MOTOR VEHICLE POLLUTION CONTROL IN SRI LANKA

A PRELIMINARY STRATEGY FOR PROGRESS IN COLOMBO

NAREPP/IRG

A project of the United States Agency for International Development and the Government of Sri Lanka.

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EXECUTIVE SUMMARY

INTRODUCTION

The development of petroleum - powered motor vehicles has truly revolutionized society over the past century. The benefits of increased personal mobility and access to goods and services previously beyond the grasp of individuals cannot be denied. And, yet, the relentless growth in motor vehicle use has a dark downside that many have been slow to acknowledge, including a broad array of adverse public health and environmental impacts.

The environmental damages caused by motor vehicle emissions are no longer debatable; from their tailpipes come virtually all of the carbon monoxide in the air of our cities as well as much of the lead, particulate, nitrogen oxides, toxic hydrocarbons and other constituents of urban air. These pollutants cause a variety of adverse effects to public health and the environment. Various steps can be taken to reduce air pollution emissions from motor vehicles. These include incentives to remove older, higher polluting vehicles from the road; tightening new vehicle emission standards for particulate, nitrogen oxides, volatile organic compounds, and carbon monoxide; developing and using cleaner fuels with less lead and sulfur, lower volatility and fewer toxic components; enhancing inspection and maintenance (I&M) programs; and extending the useful life for pollution-control equipment.

Additional reductions in vehicular emissions can be achieved by reducing dependence on individual cars and trucks and by making greater use of van and car pools, and buses. Improving urban traffic management by installing synchronized traffic lights, reducing on-street parking, switching to "smart" roads, banning truck unloading during the day, and so forth can also improve transportation system efficiency.[1]

Motor vehicle related air pollution problems are not limited to the highly industrialized countries of the OECD nor is the search for solutions. Countries as diverse as Brazil, Taiwan, Singapore and Mexico as well as many other developing countries are rapidly moving to introduce state of the art pollution controls. In instituting these requirements, the primary strategy remains mandated standards for both vehicles and fuels but their has been no lack of creativity in using a variety of economic instruments as well. Most countries realize that tax policies must be designed to reduce any price differential that favors the use of leaded petrol and many see economic incentives as a viable approach to accelerating the introduction of state of the art controls such as catalytic converters in advance of mandatory requirements or encouraging a shift away from high polluting technologies such as diesels.

Today virtually every OECD country requires the availability and use of unleaded petrol in new cars and by the end of this year virtually all new petrol fueled cars sold in these countries will

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[1] "Advanced Vehicle/Highway Systems and Urban Traffic Problems," Staff Paper, Science, Education, and Transportation Program, Office of Technology Assessment, US Congress, September 1989.

be equipped with catalytic converters. Diesel vehicle NOx and particulate levels are also undergoing rapid reductions. Increasingly, the same problems which led to the adoption of tight standards in the highly industrialized countries have been noted in developing countries and many of these countries have taken similar steps to lower their vehicle emission rates.

The purpose of this paper is to review the status of the motor vehicle related pollution problem in a rapidly developing area, Colombo, Sri Lanka, assess the major vehicle types contributing to each aspect of the problem, project the likely future based on current trends, and suggest a package of measures which could significantly alleviate future problems.

OVERALL CONCLUSIONS

As a result of this study, it is possible to draw several conclusions:

1. Air quality measurements in Colombo indicate that a large proportion of the population is exposed to various air pollutants such as particulate matter (TSP), sulfur dioxide (SO_2), nitrogen dioxide, carbon monoxide (CO) and lead at levels above the WHO guideline values.

2. The data indicate that particulate matter is the overwhelming pollutant of concern followed by NO_2, SO_2, and lead. Carbon monoxide levels also occasionally exceed accepted standards, but particulate matter levels consistently exceed concentrations above which health effects have been identified, and frequently by a factor of two or more.

3. In terms of exposure to these pollutants, bus drivers and three wheel vehicle drivers are at the greatest risk of adverse health effects in view of the duration and extent of their exposure, but many others -- commuters, taxi drivers, utility vehicle drivers, and all those working under exposed conditions at or near congested streets, could be at risk as well, particularly as regards particulate emissions.

4. Without aggressive action by government officials, it is clear that the problems will get much worse as the vehicle population more than doubles over the next 10 to 15 years.

5. Substantial additional degradation of the environment is not inevitable but amelioration will require a comprehensive package of strategies impacting on existing vehicles, fuels and new vehicles.

6. Focusing on particulate emissions first, it can be seen that the I/M program can begin to reduce particulate emissions significantly from the levels to which they are otherwiseexpected to rise by 2005. Tight motorcycle standards will also lower particulate. Further, reducing the sulfur and lead content of diesel fuel and gasoline, respectively, will lower sulfur and lead emissions dramatically. Requiring (or effectively encouraging) a gradual shift of selective diesel vehicles to convert from diesel to gasoline

engines will have a major impact on the remaining particulate emissions. The conversion of buses to CNG would have a significant effect on some of the densely populated, high bus use urban corridors.

7. I/M would also have a significant impact on HC and CO emissions. Tight motorcycle standards, by either eliminating or cleaning up two stroke engines, would have an additional benefit for HC. The conversion of some diesels to petrol fuel will actually increase CO and HC emissions somewhat but these increases would be more than offset by the introduction of the other vehicle standards and the catalyst durability provided by unleaded petrol.

8. Very significant progress in reducing pollution across the board can result from adoption of this comprehensive but feasible package of measures. They are mutually reinforcing such that the whole is greater than the sum of the individual parts.

9. Additional benefits could result from constraints on vehicle growth.

All of the above strategies require a strong, well coordinated enforcement program. This in turn will require clear lines of authority and responsibility with accountability built in.

LIMITATIONS OF THE STUDY

This study should be considered preliminary in nature. It relied on available data and should be able to point policy makers in the correct general direction. Most of its conclusions especially with regard to control strategies appear to the author to be incontrovertible However, it is only a first step. Each of the major strategies certainly require additional detailed analysis. Further, it would benefit from the collection of additional data in several key areas. Major data needs are highlighted below:

1. Colombo would benefit from a continuous, well designed air quality monitoring network using today's state of the art monitoring instrumentation.

2. It is suspected that public exposure to lead and carbon monoxide is greater than the currently available data indicates. Special studies which sample blood lead levels, especially in children, cry out to be conducted in Colombo. In addition, personal exposure CO monitors could be used to gain a much better insight into the actual CO exposures in different parts of the city.

3. Estimates of vehicle emissions have been based on personal judgements, relying on an understanding of the major factors which influence emissions and on the characteristics of the vehicle fleet. As a long term strategy, it seems critical to plan on testing of vehicles to determine actual emissions rates.

4. While mobile sources are undoubtedly the major emissions source in Colombo, they are not the only source. Efforts should be initiated to estimate the emissions from other source categories.

5. The vehicle population of Sri Lanka in general and Colombo in particular is not well defined from the standpoint of emissions characterization. For example, lorries should be better subdivided to distinguish between large goods moving vehicles and smaller vans. Other vehicle categories which could lend themselves to discrete emissions control strategies - taxicabs and three wheel vehicles to cite two examples - should be separated from the car population.

CHAPTER 1. INTRODUCTION

The development of petroleum - powered motor vehicles has truly revolutionized society over the past century. The benefits of increased personal mobility and access to goods and services previously beyond the grasp of individuals cannot be denied. And, yet, the relentless growth in motor vehicle use has a dark downside that many have been slow to acknowledge, including a broad array of adverse public health and environmental impacts.

The environmental damages caused by motor vehicle emissions are no longer debatable, and on a global basis they are increasing. The cars, trucks, and buses that make life better in so many ways emit more than 800 million tons of carbon per year. From their tailpipes come virtually all of the carbon monoxide in the air of our cities. They are a major source of toxic compounds such as diesel particulate matter. Less directly, they cause much of the ozone and smog. And motor vehicles play a significant role in stratospheric ozone depletion and global warming.

Over the last forty years, the global vehicle fleet has grown from under 50 million to more than 600 million, and there is every indication that this growth will continue. Over the next twenty years, the global fleet could double to one billion. Unless transportation technology and planning are fundamentally transformed, emissions of greenhouse and other polluting gases from these vehicles will continue to increase, many relatively clean environments will deteriorate, and the few areas that have made progress will see some of their gains eroded.

The worldwide challenges that these problems pose for motor vehicle manufacturers and policy-makers are unprecedented. While development of appropriate policies and technologies develops, countries can benefit from adoption of currently available policies and technologies. Various steps can be taken to reduce air pollution emissions from motor vehicles. These include incentives to remove older, higher polluting vehicles from the road; tightening new vehicle emission standards for particulate, nitrogen oxides, volatile organic compounds, and carbon monoxide; developing and using cleaner fuels with less lead and sulfur, lower volatility and fewer toxic components; enhancing inspection and maintenance (I&M) programs; and extending the useful life for pollution-control equipment. The potential overall impacts of tighter standards, enhanced inspection and maintenance, and extended useful life are especially significant because they help ensure that the benefits of clean-air technology will persist for the vehicle's full life.

Additional reductions in vehicular emissions can be achieved by reducing dependence on individual cars and trucks and by making greater use of van and car pools, buses, trolleys, and trains. Improving urban traffic management by installing synchronized traffic lights, reducing on-street parking, switching to "smart" roads, banning truck unloading during the day, and so forth can also improve transportation system efficiency.[2]

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[2] "Advanced Vehicle/Highway Systems and Urban Traffic Problems," Staff Paper, Science, Education, and Transportation Program, Office of Technology Assessment, US Congress, September 1989.

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Today virtually every OECD country requires the availability and use of unleaded petrol in new cars and by the end of this year virtually all new petrol fueled cars sold in these countries will be equipped with catalytic converters. Diesel vehicle NOx and particulate levels are also undergoing rapid reductions. Increasingly, the same problems which led to the adoption of tight standards in the highly industrialized countries have been noted in developing countries and many of these countries have taken similar steps to lower their vehicle emission rates.

The purpose of this paper is to review the status of the motor vehicle related pollution problem in a rapidly developing area, Colombo, Sri Lanka, assess the major vehicle types contributing to each aspect of the problem, project the likely future based on current trends, and suggest a package of measures which could significantly alleviate future problems.

CHAPTER 2. HEALTH EFFECTS OF VEHICULAR EMISSIONS

Available air quality measurements in Colombo indicate that a large proportion of the population is exposed to various air pollutants such as particulate matter (TSP), sulfur dioxide (SO_2), nitrogen oxides, carbon monoxide (CO) and lead above or near the WHO guideline values. The data indicate that particulate matter is the overwhelming pollutant of concern followed by nitrogen dioxide, sulfur dioxide and lead in that order. Carbon monoxide levels also occasionally exceed accepted standards, but particulate matter levels consistently exceed concentrations above which health effects have been identified, and frequently by a factor of two or more. In terms of exposure to these pollutants, bus and three wheel vehicles drivers appear to be at the greatest risk of adverse health effects in view of the duration and extent of their exposure, but many others -- commuters, taxi drivers, utility vehicle drivers, and all those working under exposed conditions at or near congested streets, are at high risk as well, particularly as regards particulate emissions.

2.1. PARTICULATE

During the 1980s the USEPA re-evaluated their original particulate (TSP) standard which had been set in 1971. The US Clean Air Act requires the EPA to periodically review the scientific basis for the existing ambient air quality standards and to propose standard revisions if warranted. The existing particulate standards were based on total suspended particulate (TSP) as measured with a high-volume sampler. High-volume samplers collect particulate matter with an approximate mass mean diameter of 30 to 40 microns. The 1971 health based standards for TSP were 260 ug/M3 24-hour maximum not to be exceeded more than once per year, and an annual geometric mean standard of 75 ug/M3.

In reviewing the standard the investigators found that lung penetration and deposition studies indicate that particles greater than about 10 micrometers (microns) are captured in the nasopharyngeal and tracheobronchial regions of the respiratory tract and do not reach the lower regions of the lungs. Particles smaller than 10 micrometers (PM-10) penetrate into more sensitive regions such as the alveoli where the critical gas exchange takes place with penetrations increasing as the particles become smaller. They recommended new standards to protect against effects of these fine particles, particularly premature mortality, aggravation of existing respiratory disease, and lung function declines in children. The investigators reaffirmed the need for both a short term (24-hr) and long term standard (annual), and developed the basis for these standards.

2.1.1. Basis for 24-hr Standard

Studies in Britain showed that mortality increases as British smoke/sulfur dioxide concentrations rose above 750 ug/m^3 to 1000 ug/m^3, and statistical association showed effects at much lower levels. Effects on bronchitics were observed at British Smoke levels of 250 ug/m^3, and recent reanalyses of London mortality data show risks of premature mortality to sensitive individuals extends to levels substantially lower than those which occurred in the "episodes" (reliable

conversion of British Smoke to PM-10 is not possible, but short term effects were apparent during these episode conditions). More recent studies of children in Stuebenville, Ohio, and Ljmond, Netherlands, show physiologically small but statistically significant decreases in lung function when exposed to peak TSP levels of 250-420 ug/m^3 (corresponding to PM-10 levels estimated at 140-250 ug/m^3).

With PM-10 selected as the indicator, the USEPA chose for their 24-hr standard a value of 150 ug/m^3, near the lower end of the concentration range showing noticeable effects.

2.1.2. Basis for Annual Standard

Early US studies of adults indicated improved lung respiratory lung function effects as long term TSP exposure levels decreased from 180 to 130 ug/m^3, and no improvements as levels dropped below 130 ug/m^3 to 80 ug/m^3. A 1973 study in two Connecticut towns with a median TSP level of 110 ug/m^3 showed no effects on lung function but some respiratory symptoms. A more recent six city study showed increased respiratory symptoms and illnesses in children across the range of 40 to 115 ug/m^3 TSP.

The USEPA selected an annual arithmetic mean of 50 ug/m^3 PM as the long term standard. Like the short term standard, this concentration is near the lower end of the observed effects level.

2.1.3. Results From The Most Recent Studies

Other recent studies focusing on non cancer health risks associated with urban particles have reinforced the above concerns. By correlating daily weather, air pollutants and mortality in five US cities, scientists have discovered that non accidental death rates tend to rise and fall in near lock step with daily levels of particulates.[3]

Because the correlation held up even for very low levels -- in one city to just 23 percent of the US limit on particulates -- these analyses suggest that as many as 60,000 US residents per year may die from breathing particulates at or below legally allowed levels.

2.1.4. Special Concerns With Diesel Particulate

Uncontrolled diesels emit approximately 30 to 70 times more particulate than modern gasoline-powered engines equipped with catalytic converters and burning unleaded fuel. Virtually all of these particles are small and respirable (less than 2.5 microns) and consist of a solid carbonaceous core on which a myriad of compounds adsorb. These include:

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[3] Joel Schwartz and Douglas W. Dockery. US Environmental Protection Agency, Washington, D.C. and the Harvard School of Public Health, Boston, MA.

* unburned hydrocarbons
* oxygenated hydrocarbons
* polynuclear aromatic hydrocarbons
* inorganic species such as sulfur dioxide, nitrogen dioxide and sulfuric acid.

Therefore in addition to the concerns associated with urban particulate, and the increased risk associated with the smaller of these particles (since virtually smaller of these particles (since virtually 100% of diesel particles are under 10 microns in size), diesel emissions may cause cancer and exacerbate mortality and morbidity from respiratory disease. As noted in the Harvard project, "most of the toxic trace metals, organics, or acidic materials emitted from automobiles or fossil fuel combustion are highly concentrated in the fine particle fraction". Recently, the Swedish National Institute of Environmental Medicine noted:

> "One occupational group with exposure to diesel exhaust is forklift truck drivers, and a considerable number of studies of such truck drivers have been carried out. Steenland (1986) has made a synopsis of 14 studies of this type, and nine of these showed a statistically significant association between exposure to diesel exhaust and lung cancer. Several of the studies which did not produce any statistically significant results showed a tendency to increased incidence of lung cancer. As a whole, these studies suggest that there is an excess risk of lung cancer among such truck drivers in the order of 30 to 50%."

The US EPA has noted that up to 10,000 chemicals may be absorbed on the surface of diesel particles and drawn deep into the lung with them. Many of these chemical compounds are known to be mutagenic in short term bioassays, and to be capable of causing cancer in laboratory animals. Other epidemiological studies have tended to reinforce these concerns. For example, a 1983 study of heavy construction workers found positive trends in lung cancer by length of union membership and a higher than expected rate among retirees. Further, a pilot study of US 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 who are not exposed.[4]

In addition, during late 1985 and 1986, the results of several animal studies were released which increased concerns regarding adverse health effects from diesel particulate emissions. In particular, a study carried out under the auspices of the European automobile manufacturers, the CCMC, and conducted by Battelle-Geneva reported that unfiltered diesel exhaust produced an increase in lung tumor incidence from 1% to 40%; gasoline emissions reportedly showed no effect.

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[4]Schenker, Smith, Munoz, Woski, Speizer, "Lung Cancer Among Diesel Exposed Railroad Workers, Results Of A Pilot Study," Harvard School of Public Health, 1982.

A comprehensive assessment of the available health information was carried out by the International Agency For Research on Cancer (IARC), at a meeting in Lyon, France on June 14-21, 1988.[5] The term 'carcinogen' is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors. Based on its evaluation of all available evidence regarding diesel exhaust, IARC reached the following conclusions:

> There is sufficient evidence for the carcinogenicity in experimental animals of whole diesel engine exhaust.
>
> There is inadequate evidence for the carcinogenicity in experimental animals of gas phase diesel engine exhaust (with particles removed).
>
> There is sufficient evidence for the carcinogenicity in experimental animals of extracts of diesel engine exhaust particles.
>
> There is limited evidence for the carcinogenicity in humans of diesel engine exhaust.

Based on these findings, IARC's overall evaluation was that diesel engine exhaust is probably carcinogenic to humans.

In reaching these conclusions, several human epidemiological studies seemed to carry the most weight. As noted in the IARC report, "In the two most informative cohort studies (of railroad workers), one in the USA and one in Canada, the risk for lung cancer in those exposed to diesel engine exhaust increased significantly with duration of exposure in the first study and with increased likelihood of exposure in the second. Three further studies of cohorts with less certain exposure to diesel engine exhaust were also considered; two studies of London bus company employees showed elevated lung cancer rates that were not statistically significant, but a third, of Swedish dockers showed a significantly increased risk of lung cancer.

In only two case-control studies of lung cancer (one of US railroad workers and one in Canada) could exposure to diesel engine exhaust be distinguished satisfactorily from exposures to other exhausts; modest increases in risk for lung cancer were seen in both, and in the first the increase was significant. In three further case-control studies, in which exposure to diesel engine exhaust in professional drivers and lung cancer risk were addressed, the Working Group considered that the possibility of mixed exposure to engine exhausts could not be excluded. None of these studies showed a significant increase in risk for lung cancer, although the risk was elevated in two.

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[5] "Diesel and Gasoline Engine Exhausts and Some Nitroarenes", Working Group on the Evaluation of Carcinogenic Risks to Humans, International Agency For Research on Cancer, World Health Organization, 1989.

In the three cohort studies (on railroad workers, bus company workers and 'dockers', respectively) in which bladder cancer rates were reported, the risk was elevated, although not significantly so. Four of the case-control studies of bladder cancer were designed to examine groups whose predominant engine exhaust exposure was assumed to be to that from diesel engines. Three showed a significantly increased risk for bladder cancer. In one of these, the large US study, a significant trend was also seen with duration of exposure; and in an analysis of one subset of self-reported diesel truck drivers, a substantial, significant relative risk was seen for bladder cancer."

More recent studies have suggested that the diesel particle itself, stripped of the organic and other materials on the surface, may also be carcinogenic. Confirmatory studies under the auspices of the Health Effects Institute, a jointly funded Industry - Government program, appear to be verifying these results.

In the US, the EPA recently assessed the overall cancer risk associated with air pollution and as illustrated below concluded that diesel particulate reflected the greatest risk from mobile sources. (In addition, the EPA projections indicate that strategies designed to reduce diesel particulate and hydrocarbon emissions will lower many of the risks in the future.)

TABLE A
SUMMARY OF RISK ESTIMATES

US CANCER INCIDENCES/YEAR

Motor Vehicle Pollutant		1986	19952005
Diesel Particulate	178-860	106-662	104-518
Formaldehyde	46-86	24-43	27-30
Benzene	100-155	60-10[illegible]	67-114
Gasoline Vapors	17-68	24-95	30-119
Other Gas Phase Organics			
1,3-Butadiene	236-269	139-172	144-171
Acetaldehyde	2	1	1
Gasoline Particulate	1-176	1-156	1-146
Dioxins	ND	ND	ND
Asbestos	5-33	ND	ND
Vehicle Interior Emissions	ND	ND	ND
Cadmium	<1	<1	<1
Ethylene Dibromide	1	<1	<1
Total	586-1650	355-1236	374-1099

In Germany, where the diesel engine has enjoyed some of its greatest success, based on its conclusion that diesel particulate reflects an occupational health hazard, the German government recently issued guidelines intended to discourage the use of diesel engines in occupational settings when possible (e.g., substitute electric fork lifts for diesels) or to reduce emissions to the greatest extent feasible (e.g., by using particulate traps or filters).

The USEPA in July 1990 issued a draft document for a series of public workshops entitled "Health Assessment Document for Diesel Emissions". The key conclusions from the study support the IARC conclusion:

" Based on EPA Cancer Assessment Guidelines, there is limited evidence for carcinogenicity in humans, and there is sufficient evidence for carcinogenicity in animals. These findings are supported by additional data from mutagenicity studies as well as the presence of known carcinogens on diesel particles. Therefore, diesel engine emissions are classified into the category B1. This means that the emissions are considered to be probable human carcinogens.

The important question from the above is how the conclusions apply to Colombo residents. All available data indicates that diesel exhaust accounts for a major portion of the respirable particulate in the ambient air along Colombo's arterial streets. We must consider this specific question: whether any of the human based studies noted above and leading to the conclusions regarding increased cancer and other risks represent situations that can be equated to the types of diesel exhaust exposures encountered by drivers, commuters, and others persons spending several hours each day on Colombo streets? The answer must certainly be yes.

2.2. LEAD

Because lead is added to petrol, motor vehicles have been the major source of lead in the air of most cities. Several studies have now shown that children with high levels of lead accumulated in their baby teeth experience more behavioral problems, lower IQ's and decreased ability to concentrate. Based on this evidence, the US National Academy of Sciences concluded that "The evidence is convincing that exposures to levels of lead commonly encountered in urban environments constitute a significant hazard of detrimental biological effects in children, especially those less than 3 years old. Some small fraction of this population experiences particularly intense exposures and is at severe risk." Most recently, in a study of 249 children from birth to two years of age, it was found that those with prenatal umbilical-cord blood lead levels at or above 10 micrograms per deciliter consistently scored lower on standard intelligence tests than those at lower levels.

Evidence of adverse health effects at lower and lower levels of lead continues to grow. Statistical evidence has been found to link lead in adults to increased incidence of high blood pressure.

In late 1991, the US Federal Centers For Disease Control after a careful review of the latest health information again lowered the accepted level of lead in the blood of children. Citing evidence which it said was "so overwhelming and compelling" that children suffer mental problems when their blood contains even 10 micrograms of lead per deciliter, the Agency lowered the acceptable threshold from 25 to 10. Even below 10 micrograms, the Agency noted that some studies indicate adverse effects and indicated that if such evidence continues to be confirmed that the level will be lowered even further.

2.3. LEAD SCAVENGERS

While lead additives improve petrol octane quality, they also cause many problems with vehicles, the most notable being a very significant build up of deposits in the combustion chamber and on spark plugs, which cause engine durability problems. To relieve these problems, lead scavengers have been added to petrol to encourage greater volatility in the lead combustion by-products so they would be exhausted from the vehicle.

A significant portion of these additives are emitted from vehicles which is a matter of concern because 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 US National Cancer Institute. Just within the past year, the German government has recommended a ban on the use of these scavengers because of the health concerns.

2.4. CARBON MONOXIDE

Over 90 percent of the carbon monoxide emitted in cities generally comes from motor vehicles. Because the affinity of hemoglobin in the blood is 200 times greater for carbon monoxide than for oxygen, carbon monoxide hinders oxygen transport from blood into tissues. Therefore, more blood must be pumped to deliver the same amou . of oxygen. Numerous studies in humans and animals have now demonstrated that those individuals with weak hearts are placed under additional strain by the presence of excess CO in the blood. For example, in a recent assessment conducted under the auspices of the Health Effects Institute and summarized at that group's 1988 annual meeting, it was concluded that:

> "These findings demonstrate that low levels of COHb produce significant effects on cardiac function during exercise in subjects with coronary artery disease."

In addition, fetuses, sickle cell anemics and young children may also be especially susceptible to exposure to low levels of CO.

2.5. OXIDES OF NITROGEN

NOx emissions from vehicles and other sources produce a variety of adverse health and environmental effects. NOx emissions also react chemically with other pollutants to form ozone and other highly toxic pollutants. Next to sulfur dioxide, NOx emissions are the most prominent

pollutant contributing to acidic deposition.

Exposure to nitrogen dioxide (NO_2) emissions is linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function. 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) as well as increased sensitivity to urban dust and pollen by asthmatics.

