Michael P. Walsh
3105 N. Dinwiddie Street
Arlington, Virginia 22207
USA
Phone: (703) 241 1297 Fax: (703) 241 1418

ENVIRONMENTAL CONSIDERATIONS FOR CLEANER TRANSPORTATION FUELS IN ASIA: TECHNICAL OPTIONS

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Jitu Shah, Project Director

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EXECUTIVE SUMMARY

INTRODUCTION AND BACKGROUND

During 1994, the global motor vehicle population -- including passenger cars, trucks, buses, motorcycles and three wheeled vehicles (Tuk Tuks) -- exceeded 700 million for the first time in history. Most of these vehicles remain concentrated in the highly industrialized countries of the OECD, but an increasing number of urbanized areas in developing countries, especially in Asia, now contain large numbers of vehicles. While these vehicles have brought many advantages -- increased mobility and flexibility for millions of people, more jobs, and enhanced many aspects of the quality of life -- the benefits have been at least partially offset by excess pollution and the adverse effects which result.

Reducing the pollution that comes from vehicles will usually require a comprehensive strategy encompassing vehicle demand management, inspection and maintenance, advanced vehicle technology and clean fuels. This paper will primarily address fuels. It will start with an overview of the air pollution problem in selected Asian cities followed by a selective review of some of the pollution control efforts underway in the region. The remainder of the paper will then explore the challenges and opportunities for lowering vehicle pollution through greater use of clean or alternative fuels.

OBJECTIVES

This paper provides an appreciation and methodology to be applied by decision makers for informed decision making on the production and use of cleaner transport fuels in an effort to improve air quality in urban areas of large Asian cities. The focus of the paper is to provide an overview of the challenges and opportunities for lowering vehicle emissions by means of fuel modifications or substitutions. Issues receiving particular attention are the reduction or removal of lead from gasoline and the reduction of sulfur from diesel fuel.

CONCLUSIONS AND RECOMMENDATIONS

1. Current air quality levels in the many major Asian cities already reflect serious pollution. Because the vehicle populations in most of these cities continue to grow, frequently at annual rates in excess of 10 percent per year, one should expect even more serious pollution problems in the future unless aggressive control efforts are undertaken.

2. Substantial efforts have been and continue to be underway throughout many Asian countries to address their motor vehicle pollution problems. Several conclusions can be drawn from these efforts:

Several comprehensive motor vehicle pollution control programs have been developed in the region.
A wide variety of strategies are being implemented, tailored to the particular problems and capabilities in a particular country or city - one size does not fit all.
In virtually every serious effort to reduce motor vehicle pollution, cleaner fuels - especially unleaded gasoline and lower sulfur diesel fuel - play a critical role.

3. A growing body of data on the adverse health effects of lead, especially in young children, indicates there may be no “safe” level. Reduced lead in gasoline has been shown to reduce the risk of behavioral problems, lowered IQ s and decreased ability to concentrate in exposed children.

4. Lead scavengers which accompany leaded gasoline have also been identified as human carcinogens; the elimination of lead in gasoline will therefore also reduce this cancer risk.

5. Studies in both Europe and the United States show that gasoline lead is responsible for about 90 percent of airborne lead and that 1 microgram per cubic meter of ambient lead will cause a 1-2 microgram per milliliter increase in blood lead levels. This is in addition to the lead burden which may be associated with food, drinking water and other sources.; this burden can be highly variable from country to country.

6. The availability of lead free gasoline can facilitate extensive reductions in the other major pollutants from motor vehicles, hydrocarbons, carbon monoxide and nitrogen oxides by allowing the use of catalytic converters. In addition to their direct adverse health effects, hydrocarbons and nitrogen oxides contribute to the formation of photochemical smog or ozone, which also causes a variety of adverse effects.

7. Motor vehicle emissions of hydrocarbons, carbon monoxide and nitrogen oxides cause or contribute to a wide range of adverse impacts on public health and general well being including increased angina attacks in individuals suffering from angina pectoris, greater susceptibility to respiratory infection, more respiratory problems in school children, increased airway resistance in asthmatics, eye irritation, impaired crop growth, dead lakes and forest destruction.

8. The combination of lead free gasoline and catalysts can also facilitate very substantial reductions in other harmful pollutants such as aldehydes and polynuclear aromatic hydrocarbons (PAH s).

9. These emissions reductions can occur simultaneously with equally significant improvements in fuel economy and reductions in vehicle maintenance. Also, based on studies in Canada, reduced maintenance can save about 2.4 cents per liter with the use of unleaded gasoline compared to leaded gasoline.

10. The most direct strategy for eliminating lead in gasoline is to ban its use; several countries have adopted this strategy. In Asia, Thailand has been an aggressive proponent of this approach.

11. Tax policies which price unleaded fuel substantially below leaded fuel have also been found to be very effective in stimulating the sales of unleaded fuel. Hong Kong and Singapore stand out as Asian examples.

12. Countries concerned about the available supply of unleaded petrol may wish to maintain a higher price for unleaded compared to leaded but this strategy tends to increase the risk of poisoning of any catalyst equipped vehicles in the country and prolongs the use of lead with its concomitant health risks.

13. Beyond unleaded gasoline, hydrocarbons, CO and toxic emissions can be reduced from 10 to 30% through the reformulation of gasoline by modifying parameters such as volatility, oxygenates, sulfur levels and hydrocarbon mix. Care must be taken to assure that these modifications don't increase NOx emissions.

14. The use of oxygenates such as MTBE in cold temperature environments, while clearly bringing about significant reductions of CO, has raised concerns regarding adverse health effects in certain susceptible individuals. Studies to date by both the US EPA and several states have failed to identify a serious problem but additional studies are ongoing.

15. There is a clear worldwide trend toward lower and lower levels of sulfur in diesel fuel. At a minimum, this reduces the particulate emissions from diesel vehicles; recent European studies indicate that for every 100 PPM reduction in sulfur, there will be a .16% reduction in particulate from light duty vehicles and a 0.87% reduction from heavy duty vehicles. Sulfur in fuel also contributes to sulfur dioxide (SO_2) in the atmosphere.

16. Other diesel fuel properties such as volatility, aromatic content and additives can also have positive or negative effects on diesel vehicle emissions.

17. In addition to the adoption of mandatory limits, it has been shown that tax policies can be very effective in encouraging the introduction and use of low polluting diesel fuels.

18. Alternative fuels including methanol (made from natural gas, coal or biomass) ethanol (made from grain), vegetable oils, compressed natural gas (CNG) mainly composed of methane, liquefied petroleum gas (LPG) composed of propane, butane, electricity, hydrogen, synthetic liquid fuels derived from hydrogenation of coal, and various fuel blends such as gasohol, have drawn increasing attention during the last decade. The motives for this substitution include conservation of

oil products and energy security, as well as the reduction or elimination of pollutant emissions.

19. Some alternative fuels such as natural gas do offer the potential for large, cost-effective reductions in pollutant emissions in specific cases. Care is necessary in evaluating the air-quality claims for alternative fuels, however - in many cases, the same or even greater emission reduction could be obtained with a conventional fuel, through the use of a more advanced emission control system. Which approach is the more cost-effective will depend on the relative costs of the conventional and the alternative fuel.

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1. OBJECTIVES{tc "autonum OBJECTIVES"}

This paper provides an appreciation and methodology to be applied by decision makers for informed decision making on the production and use of cleaner transport fuels in an effort to improve air quality in urban areas of large Asian cities. The focus of the paper is to provide an overview of the challenges and opportunities for lowering vehicle emissions by means of fuel modifications or substitutions. Issues receiving particular attention are the reduction or removal of lead from gasoline and the reduction of sulfur from diesel fuel.

2. INTRODUCTION AND BACKGROUND{tc "autonum INTRODUCTION AND BACKGROUND"}

During 1995, the global motor vehicle population -- including passenger cars, trucks, buses, motorcycles and three wheeled vehicles (Tuk Tuks) -- exceeded 700 million for the first time in history. While most of these vehicles remain concentrated in the highly industrialized countries of the OECD, an increasing number of urbanized areas in developing countries, especially in Asia, now contain large numbers of vehicles. Cities such as Jakarta, Bangkok and Seoul are certainly among those experiencing the most congested roads in the world. While these vehicles have brought many advantages -- increased mobility and flexibility for millions of people, more jobs, and enhanced many aspects of the quality of life -- the benefits have been at least partially offset by excess pollution and the adverse effects which result.

Motor vehicles emit large quantities of carbon monoxide, hydrocarbons, nitrogen oxides, and such toxic substances as fine particles and lead. Each of these along with their secondary by-products such as ozone can cause adverse effects on health and the environment[1]. Because of the growing vehicle population and the high emission rates from many of these vehicles, serious air pollution problems have been an increasingly common phenomena in modern life.

Reducing the pollution that comes from vehicles will usually require a comprehensive strategy encompassing vehicle demand management, inspection and maintenance, advanced vehicle technology and clean fuels. This paper will focus primarily on fuels. It will start with an overview of the air pollution problem in selected Asian cities followed by a selective review of some of the pollution control efforts underway in the region. The remainder of the paper will then explore the challenges and opportunities for lowering vehicle pollution through greater use of clean or alternative fuels.

3. THE AIR QUALITY SITUATION IN ASIA{tc "autonum THE AIR QUALITY SITUATION IN ASIA"}

Over the course of the past one to two decades, there has been an explosive growth in the vehicle population in many Asian countries and today this growth continues to spread. As a result, air pollution problems caused by vehicle emissions are beginning to emerge. The current situation in a representative cross section of countries is presented below by way of illustrating the current status.

1. Bangkok, Thailand{tc "autonum Bangkok, Thailand" \l 2}

[1]See Appendix A for a detailed review of the adverse health affects associated with vehicular related air pollution.

Results of air quality monitoring over the past 11 years indicate that the air pollutants of greatest concern in Bangkok are suspended particulate matter (SPM), especially respirable particulate matter (PM10)[2], carbon monoxide (CO), and lead, respectively. They are accounted for mostly by the transport sector. Current levels of SPM in Bangkok's air, especially along congested roads, far exceed Thailand's primary ambient air quality standard for SPM. In 1993, curbside 24-hour average concentrations exceeded the standard on 143 out of 277 measurement days.

Similarly, curbside 8-hour average concentrations of carbon monoxide are close to and sometimes exceed the Thai standard (20 mg/m^3). Concentration as high as 25 mg/m^3 have been recorded.

Lead has been reduced in recent years due to the reduction of the lead content of leaded gasoline and the increased use of unleaded gasoline.

A USAID sponsored study in 1990 which attempted to rank the environmental health risks to the 5.5 million people living in Bangkok estimated that 270,000 people are at moderate risk for health effects associated with carbon monoxide (angina to persons with chronic cardiovascular disease) and 1.3 million people at mild risk (inability to concentrate and headaches for persons in general population).[3]

Carbon Monoxide has been on the decline since 1992 in the congested streets for the 1-hour concentrations, but the 8- hour averages have not shown a similar declining trend. This may indicate that for the peak hour the introduction of new cars and emission control technology may lessen the air quality problem as the traffic volume is the same, however the peak hours may be longer, thus the longer averaging time (8-hour) may produce the stable or increasing trend. The high values observed for the 8 hour averages are about 20 mg/m^3.

Based on a careful review of available air quality data, it is estimated that roadside emissions of particulate, carbon monoxide and lead must be reduced by 85%, 47% and 13%, respectively, if acceptable air quality is to be achieved in Bangkok.[4] There is no evidence to date of any ozone or nitrogen dioxide problem. However, since certain hydrocarbons are known to be toxic, it seems prudent to adopt measures which will reduce these emissions as well.

An analyses prepared for the World Bank indicates that if ambient concentrations of suspended particulate matter and lead in Bangkok are reduced by 20% from current levels, the mid-point estimates of the annual health benefits from less sickness and lower mortality would be between US$1 billion and US$1.6 billion and between US$300 million and US$1.5 billion, respectively. Shin et al (1992) assigned various monetary values to the estimated health risks found by USAID (1990) and estimated an economic benefit of US$10.7 million annually from carbon monoxide reduction in Bangkok.[5]

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[2]PM 10 refers to particles in the size range of 10 microns or less. All of these particles are considered respirable and therefore more important than large particles from the standpoint of public health.

[3]U.S. Agency for International Development (1990), "Ranking Environmental Health Risks in Bangkok, Thailand." Vols. 1 & 2, Working Paper, USAID.

[4]These emissions, especially particulate, come from many sources in addition to mobile sources and these other sources will need to be controlled as well. It is assumed in this first order analysis that the same percentage reduction will be needed from all sources including mobile sources to achieve the required overall emissions reduction.

[5]Shin, E. et al. (1992), "Economic Valuation of the Urban Environment with Emphasis on Asia and Non-Productivity Approaches." Draft Paper prepared for UNDP/World Bank/UNCHS Urban Management Program.

