases dilution tolerance. Dilution can then be increased with very substantial reductions in NOx emissions until the burn rate again becomes limiting.