2.6. OTHER TOXICS

Toxic emissions from mobile sources are a serious problem. A variety of studies have found that in individual metropolitan areas, mobile sources are one of the most important and possibly the most important source category in terms of contributions to health risks associated with air toxics. For example, according to the US EPA, mobile sources may be responsible for between 629 and 1874 cancer cases per year. Potentially significant toxics from mobile sources will be reviewed below. Diesel particulate, one of the major toxic compounds emitted by vehicles was reviewed above.

2.6.1. Aldehydes

Formaldehyde and other aldehydes are emitted in the exhaust of both gasoline and diesel fueled vehicles. Formaldehyde is of particular interest both due to its photochemical reactivity in ozone formation and suspected carcinogenicity. Formaldehyde can also be a short-term respiratory and skin irritant, especially for sensitive individuals. Aldehyde exhaust emissions from motor vehicles correlate reasonable well with exhaust hydrocarbon (HC) emissions, and diesel vehicles generally produce aldehydes at a greater percentage rate of total HC emissions than gasoline vehicles. Formaldehyde can also be generated by photochemical reactions involving other organic emissions.

2.6.2. Benzene

Benzene is present in both exhaust and evaporative emissions. Several epidemiology studies on workers have identified benzene as a carcinogen causing leukemia in humans. Mobile sources (including refueling emissions) dominate the benzene emission inventory in most countries. For example, according to the US EPA, roughly 70% of the total benzene emissions come from vehicles. Of the mobile source contribution, 70% comes from exhaust and 14% from evaporative emissions.

2.6.3. Non-Diesel Organics

Gasoline-powered vehicles emit far less particulate than their diesel counterparts. However, the mutagenicity of the gasoline soluble organic fraction (SOF) per mass of particulate collected, is greater than diesel SOF. Because gasoline fueled vehicles accumulate so much travel, the overall impact from gasoline particulate might be significant. It should be noted that the emissions

factors and unit risk estimates for gasoline particulate are far more uncertain than those for diesel fueled vehicles.

2.6.4. Asbestos

Asbestos is used in brake linings, clutch facings and automatic transmissions. About 22 percent of the total asbestos used in the US in 1984 was used in motor vehicles. Health impacts of asbestos exposure have been known for some time, including cancer, asbestosis, and mesothelioma.

2.6.5. Metals

Toxicological impacts of metals, especially heavy metals, have been studied for some time. In addition, many are now being analyzed for their carcinogenic potential, including several for which unit risk values have been published. EPA has identified mobile sources as a significant contributor to nationwide metals inventories including 1.4% of beryllium and 8.0% of nickel. The California Air Resources Board is also analyzing these metals as mobile source pollutants, as well as arsenic, manganese and cadmium. Because of a relatively high unit risk value, emissions of chromium may also be a concern although the health risk tends to be associated with hexavalent chromium which doesn't appear to be prevalent in mobile source emissions.

2.7. EPIDEMIOLOGY STUDIES IN MANILA

A recent study carried out in Manila reached conclusions which may be especially relevant for Colombo. The study covered a cross-section of people exposed extensively to vehicular emissions concerning their respiratory status in 1990 to 1991. It covered 314 jeepney[6] drivers, 262 drivers of air conditioned (AC) buses, and 332 commuters. The study included health questionnaire interviews, pulmonary function tests (PFT), and environmental measurements of personal exposures with respect to TSP, SO_2, CO, total organics (TO), and Lead.

Five key objectives were listed for the study:

a. To measure the prevalence of chronic respiratory symptoms and illnesses the sample population.

b. to determine their lung capacity by measuring their pulmonary function, e.g. forced vital capacity and forced expiratory volume at one minute.

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[6] Jeepneys are a special kind of open minibus with 14 - 24 passenger capacity predominantly equipped with second hand imported Isuzu KC or Isuzu 240 diesel engines. Jeepneys are unique to the Philippines and they play a dominant role in the entire public transportation industry in that country, especially in Manila.

c. To determine personal exposure of study subjects to air pollutants; e.g. TSP, SO_2, CO, and to a more limited extent of CO and lead.

d. To correlate the prevalence of chronic respiratory illnesses to levels of air pollutants; and

e. To correlate the pulmonary function tests of the study subjects with the levels of air pollutants.

As expected, the study found personal exposure to the various air pollutants to be much higher among jeepney drivers than for AC bus drivers, who again had higher exposure than commuters. The study measured 6 hours concentration for everyone, and extrapolated the results to 24-hour concentrations, by assuming that jeepney and AC bus drivers are exposed during 12 work hours a day (but not while at home or not working), while commuters are not exposed outside of the 6 hours during which the measurements were taken.

The study found that WHO's ambient air guidelines were consistently exceeded -- in most cases by a large margin -- for TSP as is also the case in Colombo. Jeepney drivers, being the most exposed of all involved groups, were found to consistently have exposure levels beyond WHO's health guidelines as well as National Ambient Standards for lead, TSP and SO_2. For bus drivers worrisome exposure was noted in the case of TSP only. In looking at the health aspects the study considered age, smoking habits as well as the length of employment in present occupation, and previous occupation. Aside from smoking habits such variables did not appear to play a major explanatory role.

Four chronic respiratory symptoms were measured (wheezing, shortness of breath, chronic cough, and chronic phlegm production), and were found to be significantly (more than twice) higher among jeepney drivers than the others in the sample. Bus drivers were seen to have higher prevalence of wheezing and shortness of breath than commuters, but no such differences were detectable with regard to chronic cough and chronic phlegm production. For all groups prevalence was considerably higher among smokers than non- and ex-smokers.
Chronic respiratory illnesses (COPD, pulmonary tuberculosis, and previous pulmonary illnesses) were found to occur twice as frequently among jeepney drivers as among the others. Similarly, for pulmonary functions, the jeepney drivers consistently showed lower values than the others.

2.8. EXPOSURE TO VEHICULAR AIR POLLUTION

Drivers seated in open vehicles for as much as 13 hours per day 20 days a month must be considered long term and highly exposed to the pollutants from diesel and gasoline fuels. The actual exposure and its composition must be established but should presumptively be considered similar to Manila's as is discussed elsewhere.

In addition, several thousand bus drivers, bus conductors, taxi drivers and drivers of other public utility vehicles in Colombo are close to a similar long-term exposure, although being inside closed vehicles (e.g. taxis) may reduce the risk slightly. Furthermore, many people who have

their work on or along the streets are exposed to the so called "canyon effects" of pollutants, even inside their commercial building workplace or residential dwellings.

2.9. IMPLICATIONS FOR FUTURE ACTION

Particulate matter is the vehicular pollutant of dominant concern, but nitrogen oxides, sulfur oxides, lead, carbon monoxide and hydrocarbons are also worrisome from a health and human well being perspective.

The preliminary control strategies developed in this study (see Chapter 5) will address actual and potential hazards from all of these pollutants. The proposed inspection and maintenance program will reduce CO and HC. The phase-down of lead in gasoline and sulfur in diesel are key to reducing these pollutants. But most important from a health perspective are the controls to reduce excessive diesel emissions, i.e. effective I & M of vehicle fleets, anti-smoke belching measures, restrictions on imports of second-hand engines, and the proposal to gradually reduce the diesel encouraging subsidy of certain types of vehicles.

CHAPTER 3. EMISSIONS WHICH CONTRIBUTE TO THE PROBLEM

A walk through the streets of Colombo indicates that motor vehicles are clearly the dominant air pollution source, although certainly not the only one. However, in order to develop an effective package of countermeasures, it is critical to have a more in depth understanding of the emissions problem. Questions to be answered include: 1) How much does each vehicle type contribute to each of the pollution problems?; 2) What are the trends with regard to each of these sources, i.e., how much will overall emissions increase or decrease if current trends continue and which vehicle types will be the dominant sources in the future. This chapter will focus on the first question while Chapter 4 will attempt to answer the second.

3.1. MOTOR VEHICLE EMISSIONS INVENTORY METHODOLOGY

Calculating motor vehicle emissions involves determining the size of the vehicle population, subdivided by vehicle type, estimating the kilometers driven per vehicle per year, measuring the emissions rate of each pollutant by vehicle category (grams per kilometer driven) and then combining them according to the following formula:

# of VEHICLES X Gm/KM X KM/YR X TONS/GRAM = TONS/YEAR.

For fuel related pollutants such as lead and sulfur, one must estimate the amount of each constituent in a volume of fuel and combine it with the fuel efficiency of the vehicle according to the following formula:

GM/GAL X GAL/MILE X MILE/KM X KM/YEAR X TONS/GRAM = TONS/YEAR

3.2. BASELINE INPUTS

The 1990 baseline figures for the motor vehicle fleet of the Sri Lanka were used as the starting point for estimating 1990 vehicular emission in Colombo. Figure 1 and Table B illustrate the rapid growth which has occurred in virtually all vehicle categories over the past fifteen years. It was estimated that approximately 50% of the country's vehicles are used in Colombo. Figure 2 and Table C illustrate that high growth rates for all vehicle categories, but especially motorcycles, have continued throughout the 1980's; the only year in which growth declined for some vehicle categories was 1987.

The growth in vehicles in the past decade is not unusual nor surprising. The growth in demand for motorized travel in recent decades in most regions of the world is well understood. As urban areas populate and expand, land which is generally at the edges of the urban area and previously considered unsuitable for development is developed. The distance of these residential locations from the city center or other sub-centers increases, increasing the need for motorized travel. Motorized travel in private vehicles supplants traditional modes of travel such as walking, by bicycle, water, and even mass transit. Needs for private vehicles are reinforced as declining population densities distant from urban centers reduce the economic viability of mass transit.

The evolution urban forms is influenced by the growth of income and accompanying increases in the acquisitions of private motor vehicles and changes in travel habits. As incomes rise, an increasing proportion of trips shifts, first to motorcycles and, as income increases further to private cars. The trend toward private motorization is not inevitable but is also influenced by public policy towards land use, housing, and transportation infrastructure. While the proportion of middle and upper income households in developing and newly industrialized countries able to afford cars and motorcycles is lower than in industrialized nations, the number of private vehicles still becomes very large as the middle and upper income groups grow in megacities. The number of vehicles and levels of congestion are comparable to or exceed that of major cities in industrialized countries. With the increase in motorized travel and congestion come increases in energy use, emissions and air pollution.[7]

Recent trends in vehicles per capita throughout Sri Lanka are summarized in Figure 3 and show a steady trend with twice as many motorized vehicles per thousand people in 1990 as in 1980. Figure 4 shows that while the trend was fairly steady, increasing at 1 to 2 vehicles per 1000 people per year during the first half of the 1980's, since 1987 it appears to have accelerated. Figure 5 which illustrates the annual incremental growth rates in population, GDP per capita and vehicles per capita, indicates that the recent spurt in GDP per capita may be the driving force behind the surge in vehicles per capita.

The vehicle type and fuel use breakdown assumed for 1990 was taken from official registration statistics and is summarized in Figure 6. Emissions factors used in this study and other important variables are summarized in Table D.

3.3. CALCULATIONS OF VEHICLE EMISSIONS

Using the methodology described in Section 3.1, and the vehicle characteristics summarized in Figures 1 and 6, emissions of particulate, sulfur oxides, lead, nitrogen oxides, carbon monoxide, carbon dioxide and hydrocarbons were calculated. Results are summarized in Figures 7 through 12, respectively. These data lead to the following overall conclusions:

1. Diesel fueled vehicles are the primary source of particulate, sulfur and NOx emissions as well as a significant source of carbon dioxide. Trucks and buses representing less than one fifth the vehicle population and 40% of the annual driving contribute approximately two thirds of the particulate and nitrogen oxides.

2. Gasoline fueled vehicles are the primary source of lead and hydrocarbons, and carbon monoxide emissions and a significant contributor to NOx.

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[7] "The 1990 TDRI Year End Conference, Industrializing Thailand And Its Impact On The Environment, Research Report No. 7, Energy and Environment: Choosing The Right Mix", December 1990.

CHAPTER 4. MOTOR VEHICLE EMISSION PROJECTIONS FOR THE YEAR 2005

4.1. METHODOLOGY

The study chose 2005 as the operative time horizon for the projected vehicular emission scenarios since the historical and projected rate of vehicle and engine replacement is rather slow. In the long term new vehicle standards will be a key strategy; even by 2005 complete vehicle turnover will not have occurred, but it will provide some sense of the potential significance of new vehicle standards and the establishment and effective functioning of the various control measures proposed in Chapter 5.

4.2. YEAR 2005 PROJECTIONS

As noted earlier, the vehicle population of the country has approximately quadrupled over the past 15 years. Based on current trends, this could certainly happen again in the next fifteen years. In carrying out this preliminary assessment, however, it was conservatively assumed that vehicle growth would slow down, reflecting increased concern with the environment, greater congestion and likely somewhat higher fuel prices. As illustrated in Figure 14, even accounting for these factors, it seems likely that without government intervention to encourage alternative paths to development, more than twice as many vehicles will be on Colombo's roads fifteen years from now as are today. Further, as illustrated in Figure 15, a greater proportion of these vehicles will be motorcycles than at present.

Emission projections for 2005, assuming no shift in relative fuel prices and no shift in government policies and incentives as regards import regulations and incentives for vehicles, engines and spare parts, will be proportional to the growth in vehicles. As a result, today's already unacceptable air quality will be that much worse with truly devastating effects on public health and the quality of life. Particulate and other levels which are already excessive will be much more so and lesser problems such as CO will likely routinely exceed internationally accepted norms. This is not inevitable, however. Policy measures which appear reasonable and doable could reverse this high pollution trend and actually lower emissions in absolute terms in spite of relatively high vehicle growth. Suggested strategies will be the subject of the next chapter.

CHAPTER 5. APPRAISAL OF EMISSION IMPROVEMENT MEASURES

Design of a comprehensive motor vehicle pollution control program can have several elements including some or all of the following:

1. setting standards which apply to new and in use vehicles,
2. requiring devices to be retrofitted to existing vehicles,
3. modifying fuels and requiring the use of certain fuels in certain vehicles, and
4. controlling traffic and improving traffic flow.

In addition, enforcement methods are usually introduced to assure that these strategies achieve their maximum emissions reductions. When viewed in the aggregate, these compliance tools should address in a comprehensive fashion the problem of controlling emissions from in-use cars. They should among other things, encourage individuals to properly maintain their vehicles and the service industry to perform this maintenance properly.

5.1. VEHICLE EMISSION CONTROL THROUGH INSPECTION AND MAINTENANCE

It is essential to strengthen the existing vehicle anti smoke campaign in Colombo in order to assure that investments in vehicle emissions control yield their intended benefits. Without the improvement in the quality of the vehicle repair industry prompted by an effective Inspection and Maintenance (I/M) program, emissions will be significantly higher than the vehicles would otherwise be capable of achieving. This is particularly important for the diesel engines but will impact on all vehicles.

This strategy is aimed at strengthening and making more efficient the current Anti-Smoke Belching campaign in the Colombo Area. Key elements would:

- expand the current inspection system to cover all vehicles annually, using more advanced equipment, test procedures and inspection stations to increase the effectiveness and accuracy of inspections;

- increase the stringency and coverage of inspections and enforcement for high use vehicles such as taxis, trucks, and buses, and existing light duty vehicles and eventually increase the coverage to modern catalyst equipped passenger cars by establishing a 1990's version enhanced I/M system with more effective test procedures;

- improve the quality control, data analysis and enforcement elements of the current I/M program; and

- improve personnel training to improve the effectiveness and cost effectiveness of repairs.

5.1.1. Strategy Objectives

Reduce excessive emissions/Km from current stock of vehicles;

Assure continued operation and efficiency of emission control investments in new and imported vehicles;

Improve the quality of the vehicle service industry;

Accelerate the scrappage or removal from the Colombo Area of older, high-polluting vehicles by requiring them to meet emissions standards or undergo repairs;

Improve maintenance standards for vehicles in the Colombo Area;

Reduce the operating costs of vehicle ownership.

5.1.2. Background - The In Use Vehicle Problem

Vehicles in use have consistently been found to emit pollutants well in excess of their design capabilities. Causes include poor maintenance, deliberate tampering or misfueling in a (usually futile) attempt to improve performance or fuel economy, and poor vehicle durability. Experience further suggests that all vehicles perform better after being maintained and adjusted properly. Inspection and Maintenance (I/M) programs are one of the best ways to bring this about by identifying cars which need remedial maintenance or adjustment and requiring repair of those cars. It encourages vehicle owners to keep their cars in a good state of repair, the service industry to do the maintenance properly and the manufacturer to make vehicles more serviceable and durable.

5.1.3. Emission Improvements

Based on all the data available, it is estimated that a well run I/M program is capable of very significant emissions reductions, on the order of 40% for HC and CO without increasing NOx. A study conducted for the State of California concluded that bus I/M could reduce overall particulate by 35%. (As used in this analysis, the term I/M means any method of systematic inspection and corrective maintenance including but not limited to an actual emissions test.) A more recent analysis conducted for California has found that poor maintenance and tampering increase actual particulate emissions from 76 to 85 percent. Studies conducted by the Colorado Department of Health have also found that smoke opacity levels can be reduced significantly through maintenance and repairs of light duty diesel vehicles.

5.1.4. Fuel Economy Impact

While the results are quite variable, it seems to be the consensus that there is a significant fuel economy improvement attributable to the improved vehicle maintenance practices associated with

an effective I/M program. Values reported in the literature range from zero to about 7 percent; in calculating cost effectiveness the US EPA uses a figure of 3.5 %. A TNO study conducted in the Netherlands showed a 6% improvement in fuel consumption. This improvement translates directly into dollar savings to the vehicle owner.

5.1.5. Driveability Benefits

While difficult to quantify, improved vehicle maintenance as a result of an I/M program can be expected to improve overall vehicle performance and driveability. Vehicle owners perceived improved driveability on 35 to 45% of the vehicle repaired in the Oregon program compared to 5 to 13% noting worse driveability.

5.1.6. Link With Safety

A number of I/M programs are conducted in conjunction with a safety inspection. This is usually done by checking such items as lights (low-beams, high-beams, running lights, brake lights, backup lights, emergency flashers, and turn signals), brakes, tires, horn, windshield wipers, and vehicle glass.

5.1.7. Test Alternatives

Inspection and Maintenance tests can take many forms. In their simplest form, vehicle exhaust gases are sampled while the engine is idling and those vehicles with excessive carbon monoxide or hydrocarbons are required to undergo remedial maintenance and pass a retest. Some programs include a tampering check which can range from a quick visual inspection under the hood of the car to see that emissions controls have not been removed to a more thorough check which can include efforts to identify misfueling with leaded gasoline. Frequently, the idle test will include an acceleration of the engine to 2500 rpm and occasionally the vehicle will be placed under load on a dynamometer. For diesel vehicles especially, placing a vehicle under load is extremely critical. What this indicates is that I/M programs reflect a level of effort in proportion to the overall benefits desired. Significant benefits can be obtained with relatively little effort and additional gains are possible as the level of effort increases.

5.1.8. Administrative Options

The program types can be broken down into two categories: decentralized and centralized. Decentralized programs generally involve having I/M tests performed at local repair shops (private garages) and auto dealerships. In most cases, the establishment performing the test must have applied for and received an inspection license from the state. A vehicle which fails the inspection test may be repaired at the same facility and then reinspected. Almost two thirds of the programs are decentralized.

Centralized programs involve the testing of vehicles at specialized test facilities capable of handling a high volume of vehicles. Centralized programs may be contractor-run, state-run, or

locally-run. The centralized program, however, is never run by an organization which is involved in automotive repair. Therefore, vehicles which fail have to be repaired at another location. and returned to the centralized site for reinspection. Of the centralized programs, contractor-run programs are, by far, the most prevalent, at least in the US, accounting for one fourth of the total number of programs. State-run and local-run programs each account for only a few of the total.

Recent EPA audits have identified some I/M programs which appear to do a poorer job than others. The major problems are related to low failure rates (substantially fewer vehicles failing the program than anticipated based upon the test standards adopted) in decentralized I/M programs with manual analyzers. The two major causes of the low failure rates are poor instrument quality control and, in some cases, cheating.

The best techniques identified to solve these problems include computerized analyzers with tight control of stickers and test documentation coupled with more widespread covert surveillance with stiff penalties for violations.

5.1.9. Enforcement

There is a significant difference between various I/M programs concerning the method of enforcement used. The most popular and most effective method is to require compliance with the I/M program requirements as a prerequisite for vehicle registration renewal. Others rely on the "sticker" method which requires that all appropriate vehicles (those included in the program) display (usually on the windshield) a current sticker. If a vehicle is required to be tested and does not display a current sticker, an enforcement officer may fine the vehicle owner.

5.1.10. Conclusions Regarding I/M

1. I/M programs have been demonstrated to lower emissions from existing vehicles in two ways;

   a. By lowering emissions from vehicles which fail the test and are required to be repaired.
   b. By encouraging owners of vehicles to take proper care of them and to avoid the potential costs of repairing vehicles which have been tampered with or misfueled.

2. Based on extensive data collected from vehicles which have experienced an actual, operating I/M program, the simplest inspection test, the idle test, has been demonstrated to be quite successful in identifying those petrol cars which are most in need of remedial maintenance and are polluting excessively. Diesels usually require a load on the engine.

3. Repairs performed on these high polluters have been successfully performed by actual mechanics in repair garages resulting in substantially lower emissions at reasonable cost.

4. The lower emissions are sustained for sufficient time to actually improve air quality.

5. New cars with the most advanced technology are capable of very low or very high emissions depending in large part on routine maintenance, tampering and misfueling. By assuring good maintenance practices and discouraging tampering and misfueling, I/M remains the best demonstrated means for protecting a national investment in this advanced emission control technology and achieving the air quality gains which are needed.

6. More advanced I/M techniques than are currently in general use offer significant potential to further increase the overall benefits from I/M in the future.

7. As a general matter, maximum I/M effectiveness occurs with centralized I/M systems.

As a companion to the mandatory periodic I/M program, the Police should continue to enforce on the road smoke levels. This effort will be enhanced by the introduction of smoke meters[8] because they will allow the police not only to assure objective testing but also to set up specific smoke teams with management oversight to assure that they focus attention on this problem.

In addition, clean, well maintained vehicles require high quality spare parts. Consideration should be given by the government of adopting a policy which would lower the import duty on certain spare parts such as diesel fuel injectors which are critical to maintaining low pollution diesel performance.

5.2. CLEANER FUELS

5.2.1. Lead Content of Gasoline

Colombo has one of the dirtiest fuels in the Region if not in the world. While unleaded gasoline is being phased in throughout the region and the level of lead in leaded gasoline is increasingly at 0.15 grams per liter or less, Colombo still has no unleaded gasoline at all, and adds 0.45 grams per liter of lead to the gasoline.

Solving the lead problem in Colombo should be very straight forward, and involves merely not adding lead to gasoline. However, as a result of such a transition, the gasoline must be further refined at the refinery to achieve the same octane level, or other less harmful additives will need to be substituted, such as oxygenates.

The incremental lead removal costs, a couple of cents per gallon, are so small that they are well within the normal market induced gasoline price fluctuations, and would thus hardly be noticed in the accounts of the driving population if the refineries were to recover the above conversion costs through increased gasoline prices.

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[8] Approximately twenty five Hartridge smoke meters have been subsidized by the German government and are expected to be in use in Colombo by October. In addition, UNIDO is evidently considering the purchase of additional meters for use by the police.

However, refineries are unlikely to phase out lead unless directed to do so by the authorities. A lead reduction program towards 0.15 grams per liter in gasoline should begin immediately following a government directive to the refineries. The justification for such a directive could clearly be based solely on the health hazards described above. At the same time tax policy should be modified to encourage the introduction of unleaded fuel. This would not only further reduce the lead emissions, it would open up the possibility of introducing catalytic technology into the vehicle population with potential significant benefits to the emissions of CO, HC and NOx. With no unleaded petrol at present, Colombo is in the perverse situation where, used vehicles which are imported into the country from Japan, and which are routinely already equipped with catalytic converters[9] have these converters removed or destroyed because they cannot function with leaded petrol.[10] Any unleaded petrol introduced should be priced at no more than the leaded competition and depending on the available supply possibly priced less. Over a gradual but not too lengthy time period, unleaded petrol should be the norm and priced well below leaded.

Unleaded petrol is increasingly the norm throughout the world. Three out of four new cars manufactured in 1992 come equipped with catalytic converters and must use unleaded petrol. Most others manufactured this year and for many previous yeas can use unleaded petrol. For example, over 95% of the gasoline used in Japan for more than a decade has been unleaded, with leaded fuel mainly confined to agricultural equipment. Therefore virtually all of the used vehicles from Japan and most of the new ones could thrive on unleaded fuel.

The major advantage of lead as a fuel additive is that it is a cheap source of octane, a fuel constituent that allows high performance and efficiency. Modern refineries can produce the necessary octane without lead. Those that can't still have the option of using alternative octane enhancers which while slightly more expensive in direct costs, more than pay for themselves in reduced vehicle maintenance.

5.2.2. Sulphur Content of Diesel Fuel

Sulfur is present to a greater or lesser extent in all crude oils and, as a result of the distillation process, some sulfur compounds which boil in the same range are present in streams used for diesel fuel blending. During combustion, they burn to form acidic by products (sulfur dioxide, SO_2, and trioxide, SO_3) together with other gases and also solid compounds such as sulfates. The gases will have an influence on exhaust odor, while the sulfates will contribute to particulate.