2. Beijing, China{tc "autonum Beijing, China" \l 2}

In spite of a relatively low vehicle population, air pollution problems caused by motor vehicles have started to emerge in the major cities of China such as Beijing. One reason is that the vast majority of the vehicles in use in China are driven in the major cities. For example, the number of automobiles operating in Beijing is about 8.7 percent of the total in all of China. In addition, many Chinese made vehicles still use designs which were developed twenty years ago, with the result that CO and HC emission rates for these engines are about 10 to 20 times the levels emitted from modern engines. Furthermore the average operating speed of motor vehicles in Beijing and other major cities is quite low due to the crowded and mixed traffic (motor vehicle, motor cycle, bicycle, tractor, even carts). The average speed inside the third ring road of Beijing was only 23.8 km/h to 27.8 km/h in 1988, which resulted in a high level of CO and HC emissions.

In addition, the space devoted to roads in the major cities of China is much less than in many other countries. For example, the area occupied by roads in Beijing is about 9 percent of the city total area while in London this ratio is 23 percent, Tokyo 24 percent, and New York 35 percent; this results in a higher density of motor vehicles on the streets, a further reduction of vehicle speeds, and subsequently higher CO and HC emissions.

As a result, pollution levels are already quite high especially for carbon monoxide (CO) and hydrocarbons (HC). CO and HC levels frequently exceed healthy levels, and their patterns are similar to vehicle traffic, i.e., they tend to peak during the morning and evening peak traffic time. Within the city proper in Beijing, the average concentration of CO exceeds the National Ambient Air Quality Standards of 4 mg/m^3 for the daily average. Furthermore, the peak concentration levels in the streets and in the residential areas near the streets are much higher. As the vehicle population grows, the proportion of the days in which the standards are exceeded has been increasing.

According to an air quality survey of Beijing in the late 1980s, motor vehicles contribute about half of the total CO, HC, and NOx emissions coming from all pollutant sources.

Lead is another pollutant of concern; the concentrations of lead in Beijing are 1-1.5 ug/m3, and even reach 14-25 ug/m3 in some extreme cases.

In the last few years, improved street conditions has been increasing the average running speed. As a result, CO and HC emission levels have started to come down to some extent. On the other hand, NOx emissions have gone up somewhat. This has contributed to an increase in the number of days with maximum hourly average concentrations of ozone above the standard.

3. Hong Kong{tc "autonum Hong Kong" \l 2}

Particulate is the most serious pollution problem at present in Hong Kong, and motor vehicles are estimated to be responsible for approximately 50% of the PM-10 emissions. Using the methodology developed by the California Air Resources Board, Hong Kong officials estimate that diesel particulate causes approximately 290 premature deaths from lung cancer each year.[6]

4. Kuala Lumpur, Malaysia{tc "autonum Kuala Lumpur, Malaysia" \l 2}

[6] personal communication with Mr. Kong Ha, Hong Kong Environmental Protection Agency.

Based on an analysis of available data in the Kelang Valley Region in 1992, it was concluded that the air pollution problem is relatively serious in comparison with the accepted air quality guidelines.[7] The annual average and daily average of PM 10 at Shah Alam exceeded the guideline and annual averages of PM10 at Klang and Petaling Jaya were around the guideline level. Carbon monoxide at City Hall and Petaling Jaya exceeded the guideline level for 8 hours. Ozone at all the fixed stations exceeded the guideline. Annual averages of each pollutant were found to be the highest at City Hall, Petaling Jaya or Shah Alam; the areas around these stations were considered to be highly polluted.

Further it was found that the diurnal pattern of CO and NOx tended to follow the two peak pattern at most stations; at some of the stations, the diurnal pattern of suspended particulate and hydrocarbons also followed this two peak pattern. This is significant because it indicates that vehicular traffic with its clear morning and evening peaks is having a major influence on air quality.

Follow up studies in 1994 continue to show serious problems.[8] For example, particulate routinely exceeds guideline limits and may be actually worsening at many sites. Nitrogen dioxide and particulate matter were the most pervasive air pollutants in 1994, particularly in the Kuala Lumpur - Petaling Jaya - Shah Alam belt which has an estimated population of about 2 million people. Motor vehicles were again found to be the main sources of air pollution, although other sources such as industries and construction activities also contributed to local effects.

One bright spot has been the continued reduction in lead as a result of the reduction in the lead content of gasoline. There has been a marked decrease in the average ambient lead concentration in the Klang Valley region over the period from 1988 to 1994.

5. Ho Chi Minh, Viet Nam{tc "autonum Ho Chi Minh, Viet Nam" \l 2}

The available air quality data is limited and is based on the use of old equipment and measurement techniques. In addition, automated continuous monitoring doesn’t exist making it difficult to determine actual patterns or trends and for many pollutants making comparisons with air quality standards difficult. Nonetheless, an informed judgement would indicate that particulate and lead are already serious air pollution problems.

During 1993, a monitoring study was carried out by the Institute of Hygiene and Public Health. Results show that particulate, or dust, is a very serious problem at present and that CO and even NO_2 also exceeds current Viet Nam standards. While many sources certainly contribute to these problems, vehicle emissions seem to be the dominant one, at least in the vicinity of these monitors.

6. Manila, The Philippines{tc "autonum Manila, The Philippines" \l 2}

Since there has been a dearth of good air quality data for Metro Manila, the Asian Development Bank has focused particular attention on this issue.[9] As expected, the measured concentrations of PM10[10] routinely exceeded

[7]“Air Quality Management Study For Kelang Valley Region”, Japan International Cooperation Agency, August 1993.

[8]Personal Communication with Dr. Aku Bakar.

[9]Five monitoring stations on major streets in Metro Manila were established under TA 1414: the Ermita station at Pedro Gil and Taft, the ADB/EDSA station, the DENR/NCR station on Quezon Avenue, the Monumento/MCU

acceptable levels by a factor of over three. Measured total suspended particulate (TSP) exceeded acceptable levels by even larger percentages. Drivers of the more than 50,000 Jeepneys in the metropolis are the most exposed of all population sectors.[11] Lead concentrations at the ADB/EDSA station also exceeded Government standards.[12]

With regard to gaseous pollutants, monitoring indicate that both carbon monoxide and nitrogen dioxide occasionally exceed standards. Measurement for sulfur dioxide and total oxidants indicated concentrations were within the acceptable standards at present.

7. Conclusions{tc "autonum Conclusions" \l 2}

As the above examples illustrate, current air quality levels in the many major Asian cities already reflect serious pollution. Because the vehicle populations in most of these cities continue to grow, frequently at annual rates in excess of 10 percent per year, one could expect even more serious pollution problems in the future unless aggressive control efforts are undertaken. Fortunately, several countries in the region have developed significant pollution control efforts and these will be the subject of the next section.

4. VEHICLE POLLUTION CONTROL EFFORTS UNDERWAY IN ASIA{tc "autonum VEHICLE POLLUTION CONTROL EFFORTS UNDERWAY IN ASIA"}

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station on EDSA, and a station at San Lorenzo Village. All stations monitored particulate matter, three stations included lead analyses, and the Ermita station also monitored the gaseous pollutants of carbon monoxide, nitrogen dioxide, and, for short periods, total oxidants, sulfur dioxide, and hydrocarbons. The DENR/NCR station also monitored carbon monoxide and nitrogen oxides for a two month period.

[10]Particulate matter having a mass mean diameter of less than 10 microns - generally considered the "inhaleable particles".

[11]WHO funded a study of a sample population exposed to vehicular emissions in 1990 and 1991. It concluded that chronic respiratory symptoms are significantly higher among jeepney drivers than among commuters and air conditioned bus drivers. About 93% of the jeepney drivers are exposed to suspended particulate levels 2 to 10 times the health guideline; 100% were found to be exposed to lead levels above 0.5 - 1.0 micrograms per cubic meter as compared to the WHO health guideline of 0.5.

[12]The World Health Organization is sponsoring a study regarding "The Impact Of Vehicular Emissions On Vulnerable Populations In Metro Manila"; preliminary results indicate that 10% of the school children (ages 6 - 14 years) have blood lead levels of 20 micrograms per deciliter or higher. This is twice the level of concern identified in the umbilical cord study. All of the street child vendors tested (ages 6 - 15) were above 10 and many had blood lead levels over 30, an alarming statistic.

A great deal has been learned about reducing emissions from vehicles and strategies exist to both lower emissions per kilometer driven and reduce actual driving. Application of both approaches can be used to ameliorate the otherwise likely future pollution increases in Asian cities.

Generally, the goal of a motor vehicle pollution control program is to reduce emissions from motor vehicles in-use to the degree reasonably necessary to achieve healthy air quality as rapidly as possible or, failing that for reasons of impracticality, to the practical limits of effective technological, economic, and social feasibility. Achievement of this goal generally requires a comprehensive strategy encompassing emissions standards for new vehicles, clean fuels, strategies designed to assure that vehicles are maintained in a manner which minimizes their emissions and traffic and demand management and constraints. These emission reduction goals should be achieved in the least costly manner.

Standards for permissible levels of exhaust and evaporative emissions from motor vehicles should be based on a realistic assessment of costs and benefits keeping in view the technical and administrative feasibility of proposed countermeasures. Technological approaches[13] to achieve the desired emission standards may include fitting new vehicles with emission control devices or requiring such devices to be retrofitted to existing vehicles, modifying fuels or requiring the use of alternative fuels in certain vehicles, and traffic and demand management and policy instruments. However, many of the potential benefits of these countermeasures will be squandered if they are not buttressed by regulatory and economic instruments which assure that vehicle owners, manufacturers and fuel suppliers have sufficient incentives to achieve the desired goals. A key element of the overall strategy, therefore, must be effective enforcement to ensure adequate compliance with standards.

Several developing countries of Asia have made progress with some or all elements of these strategies; specific examples illustrating these efforts will be summarized below.

1. Bangkok, Thailand{tc "□autonum□ Bangkok, Thailand"}

Based on a review of available air quality data, it is estimated that roadside emissions of particulate, carbon monoxide and lead must be reduced by 85%, 47% and 13%, respectively, if acceptable air quality is to be achieved in Bangkok. Recent data indicates that ozone levels downwind of the city may also be approaching unhealthy

[13]See Appendices B and C for a review of gasoline and diesel fueled vehicle pollution control technologies, respectively.

levels; therefore, it seems prudent to adopt measures which will reduce HC and NOx emissions, the ozone precursors, as well.

In response to the serious air pollution threat, Thailand's current Seventh Plan has placed a high priority on improving air quality and definite targets have been set to control the amount of suspended particulate matter, carbon monoxide, and lead on Bangkok's major streets.

1. Current Program{tc "autonum Current Program" \l 3}

A number of measures have been adopted to mitigate air pollution problems, particularly those caused by the transport sector. They are aimed not only at exhaust gas emission controls but also at the improvement of fuel and engine specifications, implementation of an in-use vehicle inspection and maintenance program, public transport improvement through mass transit systems, and the improvement of traffic conditions through better traffic management. Measures directed toward reducing vehicle emissions include:

1. introduction of unleaded gasoline at prices below that of leaded gasoline (introduced in May 1991),

2. reduction of the maximum allowable lead in gasoline from 0.4 to 0.15 grams per liter (effective as of January 1, 1992),

3. The phase out leaded gasoline as of January 1, 1996,

4. reduction of the sulfur content of diesel fuel from 1.0 to 0.5% as of April 1992 in the Bangkok Metropolitan Area and after September 1992 throughout the whole country; the use of low sulfur diesel fuel has been mandatory in Bangkok since September 1993.

5. reduction of the 90% distillation temperature of diesel fuel from 370 degrees C to 357 degrees as of April 1992 in the Bangkok Metropolitan Area and after September 1992 throughout the whole country.

6. required all new cars with engines larger than 1600 cc to meet the ECE R-83 standards after January 1993; all cars were required to comply after September 1, 1993.

7. Taxis and Tuk-Tuks have already been largely converted to operate on LPG.

8. ECE R40 requirements for motorcycles were introduced in August 1993 and followed soon afterward by ECE R40.01; the government has decided on a third step of control which started to be phased in during 1995.

9. ECE R49.01 standards for heavy duty diesel engine vehicles are now in effect.

10. The government has decided to reduce the sulfur level in diesel fuel from the current 0.5 Wt.% to 0.25 by 1996 and 0.05 by the year 1999.

Currently, noise and emission testing are required and are conducted under the Land Transport Department's general vehicle inspection program. All new vehicles are subject to such inspection. For in-use vehicles, only those registered under the Land Transport Act (buses and heavy-duty trucks) and commercial vehicles registered under the Motor Vehicles Act (taxis, Tuk-Tuks and rental vehicles) are subject to inspection during annual registration renewals. It is expected that Land Transport Department will require all in-use vehicles to be inspected soon. Vehicles in use for ten or more years are subjected to an annual inspection while the newer vehicles will be subjected to inspection at different time periods. This will be determined by the LTD. Private inspection centers are being licensed.

2. **Future Plans**{tc "autonum Future Plans" \l 3}

Further investigations are underway to introduce more stringent standards for motorcycles as well as light and heavy trucks, and to purchase 200 CNG buses to reduce the smoke problem.