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[9] Catalytic converters have been installed on new cars in Japan for more than fifteen years.

[10] As lead in petrol passes through an engine it comes in contact with the catalytic converter. The precious metals which are the primary active ingredients in the converter to facilitate the reduction of CO, HC and NOx are poisoned by lead and rendered inactive in a very short period of time.

In addition to a direct reduction in emissions of SO_2 and sulfate particles, reducing the sulphur content of diesel fuel reduces the indirect formation of sulfate particles from SO_2 in the atmosphere. In Los Angeles, it is estimated that each pound of SO_2 emitted results in roughly one pound of fine particulate matter in the atmosphere. In this case, therefore, the indirect PM emissions due to SO_2 from diesel vehicles are seen as very significant.[11]

Further, in the longer term as new vehicle standards are tightened, low sulfur diesel fuel will be necessary to allow the use of certain diesel particulate control technologies. Precious metal catalysts which are already in use on diesel vehicles in certain areas of the world to reduce particulate cannot be used with high sulfur fuel because they tend to also convert the SO_2 emissions from such vehicles to the hazardous form of SO_3.

The technology for reducing the sulfur levels in diesel fuel is well understood - essentially additional hydro-desulfurization at the refinery. It has been estimated that low sulfur fuel can increase the price of diesel fuel by a few cents per gallon.

5.3. CLEAN TWO STROKE MOTORCYCLES (MC)

Motorcycles represent a large and growing portion of the Colombo vehicle population. Because about forty percent of them are equipped with two stroke engines (which combine the fuel and lubricant in the combustion process), their contribution to the overall air pollution burden of the city is disproportionate to their numbers. For example, it has been estimated that these motorcycles emit up to fifty percent more hydrocarbons per kilometer driven than do much larger passenger cars; for particulate they emit almost as much as buses and lorries, per kilometer driven.

Technology exists to replace the high polluting two stroke engines with cleaner engines. For example, the same vehicles could be powered by much cleaner four stroke engines (where the lubricant and fuel are separated). Alternatively, the two stroke engines could be required to be much cleaner. For example, in Taiwan, two levels of controls have been imposed on motorcycles. The first, relatively modest stage went into effect in 1988; more stringent standards began on July 1, 1991. This latter requirement is intended to either require substantial control of or the elimination of two stroke motorcycles. The new motorcycle standards are 4.5 grams per kilometer for CO (from 8.8), and 3.0 for HC and NOx combined (from 6.5), based on the ECE R40 test procedure. In anticipation that two stroke engines will still be able to comply, the Taiwan EPA is considering an additional tightening of motorcycle standards in 1993 or 1994.

It is proposed that Colombo implement the same requirements for imported motorcycle engines as Taiwan.

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[11] SO_2 conversion to particulate matter is highly dependent on local meteorological conditions, however, so the effects could be greater or less in other cities such as Colombo.

5.4. SHIFT IN CERTAIN DIESEL VEHICLES TO GASOLINE

As noted in Chapter 2, following a meeting in Lyon on June 14-21, 1988, the World Health Organization International Agency for Research On Cancer (IARC) Working Group concluded that there is sufficient evidence to conclude that diesel exhaust is probably carcinogenic in humans. While improving maintenance as a result of the I/M program discussed above will be helpful in reducing emissions, the only truly effective solution is to reduce the reliance on diesel engines where economically and socially feasible. This has been the pattern with certain vehicles in other major cities such as Bangkok, Seoul and Tokyo. Especially with a fleet of used engines which it appears impossible to satisfactorily regulate otherwise, substitution of an inherently clean alternative (at least with regard to particulate) makes the most sense.

It is therefore proposed to require the gradual phaseout of diesel engines from urban vans which are not primarily used as lorries. While in fact the cost of gasoline engines will be less than the comparable diesels, and the maintenance expenses lower, the primary cause of diesel dominance in this vehicle category is the price subsidy given to diesel fuel. Therefore it will be necessary to provide an incentive for the conversion of diesel vans to gasoline. Raising the diesel fuel price could effectively eliminate the economic incentive for diesel usage and make the choice of gasoline or diesel revenue neutral. However, this would raise concerns regarding increased costs to bus companies and lorries. The best solution would appear to be a modification of vehicle taxes to shift the economic advantages to gasoline rather than diesel.

In addition to reducing particulate emissions directly, since gasoline vehicles are inherently cleaner than diesels with regard to particulate, this strategy has several additional advantages:

1. It is more compatible with the existing refinery capability.

The present situation with a growing shortage of diesel fuel indicates that diesel is underpriced and gasoline overpriced. This is a direct result of government intervention into the marketplace. To meet the demand for diesel by expanding refinery capacity and importing more crude is a capital intensive and cost inefficient solution from a national economic perspective.

2. Greater gasoline use would help lower diesel sulfur levels.

An additional irony of the distorted diesel - gasoline market is that diesel fuel sulfur levels remain too high because the hydro-desulfurization capability is limited by a shortage of hydrogen. Shifting the refinery mix to a greater production of gasoline relative to diesel would produce additional hydrogen as a by product; this hydrogen could be used in the desulfurization process to lower sulfur levels even more.

There appears to be a virtual win-win situation facing decision makers here:

* The air quality will improve for drivers, passengers and all those who are residentially or through employment exposed to vehicular air pollution. This will for some have

tangible positive health impacts, which again could improve labor productivity and earnings potentials, and it would make leisure time more pleasant. Less resources would be needed for washing, cleaning, painting, corrosion repair, etc.

* The refineries will be able to achieve a much better supply-demand balance for their output mix, and thus avoid costly expansion investments to cater to diesel demand increases.

The need to expend precious national resources on the importation of diesel fuel would be eliminated.

5.5. VEHICLE STANDARDS

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. (See Appendices A and B) It is now technically possible to reduce CO, HC and NOx emissions from petrol fueled vehicles by more than 90% from typical levels in Colombo. While diesel technology is not quite as advanced, it is capable of 60 to 70% reductions today and continuing to improve rapidly. While introduction of these technologies on a portion of the fleet will not eliminate the pollution problems overnight since replacement of the fleet is a gradual process, over time it has been demonstrated around the world to be a very effective antidote to continued growth in vehicle pollution.

A particular aspect of new vehicle standards which is critical is the overall enforcement. Tight standards are meaningless if individuals are allowed to import vehicles with no pollution controls; therefore, a policy of tight standards must be coupled with an overall policy of gradually restricting the importation of new or used high pollution vehicles or engines.

5.6. ASSESSMENT OF EMISSION IMPACTS.

Reductions in pollution associated with the various strategies are summarized in Figures 16 and 17 for gaseous and particulate emissions, respectively. Focusing on particulate emissions first, it can be seen that the I/M program can begin to reduce particulate emissions significantly from the levels to which they are otherwise expected to rise by 2005. Further, reducing the sulfur and lead content of diesel fuel and gasoline, respectively, will lower sulfur and lead emissions dramatically. Requiring (or effectively encouraging) a portion of the urban vans to shift from diesel to gasoline engines and tightening requirements on two stroke motorcycles will have a major impact on the remaining particulate emissions, lowering them almost to today's levels. Since less diesel fuel will be used, sulfur emissions will also decline; since more gasoline will be consumed, lead levels will actually increase slightly. In both these latter cases, emissions will remain below today's levels. An additional measure which would further reduce particulate emissions is the conversion of buses to CNG; while this will only have a modest effect on total emissions throughout the region, it is estimated that it would have a significant effect on some of the densely populated, high bus use urban corridors. A gradual tightening of new vehicle

standards would also lower emissions and as more and more vehicles are phased in this impact will rise over time in the period beyond 2005.

Looking to gaseous emissions, Figure 16 illustrates that I/M would also have a significant impact on HC and CO emissions. Tight motorcycle standards, by either reducing or cleaning up two stroke engines, would have an additional benefit for HC. The conversion of selected diesel vans to petrol fuel would actually increase CO and HC emissions somewhat but these increases would be more than offset by the introduction of tighter new vehicle standards. And again, the benefits of new vehicle standards will continue to increase beyond 2005.

Tables E and F indicate that very significant progress in reducing pollution across the board can result from adoption of this comprehensive but feasible package of measures. In spite of a more than doubling of the vehicle population, emissions in 2005 could be less than they are today, thereby bringing levels of these hazardous emissions more in line with international accepted air quality levels. Over time these levels could be lowered further.

5.7. THE CRITICAL ROLE OF ENFORCEMENT

Of course there are many good rules and regulations, and there have been important enthusiastic initiatives accompanied by public information campaigns, e.g. the Anti-Smoke Belching Campaign. Many such initiatives have been of a project nature, i.e. as an ad hoc arrangement void of any provision for integration into a permanent public agency empowered to take responsibility for sustained monitoring and enforcement. The activity is thus sustained for the duration of the project only. Budgetary provisions for sustained activity after project completion have been missing, and the likelihood is that such initiatives falter and die once project funding is dried up. The lack of permanent integration towards sustained operations appears to be the overwhelming characteristic of the prevailing situation.

While the anti smoke belching initiative and activity and the accompanying public information campaign was an important measure to be maintained for public awareness raising, it cannot remedy the structural deficiency of the Colombo vehicle fleet as regards low fuel efficient - and highly polluting engines. It will be important with this program to remove some of the worst smoke-belchers from the streets, but the large majority of old and second hand engines will continue to emit more than what modern, well-tuned and maintained engines do.

Therefore, a comprehensive vehicle inspection and maintenance program linked directly to annual vehicle registrations is proposed as a key immediate action measure in this study. Further, the institutional arrangements between various Ministries involved in vehicle pollution control need to be streamlined and tightened up. Clear lines of authority and responsibility with accountability will be critical to the success of any future efforts in this area.

CHAPTER 6. ECONOMIC AND INSTITUTIONAL BARRIERS IMPLEMENTATION

Implementation of the strategy package outlined above is undoubtedly technologically feasible but this is usually only half the answer. In addition, several other impediments to implementation must normally be overcome. Change of any kind upsets the status quo and therefore requires that there be an understanding of the reasons for the change and the political will to proceed. Those who perceive that their self interest is threatened by the change must be counterbalanced by others who perceive that they will benefit. In addition, it is often the case that those who are threatened by the change, misunderstand the full impact. Therefore a key element in proceeding with a motor vehicle pollution control strategy must be a broad based public information campaign. Major elements of the campaign must include a focus on the public health and other consequences of business as usual. Further, an accurate assessment of the true costs and other consequences of action must be made publicly available. In many cases, it will be possible too show that individual strategies will result in economic benefits as well as costs and in a few cases the economic benefits will exceed the costs, even if one ignores the health benefits which are clearly the prime motivation but which are frequently difficult to quantify.

Success will also depend on political will to act and take the case for action to the people. So armed, the strategies identified above should all be practical, as discussed below.

6.1. LEAD IN PETROL

Most countries worldwide are drastically reducing the lead content in gasoline. The scope for following suit in the Sri Lanka looks promising, and the health gains could be substantial. Solving the lead problem in Colombo should be straight forward. It simply involves not adding lead to gasoline. However, as a result of such a transition, the gasoline must either be further refined to achieve the same octane level or other less harmful additives must be substituted.

Reducing lead in petrol will extend spark plug life and increase the interval necessary for oil changes. In addition, exhaust system and muffler life will be extended. Over the life of a vehicle, therefore, the cost to the consumer of switching completely to unleaded petrol should be virtually nil or even a net saving.

However, the refineries are unlikely to phase out lead unless directed to do so by the authorities. A lead reduction program towards 0.15 grams per liter in gasoline should begin immediately following a government directive to the refineries. Such action is fully justified solely on the basis of the health hazards described above. In addition, a grade of unleaded petrol must be introduced if catalytic converter technology is to be feasible and if the path can be paved toward eventual elimination of leaded in petrol. Tax policy can be modified in a revenue neutral manner to encourage consumers to purchase the unleaded petrol when it becomes available.[12]

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[12] When Hong Kong introduced unleaded petrol in the Spring of 1991, prices were modified to make unleaded cheaper to the consumer than leaded. As a result, in one month, unleaded sales soared from 0 to over 50%.

6.2. LOW SULFUR FUEL

Sulfur is present to a greater or lesser extent in all crude oils and, as a result of the distillation process, some sulfur compounds which boil in the same range are present in streams used for diesel fuel blending. The technology for reducing the sulfur levels in diesel fuel is well understood - essentially additional hydro-desulfurization at the refinery. It has been estimated that low sulfur fuel can increase the price of diesel fuel by a few cents per gallon. Partially offsetting this increased price is the increased engine durability which is likely to occur since the acids which form in the lubricating oil as a result of the sulfur in the fuel are a significant cause of engine wear.

6.3. INSPECTION AND MAINTENANCE

Sufficient flexibility exists in the design of inspection maintenance programs such that an approach can be tailored to the needs of Colombo in such a way that government expenditures can be minimized and overall costs to the public can be virtually eliminated.

The program types can be broken down into two categories: decentralized and centralized. Decentralized programs generally involve having I/M tests performed at local repair shops (private garages) and auto dealerships. In most cases, the establishment performing the test must have applied for and received an inspection license from the state. A vehicle which fails the inspection test may be repaired at the same facility and then reinspected.

Centralized programs involve the testing of vehicles at specialized test facilities capable of handling a high volume of vehicles. Centralized programs may be contractor-run, state-run, or locally-run. The centralized program, however, is never run by an organization which is involved in automotive repair. Therefore, vehicles which fail have to be repaired at another location, and returned to the centralized site for reinspection. Of the centralized programs, contractor-run programs are, by far, the most attractive, accounting for one fourth of the total number of programs in the US, for example. The advantage of a contractor run approach is that the cost to the government is virtually eliminated. In a typical design, a contract is signed which guarantees the contractor a minimum number of tests for a period of time (usually five years) for a fixed fee per test. In return the contractor is required to make the entire investment required, build and instrument all the facilities, and operate the lanes. A portion of the inspection fee can be designated for the appropriate government agency to cover the costs of government oversight. Such oversight is necessary as a check to be sure that the contractor is properly testing vehicles, has good quality control procedures, etc.

While the consumer must pay the cost of the inspection and any required repairs, this cost can be offset by the reduced fuel consumption and greater durability which usually accompanies proper repairs to grossly emitting vehicles. It should be noted that this should be true on average; individual consumers with vehicles requiring major repairs may not be able to fix their

vehicles sufficiently to pass the test, or such repairs may be so expensive as not to be offset by any improved efficiency. Such vehicles must be repaired or retired for the greater public health good of the community as a whole.

6.4. ADOPTION OF VEHICLE EMISSION STANDARDS

Standards on new vehicles impose an additional cost on the purchasers of these vehicles, usually in the case of the most stringent requirements, on the order of approximately 3 to 5% of the manufacturer's retail price for the vehicle. This is a relatively modest price to pay for the dramatic pollution reduction which can result as these vehicles gradually replace the existing vehicle fleet.

As a phase in strategy prior to mandating the adoption of low emission vehicles, tax policies could be modified in a revenue neutral fashion to make it cheaper to import low pollution vehicles and more expensive to bring dirty vehicles into the country. For example, any vehicle which has a certificate as complying with new vehicle standards of Japan, the EC or the US could pay a lower duty whereas vehicles without such a certificate would pay a higher duty, one designed to assure that the absolute price is higher for the dirty vehicle than for the clean vehicle.

6.5. A SELECTIVE SHIFT FROM DIESEL TO GASOLINE VEHICLES

The needs and advantages of this course have been discussed above. (See section 5.4.)

CHAPTER 7. IMPLEMENTATION

In a perfect world, with unlimited resources, one might wish to implement all of the above strategies, simultaneously, at the very start of a program. This is very rarely, if ever, feasible or practical, however, and could even be counterproductive.

Therefore, it is necessary to make decisions about how to phase in the various strategies. One such approach is to devote the early stages of the program to laying a firm foundation for further action. Primary steps are the adoption of necessary and feasible standards, widespread distribution of necessary fuels, the imposition of limitations on importing vehicles which have not been certified solely to individuals (rather than commercial companies), introduction of voluntary I/M programs (which means every vehicle must be inspected but repair and retest is not yet mandatory), and the design and construction of necessary government testing facilities for future programs.

In the second phase, the requirements are gradually tightened. I/M becomes mandatory and is gradually made more stringent, importation of non certified cars is severely restricted, and selective EPA testing is used to verify certification or type approval results provided by vehicle manufacturers.

Finally, as the fundamental structure gets accepted, it can be gradually and routinely tightened. For manufacturers, standards can be made more stringent by linking them directly to requirements in other regions of the world where vehicles are primarily manufactured. For example, a requirement can be imposed that all vehicles imported into a country such as Sri Lanka must be approved and covered by a certificate issued by either Japan, the EC or the US. Fuels can also continue to be improved as the state of the art advances around the world. I/M program standards and enforcement can be further tightened.

CHAPTER 8. OVERALL CONCLUSIONS

As a result of this study, it is possible to draw several conclusions:

1. Air quality measurements in Colombo indicate that a large proportion of the population is exposed to various air pollutants such as particulate matter (TSP), sulfur dioxide (SO_2), nitrogen dioxide, carbon monoxide (CO) and lead at levels above the WHO guideline values.

2. The data indicate that particulate matter is the overwhelming pollutant of concern followed by NO_2, SO_2, and lead. Carbon monoxide levels also occasionally exceed accepted standards, but particulate matter levels consistently exceed concentrations above which health effects have been identified, and frequently by a factor of two or more.

3. In terms of exposure to these pollutants, bus drivers and three wheel vehicle drivers are at the greatest risk of adverse health effects in view of the duration and extent of their exposure, but many others -- commuters, taxi drivers, utility vehicle drivers, and all those working under exposed conditions at or near congested streets, could be at risk as well, particularly as regards particulate emissions.

4. Without aggressive action by government officials, it is clear that the problems will get much worse as the vehicle population more than doubles over the next 10 to 15 years.

5. Substantial additional degradation of the environment is not inevitable but amelioration will require a comprehensive package of strategies impacting on existing vehicles, fuels and new vehicles.

6. Focusing on particulate emissions first, it can be seen that the I/M program can begin to reduce particulate emissions significantly from the levels to which they are otherwise expected to rise by 2005. Tight motorcycle standards will also lower particulate. Further, reducing the sulfur and lead content of diesel fuel and gasoline, respectively, will lower sulfur and lead emissions dramatically. Requiring (or effectively encouraging) a gradual shift of selective diesel vehicles to convert from diesel to gasoline engines will have a major impact on the remaining particulate emissions. The conversion of buses to CNG would have a significant effect on some of the densely populated, high bus use urban corridors.

7. I/M would also have a significant impact on HC and CO emissions. Tight motorcycle standards, by either eliminating or cleaning up two stroke engines, would have an additional benefit for HC. The conversion of some diesels to petrol fuel will actually increase CO and HC emissions somewhat but these increases would be more than offset by the introduction of the other vehicle standards and the catalyst durability provided by unleaded petrol.

8. Very significant progress in reducing pollution across the board can result from adoption of this comprehensive but feasible package of measures. They are mutually reinforcing such that the whole is greater than the sum of the individual parts.

9. Additional benefits could result from constraints on vehicle growth.

All of the above strategies require a strong, well coordinated enforcement program. This in turn will require clear lines of authority and responsibility with accountability built in.

APPENDIX A: PETROL ENGINE CONTROL TECHNOLOGIES

Before controls were required, fumes from engine crankcases were vented directly to the atmosphere. Crankcase emissions controls, closing the crankcase vent port, were introduced on new cars in the early 1960's. The result is that today, control of these emissions is no longer considered a significant technical concern.

The evaporative emissions of hydrocarbons 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 canisters, which absorb these emissions to be 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.

9.1. Combustion and Emissions

Emissions of hydrocarbons, which include 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.

9.2. 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.

9.2.1. Air/Fuel Ratio and Mixture Preparation

The air/fuel ratio has a major effect on all three major pollutants (CO, HC and NOx) 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.

9.2.2. 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.

9.2.3. 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, increases in compression ratios 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 these parameters 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. This 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 to 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.

9.2.4. Intake Charge Dilution by Exhaust Gas Recirculation

3Dilution 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 (EGR) 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.

9.2.5. 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.

9.3. Exhaust Aftertreatment Devices

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

9.3.1. 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. 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.

A major impediment to the use of catalysts is lead in gasoline. Existing, proven catalyst systems are poisoned by the lead in vehicle exhaust.

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, reactive hydrocarbons and polynuclear hydrocarbons.

9.3.2. 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 US NOx standard was made more stringent (1.0 grams per mile) in 1981. 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 occasional tankful of leaded gasoline will have a small but lasting effect on the level of emitted pollutants.

9.3.3. 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. They thus promote

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. Because of these problems, systems of this type have gradually faded from use.

9.3.4. Lean Burn

At one point, it was believed that additional combustion advances, especially lean burn, might actually allow the catalyst itself to ultimately be eliminated; however, recent experience indicates that low HC and NOx levels are not possible across the range of normal driving conditions through the use of these concepts alone. At least an oxidation catalyst is needed to control HC emissions. Also, under higher speed, higher load driving modes, such as those reflected in the recently agreed upon European extra urban driving cycle, supplemental NOx control may also be needed. Recent European studies under high speed driving conditions have demonstrated that three way catalysts are necessary to minimize NOx emissions. In addition, as concern with toxic pollution increases, it appears that lean burn engines would not be as effective as conventional catalyst equipped engines in lowering polynuclear organics and other noxious compounds from motor vehicle exhausts unless they are equipped with catalytic converters.

9.4. Costs

New car price increases as a function of various emissions standards are estimated below. For interests of standardization, all emissions standards are based on the US 1975 test procedure along with the US compliance program.

Model Year	HC/CO/NOx	Initial Cost Increase
1968-69	5.9/50.8/-	50
1970-71	3.9/33.3/-	70
1972	3.0/28.8/-	85
1973-74	3.0/28.0/3.1	125
1975-76	1.5/15.0/3.1	200
1977-79	1.5/15.0/2.0	225
1980	.41/7.0/2.0	300
1981	.41/3.4/1.0	500

APPENDIX B: DIESEL CONTROL TECHNOLOGY

10.1. FACTORS AFFECTING EMISSIONS

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. The quantity of fuel injected with each stroke determines the engine power output.

The high pressure injection atomizes the fuel. As the atomized fuel is injected into the chamber, the periphery of each jet mixes with the hot 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 diffusion burning phase, except under very light loads.

A mixture of fuel and exactly as much air as is required to burn the fuel completely is called a "stoichiometric mixture". The air/fuel ratio is defined as the ratio of the actual amount of air present per unit of fuel to the stoichiometric amount. 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.

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. The minimum air/fuel ratio for complete combustion is about = 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. This minimum air fuel ratio explains why NOx reduction catalysts of the type used on gasoline automobiles, which rely on stoichiometric air-fuel ratios, are not effective for diesel engines.

10.1.1. Pollutant Formation

The principal pollutants emitted by diesel engines are oxides of nitrogen (NO_x), sulfur oxides (SOx), particulate matter (PM), and unburned hydrocarbons (HC). Diesels are also responsible for a small amount of CO, as well as visible smoke, unpleasant odors, and noise. In addition,

like all engines using hydrocarbon fuel, diesels emit significant amounts of CO_2, which has been implicated in the so called "greenhouse effect." With thermal efficiencies typically in excess of 40%, however, diesels are the most fuel efficient of all common types of combustion engines. As a result, they emit less CO_2 to the atmosphere than any other type of engine doing the same work.

The NO_x, HC, and most of the particulate emissions from diesels are formed during the combustion process, and can be reduced by appropriate modifications to that process, as can most of the unregulated pollutants. The sulfur oxides, in contrast, are derived directly from sulfur in the fuel, and the only feasible control technology is to reduce fuel sulfur content. Most SOx is emitted as gaseous SO_2, but a small fraction (typically 2-4 percent) occurs in the form of particulate sulfates.

Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and sulfates. In older diesels, soot was typically 40 to 80 percent of the total particulate mass. Developments in in-cylinder emissions control have reduced the soot contribution to particulate emissions from modern emission controlled engines considerably, however. Most of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction of the particulate matter, or SOF. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion. The relative importance of each of these sources varies from engine to engine.

In-cylinder emission control techniques have been most effective in reducing the soot and fuel derived SOF components of the particulate matter. As a result, the relative importance of the lube oil and sulfate components has increased. In the emission controlled engines under development, the lubricating oil accounts for as much as 40 percent of the particulate matter, and the sulfates may account for another 25 percent. Lube oil emissions can be reduced by reducing oil consumption, but this may adversely affect engine durability. The only known way to reduce sulfate emissions is to reduce the sulfur content of diesel fuel.

The gaseous hydrocarbons and the SOF component of the particulate matter emitted by diesel engines include many known or suspected carcinogens and other toxic air contaminants. These include polynuclear aromatic compounds (PNA) and nitro-PNA, formaldehyde and other aldehydes, and other oxygenated hydrocarbons. The oxygenated hydrocarbons are also responsible for much of the characteristic diesel odor.