A comprehensive motor vehicle pollution control strategy is being designed for Bangkok. The most critical data needs appear to be those related to motorcycle and diesel vehicle particulate emissions factors. Unfortunately, it appears that locally generated data in this area is at least a year away. Further, better characterization of the particulate would be very helpful. In addition as the new air quality monitoring network gets deployed, it will be critical to periodically update the air quality targets.

3. **Conclusions**{tc "autonum Conclusions" \l 3}

Bangkok, like many other megacities in the world, has serious problems associated with the use of energy in transport sector. Several factors, including population growth and rapid economic expansion and etc., are fundamental factors needed to be considered for long-term planning. Rapid industrialization and urbanization, coupled with the lack of land use planing in the past, has contributed to the atmospheric pollution associated with the transport sector. This problem has been intensified by the inadequate road infrastructures to absorb the rapidly growing vehicle population which in turn causes congestion and by the lack of mass transport system to offer good substitutes for private vehicles. These two factors encourage people to rely more on their private vehicles and hence have further contributed to the congestion problem.

It is recognized that this problem can be alleviated through several means including the following measures: source reduction through improvement of fuel quality, inspection/maintenance program, vehicle standards, and traffic and demand management (such as having good mass rapid transit system). A great deal of work remains to be done, especially in the policy arena to control travel demand (demand side management).

2. Singapore{tc "autonum Singapore" \l 2}

In Singapore, motor vehicle emissions are a significant source of air pollution. The vehicle population has been steadily increasing over the past decade as a consequence of rapid urbanization and economic growth. At the beginning of 1993, the vehicle population stood at approximately 550 thousand.

1. Land Transport Policy{tc "autonum Land Transport Policy" \l 3}

Singapore's land transport policy strives to provide free-flowing traffic within the constraint of limited land. A four-pronged approach has been adopted to achieve this. Firstly, the need to travel is minimized through systematic town planning. Secondly an extensive and comprehensive network of roads and expressways, augmented by traffic management measures, has been built to provide quick accessibility to all parts of Singapore. Thirdly, a viable and efficient public transport system that integrates both the Mass Rapid Transit (MRT) and bus services, is promoted. Finally, the growth and usage of vehicles are managed to prevent congestion on the road.

2. Mobile Source Controls{tc "autonum Mobile Source Controls" \l 3}

Singapore's strategy for reducing pollution from motor vehicles is two-pronged: improving the engines and fuel quality to reduce emissions and using traffic management measures to control the growth of vehicle population and fuel consumption. The Pollution Control Department works closely with the Registry of Vehicles to implement the two-pronged strategy.

Between 1981 and 1987, the lead content in leaded petrol was gradually reduced from 0.8 to 0.15 grams per liter. The use of unleaded petrol was promoted in Feb. 1990 through a differential tax system which made unleaded petrol 10 cents per liter cheaper than leaded petrol at the pump. All petrol-driven vehicles registered for use in Singapore after 1 July 1991 must be able to use unleaded petrol. These measures have resulted in the greater use of unleaded petrol. About 57% of all petrol sold in Singapore at the end of 1993 was unleaded. The sulfur content in diesel is currently limited to 0.5% by weight and will be reduced to 0.3% by weight from 1 July 1996 onwards.

The emission standards for petrol vehicles have been progressively tightened since 1984 and the standards currently in force are the European Union Consolidated Emissions Directive 91/441 and the Japanese emission standards (Article 31 of Safety Regulations for Road Vehicles).

Since October 1992, motorcycles and scooters have been required to comply with the emission standards stipulated in the U.S. Code of Federal Regulation 86.410-80 before they can be registered for use in Singapore.

Since January 1991, all diesel vehicles have been required to comply with smoke standards stipulated in the UN/ECE Regulation No. 24.03 before they can be registered for use in Singapore.

All in-use vehicles are required to undergo periodic inspections to check their roadworthiness and exhaust emissions while idling. Vehicles which fail the inspections are not allowed to renew their road tax.

3. Traffic Management Measures{tc "□autonum□ Traffic Management Measures" \l 3}

The situation in Singapore is a unique one. Singapore is essentially a city-state with a large population living on a small land mass. Urbanization, industrialization and infra-structural development are still progressing in earnest, fueled by a growing economy. With such a combination of factors, it is easy to see that there is a potential for serious environmental problems from both stationary and mobile sources if the sources are not managed or controlled properly. In the case of motor vehicles, the need to control their impact on traffic flow and the environment has given rise to a unique set of traffic management measures.

1. Vehicle Registration and Licensing{tc "□autonum□ Vehicle Registration and Licensing" \l 4}

The expense of owning and operating a vehicle in Singapore has served as a dampener to the growth in the vehicle population. Car owners wishing to register their cars must pay a 45% import duty on the car's open market value (OMV) a registration fee of $1,000 for a private car ($5,000 for a company-registered car) and an Additional Registration Fee (ARF) of 150% of the OMV.
In addition, car owners pay annual road taxes based on the engine capacity of their vehicles. The road tax of company-registered cars is twice as high as for individuals.
For diesel vehicles, a diesel tax which is six times the road tax of an equivalent petrol vehicle is payable.
To encourage people to replace their old cars with newer, more efficient models, a Preferential Additional Registration Fee (PARF) system was introduced in 1975. Private car owners who replace their cars within ten years are given PARF benefits that they can use to offset the registration fees they have to pay for their new cars. For cars registered on or after 1 Nov. 1990, the PARF benefits would vary according to the age of the vehicle at deregistration. For cars registered before 1 November 1990, a fixed PARF benefit would be given upon deregistration based on the engine capacity of the car. To provide a higher PARF benefit to car owners who deregister their cars before ten years, all PARF-eligible cars registered on or after 1 November 1990 receive higher fees if the vehicle is newer.

2. Vehicle Quota System{tc "□autonum□ Vehicle Quota System" \l 4}

As high taxes alone would not ensure that the vehicle population grow at an acceptable rate, a vehicle quota system was introduced to achieve that objective. Since 1 May 1990, any person who wishes to register a vehicle must first obtain a vehicle entitlement in the appropriate vehicle class, through bidding. Tender for specified number of vehicle entitlements is conducted monthly. Successful bidders pay the lowest successful bid price of the respective category in which they bid. A vehicle entitlement is valid for ten years from the date of registration of the vehicle. On expiration of the vehicle entitlement, if the owner wishes to continue using the vehicle, he needs to revalidate the entitlement for another five or ten years by paying a revalidation fee (pegged at the 50% or 100% of the prevailing quota premium respectively).

3. Weekend Car Scheme{tc "autonum Weekend Car Scheme" \l 4}

The weekend car scheme was introduced on 1 May 1991 to allow more people to own private cars without adding to traffic congestion during peak hours. Cars registered under the scheme enjoy substantial tax concessions which include a 70% reduction in road tax and a tax rebate of up to a maximum of $15,000 on registration. Weekend cars are identifiable by their red license plates, fixed in place with a tamper-evident seal. They can only be driven between 7 pm and 7 am during the week, after 3 pm on Saturdays and all day on Sundays and public holidays. Weekend cars can be driven outside those hours but owners must display a special day license. Each weekend car owner is given five free day licenses per year and can buy additional ones at $20 each.

4. Area Licensing Scheme{tc "autonum Area Licensing Scheme" \l 4}

The Area Licensing Scheme (ALS) was introduced in June 1975 to reduce traffic congestion in the city area during the peak hours. Only passenger cars were affected then. The scheme has gradually been modified to include all vehicles except ambulances, fire engines, policy vehicles and public buses.

5. Public Transportation{tc "autonum Public Transportation" \l 4}

Public transport in Singapore is widely available and includes a mass rapid transit (MRT) system, a comprehensive bus network and over 13,000 taxis.

4. Conclusions{tc "autonum Conclusions" \l 3}

Besides technical control measures (controls on engines and fuel quality), the use of traffic control measures has significantly contributed to the protection of the air quality in Singapore. Although the present measures appear to be adequate, Singapore will continue to look ahead for ways to improve them further. Pilot studies of three electronic road pricing systems are being carried out in Singapore and the most suitable system will be selected for implementation in 1997.

3. Hong Kong{tc "autonum Hong Kong" \l 2}

Hong Kong's vehicle pollution control effort continues to focus on diesel particulate control because particulate is the most serious pollution problem at present in Hong Kong, and motor vehicles are estimated to be responsible for approximately 50% of the PM-10 emissions.

1. Current Program{tc "autonum Current Program" \l 3}

With regard to diesel fuel, as of April 1, 1995, the sulfur level was reduced to 0.2% and it is planned to lower it to 0.05% by 1997 or 1998.

Diesel vehicle emissions standards were also tightened on April 1, 1995. All new passenger cars and taxis after that date must comply with either the US 1990 standards (PM=0.12 grams per kilometer, NOx=0.63) or the European Union Step 1 standards (93/59/EEC PM=0.14, HC+NOx=0.97) or the Japanese standards (PM=0.34, NOx=0.72 for vehicles weighing less than 1.265 tonne or 0.84 for those above). Similar requirements will apply to all light and medium goods vehicles and light buses. For goods vehicles and buses with a design weight of 3.5 tonnes or more, either the 1990 US (PM=0.80 g/kWh, NOx 8.04) or the EURO 1 standards (PM=0.61 for engines producing less than 85 kW or 0.36 for engines producing more; NOx=8.0 for all engines) will apply.

In use smoke limits based on the EEC free acceleration test (72/306/EEC) will be lowered to 50 HSU; in certification, the limits will be 40 HSU.

Encouraged by a price differential of 1 HK$ per liter price reduction for unleaded petrol compared to leaded, unleaded petrol is now responsible for 71% of total petrol sales. Notably, the benzene content of the unleaded petrol is only 3.44%, virtually the same as leaded petrol.

2. Future Plans{tc "autonum Future Plans" \l 3}

An analysis of the motor vehicle related urban particulate problem indicates that 17% comes from buses, 63% from goods vehicles and the remainder from all vehicles under 5.5 tons.

As a matter of policy, Hong Kong is still trying to convert all light duty diesel vehicles including taxis to petrol. Analyses are also being carried out regarding the possibility of converting some or all taxicabs to either CNG or electric.

With regard to I/M, the government still has plans to introduce a mandatory program by May of 1996.

Hong Kong also remains interested in the possibility or retrofitting buses with either catalysts or diesel particulate filters. They have submitted a proposal to the

Asia-US partnership to fund such an effort and have also initiated discussions with potential suppliers in Europe.

4. South Korea{tc "autonum South Korea" \l 2}

A series of recent amendments in the Air Quality Control Law will gradually tighten Korea's vehicle emissions standards as summarized below.

Emission Standards For New Gasoline and LPG Vehicles

Vehicle Type	Date Of Implementation	Test	CO	NOx	Exhaust HC	Evap HC (g/test)
Small Size Car[14]	1987 7/1	CVS-75 g/km	8.0	1.5	2.1	4.0
"	2000 7/1	CVS-75	2.11	0.62	0.25	2.0
Passenger Car	1980 1/1	10-Mode	26.0	3.0	3.8	-
"	1984 7/1	10-Mode	18.0	2.5	2.8	-
"	1987 7/1	CVS-75	2.11	0.62	0.25	2.0
"	2000 1/1	CVS-75	2.11	0.25	0.16	2.0
Light Duty Truck[15]	1987 7/1	CVS-75	6.21	1.43	0.50	2.0
"	2000 1/1	CVS-75[16]	2.11	0.62	0.25	2.0
"	2000 1/1	CVS-75[17]	6.21	1.43	0.50	2.0
Heavy Duty Vehicle	1980 1/1	6-Mode	1.6%	2200 ppm	520 ppm	
"	1987 7/1	US Transient	15.5	10.7	1.3	4.0
"	1991 2/1	13 Mode	33.5	11.4	1.3	_
"	2000 2/1	13 Mode	33.5	5.5	1.4	-

Emissions Standards For New Diesel Vehicles

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[14] Less than 800 cc of Engine Displacement

[15] GVW < 3 tons

[16] GVW < 2 Tons

[17] GVW Between 2 and 3 Tons

Vehicle Type	Date of Implementation	Test	CO	NOx	HC	PM	Smoke
Passenger Car	1980 1/1	Full Load	-	-	-	-	50%
"	1984 7/1	6-Mode	980 ppm	1000/590[18]	670	-	50%
"	1988 1/1	6-Mode	980	850/450	670	-	50%
"	1993 1/1	CVS-75	2.11	0.62	0.25	0.12	-
"	1996 1/1	CVS-75	2.11	0.62	0.25	0.08	-
"	2000 1/1	CVS-75	2.11	0.62	0.25	0.05	-
Light Duty Truck[19]	1980 1/1	Full Load	-	-	-	-	50%
"	1984 7/1	6-Mode	980	1000/590	670	-	50%
"	1988 1/1	6-Mode	980	850/460	670	-	50%
"	1993 1/1	6-Mode	980	750/350	670	-	40%
"	1996 1/1	CVS-75	6.21	1.43	0.5	0.31 (0.16)[20]	–
Light Duty Truck < 2 Tons	2000 1/1	CVS-75	2.11	0.75	0.25	0.12	-
All Other Light Duty Trucks	2000 1/1	CVS-75	6.21	1.00	0.5	0.16	-
Heavy Duty Vehicle	1980 1/1	Full Load	-	-	-	-	50%
"	1984 7/1	6-Mode	980	1000/590	670	-	50%
"	1988 1/1	6-Mode	980	850/450	670	-	50%
"	1993 1/1	6-Mode	980	750/350	670	-	40%
"	1996 1/1	13-Mode	4.9	11.0	1.2	0.9	35%
"	2000 1/1	13 Mode	4.9	6.0	1.2	0.25 .1[21]	25%

[18] Direct Injection/Indirect Injection

[19] GVW < 3 tons

[20] GVW < 2 Tons

[21] City Bus Only

The sulfur level in diesel fuel was reduced to a maximum of 0.4 Wt.% during the period from February 2, 1991 through December 31, 1992; to 0.2 during the period from January 1, 1993 through December 31, 1995; and 0.1 thereafter.

Korea is also investigating possible improvements to their I/M program including the possible addition of IM240.

Research remains active in the use of diesel particulate filters. Three types of approaches are under investigation - burner systems which are seen as prime candidates for large vehicles; electrically heated systems which are seen as prime candidates for medium sized vehicles, and Cerium fuel additive systems which are seen as the prime candidates for smaller vehicles.

Research is also underway in Korea on electrically heated catalysts, CNG engines, two stroke engines and lean NOx catalysts.

5. **Taiwan**{tc "autonum Taiwan" \l 2}

The Taiwan EPA has developed a comprehensive approach to motor vehicle pollution control. Building on its early adoption of US '83 standards for light duty vehicles (starting July 1, 1990) it recently moved to US '87 requirements, which include the 0.2 gram per mile particulate standard, as of July 1, 1995. Heavy duty diesel particulate standards almost as stringent as US '90, 6.0 grams per brake horsepower hour NOx and 0.7 particulate, using the US transient test procedure, went into effect on July 1, 1993. It is intended that US'94 standards, 5.0 NOx and 0.25 particulate, will be adopted soon, probably for introduction by July 1, 1997.

Diesel fuel currently contains 0.3 Wt. % S. A proposal to reduce levels to 0.05% by 1997 is currently under consideration.

The Executive Yuan on December 10, 1992 approved increases of up to 1,700 percent for the amount of fines to be levied against motorists who violate the Air Pollution Control Act. The new fine schedule raises the former maximum fine for motor vehicle pollution from $138 to $2,357. All forms of motorized transportation are included in the new fine schedule, including airplanes, boats, and power water skis. The new fines took effect in early 1993 after official public notice.

Clearly the most distinctive feature of the Taiwan program, however, is its motorcycle control effort, reflecting the fact that motorcycles dominate the vehicle fleet and are a substantial source of emissions.

> The first standards for new motorcycles were imposed in 1984; 8.8 grams per kilometer for CO and 6.5 grams per kilometer for HC plus NOx, combined, using the ECE R40 test procedure.

In 1991. the limits were reduced to 4.5 grams per kilometer for CO, and 3.0 for HC and NOx combined. These requirements were phased in over two years and by July 1, 1993 were applied to all new motorcycles sold in Taiwan. As a result of these requirements, the engines of four stroke motorcycles have been redesigned to use secondary air injection. All new two stroke motorcycles are fitted with catalytic converters.

Since 1992, electric motorcycles have been available in the market but sales have been modest.

Motorcycle durability requirements have been imposed since 1991. All new motorcycles tested since that time are required to demonstrate that they can meet emissions standards for a minimum of 6,000 kilometers.

Since 1991, all new motorcycles must be equipped with evaporative controls.

In order to reduce the pollution from in-use motorcycles, the EPA is actively promoting a motorcycle Inspection and Maintenance (I/M) system. In the first phase, from February through May, 1993, the EPA tested approximately 113,000 motorcycles in Taipei City. Of these, 49% were given a blue card indicating that they were clean, 21% a yellow card indicating that their emissions were marginal, and 30% were failed.

Between December 1993 and May 1994, approximately 142,000 motorcycles were inspected with 55% receiving blue cards, up 6% from the earlier program, and 27% failed, a drop of 3%. The major repair for failing motorcycles was replacement of the air filter at an average cost of $20.

In continuing regulations for the control of motorcycle emissions, the EPA has drafted the Third Stage Emission Regulation to be implemented from 1998. The new standards will lower CO to 3.5 grams per kilometer, and HC plus NOx to 2. In addition, the durability requirement will be increased to 20,000 kilometers. Finally, the market share for electric powered motorcycles will be mandated at 5%. In addition, the EPA will extend the periodic motorcycle I/M program.

6. Conclusions{tc "autonum Conclusions" \l 2}

As the above examples illustrate, substantial efforts have been and continue to be underway throughout many Asian countries to address their motor vehicle pollution problems. Several conclusions can be drawn from these efforts:

Several comprehensive motor vehicle pollution control programs have been developed in the region.

A wide variety of strategies are being implemented, tailored to the particular problems and capabilities in a particular country or city - one size does not fit all.

In virtually every serious effort to reduce motor vehicle pollution, cleaner fuels - especially unleaded gasoline and lower sulfur diesel fuel - play a critical role.

The remainder of this report will address the low pollution opportunities and challenges associated with clean fuels.

5. GASOLINE{tc "autonum GASOLINE"}

Many characteristics of gasoline can impact on overall vehicle emissions but far and away the most critical issue in most developing countries is whether or not to reduce or eliminate the use of lead based additives. Not many years ago, almost all gasoline used around the world contained lead and in many cases at concentrations above .4 grams per liter. Since the early 1970's, there has been a steady movement toward reduced lead in leaded gasoline and increasingly, the complete elimination of lead. Countries as diverse as Austria, Brazil, Japan, the US and Thailand have or will soon completely eliminate lead from gasoline. In addition, over 80% of all new cars produced in the world this year will require the exclusive use of unleaded gasoline to protect their emissions control systems. This section of the report will review the reasons for the shift to unleaded gasoline, address some of the arguments raised against the use of unleaded gasoline, and finally summarize other fuel characteristics used in so called reformulated gasolines to reduce overall vehicle emissions. It will conclude with some recommendations regarding how to proceed toward cleaner gasoline.

1. THE BENEFITS OF REDUCING LEAD IN GASOLINE{tc "autonum THE BENEFIT

In many ways, lead has been an ideal material. It resists corrosion and weathering, is plentiful in readily accessible areas, and is easily melted down for use. Because of these characteristics, it has been widely used by man for centuries - in plumbing, printing, hunting, building and more recently as electrical insulation, radiation shielding and in paints and batteries. The very qualities which have made it an ideal material, however, may also lead to the relatively long environmental residence time which is indicated in Table 1, below.[22]

Table 1
Environmental Residence Times For Various Pollutants

Pollutant	Situation	Time	% Remaining
2,4,5-T (herbicide)	soil	several weeks	50%
MCPA (herbicide)	soil	several days	50%
DDT	soil	four months	74%
Oil	sea water	4-5 weeks	70%
Lead	soil	70-200 yrs	90%

[22] "Lead In The Environment", Ninth Report, Royal Commission on Environmental Pollution, April 1983

Because of the growing number of uses and the long residence time, human lead exposure have been increasing for many generations and will likely continue to do so as more lead accumulates in the future. It is now estimated that lead exposures to modern man are 100 times greater than background or “natural” levels.[23] Studies of annual arctic ice layers in Greenland also show how lead levels have risen over the whole of the earth s surface. At this point in history, lead has been dispersed so widely that “it is doubtful whether any part of the earth s surface or any form of life remains uncontaminated by anthropogenic lead.”[24] More recent evidence continues to show “unambiguous evidence of the gasoline-related sources of lead in aged Greenland snow and ice.”[25]

One of the major uses of lead in the modern world is in gasoline. In 1921 it was discovered that the addition of lead to gasoline raised octane levels. This is desirable because higher octane gasolines allow higher compression ratio engines with concomitant improvements in thermal efficiency and fuel economy. However, the addition of lead to gasoline has caused a whole series of problems for automotive designers, among them troublesome combustion chamber deposits on pistons, spark plugs and valves and increased piston ring wear and blow by rates. More importantly, as discussed in Appendix A, evidence has been accumulating that children in cities are suffering adverse health consequences when the lead added to gasoline is emitted from vehicles. In addition, lead deposits within engine combustion chambers lead to higher emissions of hydrocarbons, which directly and indirectly cause adverse consequences to health and well being. Further, the use of lead precludes the use of the catalytic converters that have been demonstrated to substantially reduce these hydrocarbons as well as other noxious gases in vehicle exhaust. Ironically, the evidence also indicates that by precluding use of these advanced technologies the presence of lead may also actually impair overall fuel efficiency by encouraging less optimal techniques to be used to bring about even modest reductions in pollution.

In spite of these concerns, much of the discussion regarding removal of lead from gasoline has focused almost exclusively on the costs and difficulties and very little on the benefits. The purpose of this section is to redress this imbalance by summarizing some of these potential benefits.

1. Reduced Lead Health Risks{tc "autonum Reduced Lead Health Risks" \l 3}

Gasoline lead affects human health through several media. First, of course is air and it is generally recognized that over 90 percent of atmospheric lead concentrations in most urban areas which use leaded gasoline are associated with gasoline lead emissions. Beyond this, however, gasoline lead increases the amount of lead ingested through the digestive system. This is especially true with children who not only receive this lead through the normal food chain, but through their playing in streets and yards which are contaminated with lead. When viewed in this context it is not surprising that “both average blood lead levels and cases of lead poising in children correlate more strongly

[23] “Health Aspects of Petrol Lead Additives”, by Phillippe Granjean, M.D., Odense University, Presented at Conference Lead In Petrol May 1983

[24] “Lead In The Environment”, Ninth Report, Royal Commission on Environmental Pollution, April 1983

[25] ”Present Century Snow Core Record of Organolead Pollution in Greenland”, Lobinski, Boutron, Candelone, Hong, Szpunar-Lobinska, Adams, Environmental Science and Technology, 1994, 28, 1467-1471.

to gasoline lead than to lead in the air alone."[26] Because of this close relationship, reducing the lead content of gasoline has been demonstrated to significantly reduce the health risks in urban areas in the United States. For example, based on data collected in more than 60 United States cities by the Center for Disease Control (CDC), the decline in mean blood lead levels computed by six month intervals almost parallels the amount of lead used in the production of gasoline from 1976 to 1980.[27] This study is generally referred to as the NHANES II study.

After a careful review of the NHANES II data, Dr. Vernon Houk, Acting Director of CDC s Center For Environmental Health, explained:

> "This reduction was real. It was not due to chance, laboratory error, nor sampling of age, sex, race, urban vs. rural areas, income levels, or geographic regions. The most significant environmental change during this time was the reduced amount of lead used in the production of gasoline... (This data) clearly demonstrates that as we have removed lead from gasoline, we have also removed lead from ourselves and our children."[28]

In addition, leaded gasoline is the only source that can explain the fact that in the US blood lead levels peak sharply each summer just as gasoline lead use peaks and the fact that lead levels in the front yards of urban homes are two to three times greater than the back yards.

In Europe, Ispra completed a study designed to determine the relationship between gasoline lead and human uptake.[29] The study design entailed replacing the typical petrol lead with an alternative which has a different isotopic ratio. In this way it was hoped to follow the pathway of the gasoline lead through the environment of the Northern Italian Region of Piedmont, where the study was conducted. Conclusions of the study were:

1. Gasoline lead is responsible for about 90 percent of the airborne lead in Turin and about 6

2. The gasoline lead seems most related to the finest lead particles in the air.

3. The petrol fraction of blood lead in Turin is on the order of 24 to 27 percent; in nearby countryside, the range is from 12 to 21 percent; and in the further countryside, from 11 to 19 percent.

In assessing the study, its Director, Dr. Facchetti, noted that the relationship between airborne lead and blood lead seems approximately the same in Europe and the United States, i.e., an increase of about 1 microgram per cubic meter of ambient lead will result in an increase of about 1 - 2 micrograms per milliliter of blood lead.[30] In addition, Dr. Facchetti noted that the ISPRA experiment probably understated the overall impact of gasoline lead to blood lead because:

1. Only about 90 percent of the local gasoline contained the unique isotope.

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[26] "Health Effects of Gasoline Lead Emissions", Joel Schwartz, U.S. EPA, April 6,1983

[27] "Trends In Blood Lead Levels of the United States Populations", J. Lee Annest, in Lead Versus Health, 1983

[28] United States Court of Appeals, No. 82-2282, Small Refiner Lead Phase-Down Task Force, et. al. v. U.S. EPA, April 22, 1983

[29] "The Isotopic Lead Experiment," Facchetti, May 10, 11, 1983
"Isotopic Lead Experiment, Status Report," Facchetti and Geiss, Commission of the European Communities, 1982.

[30] "The Isotopic Lead Experiment," Facchetti, May 10,11, 1983.