Oxides of nitrogen (NO_x) from diesels is primarily NO_2. This gas forms from nitrogen and free oxygen at high temperatures close to the flame front. The rate of NO_x formation in diesels 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 presenting temperature of the initial mixture. 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 NO_x 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 [1] indicates that most NO_x 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 NO_x emissions.

NO_x 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 near stoichiometric conditions, reducing the flame temperature by "lean burn" techniques, as in spark-ignition engines, is impractical.

Particulate matter (or soot) is formed only during the diffusion burning phase of combustion. Primary soot particles are small spheres of graphitic carbon, approximately 0.01 mm in diameter. These are formed by the rapid polymerization of acetylene at moderately high temperatures under oxygen deficient conditions. The primary particles then agglomerate to form chains and clusters of linked particles, giving the soot its characteristic fluffy appearance. During the diffusion burning phase, the local gas composition at the flame front is close to stoichiometric, with an oxygen rich region on one side and a fuel rich region on the other. The moderately high temperatures and excess fuel required for soot formation are thus always present.

Most of the soot formed during combustion is subsequently burned during the later portions of the expansion stroke. Typically, less than 10% of the soot formed in the cylinder survives to be emitted into the atmosphere. Soot oxidation is much slower than soot formation, however, and the amount of soot oxidized is heavily dependent on the availability of high temperatures and adequate oxygen during the later stages of combustion. Conditions which reduce the availability of oxygen (such as poor mixing, or operation at low air/fuel ratios), or which reduce the time available for soot oxidation (such as retarding the combustion timing) tend to increase soot emissions.

The SOF component of diesel particulate matter consists of heavy hydrocarbons condensed or adsorbed on the soot. A significant part of this material is unburned lubricating oil, which is vaporized from the cylinder walls by the hot gases during the power stroke. Some of the heavier hydrocarbons in the fuel may also come through unburned, and condense on the soot particles.

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[1] Wade, W.R., C.E. Hunter, F.H. Trinker, and H.A. Cikanek (1987) "The Reduction of NOx and Particulate Emissions in the Diesel Combustion Process", ASME Paper No. 87-ICE-37, American Society of Mechanical Engineers, New York, NY.

Cartellieri, W.P., and W.F. Wachter (1987) "Status Report on a Preliminary Survey of Strategies to Meet US-1991 HD Diesel Emission Standards Without Exhaust Gas Aftertreatment", SAE Paper No. 870342, Society of Automotive Engineers, Warrendale, PA.

Finally, heavier hydrocarbons may be synthesized during combustion, possibly by the same types of processes which produce soot. Pyrosynthesis of polynuclear aromatic hydrocarbons during diesel combustion has been demonstrated by Williams et al. (1987). [2]

Diesel hydrocarbon emissions (as well as the unburned fuel portions of the particulate SOF) occur primarily at light loads. They are due to excessive fuel/air mixing, which results in some volumes of air/fuel mixture which are too lean to burn. Other HC sources include fuel deposited on the combustion chamber walls or in combustion chamber crevices by the injection process; fuel retained in the orifices of the injector which vaporizes late in the combustion cycle; and partly reacted mixture which is subjected to bulk quenching by too rapid mixing with air. Aldehydes (as partially reacted hydrocarbons) and the small amount of CO produced by diesels are probably formed in the same processes as the HC emissions.

The presence of polynuclear aromatic hydrocarbons and their nitro derivatives in diesel exhaust is of special concern, since these compounds include many known mutagens and suspected carcinogens. A significant portion of these compounds (especially the smaller two and three-ring compounds) are apparently derived directly from the fuel. Typical diesel fuel contains several percent PNA by volume. Most of the larger and more dangerous PNA's, on the other hand, appear to form during the combustion process, possibly via the same acetylene polymerization reaction that produces soot [3]. Indeed, the soot particle itself can be viewed as essentially a very large PNA molecule.

Visible Smoke is due primarily to the soot component of diesel particulate matter. Under most operating conditions, the exhaust plume from a properly adjusted diesel engine is normally invisible, with a total opacity (absorbance and reflectance) of two percent or less. Visible smoke emissions from heavy duty diesels are generally due to operating at air/fuel ratios at or below the smoke limit, or to poor fuel/air mixing in the cylinder. These conditions can be prevented by proper design. The particulate reductions required to comply with the US 1991 emissions standards essentially eliminate visible smoke emissions from properly functioning engines.

Noise from Diesel engines is due principally to the rapid combustion (and resulting rapid pressure rise) in the cylinder during the premixed burning phase. The greater the ignition delay, and the more fuel is premixed with the air, the greater this pressure rise and the resulting noise emissions will be. Noise emissions and NO_x emissions thus tend to be related reducing the amount of fuel burned in the premixed burning phase will tend to reduce both. Other noise

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[2] Williams, P.T., G.E. Andrews, and K.D. Bartle (1987) "Diesel Particulate Emissions: The Role of Unburnt Fuel in the Organic Fraction Composition", SAE Paper No. 870554, Society of Automotive Engineers, Warrendale, PA.

[3] Williams, P.T., G.E. Andrews, and K.D. Bartle (1987) "Diesel Particulate Emissions: The Role of Unburnt Fuel in the Organic Fraction Composition", SAE Paper No. 870554, Society of Automotive Engineers, Warrendale, PA.

sources include those common to all engines, such as mechanical vibration, fan noise, and so forth. These can be minimized by appropriate mechanical design.

Odor characteristic of diesel engines is believed to be due primarily to partially oxygenated hydrocarbons (aldehydes and similar species) in the exhaust. These are believed to be due primarily to slow oxidation reactions in volumes of air/fuel mixture too lean to burn normally. Unburned aromatic hydrocarbons may also play a significant role. The most significant aldehyde species are benzaldehyde, acetaldehyde, and formaldehyde, but other aldehydes such as acrolein (a powerful irritant) are significant as well. Aldehyde and odor emissions are closely linked to total HC emissions experience has shown that modifications which reduce total HC tend to reduce aldehydes and odor as well.

10.1.2. Influence of Engine Variables

The engine variables having the greatest effects on diesel emission rates are the air/fuel ratio, 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 emission control involve manipulating one or more of these variables.

10.1.2.1. Air-fuel ratio

The ratio of air to fuel in the combustion chamber has an extremely important effect on emission rates for hydrocarbons and particulate matter. As discussed above, the power output of the engine is determined by the amount of fuel injected at the beginning of each power stroke. At very high air/fuel ratios (corresponding to very light load), the temperature in the cylinder after combustion is too low to burn out residual hydrocarbons, so emissions of gaseous HC and particulate SOF are high. At lower air-fuel ratios, less oxygen is available for soot oxidation, so soot emissions increase. As long as the air fuel ratio remains above about 1.6, this increase is relatively gradual. Soot and visible smoke emissions in a Direct Injection Diesel Engine show a strong nonlinear increase below the smoke limit at about A/F = 1.5, however.

In naturally aspirated engines (those without a turbocharger), the amount of air in the cylinder is independent of the power output. Maximum power output for these engines is normally "smoke limited"-- that is, limited by the amount of fuel that can be injected without exceeding the smoke limit. Maximum fuel settings on these engines represent a compromise between smoke emissions and power output. Where diesel smoke is regulated, this compromise must result in smoke opacity below the regulated limit. Otherwise, opacity is limited by the manufacturer's judgement of commercially acceptable smoke emissions.

In turbo charged engines, increasing the fuel injected per stroke increases the energy in the exhaust gas, causing the turbo charger to spin more rapidly and pump more air into the combustion chamber. For this reason, power output from turbo charged engines is not usually smoke limited, although this depends on the rated power of the engine. Instead, it is limited by design limits on variables such as turbocharger speed and engine mechanical stresses. However,

turbo-charged engines are smoke limited at low speeds.

Turbo charged engines do not normally experience low air/fuel ratios during steady state operation. Low air/fuel ratios can occur during transient accelerations, since the inertia of the turbo charger rotor keeps it from responding instantly to an increase in fuel input. Thus, the air supply during the first few seconds of a full power acceleration is less than the air supply in steady state operation. To overcome this problem, turbo charged engines in highway vehicles commonly incorporate an acceleration smoke limiter. This device limits the fuel flow to the engine until the turbo charger has time to respond. The setting on this device must compromise between acceleration performance driveability and low smoke emissions. In the US, acceleration smoke emissions are limited by regulation; elsewhere, they are limited by the manufacturer's judgement of commercial acceptability.

10.1.2.2. 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 NO_x 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 piston top - dead - center, the higher the fuel efficiency, and the lower the soot emissions. Too rapid mixing, however, can increase hydrocarbon emissions -- especially at light loads as small volumes of air/fuel mixture are diluted below the combustible level before they have a chance to burn. Unnecessarily intense mixing also dissipates energy through turbulence, increasing fuel consumption.

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 NO_x and HC 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. Turbo charger 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

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mixing, and result in greatly increased emissions.

10.1.2.3. 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 top-dead-center. 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, although this could be 10 to 25 degrees for engines in Europe).

Since fuel is injected before the piston reaches top-dead-center, 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 top dead center increases the maximum temperature and pressure attained in the cylinder. Both of these effects tend to increase NO_x 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, NO_x 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 NO_x , 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.

10.1.2.4. 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 NO_x 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 NO_x .

Emissions of gaseous HC and of the SOF fraction of the particulate matter are reduced at higher compression ratios, as the higher cylinder temperature increases the burnout of hydrocarbons. Soot emissions may increase at higher compression ratios, however. Since the higher compression is achieved by reducing the volume of the combustion chamber, this results in a larger fraction of the air charge being seqùestered in "crevice volumes" such as the top and sides of the piston, where it is not available for combustion early in the power stroke. Thus, the effective air/fuel ratio in the combustion chamber decreases, and soot emissions go up. This effect can be limited (and overall air utilization and power output improved) by reducing crevice volumes to the maximum extent possible.

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.

10.1.2.5. Charge temperature

Reducing the temperature of the air charge going into the cylinder has benefits for both PM and NO_x emissions. Reducing the charge temperature directly reduces the flame temperature during combustion, and thus helps to reduce NO_x 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. Excessively cold charge air can reduce the burnout of hydrocarbons, and thus increase light load HC emissions, however. This can be counteracted by advancing injection timing, or by reducing charge air cooling at light loads.

10.1.2.6. Charge composition

NO_x 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, particulate SOF 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, however, 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.

10.1.2.7. 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. This "tradeoff" is not absolute -- various NOx control techniques have varying effects on soot and HC emissions, and the importance of these effects varies as a function of engine speed and load. These tradeoffs do place limits on the extent to which any one of these pollutants can be reduced, however. To minimize emissions of all three pollutants simultaneously requires careful optimization of the fuel injection, fuel/air mixing, and combustion processes over the full range of engine operating conditions.

10.1.3. Influence of Fuel Qualities

The quality and composition of diesel fuel can have important effects on pollutant emissions. The area of fuel effects on diesel emissions has seen a great deal of study in the last few years, and a large amount of new information has become available. These data indicate that the fuel variables having the most important effects on emissions are the sulfur content and the fraction of aromatic hydrocarbons contained in the fuel. Other fuel properties may also affect emissions, but generally to a much lesser extent. A recent, extensive study carried out for the Dutch Ministry of Environment for the EEC's Motor Vehicle Emissions Group (MVEG), however, indicates that the volatility of the diesel fuel (85 or 90% distilled temperatures) is the most important factor followed in importance by sulphur and aromatics content, in that order. The apparent discrepancy with the US findings might be the result of lower volatility of European diesel fuels, compared to those in the US. The subject is currently being studied. Finally, the use of fuel additives may have a significant impact on emissions.

10.1.3.1. Sulphur Content

Diesel fuel for highway use normally contains between 0.1 and 0.5 percent by weight sulfur, although some (mostly less developed) nations permit 1% or even higher sulfur concentrations. Sulfur in diesel fuel contributes to environmental deterioration both directly and indirectly. Most of the sulfur in the fuel burns to SO_2 , which is emitted to the atmosphere in the diesel exhaust. Because of this, diesels are significant contributors to ambient SO_2 levels in some areas. This

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makes them indirect contributors to ambient particulate levels and acid deposition as well. In the US, diesel fuel accounted for about 620 thousand tons of SO_2 in 1984, or about 3% of all SO_2 emissions during the same period. For Europe, diesel fuel for road traffic adds approximately 1.6 per cent of total SO_2 emissions, a share which is growing.

Most of the fuel sulphur which is not emitted as SO_2 is converted to various metal sulfates and to sulfuric acid during the combustion process or immediately afterward. Both of these materials are emitted in particulate form. The typical rate of conversion in a heavy duty diesel engine is about 2 to 3 percent of the fuel sulphur; and about 3 to 5 percent in a light duty engine. Even at this rate, sulphate particles typically account for 0.05 to 0.10 g/BHP-hr of particulates in heavy duty engines. In a Dutch program, a sulphur change from 0.28 to 0.07 per cent resulted in a 10 to 15 per cent decrease in particulate emissions. The effect of the sulphate particles is increased by their hygroscopic nature -- they tend to absorb significant quantities of water from the air.

Certain precious metal catalysts can oxidize SO_2 to SO_3, which combines with water in the exhaust to form sulfuric acid. The rate of conversion with the catalyst is dependent on the temperature, space velocity, and oxygen content of the exhaust, and on the activity of the catalyst -- generally, catalyst formulations which are most effective in oxidizing hydrocarbons and CO are also most effective at oxidizing SO_2. The presence of significant quantities of sulfur in diesel fuel thus limits the potential for catalytic converters or catalytic trap-oxidizers for use in controlling PM and HC emissions.

Sulphur dioxide in the atmosphere oxidizes to form sulfate particles, in a reaction similar to that which occurs with the precious metal catalyst. Viewed in another way, the presence of the catalyst merely speeds up a reaction which would occur anyway (although this can have a significant effect on human exposure to the reaction products). According to analysis by the California Air Resources Board staff, [4] roughly 1.20 lb. of secondary particulate is formed per pound of SO_2 emitted in the South Coast Air Basin. For a diesel engine burning fuel of 0.29 weight percent sulfur at 0.42 lb. of fuel per horsepower/hour, this is equivalent to 0.85 grams per horsepower-hour. For comparison, the average rate of primary or directly emitted particulate emissions from heavy duty diesel engines in use was about 0.8 grams/BHP-hr. [5]

Quite aside from its particulate forming tendencies, sulfur dioxide is recognized as a hazardous pollutant in its own right. The health and welfare effects of SO_2 emissions from diesel vehicles are probably much greater than those of an equivalent quantity emitted from a utility stack or

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[4] California Air Resources Board staff (1984). "Status Report: Diesel Engine Emissions Reductions through Modification of Motor Vehicle Diesel Fuel Specifications," CARB, Sacramento, CA.

[5] Engine Manufacturer's Association (1985). "Heavy Duty Diesel Engine In-Use Emission Testing Meeting," briefing package for a presentation to the California Air Resources Board Staff, El Monte, CA.

industrial boiler, since diesel exhaust is emitted close to the ground level in the vicinity of roads, buildings, and concentrations of people.

10.1.3.2. Volatility

Diesel fuel consists of a mixture of hydrocarbons having different molecular weights and boiling points. As a result, as some of it boils away on heating, the boiling point of the remainder increases. This fact is used to characterize the range of hydrocarbons in the fuel in the form of a "distillation curve" specifying the temperature at which 10%, 20%, etc. of the hydrocarbons have boiled away. A low 10% boiling point is associated with a significant content of relatively volatile hydrocarbons. Fuels with this characteristic tend to exhibit somewhat higher HC emissions than others. Formerly, a relatively high 90% boiling point was considered to be associated with higher particulate emissions. More recent studies [6] have shown that this effect is spurious -- the apparent statistical linkage was due to the higher sulfur content of these high-boiling fuels.

In a Dutch study for the EC MVEG, however, the test fuels were composed of two sets at clearly different 85 or 90 per cent boiling points, among which sulphur content varied independently. A highly significant effect of 85 or 90 per cent boiling point temperatures was found, in addition to a significant effect of sulphur and a probably significant effect of aromatics contents. A typical effect of a 20° C change in 85 per cent boiling point is 0.05 g/kWh at present particulate levels. As mentioned earlier, this may be related to generally higher 85 or 90 per cent points, which in the test fuels went up to 350 or 360° C. Commercial diesel fuels in Europe show values up to about 370° C.

10.1.3.3. Aromatic Hydrocarbon Content

Aromatic hydrocarbons are hydrocarbon compounds containing one or more "benzene-like" ring structures. They are distinguished from paraffins and napthenes, the other major hydrocarbon constituents of diesel fuel, which lack such structures. Compared to these other components, aromatic hydrocarbons are denser, have poorer self ignition qualities, and produce more soot in burning. Ordinarily, "straight run" diesel fuel produced by simple distillation of crude oil is fairly low in aromatic hydrocarbons. Catalytic cracking of residual oil to increase gasoline and diesel production results in increased aromatic content, however. A typical straight run diesel might contain 20 to 25% aromatics by volume, while a diesel blended from catalytically cracked stocks could have 40-50% aromatics.

Aromatic hydrocarbons have poor self ignition qualities, so that diesel fuels containing a high fraction of aromatics tend to have low cetane numbers. Typical cetane values for straight run

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[6] Wall, J.C. and S.K. Hoekman (1984). "Fuel Composition Effects on Heavy Duty Diesel Particulate Emissions," SAE Paper No. 841364, Society of Automotive Engineers, Warrendale, PA.

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diesel are in the range of 50-55; those for highly aromatic diesel fuels are typically 40 to 45, and may be even lower. This produces more difficulty in cold starting, and increased combustion noise, HC, and NOx due to the increased ignition delay.

Increased aromatic content is also correlated with higher particulate emissions. Aromatic hydrocarbons have a greater tendency to form soot in burning, and the poorer combustion quality also appears to increase particulate SOF emissions. Increased aromatic content may also be correlated with increased SOF mutagenicity, possibly due to increased PNA and nitro-PNA emissions. There is also some evidence that more highly aromatic fuels have a greater tendency to form deposits on fuel injectors and other critical components. Such deposits can interfere with proper fuel/air mixing, greatly increasing PM and HC emissions.

10.1.3.4. Other fuel properties

Other fuel properties may also have an effect on emissions. Fuel density, for instance, may affect the mass of fuel injected into the combustion chamber, and thus the air/fuel ratio. This is because fuel injection pumps meter fuel by volume, not by mass, and the denser fuel contains a greater mass in the same volume. Fuel viscosity can also affect the fuel injection characteristics, and thus the mixing rate. The corrosiveness, cleanliness, and lubricating properties of the fuel can all affect the service life of the fuel injection equipment-- possibly contributing to excessive in-use emissions if the equipment is worn out prematurely.

10.1.3.5. Fuel additives

Several generic types of diesel fuel additives can have a significant effect on emissions. These include cetane enhancers, smoke suppressants, and detergent additives. In addition, some additive research has been directed specifically at emissions reduction in recent years. Although some moderate emission reductions have been demonstrated, there is yet no consensus on the widespread applicability or desirability of such products.

Cetane enhancers are used to enhance the self ignition qualities of diesel fuel. These compounds (generally organic nitrates) are generally added to reduce the adverse impact of high aromatic fuels on cold starting and combustion noise. These compounds also appear to reduce the aromatic hydrocarbons' adverse impacts on HC and PM emissions, although PM emissions with the cetane improver are generally still somewhat higher
than those from a higher quality fuel able to attain the same cetane rating without the additive. In the MVEG study cited earlier, no significant effect of ashless cetane improving additives could be detected on NOx or particulates.

Smoke suppressing additives are organic compounds of calcium, barium, or (sometimes) magnesium. Added to diesel fuel, these compounds inhibit soot formation during the combustion process, and thus greatly reduce emissions of visible smoke. Their effects on the particulate SOF

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are not fully documented, but one study [7] has shown a significant increase in the PAH content and mutagenicity of the SOF with a barium additive. Particulate sulfate emissions are greatly increased with these additives, since all of them readily form stable solid metal sulfates, which are emitted in the exhaust. The overall effect of reducing soot and increasing metal sulfate emissions may be either an increase or decrease in the total particulate mass, depending on the soot emissions level at the beginning and the amount of additive used.

Detergent additives (often packaged in combination with a cetane enhancer) help to prevent and remove coke deposits on fuel injector tips and other vulnerable locations. By thus maintaining new engine injection and mixing characteristics, these deposits can help to decrease in-use PM and HC emissions. A study for the California Air Resources Board [8] estimated the increase in PM emissions due to fuel injector problems from trucks in use as being more than 50% of new-vehicle emissions levels. A significant fraction of this excess is unquestionably due to fuel injector deposits.

10.2. TECHNOLOGICAL ADVANCES TO REDUCE EMISSIONS

As noted above, diesel engine emissions are determined by the characteristics of the combustion process within each cylinder. Primary engine parameters affecting diesel emissions are the fuel injection system, the engine control system, the air intake port and combustion chamber design, and the air charging system. Actions to reduce lubricating oil consumption can also impact HC and PM emissions. Further, beyond the engine itself, exhaust aftertreatment systems such as trap oxidizers and catalytic converters can play a significant role. Finally, modifications to conventional fuels as well as alternative fuels can impact emissions. The following sections will review the status of each of these areas.

10.2.1. Engine Modifications

10.2.1.1. Air motion and combustion chamber design

The geometries of the combustion chamber and the air intake port control the air motion in the diesel combustion chamber, and thus play an important role in air/fuel mixing and emissions. A number of different combustion chamber designs, corresponding to different basic combustion

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[7] Draper, W.M., J. Phillips, and H.W. Zeller (1988). "Impact of a Barium Fuel Additive on the Mutagenicity and Polycyclic Aromatic Hydrocarbon Content of Diesel Exhaust Particulate Emissions," SAE Paper No. 881651, Society of Automotive Engineers, Warrendale, PA.

[8] Weaver, C.S. and R.F. Klausmeier (1988). Heavy Duty Diesel Vehicle Inspection and Maintenance Study: Final Report (4 Volumes), report under ARB Contract No. A4-151-32, Radian Corporation, Sacramento, CA.

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systems, are in use in heavy duty diesel engines at present. This section outlines the basic combustion systems in use, their advantages and disadvantages, and the effects of changes in combustion chamber design and air motion on emissions.

10.2.1.2. Combustion systems

Diesel engines used in heavy duty vehicles use several different types of combustion systems. The most fundamental difference is between direct injection (DI) engines and indirect injection (IDI) engines. In an indirect injection engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main combustion chamber above the piston. In the more common direct injection engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. DI engines can be further divided into high swirl and low swirl.

Fuel/air mixing in the direct injection engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it enters. In high swirl DI engines, a strong swirling motion is imparted to the air entering the combustion chamber by the design of the intake port. These engines typically use moderate to high injection pressures, and three to five spray holes per nozzle. Low swirl engines rely primarily on the fuel injection process to supply the mixing. They typically have very high fuel injection pressures and six to nine spray holes per nozzle.

In the indirect injection engine, much of the fuel/air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the prechamber during combustion. These engines typically have better high speed performance than direct injected engines, and can use cheaper fuel injection systems. Historically, IDI diesel engines have also exhibited lower emission levels, especially NOx, than DI engines but, with recent developments in DI engine emission controls, this is no longer the case. The main disadvantage of the IDI engine is that the extra heat and frictional losses due to the prechamber result in a 5-10 percent reduction in fuel efficiency compared to a DI engine.

A number of advanced, low emitting and fuel efficient high swirl DI engines have recently been introduced and it appears that these engines will completely displace the existing IDI designs.

10.2.1.3. DI combustion chamber design

Changes in the engine combustion chamber and related areas have demonstrated a major potential for emission control. Design changes to reduce the crevice volume in DI diesel cylinders increase the amount of air available in the combustion chamber. Changes in combustion chamber geometry -- such as the use of a reentrant lip on the piston bowl -- can markedly reduce emissions by improving air/fuel mixing and minimizing wall impingement by the fuel jet. Optimizing the intake port shape for best swirl characteristics has also yielded significant benefits. Several manufacturers are considering variable swirl intake ports, to optimize swirl characteristics across a broader range of engine speeds.

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10.2.1.4. Fuel injection

The fuel injection system, one of the most important components in a diesel engine, includes the process by which the fuel is transferred from the fuel tank to the engine, and the mechanism by which it is injected into the cylinders. The precision, characteristics and timing of the fuel injection determine the engine's power, fuel economy, and emissions characteristics.

The major areas of concentration in fuel injection system development have been on increased injection pressure, increasingly flexible control of injection timing, and more precise governing of the fuel quantity injected. Some manufacturers are also pursuing technology to vary the rate of fuel injection over the injection period, in order to reduce the amount of fuel burning in the premixed combustion phase. Reductions in NOx and noise emissions and maximum cylinder pressures have been demonstrated using this approach. Systems offering electronic control of these quantities, as well as fuel injection rate, have been introduced. Other changes have been made to the injection nozzles themselves, to reduce or eliminate sac volume and to optimize the nozzle hole size and shape, number of holes, and spray angle for minimum emissions.

High fuel injection pressures are desirable in order to improve fuel atomization and fuel/air mixing, and to offset the effects of retarded injection timing by increasing the injection rate. It is well established that higher injection pressures reduce PM and/or smoke emissions. High injection pressures are most important in low swirl, direct injection engines, since the fuel injection system is responsible for most of the fuel/air mixing in these systems. For this reason, low swirl engines tend to use unit injector systems, which can achieve peak injection pressures in excess of 1,500 bar.

10.2.1.5. Engine control systems

Traditionally, diesel engine control systems have been closely integrated with the fuel injection system, and the two systems are often discussed together. These earlier control systems (still in use on most engines) are entirely mechanical. The last few years have seen the introduction of an increasing number of computerized electronic control systems for diesel engines. With the introduction of these systems, the scope of the engine control system has been greatly expanded.

The advent of computerized electronic engine control systems has greatly increased the potential flexibility and precision of fuel metering and injection timing controls. In addition, it has made possible whole new classes of control functions, such as road speed governing, alterations in control strategy during transients, synchronous idle speed control, and adaptive learning -- including strategies to identify and compensate for the effects of wear and component to component variation in the fuel injection system.

By continuously adjusting the fuel injection timing to match a stored "map" of optimal timing vs. speed and load, an electronic timing control system can significantly improve on the NOx/particulate and NOx/fuel economy trade-offs possible with static or mechanically variable injection timing. Most electronic control systems also incorporate the functions of the engine governor and the transient smoke limiter. This helps to reduce excess particulate emissions due to mechanical friction and lag time during engine transients, while simultaneously improving

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engine performance. Potential reductions in PM emissions of up to 40% have been documented with this approach.

10.2.1.6. Turbocharging and intercooling

A turbocharger consists of a centrifugal air compressor feeding the intake manifold, mounted on the same shaft as an exhaust gas turbine in the exhaust stream. By increasing the mass of air in the cylinder prior to compression, turbocharging correspondingly increases the amount of fuel that can be burned without excessive smoke, and thus increases the potential maximum power output. The fuel efficiency of the engine is improved as well. The process of compressing the air, however, increases its temperature, increasing the thermal load on critical engine components. By cooling the compressed air in an intercooler before it enters the cylinder, the adverse thermal effects can be reduced. This also increases the density of the air, allowing an even greater mass of air to be confined within the cylinder, and thus further increasing the maximum power potential.

Increasing the air mass in the cylinder and reducing its temperature can reduce both NOx and particulate emissions as well as increase fuel economy and power output from a given engine displacement. Most heavy duty diesel engines are presently equipped with turbochargers, and most of these have intercoolers. In the US, virtually all engines will be equipped with these systems by 1991. Recent developments in air charging systems for diesel engines have been primarily concerned with increasing the turbocharger efficiency, operating range, and transient response characteristics; and with improved intercoolers to further reduce the temperature of the intake charge. Tuned intake air manifolds (including some with variable tuning) have also been developed, to maximize air intake efficiency in a given speed range.

10.2.1.7. Lubricating oil control

A significant fraction of diesel particulate matter consists of oil derived hydrocarbons and related solid matter; estimates range from 10 to 50%. Reduced oil consumption has been a design goal of heavy duty diesel engine manufacturers for some time, and the current generation of diesel engines already uses fairly little oil compared to their predecessors. Further reductions in oil consumption are possible through careful attention to cylinder bore roundness and surface finish, optimization of piston ring tension and shape, and attention to valve stem seals, turbocharger oil seals, and other possible sources of oil loss. Some oil consumption in the cylinder is required with present technology, however, in order for the oil to perform its lubricating and corrosion protective functions.

10.2.2. Aftertreatment Systems

10.2.2.1. Trap oxidizers

A trap oxidizer system consists of a durable particulate filter (the "trap") positioned in the engine exhaust stream, along with some means for cleaning the filter by burning off ("oxidizing") the collected particulate matter. The construction of a filter capable of collecting diesel soot and other particulate matter from the exhaust stream is a straightforward task, and a number of

effective trapping media have been developed and demonstrated. The most challenging problem of trap oxidizer system development has been with the process of "regenerating" the filter by burning off the accumulated particulate matter.

Diesel particulate matter consists primarily of a mixture of solid carbon coated with heavy hydrocarbons. The ignition temperature of this mixture is about 500-600 degrees C, which is above the normal range of diesel engine exhaust temperatures. Thus, special means are needed to assure regeneration. Once ignited, however, this material burns to produce very high temperatures, which can easily melt or crack the particulate filter. Initiating and controlling the regeneration process to ensure reliable regeneration without damage to the trap is the central engineering problem of trap oxidizer development.

Traps -- Presently, most of the trap oxidizer systems under development are based on the cellular cordierite ceramic monolith trap. These traps can be formulated to be highly efficient (collecting essentially all of the soot, and a large fraction of the particulate SOF), and they are relatively compact, having a large surface area per unit of volume. They can also be coated or impregnated with catalyst material to assist regeneration.

The high concentration of soot per unit of volume with the ceramic monolith, however, makes these traps sensitive to regeneration conditions. Trap loading, temperature, and gas flow rates must be maintained within a fairly narrow window. Otherwise, the trap fails to regenerate fully, or cracks or melts due to overheating.

An alternative trap technology is provided by ceramic fiber coils. These traps are composed of a number of individual filtering elements, each of which consists of a number of thicknesses of silica fiber yarn wound on a punched metal support. A number of these filtering elements are suspended inside a large metal can to make up a trap.

Numerous other trapping media have been tested or proposed, including ceramic foams, corrugated mullite fiber felts, and catalyst coated stainless steel wire mesh.

Regeneration -- Numerous techniques for regenerating particulate trap oxidizers have been proposed, and a great deal of development work has been invested in many of these. These approaches can generally be divided into two groups: passive systems and active systems. Passive systems must attain the conditions required for regeneration during normal operation of the vehicle. The most promising approaches require the use of a catalyst (either as a coating on the trap or as a fuel additive) in order to reduce the ignition temperature of the collected particulate matter. Regeneration temperatures as low as 420 degrees C have been reported with catalytic coatings, and even lower temperatures are achievable with fuel additives.

Active systems, on the other hand, monitor the buildup of particulate matter in the trap and trigger specific actions intended to regenerate it when needed. A wide variety of approaches to triggering regeneration have been proposed, from diesel fuel burners and electric heaters to catalyst injection systems.

Passive regeneration systems face special problems on heavy duty vehicles. Exhaust temperatures

from heavy duty diesel engines are normally low, and recent developments such as charge air cooling and increased turbo charger efficiency are reducing them still further. Under some conditions, therefore, it would be possible for a truck to drive for many hours without exceeding the exhaust temperature (around 400-450 degrees C) required to trigger regeneration.

Engine and catalyst manufacturers have experimented with a wide variety of catalytic material and treatments to assist in trap regeneration. Good results have been obtained both with precious metals (platinum, palladium, rhodium, silver) and with base metal catalysts such as vanadium and copper. Precious metal catalysts are effective in oxidizing gaseous HC and CO, as well as the particulate SOF, but are relatively ineffective at promoting soot oxidation. Unfortunately, these metals also promote the oxidation of SO_2 to particulate sulfates such as sulfuric acid (H_2SO_4). The base metal catalysts, in contrast, are effective in promoting soot oxidation, but have little effect on HC, CO, NO_x or SO_2. Many experts believe that ultimately precious metal catalysis must be an important element of an effective particulate control system because it specifically attacks the "bad actors."

Catalyst coatings also have a number of advantages in active systems, however. The reduced ignition temperature and increased combustion rate due to the catalyst mean that less energy is needed from the regeneration system. Regeneration will also occur spontaneously under most duty cycles, greatly reducing the number of times the regeneration system must operate. The spontaneous regeneration capability also provides some insurance against a regeneration system failure. Finally, the use of a catalyst may make possible a simpler regeneration system.

Although normal heavy duty diesel exhaust temperatures are not high enough under all operating conditions to provide reliable regeneration for a catalyst coated trap, the exhaust temperature can readily be increased by changes in engine operating parameters. Retarding the injection timing, bypassing the intercooler, throttling the intake air (or cutting back on a variable geometry turbo charger), and/or increasing the EGR rate all markedly increase the exhaust temperature. Applying these measures all the time would seriously degrade fuel economy, engine durability, and performance. The presence of an electronic control system, however, makes it possible to apply them very selectively to regenerate the trap. Since they would be normally needed only at light loads, the effects on durability and performance would be imperceptible.

Fuel additives may play a key role in trap based systems although concerns have been raised about possible toxicity if metallic additives were widely used. Cerium based additives which don't appear to raise these concerns have been found especially promising in recent fleet studies in Athens buses; they were able to lower engine out particulate emissions as well as facilitate regeneration.

10.2.2.2. Catalytic converters

Like a catalytic trap, a diesel catalytic converter oxidizes a large part of the hydrocarbon constituents of the SOF, as well as gaseous HC, CO, odor creating compounds, and mutagenic emissions. Unlike a catalytic trap, however, a flow through catalytic converter does not collect any of the solid particulate matter, which simply passes through in the exhaust. This eliminates the need for a regeneration system, with its attendant technical difficulties and costs. The

particulate control efficiency of the catalytic converter is, of course, much less than that of a trap. However, a particulate control efficiency of even 25 to 35 percent is enough to bring many current development engines within the target range for the US 1994 emissions standard.

Diesel catalytic converters have a number of advantages. First, in addition to reducing particulate emissions, the oxidation catalyst greatly reduces HC, CO, and odor emissions. The catalyst is also very efficient in reducing emissions of gaseous and particle bound toxic air contaminants such as aldehydes, PNA, and nitro-PNA. While a precious metal catalyzed particulate trap would have the same advantages, the catalytic converter is much less complex, bulky, and expensive. Unlike the trap, the catalytic converter has little impact on fuel economy or safety, and it will probably not require replacement as often. Also, unlike the trap oxidizer, the catalytic converter is a relatively mature technology -- millions of catalytic converters are in use on gasoline vehicles, and diesel catalytic converters have been used in underground mining applications for more than 20 years.

The disadvantage of the catalytic converter is the same as with the precious metal catalyzed particulate trap: sulfate emissions. The tendency of the precious metal catalyst to convert SO_2 to particulate sulfates requires the use of low sulfur fuel: otherwise, the increase in sulfate emissions would more than counterbalance the decrease in SOF. Also on the road durability has not yet been demonstrated in heavy duty applications for the required 270,000 mile useful life.

10.2.2.3. NOx reduction techniques

Under appropriate conditions, NOx can be chemically reduced to form oxygen and nitrogen gases. This process is used in modern closed-loop, three-way catalyst equipped gasoline vehicles to control NOx emissions. However, the process of catalytic NOx reduction used on gasoline vehicles is inapplicable to diesels. Because of their heterogeneous combustion process, diesel engines require substantial excess air, and their exhaust thus inherently contains significant excess oxygen. The three-way catalysts used on automobiles require a precise stoichiometric mixture in the exhaust in order to function--in the presence of excess oxygen, their NOx conversion efficiency rapidly approaches zero.

A number of aftertreatment NOx reduction techniques which will work in an oxidizing exhaust stream are currently available or under development for stationary pollution sources. These include selective catalytic reduction (SCR), selective non-catalytic reduction (Thermal Denox(tm)), and reaction with cyanuric acid (RapReNox(tm)). However, each of these systems requires a continuous supply of some reducing agent such as ammonia or cyanuric acid to react with the NOx. Because of the need for frequent replenishment of this agent, and the difficulty of ensuring that the replenishment is performed when needed, such systems are considered impractical for vehicular use. Even if the replenishment problems could be resolved, these systems would raise serious questions about crash safety and possible emissions of toxic air contaminants.

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10.2.3. Fuel Modifications

Modifications to diesel fuel composition have drawn considerable attention as a quick and cost effective means of reducing emissions from existing vehicles. Regulations mandating low sulfur fuel (0.05 Wt. %) have been promulgated in both Europe and the US. In addition to a direct reduction in emissions of SO_2 and sulfate particles, reducing the sulphur content of diesel fuel reduces the indirect formation of sulfate particles from SO_2 in the atmosphere.

A number of well controlled studies have demonstrated the ability of detergent additives in diesel fuel to prevent and remove injector tip deposits, thus reducing smoke levels. The reduced smoke probably results in reduced PM emissions as well, but this has not been demonstrated as clearly, due to the great expense of PM emissions tests on in use vehicles. Cetane improving additives are also likely to result in some reduction in HC and PM emissions in marginal fuels.

10.2.4. Alternative Fuels

The possibility of substituting cleaner burning alternative fuels for diesel fuel has drawn increasing attention during the last decade. Motivations advanced for this substitution include conservation of oil products and energy security, as well as the reduction or elimination of particulate emissions and visible smoke. Care is necessary in evaluating the air quality claims for alternative fuels, however. While many alternative fuel engines do display greatly reduced particulate and SO_2 emissions, emissions of other gaseous pollutants such as unburned hydrocarbons, CO, and in some cases NOx and aldehydes may be much higher than from diesels.

The principal alternative fuels presently under consideration are natural gas and methanol made from natural gas, and in limited applications, LPG.

10.2.4.1. Natural gas

Natural gas has many desirable qualities as an alternative to diesel fuel in heavy duty vehicles. Clean burning, cheap, and abundant in many parts of the world, it already plays a significant vehicular role in a number of countries. The major disadvantage of natural gas as a motor fuel is its gaseous form at normal temperatures.

Pipeline quality natural gas is a mixture of several different gases but the primary constituent is methane, which typically makes up 90-95 percent of the total volume. Methane is a nearly ideal fuel for Otto cycle (spark ignition) engines. As a gas under normal conditions, it mixes readily with air in any proportion, eliminating cold start problems and the need for cold start enrichment. In its purest form, it is flammable over a fairly wide range of air fuel ratios. With a research octane number of 130 (the highest of any commonly used fuel), it can be used with engine compression ratios as high as 15:1 (compared to 8-9:1 for gasoline), thus giving greater efficiency and power output. The low lean flammability limit permits operation with extremely lean air fuel ratios -- having as much as 60 percent excess air. On the other hand, its high flame temperature tends to result in high NOx emissions, unless very lean mixtures are used.

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Because of its gaseous form and poor self ignition qualities, methane is a poor fuel for diesel engines. Since diesels are generally somewhat more efficient than Otto cycle engines, natural gas engines are likely to use somewhat more energy than the diesels they replace. The high compression ratios achievable with natural gas limit this efficiency penalty to about 10 percent of the diesel fuel consumption, however.

Options for using natural gas in heavy duty vehicle engines are limited to the following:

-- Fumigation, or mixing the gas with the diesel intake air, to be ignited by diesel fuel injected in the conventional way;

-- Conversion of the existing diesel engine to Otto cycle operation; or

-- Replacement of the diesel engine with a conventional spark ignition engine.

Fumigation is the easiest way to use natural gas in a diesel engine. Injection and combustion of the diesel fuel ignites and burns the alternate fuel as well. Since the gas supplies much of the energy for combustion, the diesel fuel delivery for a given power level is reduced resulting in reduced smoke and particulate (PM) emissions at high load. However, incomplete combustion (especially at light loads) usually increases CO and HC emissions considerably. The increased HC emission are of less concern with natural gas than with other hydrocarbon fuels, since the principal component, methane, is non toxic and has very low photochemical reactivity. On the other hand, methane is a very active greenhouse gas, and the other, minor components of the HC emissions include some formaldehyde as well as higher molecular weight hydrocarbons.

Spark ignition engines -- The modifications required to convert a diesel engine to Otto cycle operation are machining the cylinder head to accept a spark plug instead of a fuel injector; redesign of the pistons to reduce the compression ratio; replacement of the fuel injection pump with an ignition system and distributor; replacement of exhaust valves and valve seats with wear resistant materials; and addition of a carburetor (or fuel injection system) and throttle assembly.

CO emissions are governed by oxygen availability, while NO_x emissions are primarily a function of flame temperature. For natural gas engines, typical NOx emissions at stoichiometry are about 10 to 15 g/BHp-hr. This can be reduced to less than 2 g/BHp-hr, however, through the use of a three way catalyst and closed loop mixture controls like those on light duty passenger cars. The durability of such catalysts under the high temperatures experienced in heavy duty operation has not yet been demonstrated, however. The durability of electronic control systems under heavy duty conditions is also unproven.

An alternative approach to NOx control is to operate very lean. Through the use of high energy ignition systems and careful optimization, homogeneous mixtures can be lean enough to lower NO_x emissions to the 2 g/BHp-hr range. The driveability of such engines under transient conditions has not yet been demonstrated, however. The lean combustion limit can be extended even further by using a stratified charge strategy. Stationary engines using this technique have demonstrated NOx emissions less than one g/BHp-hr.

10.2.4.2. Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas is already widely used as a vehicle fuel in the US, Canada, the Netherlands, and elsewhere. As a fuel for spark ignition engines, it has many of the same advantages as natural gas, with the additional advantage of being easier to carry aboard the vehicle. Its major disadvantage is the limited supply, which would rule out any large scale conversion to LPG fuel.

The technologies available for LPG are the same as those available for natural gas: fumigation, or spark ignition using either stoichiometric or very lean mixtures. Due to the lower octane value of LPG, the compression ratio (and thus the thermal efficiency) possible with this fuel in spark ignition operation is lower than with natural gas, although still considerably higher than with gasoline. Aside from this, the engine technologies involved are very similar. Due to the lower octane value (and higher photochemical reactivity) of LPG, however, it is not as good a candidate for use in fumigation as natural gas.

Like natural gas, LPG in spark ignition engines is expected to produce essentially no particulate emissions (except for a small amount of lubricating oil), very little CO, and moderate HC emissions. NOx emissions are a function of the air fuel ratio. LPG does not burn as well under very lean conditions as natural gas, so the NOx levels achievable through lean burn technology are expected to be somewhat higher -- probably in the range of 3 to 5 g/BHp-hr. For stoichiometric LPG engines, the use of a three way catalyst and closed loop air fuel mixture control results in very low NOx emissions, assuming that such systems can be made sufficiently durable.

10.2.4.3. Methanol

Methanol has many desirable combustion and emissions characteristics, including good lean combustion characteristics, low flame temperature (leading to low NOx emissions) and low photochemical reactivity.

As a liquid, methanol can either be burned in an Otto cycle engine or injected into the cylinder as in a diesel. With a fairly high octane number of 112, and excellent lean combustion properties, methanol is a good fuel for lean burn Otto cycle engines. Its lean combustion limits are similar to those of natural gas, while its low energy density results in a low flame temperature compared to hydrocarbon fuels, and thus lower NOx emissions. Methanol burns with a sootless flame and contains no heavy hydrocarbons. As a result, particulate emissions from methanol engines are very low -- consisting essentially of a small amount of unburned lubricating oil.

Methanol's high octane number results in a very low cetane number, so that it is more difficult to use methanol in a diesel engine without some supplemental ignition source. Investigations to date have focused on the use of ignition improving additives, spark ignition, glow plug ignition, or dual injection with diesel fuel. Converted heavy duty diesel engines using each of these approaches have been developed and demonstrated.

The low energy density of methanol means that a large amount (about 3 times the mass of diesel fuel) is required to achieve for the same power output. Therefore, the diesel injection pump supplied with the engine would not be suitable in most cases; a larger volumetric capacity is required. In addition, diesel injection pumps are fuel lubricated. Since methanol is a poor lubricant, a separate oil supply to the pump is required. Other changes to the high pressure lines, injector nozzles, and so forth are required to prevent cavitation and premature wear. All of these changes are straightforward, however, and injection pumps suitable for use with methanol have been produced.

Emissions Methanol combustion does not produc e soot, so particulate emissions from methanol engines are limited to a small amount of lubricating oil. Methanol's flame temperature is also lower than that for hydrocarbon fuels, resulting in NOx emissions which are typically 50 percent lower. CO emissions are generally comparable to or somewhat greater than those from a diesel engine; these emissions can be controlled with a catalytic converter, however.

The major pollution problems with methanol engines come from emissions of unburned fuel and formaldehyde. Methanol (at least in moderate amounts) is relatively innocuous -- it has low photochemical reactivity, and --while acutely toxic in large doses -- displays no significant chronic toxicity effects. Formaldehyde, the first oxidation product of methanol, is much less benign, however. A powerful irritant and suspected carcinogen, it also displays very high photochemical reactivity. While all combustion engines produce some formaldehyde, some early generation methanol engines exhibited greatly increased emissions compared to diesels. The potential for large increases in formaldehyde emissions with the widespread use of methanol vehicles has raised considerable concern about what would otherwise be a very benign fuel from an environmental standpoint. DDC has made major advances in formaldehyde control and levels are currently at or below the diesel engines they replace.

Formaldehyde emissions can be reduced through changes in combustion chamber and injection system design, and are also readily controllable through the use of catalytic converters, at least under warmed up conditions. In fact, the DDC engine equipped with a catalyst has attained emissions levels as low as 0.06 formaldehyde, along with 0.2 HC, 0.8 CO, 2.2 NOx and 0.04 particulate. This system is now available commercially.

10.3. CONCLUSIONS

Diesel technology continues to hold high promise for good efficiency and an increasingly important role in addressing the global carbon dioxide problem. The major impediment to the greater use of this technology has been the clear and growing evidence that diesel particles are serious threats to public health. Increasingly therefore countries around the world are requiring low pollution levels as a condition for the use of diesels. Diesel particulate control technology has now advanced to where manufacturers have no difficulty complying with the 0.25 grams per brake horsepower hour standard which went into effect for 1991 model year US sold trucks. Without exception, manufacturers were able to comply solely with the use of engine modifications.

Compliance with the 1993 urban bus standard of 0.1 (which applies to all heavy duty vehicles

by 1994) is more problematic but appears feasible by that time using either alternative fuels, or exhaust aftertreatment systems such as trap oxidizers. One methanol fueled bus has already been certified to the 0.1 standard. Regarding 1994 heavy duty truck compliance, most manufacturers have indicated their intention to comply with the use of oxidation catalysts since "low" sulfur fuel will be available. Some if not all manufacturers are expected to be able to comply with no aftertreatment systems.

The longer term solution, with low NOx and particulates, will require low sulfur fuel, particulate filters and possibly lean NOx catalysts. Failure to develop and rapidly introduce these technologies will continue to constrain diesel growth and may lead to increasing pressure to abandon conventional diesel technology.

Programs to control emissions from heavy duty vehicles already in use can be an important complement to controls for new vehicles. Enforcement through inspection and maintenance can ensure that the anticipated benefits of emission standards are not lost because of tampering or poor maintenance. Malfunctioning diesel engines may increase PM and HC emissions by a factor of 10 or 15 over levels attained with proper maintenance.

Retrofit programs to install controls on existing vehicles can help to reduce emissions more quickly than regulations on new vehicles, but require considerable care and engineering development work to be effective. They would be most cost-effective where large numbers of vehicles of a similar type or design, such as fleets, are targeted for retrofit. Enforcement of retrofits on individually-owned vehicles could be difficult.

Recent operating experience in Europe and North America indicates that we are on the threshold of significant and rapidly advancing technological breakthroughs with regard to diesel emissions. Foremost among these are:

1. the increasing use of oxidation catalysts on light duty vehicles in Europe, especially Germany,

2. the installation of trap oxidizers on 110 buses in Athens with at present over 8 million miles of operating experience, and

3. a wide variety of trap equipped buses in several cities in the United States with a collective accumulation of over 12 million miles of operating experience.

11.1.1.1.1.2. Vehicle build - new

Given that the manufacturer has "certified" his intended design, production vehicles may not meet standards, even when new, either because they are not constructed in all material respects of the same design as the prototype (i.e., they are misbuilt), or the manufacturer has failed to translate the design effectively into mass production. The first situation is legally equivalent to introduction into commerce of an uncertified design and may be guarded against by the inspections and civil penalties mentioned above.

The second situation may result from "prototype-to-production slippage" and/or "production variability", depending on the circumstances. In that case, the vehicles may not conform to the standards, but production vehicle testing is the only way their nonconformance may be detected. Therefore, testing of production vehicles is necessary if assurance is to be gained that production vehicles actually meet standards.

11.1.1.1.1.3. Vehicle build - useful life

Vehicles may meet standards when new but may fail to meet standards during their useful life, even though properly maintained, due to excessive deterioration in-use. Such deterioration may occur because the manufacturer failed to translate effectively the design into mass production, or because the certified design is inadequate due to the inability of the accelerated certification testing to accurately simulate in-use standards. In such cases, it is desirable that the manufacturer be required to fix the vehicle at his own expense for two reasons; one, to reduce emissions from the vehicle, and two, to deter the manufacturer from building such vehicles in the future.

Mechanisms for identifying excessively polluting vehicles in-use include in-use testing, defect reporting by manufacturers and by vehicle owners, state inspection programs, and assembly-line testing. Mechanisms for requiring manufacturers to fix such vehicles are provided by the recall and warranty programs.

11.1.1.1.2. Proper maintenance

Given that vehicles may have been designed and built to meet standards, they will not do so unless properly maintained. To the extent that motor vehicles can be designed to eliminate or minimize necessary maintenance, the magnitude of this vital task of assuring proper maintenance can be reduced. A means for achieving reduced maintenance requirements might be to force technology by gradually requiring manufacturers to reduce maintenance performed during certification testing and to similarly reduce the pre-requisite maintenance for warranty purposes. However, the inability of the certification process to assess the need for time dependent (as opposed to mileage-dependent) maintenance suggests that warranty requirements would be a principal enforcement tool.