2. The study only measured the local effect and could not account for lead emitted from vehicles coming from other areas or the motor vehicle related lead transported from other areas by the atmosphere.

3. At the time the experiment was terminated, it had not yet reached equilibrium, i.e., gasoline related blood lead levels were still rising.

2. **Reduced Vehicle Maintenance**{tc "autonum Reduced Vehicle Maintenance" \l 3}

In addition to reducing health risks to children, the elimination of lead from gasoline has several additional benefits. For example, the use of lead free gasoline can save money for motorists by reducing the need for frequent replacements of spark plugs, mufflers and the automobile hardware exposed to gasoline and its combustion products.[31] A major reason is that the lead scavengers are highly corrosive and reactive. Several surveys carried out when leaded gasoline was widely used in the United States and Canada demonstrated that motorists who use lead free gasoline spend much less for exhaust system and ignition servicing than motorists who use leaded gasoline.[32] As a rough rule of thumb, spark plug change intervals are roughly doubled by the use of unleaded gasoline and at least one exhaust system and exhaust silencer (muffler) replacement is eliminated. Lead free gasoline has also been linked to a cost advantage regarding carburetor servicing but this has been more difficult to quantify.

Another significant advantage associated with the use of lead free gasoline is the lengthened oil change interval. The use of unleaded fuel has been demonstrated to significantly reduce engine rusting and ring wear and to a lesser degree sludge and varnish deposits and cam and lifter wear.[33] Because of this, oil change intervals on cars in the United States using unleaded fuel were at least twice as long as had traditionally been the case. Intervals of 10,000 miles are not uncommon with late model cars. Increased oil change intervals cannot be attributed solely to lead removal (as is indicated by some increases in vehicles using leaded gasoline) but the lead removal appears to be a major contributing factor. This is significant not only because of the reduced cost to the motorist but also because of the oil savings over the life of the vehicle and the reduction of the potential pollution problem resulting from the disposal of used oil. Experience had shown that in the United States significant quantities of used oil are disposed of in ecologically unacceptable ways such as dumping it on the ground.

According to an Australian review,[34] the cost savings associated with maintenance reductions from lead free gasoline would be significant. Expressed as 1980 Canadian cents per liter, the results of the principal studies are:

Wagner (American Oil Co.); 1971;	1.4c/liter
Gray and Azhari (Am. Oil Co.) 1972	2.1c/liter
Pahnke and Bettoney (DuPont) 1972	0.3c/liter
Adams (Ethyl Corp.) 1972	0.4c/liter
Environment Canada 1979	1.2c/liter

Using the Environment Protection Agency of Canada study, Australia concluded that the following savings would result if unleaded gasoline were used instead of leaded gasoline:

[31] "Saving Maintenance Dollars With Lead Free Fuel", Gray and Azhari, SAE # 720014.

[32] "Gasoline Lead Additive And Cost Effects of Potential 1975-1976 Emission Control Systems", Hinton et. al., SAE # 730014.

[33] "Gasoline Lead Additive And Cost Effects of Potential 1975-1976 Emission Control Systems", Hinton et. al., SAE # 730014.
"A Study of Lengthened Engine Oil-Change Intervals", Pless, SAE # 740139.

[34] "The Benefits of Unleaded Petrol", M.G. Mowle, Institution of Engineers Transportation Conference 1981

	leaded	unleaded
spark plug changes	every year	every other year
oil changes and filter	twice per year	one per year
muffler replacements	twice per 5 yrs	one per 5 yrs
exhaust pipe replacements	one per 5 yrs	None

Overall maintenance savings from unleaded fuel were estimate to average about $38 per year; for a car averaging 10 liters per 100 kilometers fuel consumption, this is equivalent to 2.4c per liter of gasoline.[35]

3. Potential For Catalysts To Reduce Emissions{tc "autonum Potential For Catalysts To Reduce Emissions" \l 3}

The impact of leaded petrol on catalyst performance was studied by the US Environmental Protection Agency in 1984.[36] Twenty-nine in use automobiles with three-way catalyst emission control systems were misfueled with leaded gasoline in order to quantify the emissions effects. The vehicles used between four and twelve tanks of leaded gasoline with an average lead content of 1.0 grams Pb per gallon. Four different test programs were conducted with different misfueling intensities (rates) and mileage accumulation schedules. The US Federal Test Procedure (FTP) and several short tests were conducted at various stages. The results of the program indicated that vehicle emissions are mainly affected by the amount of lead passing through the engine and secondarily by the rate of misfueling.

Based on the data collected, it was possible to develop quantitative relationships between lead consumption and HC, CO and NOx emissions. Emission levels for each of the 29 vehicles involved in the EPA program were normalized to the levels which existed prior to any lead contamination[37] and then plotted as a function of the total amount of lead consumed. Normalization made it possible to eliminate the influence of different emissions standards. Regression equations were then derived relating HC, CO and NOx emissions respectively to the grams of lead consumed by each vehicle. (see below).

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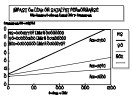
[35]"The Benefits of Unleaded Petrol", M.G. Mowle, Institution of Engineers Transportation Conference 1981

[36]"Misfueling Emissions of Three-Way Catalyst Vehicles", R. Bruce Michael, U.S. Environmental Protection Agency, presented at the Society of Automotive Engineers, Fuels and Lubricants Meeting, October 8-11, 1984, SAE Paper #841354.

[37](Emissions)/(Emissions with no lead)



As the figure above indicates, FTP emissions of HC, CO and NOx generally increase steadily with continuous misfueling. HC emissions increase the most rapidly on a percentage basis, followed by CO and, to a lesser extent, NOx. Reasonably good correlations exist for the relationship between total lead consumed and emissions increases of each pollutant, especially for HC the pollutant most affected. In the case of this latter pollutant, approximately 90% of the variability in emissions can be explained by the lead exposure.

2. THE POTENTIAL PROBLEMS WITH UNLEADED GASOLINE{tc "autonum THE POTENTIAL PROBLEMS WITH UNLEADED GASOLINE" \l 2}

Lead is added to gasoline because it is a low cost octane enhancer. If lead is not added to gasoline, therefore, it is necessary to either modify the refinery process to raise the octane level of the unleaded gasoline pool or to add alternative octane enhancing additives.

1. Refinery Modifications To Produce Unleaded Gasoline{tc "autonum Refinery Modifications To Produce Unleaded Gasoline" \l 3}

There are several options for modifying a refinery to increase the octane level of the unleaded fuel and these will be discussed below.

1. Increase the level of light and middle distillates, with emphasis on octane and iso-octane. This can be achieved by modifying the refinery profile or through the use of higher API oil. Normally, the second option is marginally more expensive as the suppliers have already incorporated the expected netback from the higher API.

If that is the case, a refiner should investigate the economics of alternative cracking systems to achieve the desired effect. In extreme cases, this process is referred to as "scrapping the bottom of the barrel".

However, in today's economic climate, severe secondary cracking process may not be economical. In this context, preferred options would include: visbreaking, catalytic cracking, hydrocracking or alkylation. Each process has advantages and costs, with visbreaking being probably the most expensive. Also, each process is associated with different by-products which would somewhat compensate for processing costs. If there is a market for gasoils, for instance, the economics of catalytic cracking of heavier fractions may look more favorable. The bottom line is the chemistry and unit operations exist to modify the molecular structure of the refined products and optimize the octane fraction. The economic competitiveness should then be examined for each alternative given the availability and characteristics of the crude and the current refinery structure. As a corollary, newer refineries would have lower marginal costs to modify the profile, as it is more likely that these would already include some advanced cracking processes.

2. Modify refinery blending to increase share of aromatics. Aromatics will increase the actual octane number without the need for molecular weight modification of the alkanes (or alkenes). It is also, normally much cheaper to divert BTX toward the fuel stream of the refinery. This option however has two major disadvantages: First, it assumes that the netbacks for aromatics are higher in the fuel stream. This is not necessarily true in Asia, where the demand for textiles and aromatic derived chemicals is at record highs. In fact, we project that the increase in demand for aromatics may be marginally higher than for olefins in the Asia region to the year 2000. Second, you have the environmental issue. If the refinery is located in the West Coast of the USA or in W. Europe, you can right out discount this alternative. Also, increasingly, there is pressure elsewhere (Japan for example) to put a lid on the emissions of BTX to the atmosphere and therefore limit the aromatic content of light distillates.

3. Shift to middle distillates. This option is rarely quoted. Light distillates are in such high demand in the US because of the fleet composition. This fact distorts the picture we have of the problem in Asia. For high income countries in Asia, one will find that middle distillates (diesel, gasoils) have a larger fraction of the refined barrel. This is because, comparatively, heavier transport vehicles are in use (mostly buses).

If the refinery is allowed to pull out from the skewed, and chemically irrational need to maximize light distillates, costs would fall down and the need for alternatives to increase octane number would ease. Other issues would arise, of course (such as flash points, heptane number, etc.), but normally you would be able to manufacture cheaper fuels over a wider molecular weight range. This in turn implies that you have a transport policy that favors the use of public transport and cross subsidizes diesel.

2. **Valve Seat Recession**{tc "autonum Valve Seat Recession" \l 3}

In addition to its effects on fuel octane level, lead in gasoline has other effects in the engine. As engine technology advanced during the era of leaded petrol, designers made use of the lubricating properties of lead to serve as a lubricant between exhaust valves and their seats, enabling them to use a lower grade metal on the valve seat itself. The use of leaded fuel with these low grade valve seats shielded them from excessive wear (known as "valve seat recession) which can occur at high speeds in engines without hardened valve seats. Retaining this protective function is the reason that the US EPA limited gasoline lead content to 0.1 g/gallon, rather than banning its use entirely in 1985. The actual incidence of valve seat recession is small even in vulnerable vehicles, however,[38] Only vehicles which travel consistently a very high loads and speeds appear to be at all vulnerable. And even for these vehicles, additives other than lead have been shown to protect valve seats. Thus, there is presently little technical argument for retaining any lead in gasoline if the refining capacity exists to provide the required octane in some other manner.

3. **Potential Health Risks Associated With Lead Substitutes In Non Catalyst Vehicles**{tc "autonum Potential Health Risks Associated With Lead Substitutes In Non Catalyst Vehicles" \l 3}

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[38]Weaver, C.S. 1986. The Effects of Low-Lead and Unleaded Fuels on Gasoline Engines. SAE Paper No. 860090. SAE International, Warrendale, Pennsylvania.

To replace the octane formerly contributed by lead additives, refiners have used a number of techniques. As noted above, increased catalytic cracking and reforming are used to increase the concentrations of high-octane hydrocarbons such as benzene, toluene, xylene, and other aromatic species, and olefins. Alkylation and isomerization are also used to convert straight-chain paraffins (which have relatively low octane) to higher-octane branched paraffins. Increased quantities of light hydrocarbons such as butane are also blended. Use of high octane oxygenated blending agents such as ethanol, methanol (with cosolvent alcohols), and especially methyl tertiary-butyl ether (MTBE) has increased greatly. In addition, the antiknock additive methylcyclopentadienyl manganese tricarbonyl (MMT) is permitted in leaded gasoline in the U.S., and in both leaded and unleaded fuel in Canada.[39]

Some of these solutions have created or aggravated environmental problems of their own. For example, the increased use of benzene and other aromatics (which tend to increase benzene emissions in the exhaust) has led to concern over human exposure to benzene. The xylenes, other alkyl aromatics, and olefins are also much more reactive in producing ozone than most other hydrocarbons. Increased use of light hydrocarbons in gasoline produces a higher Reid vapor pressure (RVP), and increased evaporative emissions.

Most of these lead substitutes are not a serious concern if the switch to lead free petrol is combined with the introduction of catalysts; as indicated in Appendix B, catalysts tend to be especially effective with many of the more reactive or toxic hydrocarbons. However, in order to maximize the health benefits of unleaded petrol use in vehicles without catalysts, it is prudent to assure that acceptable alternatives are used.

4. **Strategies To Reduce or Eliminate The Health Risks Associated With Lead Substitutes**{tc "□autonum□ Strategies To Reduce or Eliminate The Health Risks Associated With Lead Substitutes" \l 3}

1. **Low Lead Gasoline As A Transition Fuel**{tc "□autonum□ Low Lead Ga

Vehicles equipped with catalytic converters *require* unleaded gasoline to prevent the catalyst being poisoned by lead deposits. Vehicles without catalytic converters can use unleaded gasoline but do not *require* it. Reducing or eliminating gasoline lead is desirable for public health reasons, however. Therefore, one transition strategy to be used while catalyst technology is being phased in is to continue to market leaded fuel with minimal lead content.

The octane boost due to lead does not increase linearly with lead concentration. The first 0.1 g/liter of lead additive gives the largest octane boost, with subsequent increases in lead concentration giving progressively smaller returns. This means that supplying two units of low-lead gasoline will result in lower lead emissions than one unit of high-lead and one unit of unleaded gasoline having the same octane value. If octane capacity is limited, the quickest and most economical way to reduce lead emissions may thus be to reduce the lead content of existing leaded gasoline grades as much as

[39]The Canadian government has recently announced its intention to ban the use of MMT in unleaded petrol because of concerns regarding its potential impact on catalyst performance and oxygen sensors and onboard diagnostics.

possible, rather than by encouraging non-catalyst cars to use unleaded fuel. This also helps to reserve supplies of unleaded gasoline (which may be feasible to produce and distribute only in limited quantities) for those catalyst-equipped vehicles that truly require it. Reducing the allowable lead content will also reduce the refining cost difference between leaded and unleaded gasoline. If this is reflected in retail prices, it will reduce the temptation for owners of catalyst-equipped vehicles to misfuel with leaded gasoline. In the United States, as noted earlier, since 1985, the leaded content of leaded petrol has been limited to 0.1 grams per gallon. In Europe, the maximum lead content of leaded petrol is 0.15 grams per liter.

2. Non Hazardous Lead Substitutes{tc " autonum Non Hazardous Lead Substitutes" \l 4}

Blending small percentages of oxygenated compounds such as ethanol, methanol, tertiary butyl alcohol (TBA) and methyl tertiary-butyl ether (MTBE) with gasoline has the effect of reducing the volumetric energy content of the fuel, while improving the antiknock performance. Thus, the amount of lead can be reduced or even eliminated without the substitution of potentially hazardous aromatic compounds. Assuming no change in the settings of the fuel metering system, lowering the volumetric energy content will result in a leaner air-fuel mixture, thus helping to reduce exhaust CO and HC emissions.

Exhaust HC and CO emissions are reduced by the use of oxygenates, but NO_X emissions may be increased slightly by the leaner operation. The Auto/Oil study in the U.S. recently tested the effects of adding 10% ethanol (3.5 Wt.% oxygen) and adding 15% MTBE (2.7% Wt.% oxygen) to industry average gasoline. For late-model gasoline vehicles, the ethanol addition results showed a net decrease in NMHC and CO of 5.9% and 13.4%, respectively, and a net increase in NOx emissions of 5.1%. The MTBE addition results showed a net decrease in NMHC and CO of 7.0% and 9.3%, respectively, and a net increase in NOx emissions of 3.6%.

Colorado (USA) initiated a program to mandate the addition of oxygenates to gasoline during winter months when high ambient CO tends to occur. The mandatory oxygen requirement for the winter of 1988 (January to March) was 1.5% by weight, equivalent to about 8% MTBE. For the following years, the minimum oxygen content required was 2% by weight (equivalent to 11% MTBE). These oxygen requirements were estimated to reduce CO exhaust emissions by 24-34% in vehicles already fitted with 3-way catalyst systems. The success of this program lead the U.S. Congress to mandate the use of oxygenated fuels (minimum 2.7% oxygen by weight) in areas with serious winter-time CO problems.

Alcohols such as ethanol tend to increase evaporative emissions and can therefore produce higher total HC emissions than straight gasoline, unless ambient temperatures are so low that evaporative emissions are negligible. Similar adverse effects have not been reported for MTBE and other ethers. Corrosion, phase separation on contact with water, and materials compatibility - other problems sometimes experienced with alcohol fuels - are much less serious for the ethers. For this reason, MTBE and other ethers are strongly preferred as oxygenated blending agents by many fuel marketers, as well as for air-quality purposes. The costs of using ethers are also relatively moderate (approximately US$ 0.01-0.03/liter at present prices), so that this can be a relatively cost-effective approach as well.

Thus it is possible to substitute certain oxygenates in place of lead to produce unleaded petrol of maximum health benefit - no lead and no increase in other toxic compounds. In part due to the use of oxygenates, unleaded petrol in Hong Kong, for example, has virtually the same aromatic content as leaded petrol.[40]

3. Adverse Health Effects With MTBE{tc " autonum Adverse Health Effects With MTBE" \l 4}

[40]Kong Ha, 1994.

During the winters of 1993 and 1994, concerns were raised in a number of US cities which were required by the Clean Air Act to use oxygenated gasoline during the winter months that some people were suffering severe nausea, headaches and other symptoms apparently as a result of exposure to MTBE fumes or its combustion derivatives.

1. Wisconsin's Evaluation**{tc "□autonum□Wisconsin's Evaluation" \l 5}**

Following the intense public outcry this past winter over the use of oxygenated gasoline in Milwaukee, the State ordered a study of the health effects. The first phase has been completed and the results are summarized below.

> Ambient air monitoring in Milwaukee detected reformulated gasoline components. The levels found were not unusually high and did not exceed any health guidelines. As seen in other studies, refueling a vehicle at a station without stage II vapor recovery equipment resulted in the highest exposure potential.
>
> Symptom prevalence in Milwaukee differed significantly from both Chicago and the remainder of Wisconsin. In Milwaukee, people were more likely to report unusual symptoms if they had experienced a cold or the flu, smoked cigarettes, or were aware that they had purchased RFG since November 1, 1994.
>
> Symptoms prevalence in Chicago, an area required to use RFG fuels, was not different from that in Wisconsin, an area not required to use RFG fuels. This finding suggests that factors other than RFG use, significantly contributed to the differences in symptom prevalence between Milwaukee and the other two areas studied.
>
> Individual symptoms and symptom patterns attributed to exposure to reformulated gasoline are non-specific and similar to those experienced with common acute and chronic illnesses such as colds, flu and allergies. The fact that every symptom was statistically more prevalent in Milwaukee than the other two areas, including symptoms not associated with gasoline or chemical solvent exposure, suggests that factors, in addition to the introduction of RFG in that city, contributed to the survey responses.
>
> All three sample areas experienced the same rate of winter colds and flu during the 1994-199
> for such symptoms in Chicago or Wisconsin. The most plausible explanation for this finding is that many symptoms reported by Milwaukee residents may have actually been due to colds or flu and not RFG exposure.
>
> Individuals in Milwaukee and Wisconsin who reported purchasing RFG since November 1, 1994 were more likely to report specific symptoms than individuals reporting they had not purchased RFG since that date or did not know the type of

gasoline they purchased. Since all gasoline purchased in Milwaukee was RFG, this suggests that knowledge about RFG, including the likely awareness of the potential negative effects of reformulated gasoline in Milwaukee and Wisconsin, may have heightened the perception of current health status and resulted in the assumption that any health symptoms experienced were unusual and attributable to gasoline exposure.

Individuals in Chicago and Milwaukee who reported that they had purchased RFG since November 1, 1994 were more likely to report unusual smells from the gasoline than individuals who reported they had not purchased RFG since that date or did not know the type of gasoline they purchased. This finding is consistent with the fact that in chamber tests, many individuals noted that RFG had a different odor than traditional gasoline.

2. Maine’s Evaluation**{tc "□autonum□ Maine’s Evaluation" \l 5}**

In the state of Maine, health complaints began to be registered during January and February of 1995. The symptoms reported were of a non specific nature which included: dizziness, lightheadedness and respiratory symptoms. After an organized effort to ban the use of RFG in Maine was initiated, the Bureau of Health, began receiving unsolicited health surveys from York County. These health surveys were distributed by an organization called “Oxy Busters.” Subsequently, the Bureau of Health received 48 of these surveys which reported complaints linked to RFG such as: odor, headaches, breathing problems, sneezing and other concerns. These surveys have been tabulated and analyzed. In response to published newspaper reports the Bureau also received several letters and numerous telephone calls describing health problems. To date, the vast majority of complaints have originated in York County.

This report was written to provide not only an overview and evaluation of the specific health concerns that have been linked to RFG, but also place those concerns specifically in context in Maine. To do this, it was necessary to consider the health effects of gasoline without 11% MTBE, and the health effects of other air toxins in Maine and the nation.

In addition, the introduction of MTBE RFG, during the late fall and early winter, occurred at a time when exposure to other factors which have adverse health impacts, such as influenza, indoor air toxins and even weather (severe cold, dry air) would be maximized. Headaches, skin irritation and respiratory problems, such as sneezing and shortness of breath, are all increased during this season.

The health problems experienced by Maine people and attributed to RFG, are very similar to concerns raised by citizens in other parts of the country. The investigation of health effects in Alaska appears to be inconclusive and has not been confirmed by similar studies done in New Jersey and New York.

The presence of MTBE in groundwater was raised as a significant environmental health and contamination issue by persons questioning the use of MTBE RFG in Maine. Review of the available literature, evaluation of in-state sources of information, and discussions with other states, particularly the state of Colorado, confirms the fact that MTBE has been found in groundwater in Maine, as well as across the nation. (See below)

MTBE has been detected in Maine groundwater for about a decade, and occasionally in drinking water, at levels which exceeded the current Maine health-based standard of 50 parts per billion (ppb). At the present time MTBE in Maine drinking water does not pose a significant health hazard. Furthermore contamination levels should be decreasing with continued progress toward correcting the leaking underground storage tank problem. However, because the unsubstantiated possibility of significant airborne contamination of ground water by MTBE has been raised, increased surveillance for MTBE in Maine groundwater is recommended.

The Health Effects Task Force identified a sufficient quantity of available high quality research information to recommend against banning MTBE RFG because both regular gasoline and ozone represent significant public health hazards and environmental risk to Maine residents. In fact the use of MTBE RFG in Maine, in combination with Stage II vapor recovery mechanisms at service stations, could be expected to achieve some positive health impacts.

3. EPA’s Evaluation**{**tc "□autonum□ EPA’s Evaluation" \l 5**}**

Gasoline vapors and vehicle exhaust contain volatile organic compounds (VOCs) and oxides of nitrogen (NO x) that react in the atmosphere in the presence of sunlight and heat to produce ozone, a major component of smog. Vehicles also release toxic emissions, on of which (benzene) is a known human carcinogen. RFG contains less of the ingredients that contribute to these harmful forms of air pollution. Consequently, RFG reduces the exposure of the U.S. Public overall to ozone and certain air toxins.

RFG will contain oxygen additives (oxygenates)such as MTBE and ethanol. While oxygenates have been used in some fuels as octane enhances since the late 1970 s, a widespread oxygenated fuel program began in 1992 in 39 urban areas. This program was required by the 1990 Clean Air Act in cities with high carbon monoxide pollution. Oxygenates increase the combustion efficiency of gasoline, thereby reducing vehicle emissions of carbon monoxide. Carbon monoxide can also affect healthy individuals by impairing exercise capacity, visual perception, manual dexterity, learning functions, and ability to perform complex tasks.

Research completed to date suggests that oxygenates, at levels that exist in reformulated gasoline, pose no greater health risk than the gasoline they are replacing. And, as part of the total cleaner gasoline formulation, they help decrease vehicle emissions.

5. Reformulated Gasoline{tc "autonum Reformulated Gasoline" \l 3}

Beyond the substitution of less hazardous oxygenates for lead, it is possible to make additional modifications to gasoline, to “reformulate” it to reduce both regulated and unregulated emissions of concern. As part of a comprehensive policy to reduce vehicle emissions, fuel reformulation has the potential not only to offset any increased risks associated with the introduction of unleaded petrol but to complement the elimination of lead health risks with an overall reduction of the toxic and ozone forming potential of gasoline and gasoline vehicle emissions.

The potential for "reformulating" gasoline to reduce pollutant emissions attracted considerable attention in the U.S. as pressure to shift to alternative fuels increased during the mid to late 1980's. One result was a major cooperative research program between the oil and auto industries. During the early 1990's, this was followed by a similar effort in Europe. The result is that a great deal has been learned about the potential for modifying gasolines in a manner which can significantly improve air quality. An additional advantage of fuel reformulation is that it can reduce emissions from all vehicles on the road in much the same way that reducing lead in gasoline can reduce lead emissions from all vehicles.

The most significant potential emission reductions that have been identified for gasoline "reformulation" have been through reducing volatility (to reduce evaporative emissions), reducing sulfur (to improve catalyst efficiency), and adding oxygenated blend stocks (with a corresponding reduction in the high-octane aromatic hydrocarbons which might otherwise be required). The potential benefits of improving various fuel parameters are summarized below.

1. Lowering Volatility{tc "autonum Lowering Volatility" \l 4}

Fuel volatility, as measured by Reid vapor pressure (RVP) has a marked effect on evaporative emissions from gasoline vehicles both with and without evaporative emission controls. Tests on vehicles without evaporative emission controls showed that increasing the fuel RVP from 9 pounds per square inch (psi) (62 kilipascals) to approximately 12 psi (82 kPa) roughly doubled evaporative emissions.[41] The percentage effect is even greater in controlled vehicles. In going from 9 psi (62 kPa) to 12 (81 kPa) RVP fuel, the US EPA found that average diurnal emissions in vehicles with evaporative controls increased by more than 5 times, and average hot-soak emissions by 25-100%.[42] The large increase in diurnal emissions from controlled vehicles is due to saturation of the charcoal canister, which allows subsequent vapors to escape to the air.

Vehicle refueling emissions are also strongly affected by fuel volatility. In a comparative test on the same vehicle, fuel with 11.5 psi (79 KPA) RVP produced 30% greater refueling emissions than gasoline with 10 psi (64 KPA)

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[41]McArragher, J.S. et al. 1988. Evaporative Emissions from Modern European Vehicles and their Control. SAE Paper No. 880315. SAE International, Warrendale, Pennsylvania.