The fundamental requirements for achieving proper maintenance of vehicles in-use would seem to be providing (i) the incentive for car owners to obtain proper maintenance, and (ii) the ability

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and incentive for the marketplace to provide proper maintenance.

11.1.1.1.2.1. Owner incentive

Requiring maintenance through a mandatory I/M program would be the most effective "incentive" for car owners. A prerequisite for the success of an I/M program, either in terms of maximizing emission reduction benefits or in terms of obtaining public acceptance, is assurance to the public that manufacturers are doing their part, i.e., that the vehicles are designed and built to meet standards if properly maintained, and that manufacturers will bear the cost if they do not meet standards.

A significant aspect of an I/M program is the inspection test used to identify vehicles in need of maintenance. A short inexpensive test which correlates with the full test is highly desirable. Such a test would not only make the I/M program more cost effective in terms of direct emissions reductions capability, it would also make the inspections an extremely valuable surveillance tool for use in conjunction with assembly-line testing, recall, and warranty programs, and it would make I/M more palatable by activating the performance warranty.

11.1.1.1.2.2. Marketplace ability

The ability of the marketplace to provide proper maintenance is first dependent on knowing what proper maintenance is, and manufacturers are required to specify such "reasonable and necessary" maintenance in owner's manuals. Review of those instructions by EPA to assure reflection of at least state of the art technology in reduced maintenance requirements can be important. Manufacturers may also be required to design their vehicles and maintenance requirements to avoid "foreseeable" instances of improper or mis-adjustment. Where particular fuels are required as in the case of unleaded gasoline for catalyst equipped vehicles, that fuel must be made available. The service industry must be educated to the requirements of tuning for emission control rather than traditional performance and given sufficient incentive such as the mandatory requirement on their customers of passing an I/M test to provide such tuning. The aftermarket service and parts industry must be able to provide replacement parts which do not adversely affect emissions performance In addition, measures to prevent intentional tampering with emissions control systems must be undertaken.

11.1.1.2. Fuel composition

Fuel composition may be controlled, as in the case of unleaded fuel, for the purpose of proper maintenance, as discussed above. In such cases, control of fuel composition is only indirectly a measure for controlling emissions. Fuel composition may also be controlled as the direct means of controlling emissions, as is the case in reducing the lead content of leaded gasoline to control lead emissions, or could be the case in reducing sulfur content to control sulfate emissions.

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11.1.2. Control vehicle miles travelled (VMT)

Reduction of VMT is an additional means of controlling emissions, e.g., through carpooling, increased use of mass transit, parking restrictions, gas rationing, etc. Though generally politically less acceptable, such approaches tend to promote fuel conservation, can aid in urban renewal, and represent the only mobile source control measure remaining once vehicle control technology has been pushed to its limits.

Whatever success is achieved in reducing per mile emissions from vehicles can be eventually eroded by continued high growth rates in the number and use of vehicles. With very few exceptions (Singapore and Hong Kong being among the bright spots), transportation controls to reduce this growth have been a failure, not because they can't work but rather because most countries have not seriously tried to implement them.

It is now clear that technological solutions to the motor vehicle pollution problem are increasingly offset by growth in the vehicle population. Therefore, long term solution of the environment problem is dependent on coming to grips with the overall growth issue. High growth impacts on emissions in two ways. Not only does it directly increase emissions (more miles driven = more pollution), it leads to more congestion which further increases emissions.

11.2. STRATEGY EVALUATION

As the above discussion indicates, various enforcement tools are available to address each stage of a vehicle's life cycle. The certification process which requires testing of prototype cars prior to production can impact on vehicle design at low mileage and to a limited degree on the durability of emission controls. It can also impact on vehicle maintenance to the degree that review of manufacturer proposed maintenance schedules can constrain the manufacturer from requiring excessive maintenance and thereby reduce the potential effectiveness of recall and warranty and from requiring less maintenance than was performed on his certification prototype. Some prototype maintenance nevertheless is not required to be recommended to the consumer. It's major advantage, that it impacts on vehicle design early in the design process before actual production begins, is also its major weakness, that it inherently deals with somewhat artificial, prototype cars in an artificial environment. By its very nature, therefore, it cannot address production problems nor deterioration due to age or real world driving and ambient extremes nor the amount and quality of maintenance that will actually be performed in use.

Assembly Line Testing requires testing of new production vehicles and is the only technique which can be used to assure before sale that vehicles when built are in fact meeting emission standards; however, it's impact on durability of design depends on requiring allowances for deterioration which are derived from other programs, such as certification or in-use testing. Further, like certification, it cannot impact on the amount or quality of maintenance performed in use.

The recall and warranty programs which apply to vehicles for five years or 50,000 miles can provide some incentive to individuals to properly maintain their vehicles and are the only

programs which can directly affect the actual in-use durability of vehicles. These programs are subject to the limitations of dealing only with properly maintained vehicles and a generally less than perfect response on the part of individual vehicle owners, and they would appear only to impact on vehicles which have been polluting to an excessive degree already in-use and to be therefore remedies after the fact. Further, much of their potential effectiveness is lost after vehicles are in use more than one or two years. However, the major impact of these manufacturer directed in-use programs is a significant deterrent to the design and/or manufacture of vehicles which will fail to comply initially or as a result of deterioration from actual use.

Inspection/Maintenance (I/M) is the only compliance technique which assures that in-use vehicles are properly maintained. By requiring that vehicles pass a retest, it impacts directly on the quantity and quality of maintenance and also impacts on design through the warranty and recall programs which use I/M as a surveillance tool.

I/M is probably the most effective "anti-tampering" program because of the intensive surveillance built into the periodic inspection. Such surveillance is particularly helpful in addressing vehicle maladjustments which cause vehicles to exceed standards. However, where I/M is not in effect, gross tampering by dealers may be substantially deferred, by an aggressive program.

The benefits of I/M, however, are limited by the adequacy of the short test used, the ability of the service industry to make proper repairs and the potential tampering which could occur following the test to allow the vehicle to emit high emissions throughout the year.

It seems clear, therefore, that the ideal program must include all of the above elements.

APPENDIX D. DIESEL PARTICULATE FACT SHEET

Particulate matter in urban air has reflected serious health concerns since the start of the Industrial Revolution and is the classic air pollutant. As a contributor to the urban particle burden, therefore, diesel emissions therefore are immediately a concern. However, two special characteristics of diesel particles cause them to stand out as much more hazardous than other typical particles - their size and their composition.

Virtually all diesel particles are small and respirable (less than 2.5 microns) and consist of a solid carbonaceous core on which a myriad of compounds adsorb. These include:

* unburned hydrocarbons
* oxygenated hydrocarbons
* polynuclear aromatic hydrocarbons
* inorganic species such as sulfur dioxide, nitrogen dioxide and sulfuric acid.

The following two sections will review the reasons for being concerned about small particles in general and then diesels in particular.

CONCERNS WITH SMALL PARTICLES

During the 1980s the USEPA re-evaluated their original particulate standard set in 1971. The Clean Air Act requires the EPA to periodically review the scientific basis for the existing ambient air quality standards and to propose standard revisions if warranted. The existing particulate standards had been based on total suspended particulate (TSP) as measured with a high-volume sampler. High-volume samplers collect particulate matter with an approximate mass mean diameter of 30 to 40 microns. The 1971 health based standards for TSP were 260 ug/m^3 24-hour maximum not to be exceeded more than once per year, and an annual geometric mean standard of 75 ug/m^3.

In reviewing the standard the investigators found that lung penetration and deposition studies indicate that particles greater than about 10 micrometers (microns) tend to be captured in the nasopharyngeal and tracheobronchial regions of the respiratory tract and do not reach the lower regions of the lungs. Particles smaller than 10 micrometers (PM-10) will penetrate into more sensitive regions such as the alveoli where the critical gas exchange takes place with penetrations increasing as the particles become smaller. They also found that mouth breathing presents the most sensitive case, and recommended new standards to protect against effects of particulate matter, particularly premature mortality, aggravation of existing respiratory disease, and lung function declines in children. They recommended that standards be based on a 10 micrometer cutpoint, despite some arguments that the cutpoint should be 6 micrometers.

Other more recent studies have reinforced the concerns with small particles and perhaps indicated that the air quality standard should even be lowered further. By correlating daily weather, air pollutants and mortality in five US cities, scientists have discovered that non accidental death rates tend to rise and fall in near lock step with daily levels of particulates -- but not with other pollutants.

Because the correlation held up even for very low levels -- in one city to just 23 percent of the federal limit on particulates -- these analyses suggest that as many as 60,000 US residents per year may die from breathing particulates at or below legally allowed levels. Confirmation of the new findings by other researchers would make airborne particulate levels the largest known "involuntary environmental insult" to which Americans are exposed.

POTENTIAL CANCER RISKS WITH DIESEL PARTICLES

The US EPA has noted that up to 10,000 chemicals may be absorbed on the surface of diesel particles and drawn deep into the lung with them. Many of these chemical compounds are known to be mutagenic in short term bioassays, and to be capable of causing cancer in laboratory animals. Other epidemiological studies have tended to reinforce these concerns. For example, a 1983 study of heavy construction workers found positive trends in lung cancer by length of union membership and a higher than expected rate among retirees. Further, a pilot study of US 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 who are not exposed. Another study by the Swedish National Institute of Environmental Medicine noted:

> "One occupational group with exposure to diesel exhaust is forklift truck drivers, and a considerable number of studies of such truck drivers have been carried out. Steenland (1986) has made a synopsis of 14 studies of this type, and nine of these showed a statistically significant association between exposure to diesel exhaust and lung cancer. Several of the studies which did not produce any statistically significant results showed a tendency to increased incidence of lung cancer. As a whole, these studies suggest that there is an excess risk of lung cancer among such truck drivers in the order of 30 to 50%."

In addition, during late 1985 and 1986, the results of several animal studies were released which increased concerns. In particular, a study carried out under the auspices of the European automobile manufacturers, the CCMC, and conducted by Battelle-Geneva reported that unfiltered diesel exhaust produced an increase in lung tumor incidence from 1% to 40%; gasoline emissions reportedly showed no effect.

A comprehensive assessment of the available health information was carried out by the International Agency For Research on Cancer (IARC), at a meeting in Lyon, France on June

14-21, 1988. The term 'carcinogen' is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors. Based on its evaluation of all available evidence regarding diesel exhaust, IARC reached the following conclusions:

> There is sufficient evidence for the carcinogenicity in experimental animals of whole diesel engine exhaust.
> There is inadequate evidence for the carcinogenicity in experimental animals of gas phase diesel engine exhaust (with particles removed).
> There is sufficient evidence for the carcinogenicity in experimental animals of extracts of diesel engine exhaust particles.
> There is limited evidence for the carcinogenicity in humans of diesel engine exhaust.

Based on these findings, IARC's overall evaluation was that diesel engine exhaust is probably carcinogenic to humans.

In reaching these conclusions, several human epidemiological studies seemed to carry the most weight. As noted in the IARC report, "In the two most informative cohort studies (of railroad workers), one in the USA and one in Canada, the risk for lung cancer in those exposed to diesel engine exhaust increased significantly with duration of exposure in the first study and with increased likelihood of exposure in the second. Three further studies of cohorts with less certain exposure to diesel engine exhaust were also considered; two studies of London bus company employees showed elevated lung cancer rates that were not statistically significant, but a third, of Swedish dockers showed a significantly increased risk of lung cancer.

In only two case-control studies of lung cancer (one of US railroad workers and one in Canada) could exposure to diesel engine exhaust be distinguished satisfactorily from exposures to other exhausts; modest increases in risk for lung cancer were seen in both, and in the first the increase was significant. In three further case-control studies, in which exposure to diesel engine exhaust in professional drivers and lung cancer risks were addressed, the Working Group considered that the possibility of mixed exposure to engine exhausts could not be excluded. None of these studies showed a significant increase in risk for lung cancer, although the risk was elevated in two.

In the three cohort studies (on railroad workers, bus company workers and 'dockers', respectively) in which bladder cancer rates were reported, the risk was elevated, although not significantly so. Four of the case-control studies of bladder cancer were designed to examine groups whose predominant engine exhaust exposure was assumed to be to that from diesel engines. Three showed a significantly increased risk for bladder cancer. In one of these, the large US study, a significant trend was also seen with duration of exposure; and in an analysis of one subset of self-reported diesel truck drivers, a substantial, significant relative risk was seen for bladder cancer."

More recent studies have suggested that the diesel particle itself, stripped of the organic and other materials on the surface, may also be carcinogenic. Confirmatory studies under the

auspices of the Health Effects Institute, a jointly funded Industry - Government program, appear to be verifying these results.

In the US, the EPA recently assessed the overall cancer risk associated with air pollution and as illustrated below concluded that diesel particulate reflected the greatest risk from mobile sources. (In addition, the EPA projections indicate that strategies designed to reduce diesel particulate and hydrocarbon emissions will lower many of the risks in the future.)

TABLE A
SUMMARY OF RISK ESTIMATES

US CANCER INCIDENCES/YEAR

Motor Vehicle Pollutant		1986	19952005
Diesel Particulate	178-860	106-662	104-518
Formaldehyde	46-86	24-43	27-30
Benzene	100-155	60-107	67-114
Gasoline Vapors	17-58	24-95	30-119
Other Gas Phase Organics			
1,3-Butadiene	236-269	139-172	144-171
Acetaldehyde	2	1	1
Gasoline Particulate	1-176	1-156	1-146
Dioxins	ND	ND	ND
Asbestos	5-33	ND	ND
Vehicle Interior Emissions	ND	ND	ND
Cadmium	<1	<1	<1
Ethylene Dibromide	1	<1	<1
Total	586-1650	355-1236	374-1099

In Germany, where the diesel engine has enjoyed some of its greatest success, based on its conclusion that diesel particulate reflects an occupational health hazard, the German government recently issued guidelines intended to discourage the use of diesel engines in occupational settings when possible (e.g., substitute electric fork lifts for diesels) or to reduce emissions to the greatest extent feasible (e.g., by using particulate traps or filters).

The USEPA in July 1990 issued a draft document for a series of public workshops entitled

"Health Assessment Document for Diesel Emissions". The key conclusions from the study support the IARC conclusion:

> Based on EPA Cancer Assessment Guidelines, there is limited evidence for carcinogenicity in humans, and there is sufficient evidence for carcinogenicity in animals. These findings are supported by additional data from mutagenicity studies as well as the presence of known carcinogens on diesel particles. Therefore, diesel engine emissions are classified into the category B1. This means that the emissions are considered to be probable human carcinogens.

Clearly the scientific consensus today reflects the view that diesel particulate is a hazard to human health and should be minimized.

14

APPENDIX E. LEAD FACT SHEET

Because lead is added to petrol, motor vehicles have been the major source of lead in the air of most cities. Several studies have now shown that children with high levels of lead accumulated in their baby teeth experience more behavioral problems, lower IQ's and decreased ability to concentrate. Because of these concerns, the National Academy of Sciences has concluded that "The evidence is convincing that exposures to levels of lead commonly encountered in urban environments constitute a significant hazard of detrimental biological effects in children, especially those less than 3 years old. Some small fraction of this population experiences particularly intense exposures and is at severe risk." Most recently, in a study of 249 children from birth to two years of age, it was found that those with prenatal umbilical-cord blood lead levels at or above 10 micrograms per deciliter consistently scored lower on standard intelligence tests than those at lower levels.

Evidence of adverse health effects at lower and lower levels of lead continues to grow. Statistical evidence has been found to link lead in adults to increased incidence of high blood pressure.

RECENT EVIDENCE SUGGESTS NO LEAD IS ACCEPTABLE

In late 1991, the US Federal Centers For Disease Control after a careful review of the latest health information again lowered the accepted level of lead in the blood of children. Citing evidence which it said was "so overwhelming and compelling" that children suffer mental problems when their blood contains even 10 micrograms of lead per deciliter, the Agency lowered the acceptable threshold from 25 to 10. Even below 10 micrograms, the Agency noted that some studies indicate adverse effects and indicated that if such evidence continues to be confirmed that the level will be lowered even further.

NOT ADDING LEAD TO PETROL HAS OTHER BENEFITS

The incremental lead removal costs, a couple of cents per gallon, are so small that they are well within the normal market induced gasoline price fluctuations, and would thus hardly be noticed in the accounts of the driving population if the refineries were to recover the above conversion costs through increased gasoline prices.

However, lead free fuel has other economic benefits to the consumer than the obvious health benefits. Just as lead is a pollutant to humans, it is a pollutant to vehicles. It fouls engine lubricating oil and leads to an accumulations of acids which can accelerate engine wear. To prevent such wear, oil must be changed frequently when leaded petrol is used or engine durability will be reduced. It has been well established that oil change interval can be at least doubled when unleaded petrol is used instead of leaded petrol.

Beyond the lubricating oil, spark plugs are fouled by lead deposits when leaded petrol is used.

As a result, spark plugs also need to be changed twice as frequently with leaded petrol; failure to change the plugs will increase the risk of misfire with concomitant increases in wasted fuel and hydrocarbon emissions.

The acids created by leaded petrol also accumulate in the exhaust system of a vehicle and accelerate its deterioration. Exhaust system and muffler life is doubled when unleaded petrol is used instead.

LEAD ALSO DESTROYS CATALYTIC CONVERTERS

The introduction of unleaded fuel would not only reduce lead emissions, it would open up the possibility of introducing catalytic technology into the vehicle population with potential significant benefits to the emissions of CO, HC and NOx. With no unleaded petrol at present, Colombo is in the perverse situation where, used vehicles which are imported into the country from Japan, and which are routinely already equipped with catalytic converters,[1] have these converters removed or destroyed because they cannot function with leaded petrol.[2]

THE WORLD HAS MOVED TO UNLEADED PETROL

Unleaded petrol is increasingly the norm throughout the world. Three out of four new cars manufactured in 1992 come equipped with catalytic converters and must use unleaded petrol. Most others manufactured this year and for many previous yeas can use unleaded petrol. For example, over 95% of the gasoline used in Japan for more than a decade has been unleaded, with leaded fuel mainly confined to agricultural equipment. Therefore virtually all of the used vehicles from Japan and most of the new ones could thrive on unleaded fuel.

The major advantage of lead as a fuel additive is that it is a cheap source of octane, a fuel constituent that allows high performance and efficiency. Modern refineries can produce the necessary octane without lead. Those that can't still have the option of using alternative octane enhancers which while slightly more expensive in direct costs, more than pay for themselves in reduced vehicle maintenance.

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[1]Catalytic converters have been installed on new cars in Japan for more than fifteen years.

[2]As lead in petrol passes through an engine it comes in contact with the catalytic converter. The precious metals which are the primary active ingredients in the converter to facilitate the reduction of CO, HC and NOx are poisoned by lead and rendered inactive in a very short period of time.

FIGURE 1

TOTAL VEHICLE POPULATION BY CLASS OF VEHICLES

(Excluding Land Vehicles)

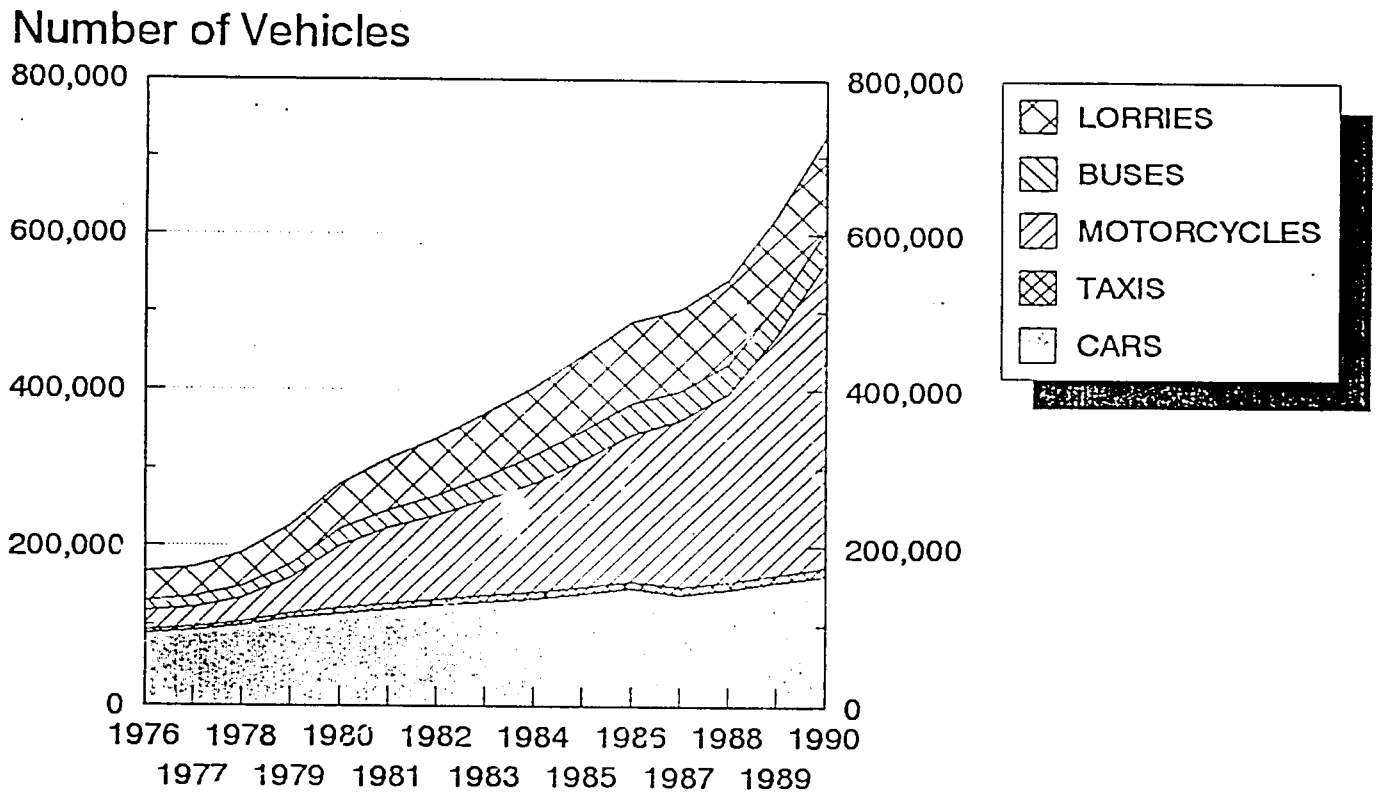


FIGURE 2:

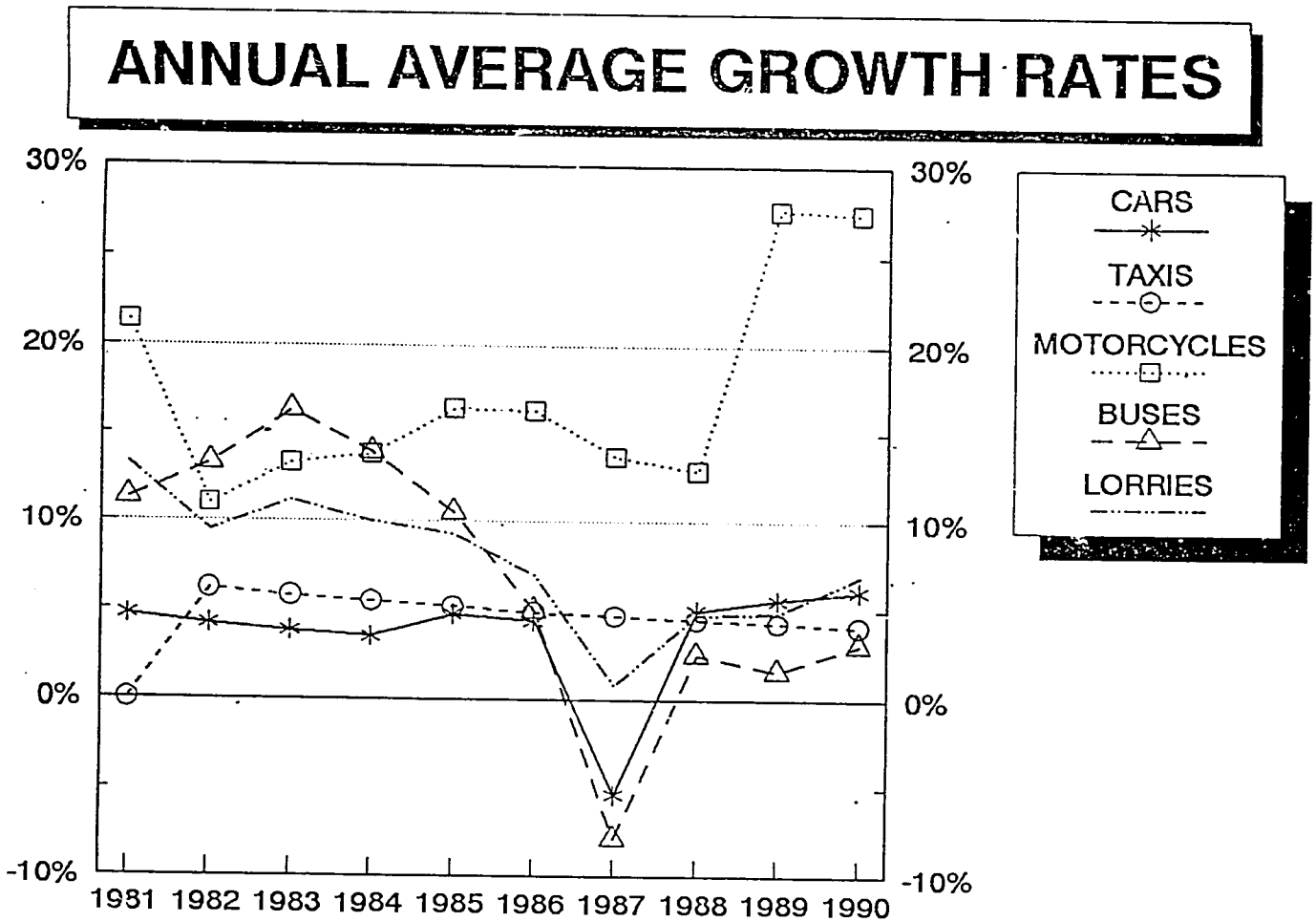

ANNUAL AVERAGE GROWTH RATES
30%
20%
10%
0%
-10%
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990
CARS
TAXIS
MOTORCYCLES
BUSES
LORRIES

FIGURE 3: TRENDS IN VEHICLES PER CAPITA

SRI LANKA

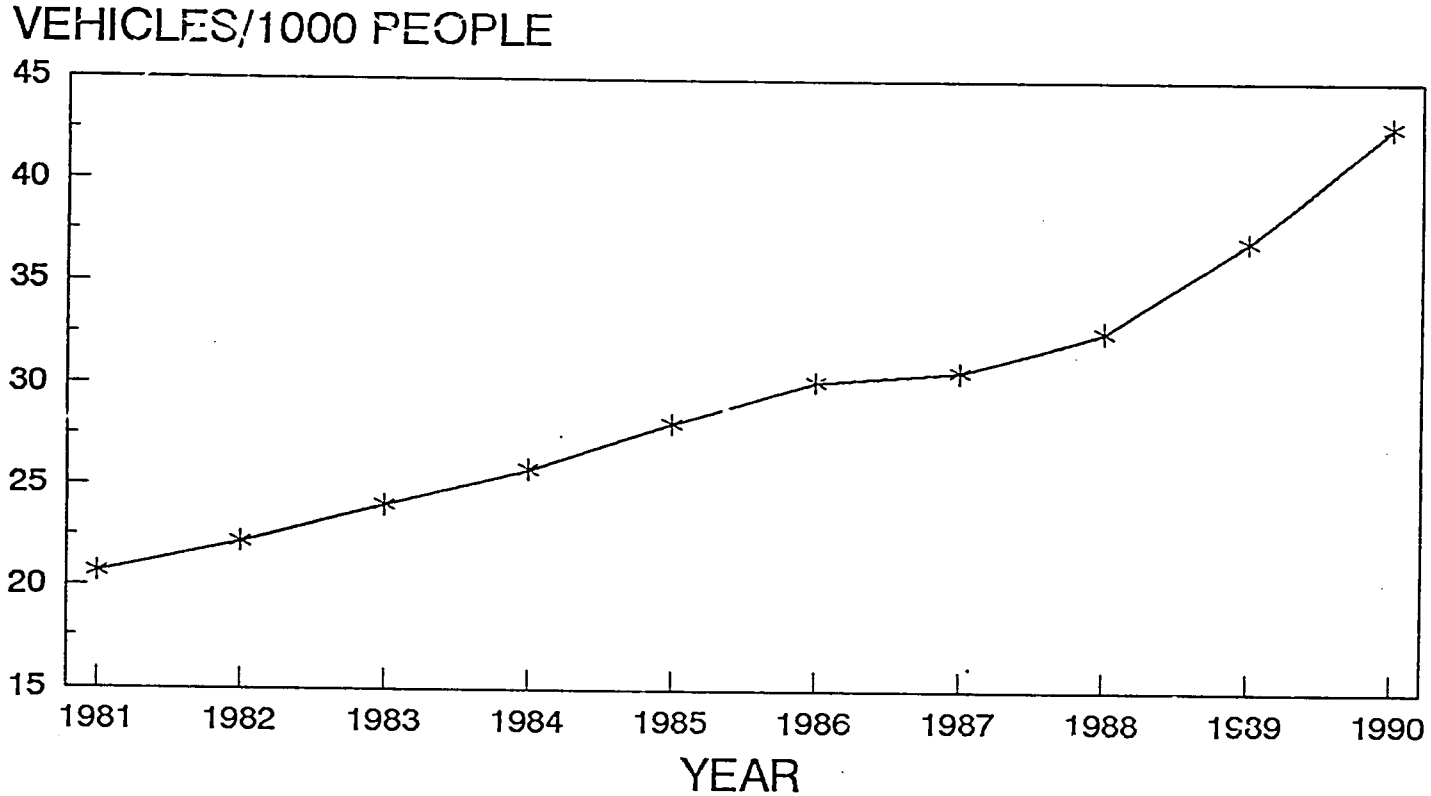


FIGURE 4: INCREMENTAL ANNUAL GROWTH

IN VEHICLES PER CAPITA

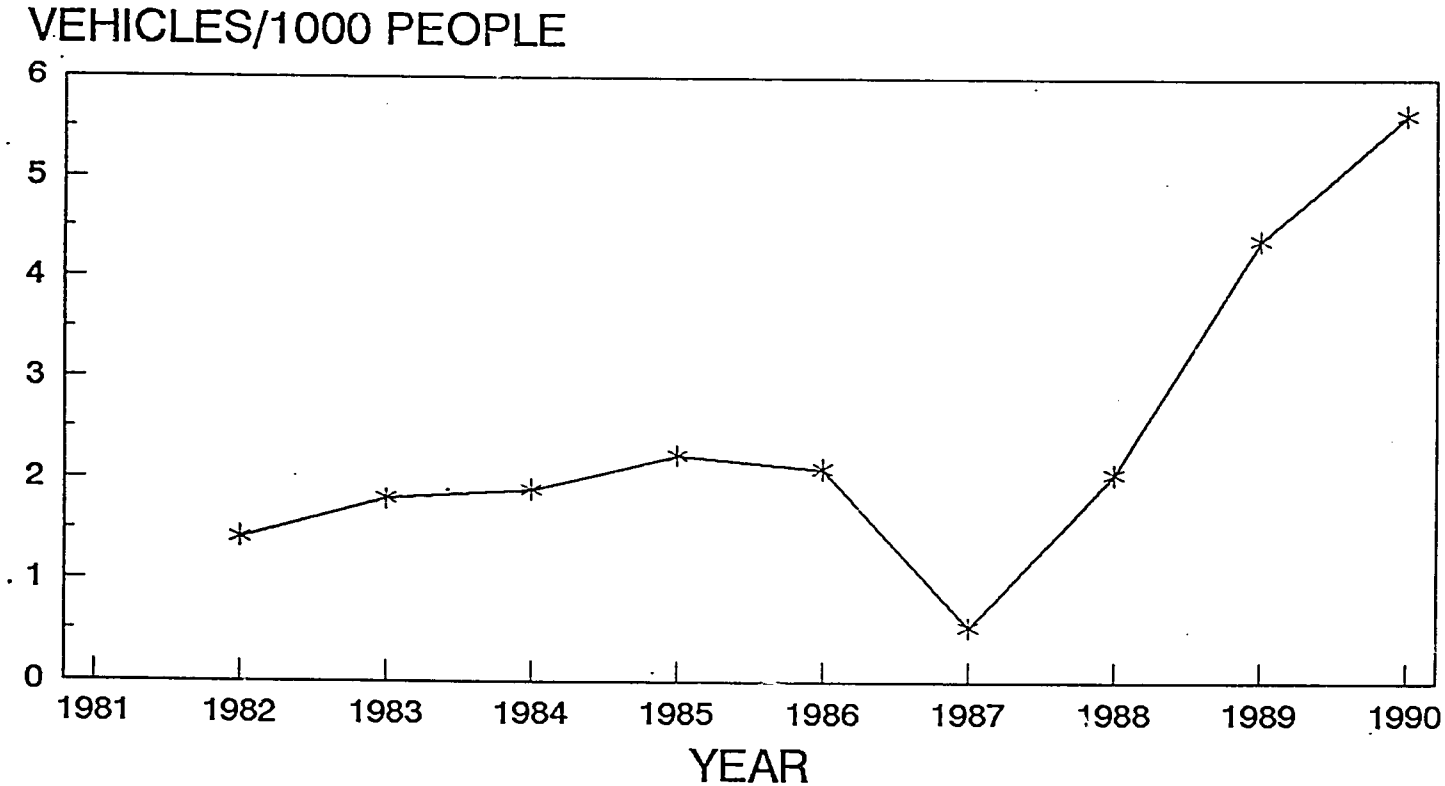


FIGURE 5: INCREMENTAL ANNUAL GROWTH RATES

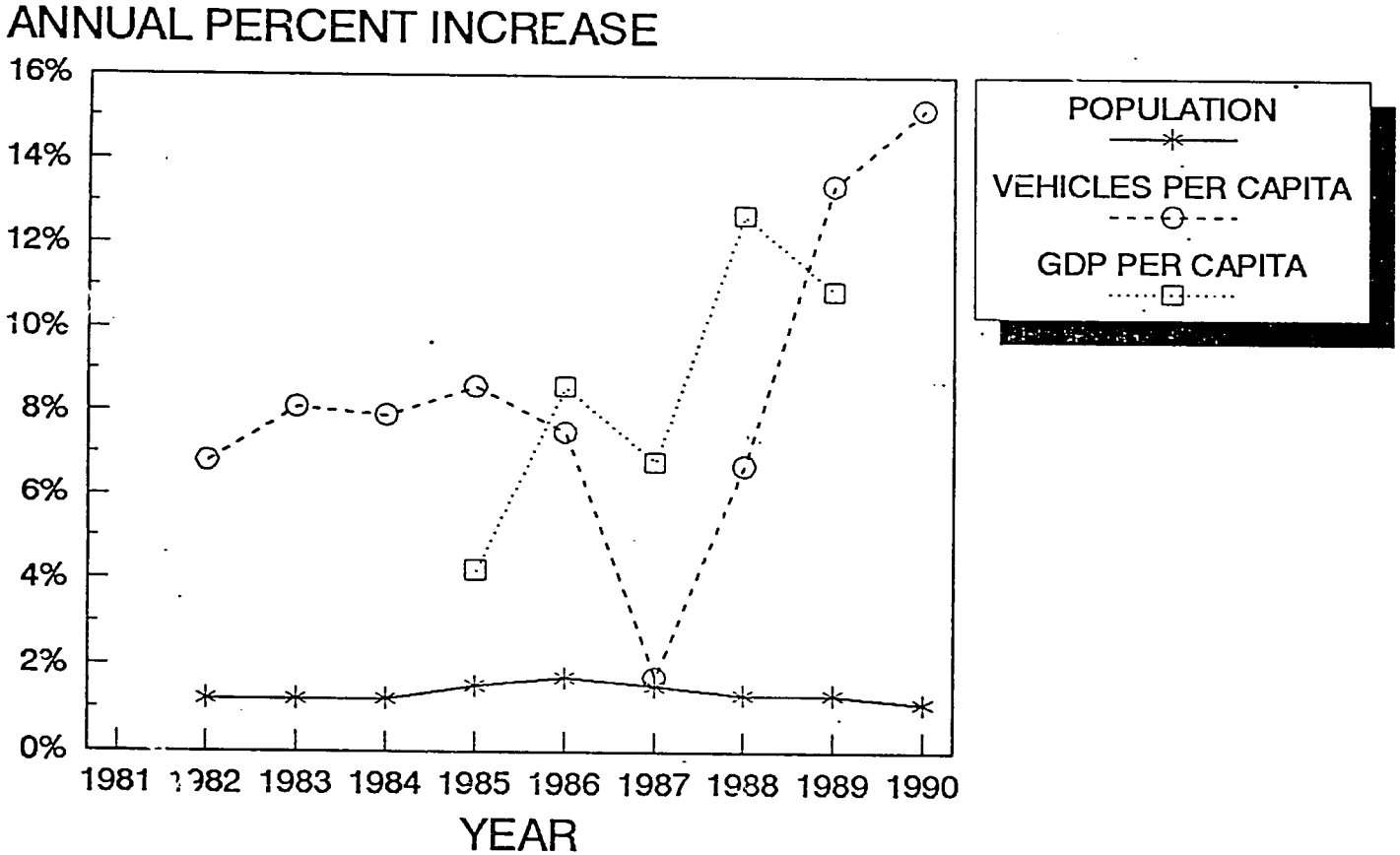


FIGURE 6: DRIVING BY VEHICLE CATEGORY - KM

1990

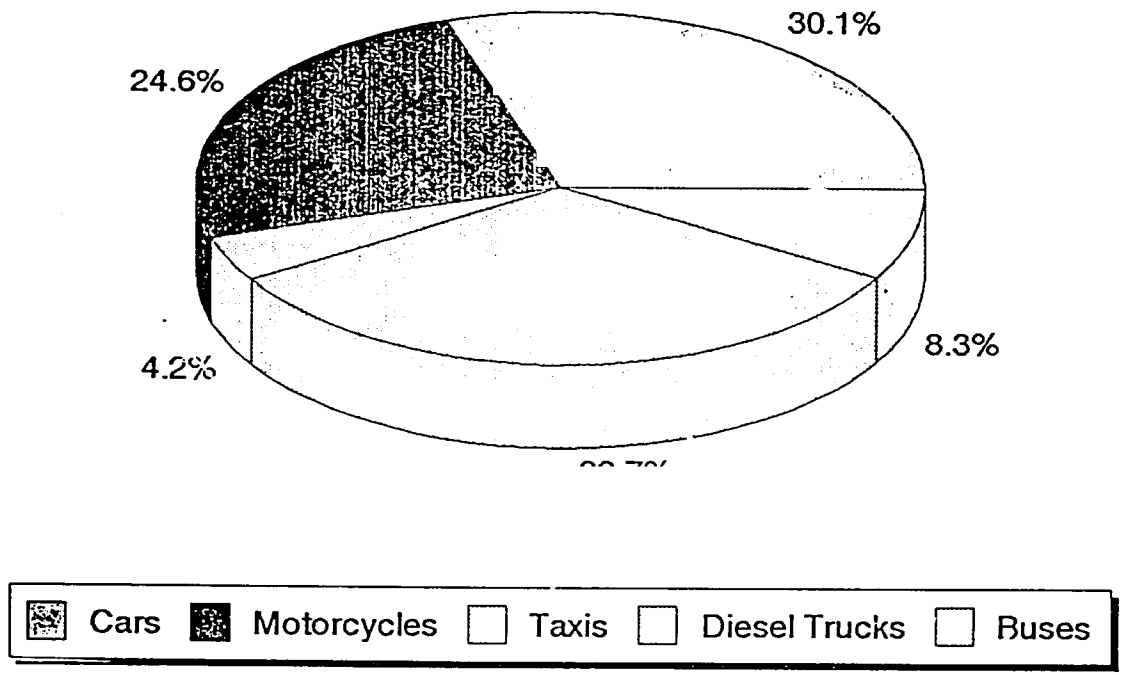
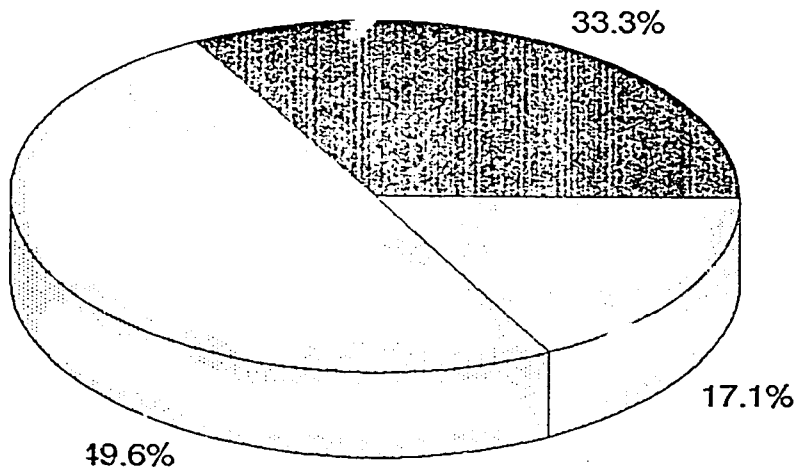


FIGURE 7: EMISSIONS BY VEHICLE CATEGORY

1990 - Organic Particulate



Cars | Motorcycles | Taxis | Diesel Trucks | Buses

FIGURE 8: EMISSIONS BY VEHICLE CATEGORY - S

1990

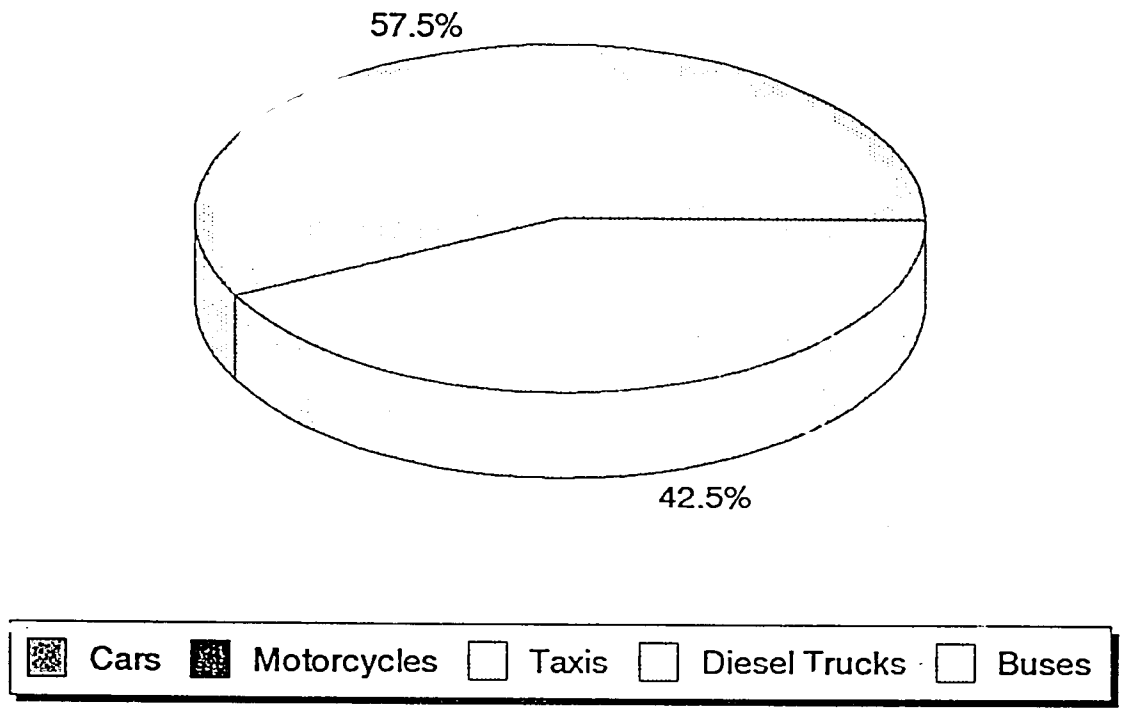


FIGURE 9: EMISSIONS BY VEHICLE CATEGORY - Lead

1990

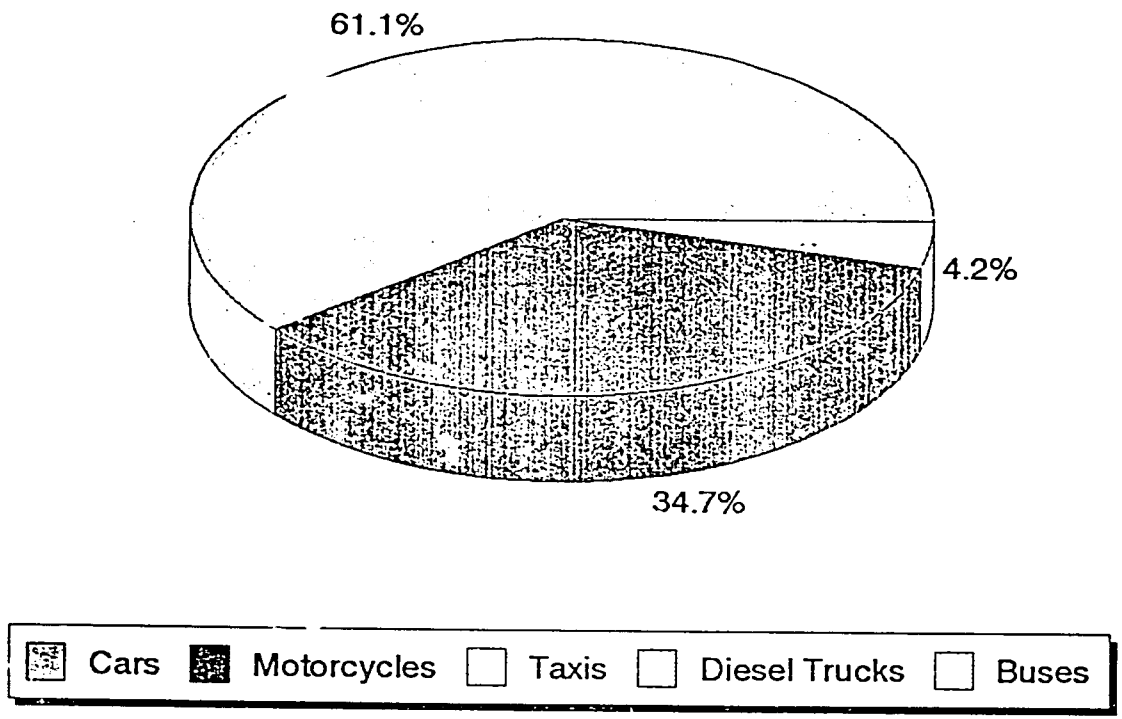


FIGURE 10: EMISSIONS BY VEHICLE CATEGORY - NOx

1990

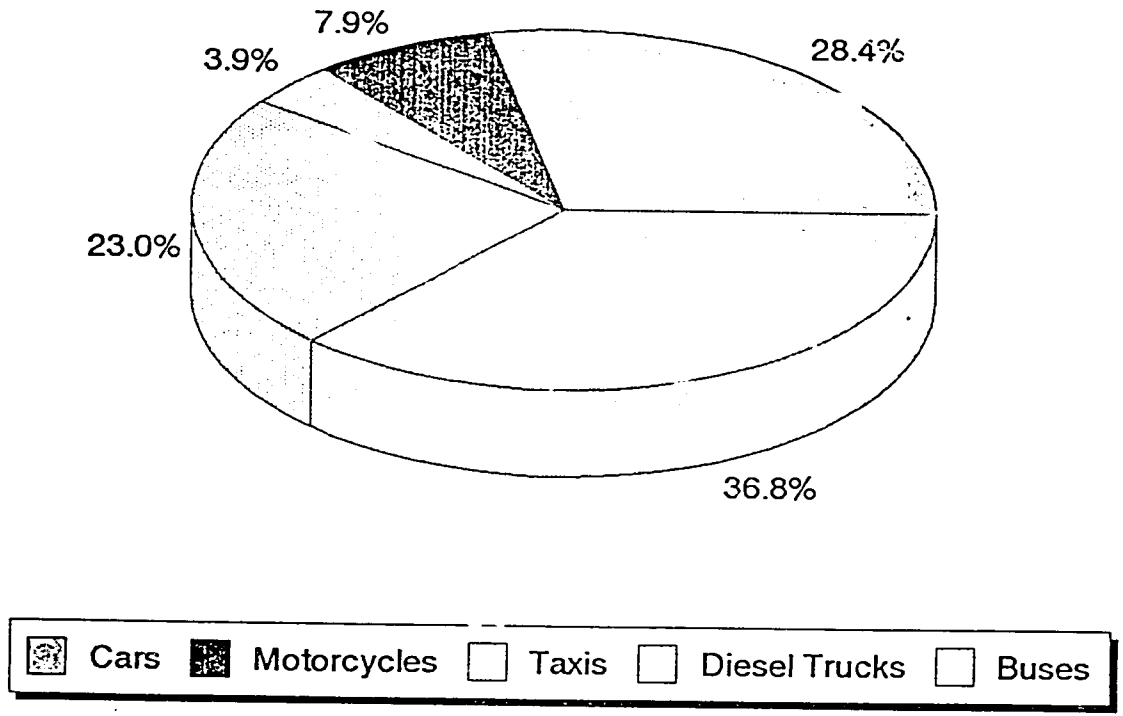


FIGURE 11: EMISSIONS BY VEHICLE CATEGORY - CO

1990

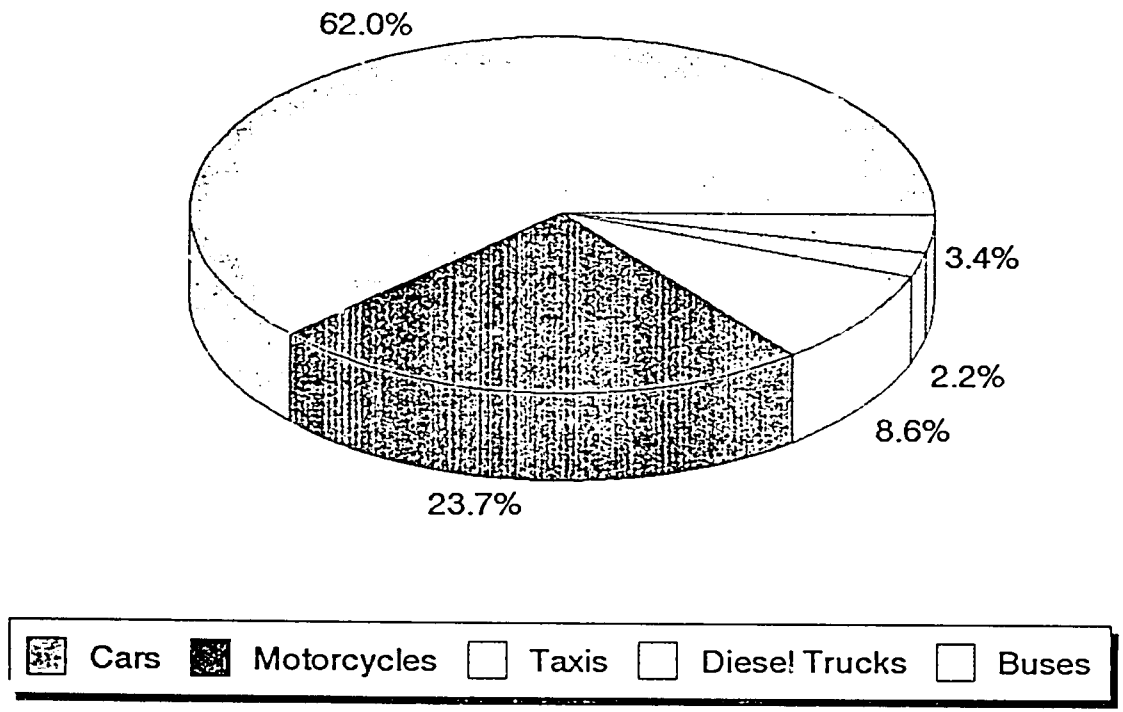
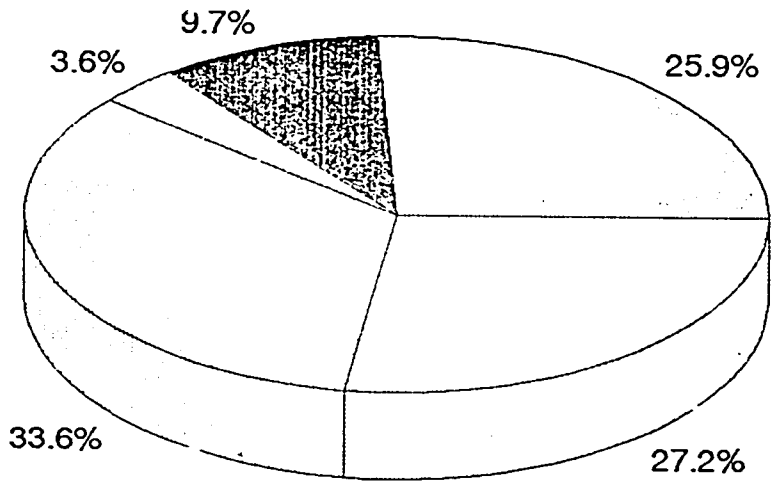