[42]U.S. EPA. 1987. Draft Regulatory Impact Analysis: Control of Gasoline Volatility and Evaporative Hydrocarbon Emissions From New Motor Vehicles, Office of Mobile Sources, United Sates Environmental Protection Agency, Washington, DC.

RVP (1.45 vs. 1.89 g/liter dispensed).[43] In response to data such as these, the U.S. EPA has established nationwide summertime RVP limits for gasoline.

An important advantage of gasoline volatility controls is that they can affect emissions from vehicles already produced and in-use and from the gasoline distribution system. Unlike new-vehicle emissions standards, it is not necessary to wait for the fleet to turn over before they take effect. The emissions benefits and cost-effectiveness of lower volatility are greatest where few of the vehicles in use are equipped with evaporative controls. Even where evaporative controls are in common use, as in the U.S., control of volatility may still be beneficial to prevent in-use volatility levels from exceeding those for which the controls were designed.

In its analysis of the RVP regulation, the U.S. EPA (1987) estimated that the long-term refining costs of meeting a 9 psi (62 KPA) RVP limit throughout the U.S. would be approximately US$0.0038 per liter, assuming crude oil at US$20 per barrel. These costs were largely offset by credits for improved fuel economy and reduced fuel loss through evaporation, so that the net cost to the consumer was estimated at only US$0.0012 per liter.

2. **Oxygenates{**tc "□autonum□ Oxygenates" \l 4**}**

As noted earlier, blending small percentages of oxygenated compounds such as ethanol, methanol, tertiary butyl alcohol (TBA) and methyl tertiary-butyl ether (MTBE) with gasoline has the effect of reducing volumetric energy content of the fuel, while improving the antiknock performance and thus making possible a potential reduction in lead and/or harmful aromatic compounds. Assuming no change in the settings of the fuel metering system, lowering the volumetric energy content will result in a leaner air-fuel mixture, thus helping to reduce exhaust CO and HC emissions.

1. Impact of Oxygenate Used

1. MTBE

It appears that MTBE or methyl tertiary butyl ether can be added to gasoline up to 2.7% without any increase in NOx. There are two opposing effects taking place with the addition of oxygenates: enleanment which tends to raise NOx, and lower flame temperatures which tend to reduce NOx. With MTBE levels above 2.7%, the lower flame temperature effect seems to prevail.

2. Ethanol

Available data indicates that ethanol can be added to gasoline at levels as high as 2.1% oxygen without significantly increasing NOx levels but above that point levels could increase significantly. For example, EPA test data on over

[43]Braddock, J.N. 1988. "Factors Influencing the Composition and Quantity of Passenger Car Refueling Emissions - Part II". SAE Paper No. 880712. SAE International, Warrendale, Pennsylvania.

100 cars indicates that oxygen levels of 2.7% or more could increase NOx emissions by 3-4%.[44] The auto/oil study concluded that there was a statistically significant increase in NOx of about 5% with the addition of 10% ethanol (3.5% O_2).

3. ETBE

Ethyl Tertiary Butyl Ether appears to be an attractive source of oxygenates but, unfortunately, to date, too little data exists regarding its NOx impact to make a reasonable judgement as to its impact. The auto/oil study found about a 6% increase in NOx but the results were not statistically significant.

3. Other Fuel Variables{tc "autonum Other Fuel Variables" \l 4}

1. Sulfur{tc "autonum Sulfur" \l 5}

Lowering sulfur in gasoline lowers emissions of CO, HC and NOx from catalyst equipped cars. As noted by the Auto-Oil study, "The regression analysis showed that the sulfur effect (lowered emissions) was significant for HC on all ten cars, for CO on five cars, and for NOx on 8 cars. There were no instances of a statistically significant increase in emissions."[45] To the extent that oxygenates are sulfur free, their addition would tend to traditionally lower gasoline sulfur levels. Based on the auto/oil study, it appears that NOx would go down about 3% per 100 PPM sulfur reduction.

2. Other{tc "autonum Other" \l 5}

According to the auto/oil study, "NOx emissions were lowered by reducing olefins, raised when T_{90} was reduced, and only marginally increased when aromatics were lowered."[46] In general, reducing aromatics and T_{90} caused statistically significant reductions in exhaust mass NMHC and CO emissions. Reducing olefins increases exhaust mass NMHC emissions; however, "the ozone forming potential" of the total vehicle emissions was reduced.[47]

With regard to toxics, the reduction of aromatics from 45% to 20% caused a 42% reduction in benzene but a 23% increase in formaldehyde, a 20% increase in acetaldehyde and about a 10% increase in 1,3-Butadiene. Reducing olefins from 20% to 5% brought about a 31% reduction in 1,3-Butadiene but had insignificant impacts on other toxics. Lowering the T_{90} from 360 to 280F resulted in statistically significant reductions in benzene, 1,3-Butadiene (37%), formaldehyde (27%) and acetaldehyde (23%).

4. Cost Effectiveness{tc "autonum Cost Effectiveness" \l 4}

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[44] Personal Communication.

[45] Auto/Oil Air Quality Improvement Research Program, Technical Bulletin No. 2, "Effects Of Fuel Sulfur Levels On Mass Exhaust Emissions", February 1991.

[46] Auto/Oil Air Quality Improvement Research Program, Technical Bulletin No. 1, "Initial Mass Exhaust Emissions Results From Reformulated Gasolines", December 1990.

[47] "Auto/Oil Air Quality Improvement Research Program - What Is It and What Has It Learned?", Colucci and Wise, June 7, 1992, Presented at XXIV Fisita Congress, London, England.

It is difficult to estimate the costs and the cost effectiveness of fuel modifications because refiners differ widely in terms of the characteristics of the fuels they produce. Individual fuel component control costs and the effects of changes in one fuel component on the other fuel components are integral parts in the determination of the cost effectiveness. In the US EPA's analysis, these two integral parts were estimated from the results of refinery modeling performed by Turner, Mason and Company (for the Auto-Oil Economics group) and Bonner & Moore Management Science (for EPA) and on survey results presented by the California Air Resources Board (CARB).

The total cost (or manufacturing cost) of producing a reformulated gasoline is the sum of the capital recovery cost and the operating cost. An example of the individual fuel component costs and the associated incremental percent reduction in VOC emissions are shown in Table 2.

Table 2
Component Control Costs and VOC Emission Reductions

Component	Control Level	Incremental Cost (c/gal)	Cumulative VOC Reduction (%)
Oxygen	2.0 Wt%	1.67-3.36 1/	9.0
Benzene	1.0 vol%	0.69	9.0
RVP	8.1 psi	0.57	17.6
RVP	7.4 psi	1.67	25.3
Sulfur	160 ppm	0.35-0.57	26.4
Oxygen	2.7 Wt%	0.59-1.18 1/	28.5
Olefins	5.0 vol%	1.81-2.44	30.2
Sulfur	50 ppm	1.45-1.86	31.2
Aromatics	20 vol%	0.61-0.98	31.4

1/ Based on MTBE.

EPA proposed a range of VOC standards and NOx standards based on particular combinations of fuel component controls which reduce VOC (and VOC plus NOx) emissions at a cost of less than $5,000 and less than $10,000 per ton, respectively. EPA believes that these ranges represent the upper limit of costs which will be incurred by many ozone nonattainment areas in achieving attainment.

Estimates of the costs and cost effectiveness of California RFG continue to come down. At the time it developed its regulations, CARB estimated the costs to be $0.12 to $0.17 per gallon. Recently, an EPA analysis placed the costs at $0.08 to $0.11 per gallon. This analysis estimated the cost effectiveness of the California RFG to be $4,100 to $5,100 per ton of VOC and NOx control; Federal phase 1 RFG was estimated to cost $3,100 per ton of VOC control.[48]

[48]"The Case For California Reformulated Gasoline - Adoption By the Northeast", Dr. R. Dwight Atkinson, May 1993.

3. CONCLUSIONS REGARDING CLEANER, LEAD FREE GASOLINE{tc "autonum CONCLUSIONS REGARDING CLEANER, LEAD FREE GASOLINE" \l 2}

1. A growing body of data on the adverse health effects of lead, especially in young children, indicates there may be no “safe” level. Reduced lead in gasoline has been shown to reduce the risk of behavioral problems, lowered IQ s and decreased ability to concentrate in exposed children.

2. Lead scavengers which accompany leaded gasoline have also been identified as human carcinogens; the elimination of lead in gasoline will therefore also reduce this cancer risk.

3. Studies in both Europe and the United States show that gasoline lead is responsible for about 90 percent of airborne lead and that 1 microgram per cubic meter of ambient lead will cause a 1-2 microgram per milliliter increase in blood lead levels. This is in addition to the lead burden which may be associated with food, drinking water and other sources.; this burden can be highly variable from country to country.

4. The availability of lead free gasoline can facilitate extensive reductions in the other major pollutants from motor vehicles, hydrocarbons, carbon monoxide and nitrogen oxides by allowing the use of catalytic converters.

5. Motor vehicle emissions of hydrocarbons, carbon monoxide and nitrogen oxides cause or contribute to a wide range of adverse impacts on public health and general well being including increased angina attacks in individuals suffering from angina pectoris, greater susceptibility to respiratory infection, more respiratory problems in school children, increased airway resistance in asthmatics, eye irritation, impaired crop growth, dead lakes and forest destruction.

6. The combination of lead free gasoline and catalysts can also facilitate very substantial reductions in other harmful pollutants such as aldehydes and polynuclear aromatic hydrocarbons (PAH s).

7. These emissions reductions can occur simultaneously with equally significant improvements in fuel economy and reductions in vehicle maintenance. Also, based on studies in Canada, reduced maintenance can save about 2.4 cents per liter with the use of unleaded gasoline compared to leaded gasoline.

8. The most direct strategy for eliminating lead in gasoline is to ban its use; several countries have adopted this strategy. In Asia, Thailand has been an aggressive proponent of this approach.

9. Tax policies which price unleaded fuel substantially below leaded fuel have also been found to be very effective in stimulating the sales of unleaded fuel. Hong Kong and Singapore stand out as Asian examples.

10. Countries concerned about the available supply of unleaded petrol may wish to maintain a higher price for unleaded compared to leaded but this strategy tends to increase the risk of poisoning of any catalyst equipped vehicles in the country and prolongs the use of lead with its concomitant health risks.

11. Beyond unleaded gasoline, hydrocarbons, CO and toxic emissions can be reduced from 10 to 30% through the reformulation of gasoline by modifying parameters such as volatility, oxygenates, sulfur levels and hydrocarbon mix. Care must be taken to assure that these modifications don't increase NOx emissions.

12. The use of oxygenates such as MTBE in cold temperature environments, while clearly bringing about significant reductions of CO, has raised concerns regarding adverse health effects in certain susceptible individuals. Studies to date by both the US EPA and several states have failed to identify a serious problem but additional studies are ongoing.

6. DIESEL FUEL{tc "autonum DIESEL FUEL"}

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 fuel variables such as the sulfur content and the fraction of aromatic hydrocarbons contained in the fuel, the volatility of the diesel fuel (85 or 90% distilled temperatures) the use of fuel additives may have a significant impact on emissions.

1. Sulfur{tc "autonum Sulfur" \l 2}

Recent diesel fuel evaluations carried out in Europe show the benefits of reduced sulfur in diesel fuel for lowering particulate. For example, preliminary data released from the auto oil study showed that lowering the diesel fuel sulfur level from 2000 ppm to 500 ppm reduced overall particulate from light duty diesels by 2.4% and from heavy duty diesels by 13%.[49] The relationship between particulates and sulfur level was found to be linear; for every 100 PPM reduction in sulfur, there will be a .16% reduction in particulate from light duty vehicles and a 0.87% reduction from heavy duty vehicles.

The US EPA has also established a clear relationship between sulfur in diesel fuel and particulate emissions.[50] The direct sulfate emissions factor (g/mile) is calculated as follows:

DSULV = 13.6078*(1.0 + WATER)*FDNSTY*SWGHTD*DCNVRT/FE

where

DSULV= the direct sulfate emissions factor for a class and model year of vehicles

DCNVRT= the fraction of sulfur in the fuel that is converted directly to sulfate (2.0 %)

FDNSTY= the density of diesel fuel (7.11 lb/gal)

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[49]The Auto-Oil Programme, Informal Briefing, Brussels, 21 March 1995.

[50]Draft Users Guide To Part5: A Program For Calculating Particle Emissions From Motor Vehicles", US EPA, February 1995.

FE= the fuel economy for the class and model year of the vehicles
SWGHTD= The weight percent of sulfur in diesel fuel
WATER= weight ratio of seven water molecules to sulfate, 7.18/98=1.2857
13.6078=units conversion factor=(453.592*3.)/100 where 453.592=the number of grams in a pound, 3=weight ratio of SO4 to sulfur, and the division by 100 is to correct for the weight percent of sulfur.