FIGURE 12: EMISSIONS BY VEHICLE CATEGORY - CO2

1990



Cars | Motorcycles | Taxis | Diesel Trucks | Buses

FIGURE 13: EMISSIONS BY VEHICLE CATEGORY - HC

1990

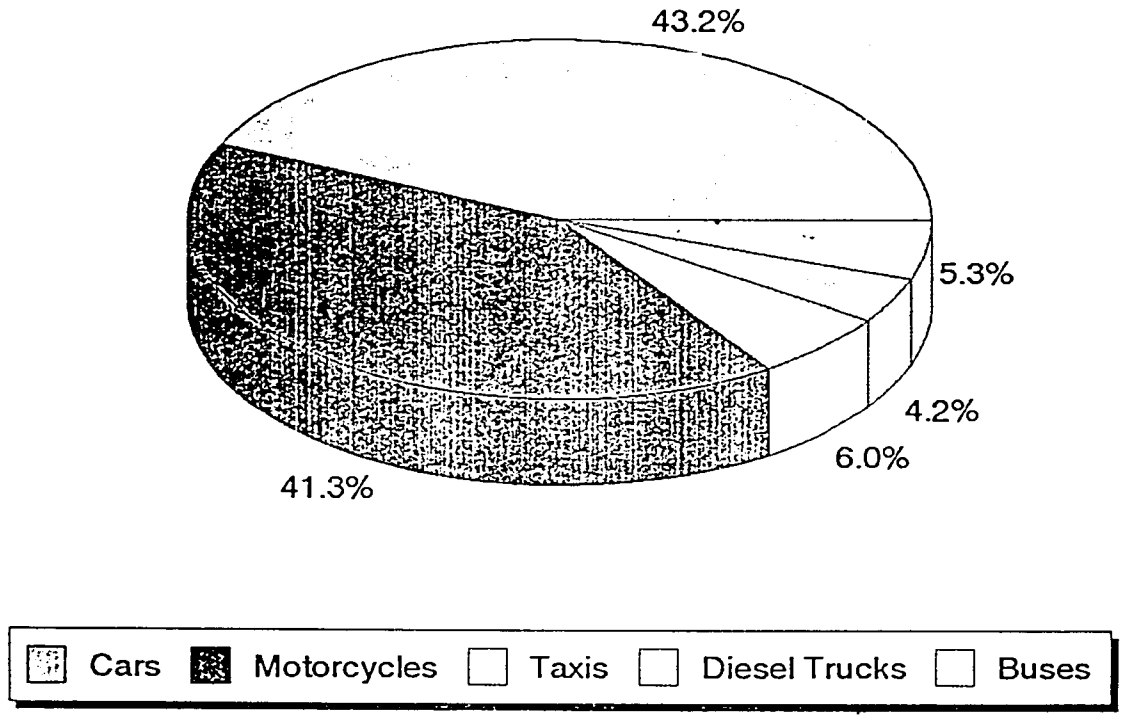


FIGURE 14:Trends In Vehicle Categories - Colombo

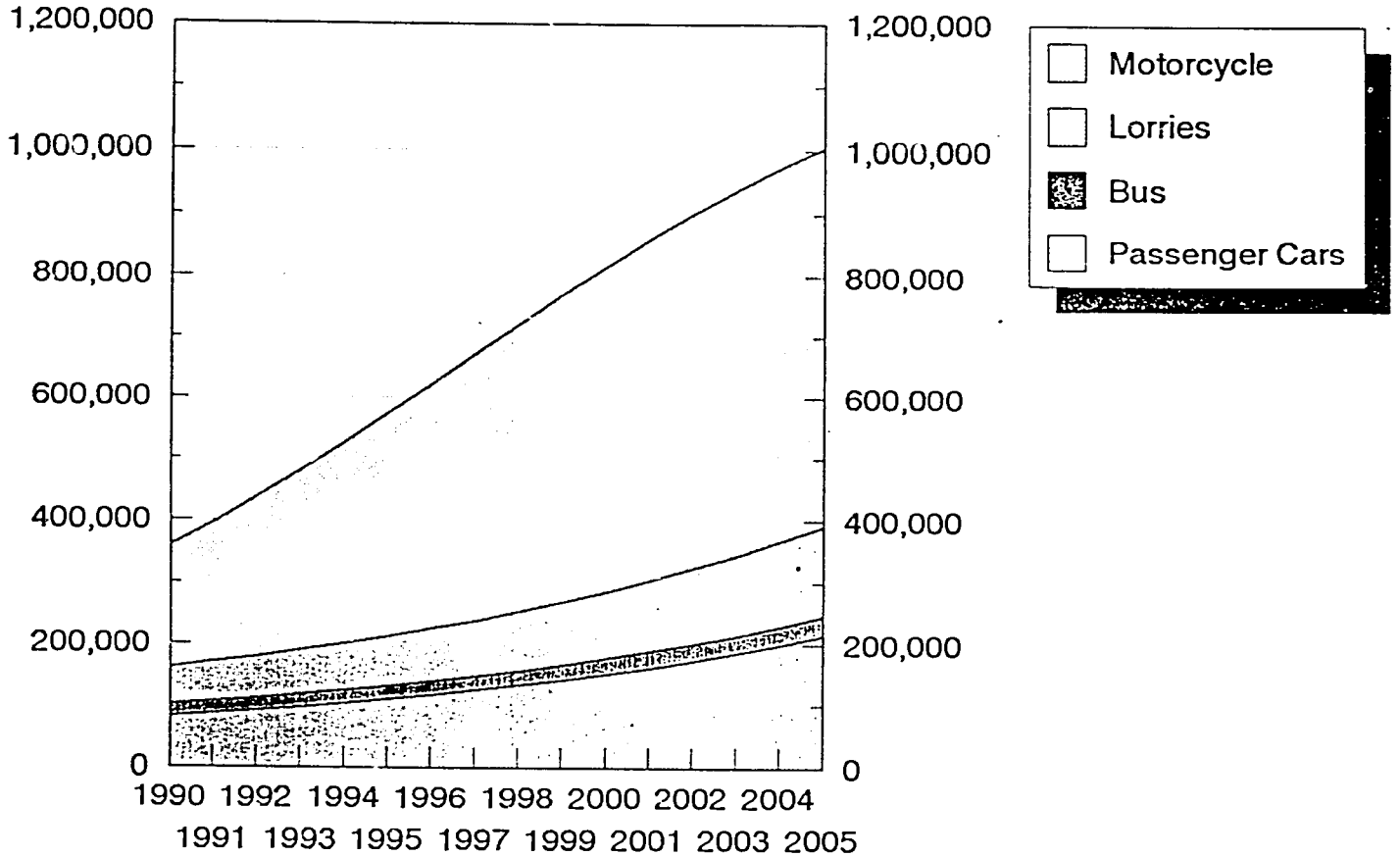


FIGURE 15: Trends In Vehicle Modes-Colombo

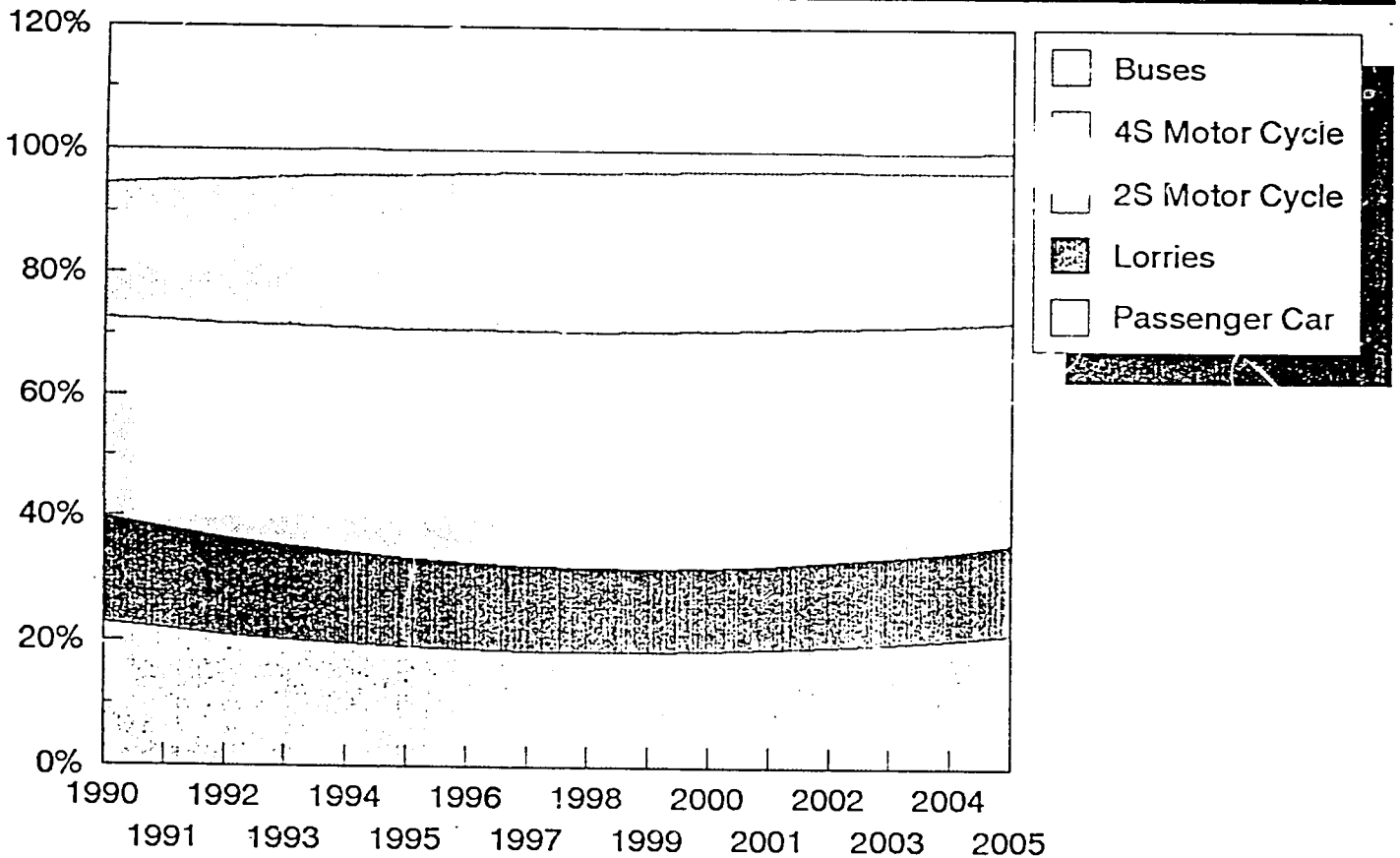


FIGURE 16:POTENTIAL IMPACT OF CONTROL STRATEGIES

GASEOUS POLLUTANTS FROM VEHICLES

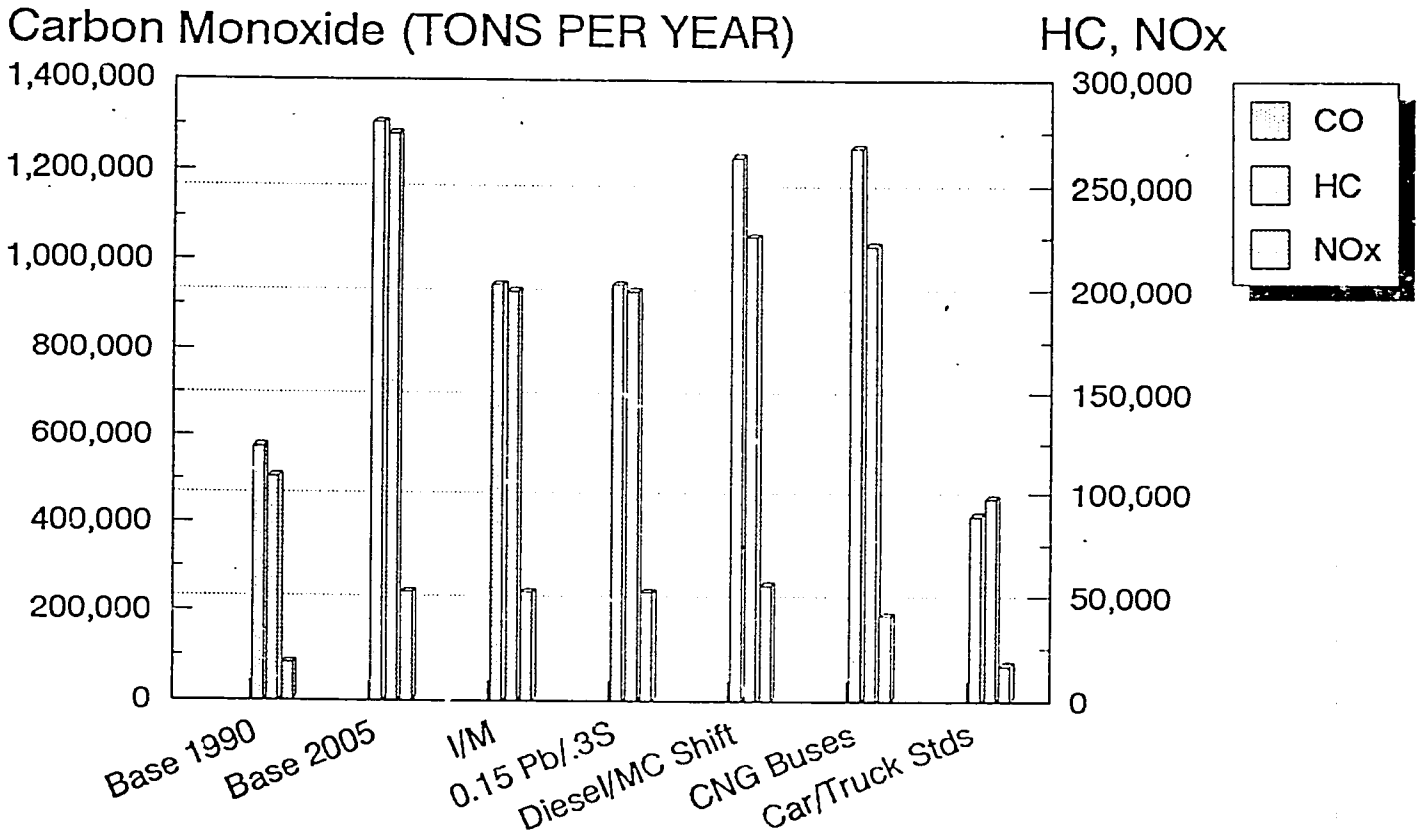


FIGURE 17:POTENTIAL IMPACT OF CONTROL STRATEGIES

PARTICULATE EMISSIONS FROM VEHICLES

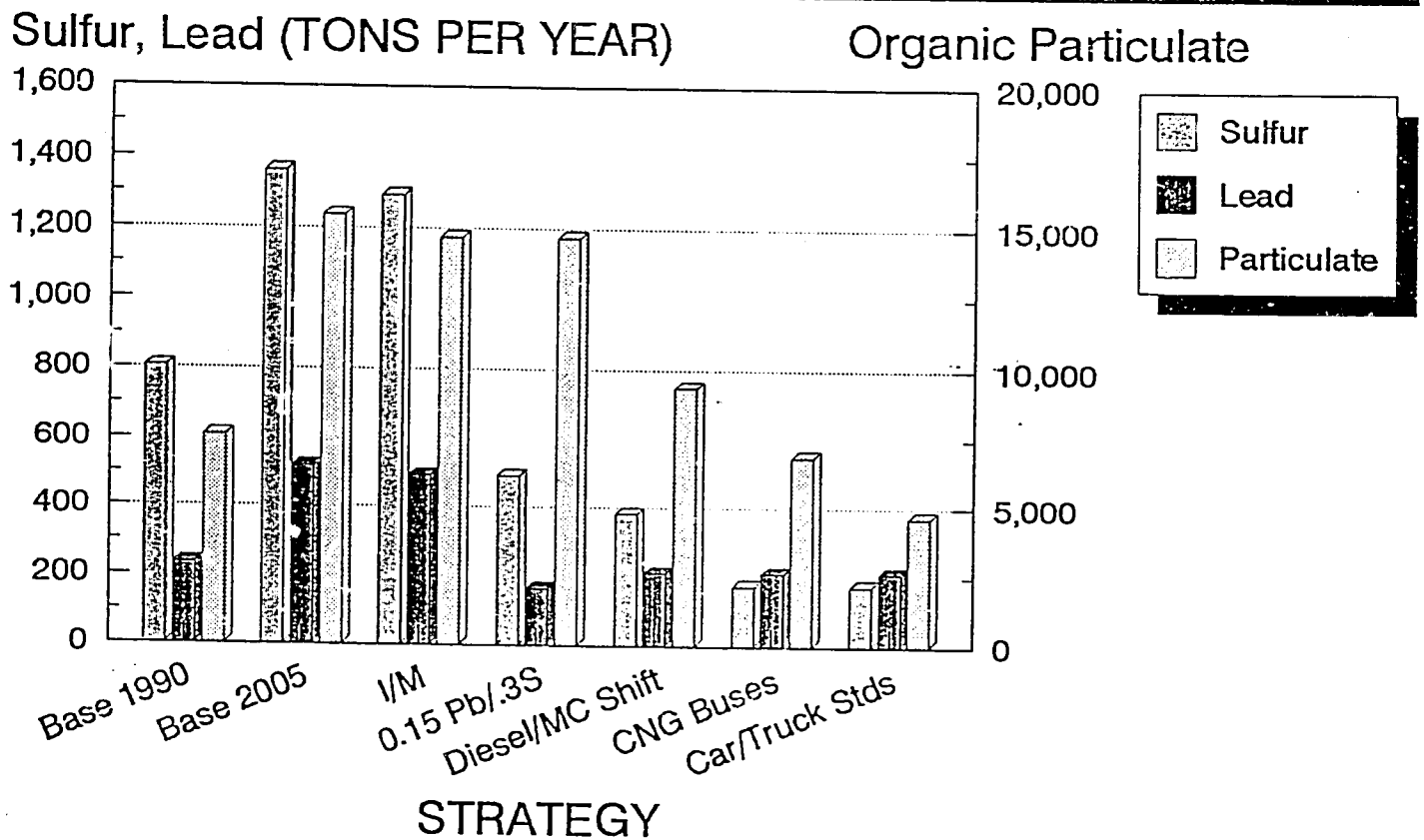


TABLE B

TOTAL VEHICLE POPULATION BY CLASS OF VEHICLES
(Excluding Land Vehicles)

	CARS	TAXIS	MOTORCYCLES	BUSES	LORRIES
1976	89,795	3,974	23,384	13,142	36,447
1977	92,910	4,100	24,350	14,123	37,326
1978	99,523	4,275	29,643	14,570	42,343
1979	109,273	5,180	45,087	17,317	48,733
1980	114,443	6,430	79,803	20,752	58,070
1981	119,826	6,430	96,851	23,092	65,803
1982	124,830	6,827	107,545	26,172	72,070
1983	129,630	7,223	121,840	30,438	80,114
1984	134,110	7,620	138,632	34,681	88,132
1985	140,570	8,017	161,373	38,309	96,306
1986	146,811	8,413	187,717	40,214	103,052
1987	139,027	8,810	213,441	37,064	103,849
1988	145,987	9,207	240,869	37,977	108,869
1989	154,176	9,603	307,392	38,603	114,231
1990	163,519	10,000	391,732	39,812	122,148

TABLE C: ANNUAL AVERAGE GROWTH RATES

	CARS	TAXIS	MOTORCYCLES	BUSES	LORRIES
1981	4.7%	0.0%	21.4%	11.3%	13.3%
1982	4.2%	6.2%	11.0%	13.3%	9.5%
1983	3.8%	5.8%	13.3%	16.3%	11.2%
1984	3.5%	5.5%	13.8%	13.9%	10.0%
1985	4.8%	5.2%	16.4%	10.5%	9.3%
1986	4.4%	4.9%	16.3%	5.0%	7.0%
1987	-5.3%	4.7%	13.7%	-7.8%	0.8%
1988	5.0%	4.5%	12.9%	2.5%	4.8%
1989	5.6%	4.3%	27.6%	1.6%	4.9%
1990	6.1%	4.1%	27.4%	3.1%	6.9%

TABLE D

Key Assumptions:

Vehicle Mode	Number 1990	Km/Yr/Vehicle	Emission Factors (Gm/Km) CO	HC	NOx	Particulate	Sulfur % Emitted	Lead %	MPG
Passenger Cars	205078	36000	62	8.3	2	0	0.95	0.75	19
2Stroke MC	245559	15000	26	12	0.2	1.3	0.95	0.75	49
4Stroke MC	368338	15000	31	8.2	1	0	0.95	0.75	37.7
Taxis	10000	50000	32	8.3	2	0	0.95	0.75	19
Buses	31898	50000	12.4	3.7	9.4	1.5	0.95	0.75	5
Lorries	144370	48000							
Light			1.9	0.7	1.4	1	0.95	0.75	16.3
Heavy			12.4	3.7	9.4	1.5	0.95	0.75	5

Fuels	
Lead in Petrol	0.45
S in Petrol	0.00
S in Diesel	0.8

MPW, 05-Jul-92

TABLE E: POTENTIAL IMPACT OF CONTROL STRATEGIES

PARTICULATE EMISSIONS FROM VEHICLES

	Sulfur	Lead	Particulate
Base 1990	805	233	7,608
Base 2005	1,359	518	15,434
I/M	1,291	492	14,662
0.15 Pb/.3S	491	164	14,662
Diesel/MC Shift	381	210	9,344
CNG Buses	173	210	6,841
Car/Truck Stds	173	210	4,641

TABLE F: POTENTIAL IMPACT OF CONTROL STRATEGIES

GASEOUS POLLUTANTS FROM VEHICLES

	CO	HC	NOx
Base 1990	573,451	108,100	17,657
Base 2005	1,303,872	273,971	51,875
I/M	944,675	199,244	51,875
0.15 Pb/.3S	944,675	199,244	51,875
Diesel/MC Shift	1,228,430	225,687	55,315
CNG Buses	1,248,454	221,208	40,605
Car/Truck Stds	415,428	97,398	16,880