The gaseous sulfur emission factor is calculated as follows:

SO SUB2 = 9.072*FDNSTY*SWGHTD*(1-CNVRT)/FE where the new terms are

SO_2 = the sulfur emission factor of a vehicle of a given class and model year.

9.072 = units conversion factor=(453.592*2)/100 where 453.592=number of grams in a pound, 2=weight ratio of SO_2 to sulfur, and the division by 100 is to convert for the weight percent of sulfur.

Clearly improvements in diesel fuel quality hold out the prospect of both substantially improving diesel emissions and increasing the prospects for advanced aftertreatment technology. Sweden and Finland have shown that very low sulfur diesel fuel is feasible and beneficial. Both countries have stimulated the use of very low sulfur fuel, less than 0.005 Wt., with the result that emissions are substantially reduced.

From January 1, 1991 Environmental Classifications were introduced for diesel fuel in Sweden with tax relief for both sulfur content and composition. These were further revised in January 1992 to the classifications summarized below.

Fuel Characteristic	Urban Diesel 1	Urban Diesel 2	Standard
Max. Sulfur, %	0.001	0.005	0.2
Max. Aromatics, %	5	20	-
Max. PAH, %	0.02	0.1	-
Distillation:			
IBP (min) C	180	180	-
10% (min)	-	-	180
95% (max)	285	295	**
Density (kg/m^3)	800-820	800-820	#
Cetane Number	50	47	##
Tax Rate ($\$/m^3$) (1)	126	165	199

Notes:

* In addition to the urban grades, one summer and three winter standard grades are specified

** 95% distillation varies with grade:
Summer; 370
Winter: 340

\# Density varies with grade
Summer: 820-860 kg/m3
Winter: 800-845 (-26 C)
Winter: 800-840 (-32 and -38 C grades)

\## 45 to 49

(1) 1994 tax rates exclude added value tax.

The Figure above illustrates the benefits which Finland has found on urban buses from its very low sulfur diesel fuel.[51]

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.

[51]"Reformulated Fuels Reduce Automotive Emissions", Seppo Mikkonen and Neste Oy, Finish Air Pollution Prevention News, 5/6/93.

Sulfur 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, 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.

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

Several options are available to reduce the sulfur content of diesel fuel, including:

1. Increase the proportion of low-sulfur crude oil in the crude state.

2. Reduce the cut point of diesel fractions from both primary distillation as well as from the fractionation of secondary processing streams to 350^{o} C - 360^{o} C.

3. Improve fractionation efficiency to eliminate inter-stream overlaps during fractionation of diesel oils.

4. Hydro-treat gas oil feedstocks to FCC and/or hydrofine FCC diesel fractions; reduce proportions of FCC oil blended into final product diesel oil to reduce olefins and avoid stability problems.

5. Install hydrocrackers that would enable production of very low sulfur content, saturated diesel oils with high octane numbers.

2. Volatility{tc "□autonum□ Volatility" \l 2}

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 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, however, the test fuels were composed of two sets at clearly different 85 or 90 per cent boiling points, among which sulfur 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 sulfur and a probably significant effect of aromatics contents. A typical effect of a 20^{o} 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^{o} C. Commercial diesel fuels in Europe show values up to about 370^{o} C.

3. Aromatic Hydrocarbon Content {tc "autonum Aromatic Hydrocarbon Content " \l 2}

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 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.

4. Other Fuel Properties {tc "autonum Other Fuel Properties " \l 2}

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.

5. Fuel Additives {tc "autonum Fuel Additives " \l 2}

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.

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 Dutch 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 are not fully documented, but one study 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 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.

6. Conclusions Regarding Clean Diesel Fuel{tc "autonum Conclusions Regarding Clean Diesel Fuel" \l 2}

1. There is a clear worldwide trend toward lower and lower levels of sulfur in diesel fuel. At a minimum, this reduces the particulate emissions from diesel vehicles; recent European studies indicate that for every 100 PPM reduction in sulfur, there will be a .16% reduction in particulate from light duty vehicles and a 0.87% reduction from heavy duty vehicles.

2. Other diesel fuel properties such as volatility, aromatic content and additives can also have positive or negative effects on diesel vehicle emissions.

3. In addition to the adoption of mandatory limits, it has been shown that tax policies can be very effective in encouraging the introduction and use of low polluting diesel fuels.

7. ALTERNATIVE FUELS[52]{tc "□autonum□ ALTERNATIVE FUELS□□Derived from analysis prepared by Chris Weaver and published in ... □"}

Alternative fuels include methanol (made from natural gas, coal or biomass) ethanol (made from grain), vegetable oils, compressed natural gas (CNG) mainly composed of methane, liquefied petroleum gas (LPG) composed of propane, butane, electricity, hydrogen, synthetic liquid fuels derived from hydrogenation of coal, and various fuel blends such as gasohol.

The possibility of substituting cleaner-burning alternative fuels for gasoline has drawn increasing attention during the last decade. The motives for this substitution include conservation of oil products and energy security, as well as the reduction or elimination of pollutant emissions. Some alternative fuels do offer the potential for large, cost-effective reductions in pollutant emissions in specific cases. Care is necessary in evaluating the air-quality claims for alternative fuels, however - in many cases, the same or even greater emission reduction could be obtained with a conventional fuel, through the use of a more advanced emission control system. Which approach is the more cost-effective will depend on the relative costs of the conventional and the alternative fuel.

Table 3: Properties of conventional and alternative fuels

Properties of Alternative and Conventional Fuels						
Fuel Type	Diesel	Gasoline	Methanol	Ethanol	Propane	Methane
Energy content (LHV) (MJ/kg)	42.5	44.0	20.0	26.9	46.4	50.0
Liquid density (kg/l)	0.84-0.88	0.72-0.78	.792	.785	.51	.4225
Liquid energy density (MJ/l)	36.55	33.0	15.84	21.12	23.66	21.13
Gas energy density (MJ/l) - @ atmospheric - @ 200 bar	 -- --	 -- --	 -- --	 -- --	 0.093 --	 0.036 7.47
Boiling point, C	140-360	37-205	65	79	-42.15	-161.6
Research octane no.	25	92-98	106	107	112	120
Motor octane no.		80-90	92	89	97	120
Cetane no.	45-55	0-5	5	5	2	0

1. Natural Gas

[52]Derived from analysis prepared by Chris Weaver and published in ...

Natural gas (which is 85-99% methane) has many desirable qualities as a fuel for spark-ignition engines. Clean-burning, cheap, and abundant in many parts of the world, it already plays a significant vehicular role in Russia, Argentina, Italy, Canada, New Zealand, and the U.S. Recent advances in the technology for natural gas vehicles and engines, new technologies and international standardization for storage cylinders, and the production of new, factory-manufactured natural gas vehicles in a number of countries have all combined to boost the visibility and market potential of natural gas as a vehicle fuel.
Nearly all of the natural gas vehicles (NGVs) now in operation are retrofits, converted from gasoline vehicles. The physical properties of natural gas make such a conversion relatively easy. Typical conversion costs are in the range of US$ 1,500 to 4,000 per vehicle, and are due mostly to the cost of the onboard fuel storage system. At present fuel prices, many high-use vehicles can recover this cost in a few years, due to savings on fuel.

In recent years, several thousand new, factory-built light-duty natural gas vehicles have been produced in the U.S. - mostly by Chrysler Corporation. Ford has announced plans to begin limited mass production of an optimized natural gas passenger car in 1996. The Chrysler and Ford vehicles incorporate fuel metering and emission control systems similar to those in modern fuel-injected gasoline vehicles. These vehicles are by far the cleanest non-electric motor vehicles ever made - easily certifying to California's stringent ultra-low emission vehicle standards. The incremental cost of these vehicles in their present, limited-volume production ranges from about US$4,000 to US$5,500 more than gasoline, or about 20% of the selling price. It has been estimated that with full mass production, these costs would drop to around US$ 1,500 to 2,500 per vehicle.

Natural gas engines can be grouped into three main types on the basis of the combustion system used. These types are: stoichiometric, lean-burn, and dual-fuel diesel. Most of the natural gas vehicles now in operation have stoichiometric engines, which have been converted from engines originally designed for gasoline. Such engines may be either bi-fuel (able to operate on either natural gas or gasoline) or dedicated to natural gas. In the latter case, the engine can be optimized for natural gas by increasing the compression ratio and making other changes, but this is not usually done in retrofit situations because of the cost. Nearly all present light-duty natural gas vehicles use stoichiometric engines, with or without three-way catalysts, as do a minority of heavy-duty natural gas vehicles.

Lean-burn engines use an air-fuel mixture with much more air than is required to burn all of the fuel. The extra air dilutes the mixture and reduces the flame temperature, thus reducing engine-out NO_X emissions, as well as exhaust temperatures. Because of reduced heat losses and various thermodynamic advantages, lean-burn engines are generally 10-20% more efficient than stoichiometric engines. Without turbocharging, however, the power output of a lean-burn engine is less than that of a stoichiometric engine. With turbocharging, the situation is reversed. Because lean mixtures knock less readily, lean-burn engines can be designed for higher levels of turbocharger boost than stoichiometric engines, and can thus achieve higher power output. The lower temperatures experienced in these engines also contribute to engine life and reliability. For these reasons, the great majority of heavy-duty natural gas engines are of the lean-burn design. These include a rapidly-growing number of heavy-duty, lean-burn engines developed and marketed specifically for vehicular use.

Dual-fuel diesel engines are a special type of lean-burn engine in which the air-gas mixture in the cylinder is ignited not by a spark plug but by injection of a small amount of diesel fuel, which self-ignites. Most diesel engines can readily be converted to dual-fuel operation, retaining the option to run on 100% diesel fuel if gas is not available. Because of the flexibility this allows, the dual-fuel approach has been popular for heavy-duty retrofit applications. Current dual-fuel engine systems tend to have very high HC and CO emissions, due to the production of mixtures too lean to burn at light loads. However, new developments such as timed gaseous fuel injection systems promise to overcome these problems.

Because natural gas is mostly methane, natural gas vehicles (NGVs) have lower exhaust NMHC emissions than gasoline vehicles, but higher emissions of methane. Since the fuel system is sealed, there are no evaporative or running-loss emissions, and refueling emissions are negligible. Cold-start emissions from NGVs are also low, since cold-start enrichment is not required, and this reduces both NMHC and CO emissions. NGVs are normally calibrated with somewhat leaner fuel-air ratios than gasoline vehicles, which also reduces CO emissions. Given equal energy efficiency, CO_2 emissions from NGVs will be lower than for gasoline vehicles, since natural gas has a lower carbon content per unit of energy. In addition, the high octane value for natural gas (RON of 120 or more) makes it possible to attain increased efficiency by increasing the compression ratio. Optimized heavy-duty NGV engines may approach diesel efficiency levels. NO_x emissions from uncontrolled NGVs may be higher or lower than comparable gasoline vehicles, depending on the engine technology, but are typically somewhat lower. Light-duty NGVs equipped with modern electronic fuel control systems and three-way catalytic converters have achieved NOx emissions more than 75% below the stringent California ULEV standards.

In the last few years, a number of heavy-duty engine manufacturers have developed diesel-derived lean-burn natural gas engines for use in emissions-critical applications such as urban transit buses and delivery trucks. These engines incorporate low-NOx technology used in stationary natural gas engines, and typically an oxidation catalyst as well. They are capable of achieving very low levels of NOx, particulate, and other emissions (less than 2.0 g/BHP-hr NOx and 0.03 g/BHP-hr particulate with high efficiency, high power output, and (it is anticipated) long life. Three such engines - the Cummins L10 engine for transit buses, and the Hercules 5.6l and 3.7l engines for school buses and medium trucks - have recently been certified in California.

Owing to the difficulty of transportation, the costs of natural gas vary greatly from country to country, and even within countries. Where gas is available by pipeline from the field, its price is normally set by competition with residual fuel oil or coal as a burner fuel. The market-clearing price of gas under these conditions is typically about $3.00 per million BTU (equivalent to about $0.41 per gallon of diesel fuel equivalent). Compression costs for CNG use can add another $0.50 to $2.00 per million BTU, however, depending on the size of the facility and the natural gas supply pressure.

The cost of LNG varies considerably, depending on specific contract terms (there is no effective "spot" market for LNG). The cost of small-scale liquefaction of natural gas is about $2.00 per million BTU, making it uneconomic in comparison to CNG in most cases. Where low-cost remote gas is available, however, LNG production can be quite economic. Typical 1987 costs for LNG delivered to Japan were about $3.20 to $3.50

per million BTU. The costs of terminal receipt and transportation would probably add another $0.50 or so to this cost at the wholesale level.

2. **Liquefied Petroleum Gas (LPG)**{tc "autonum Liquefied Petroleum Gas (LPG)" \l 2}

Liquefied petroleum gas is already widely used as a vehicle fuel in the U.S., 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. As with natural gas, nearly all LPG vehicles presently in operation are retrofitted gasoline vehicles. The costs of converting from gasoline to propane are considerably less than those of converting to natural gas, due primarily to the lower cost of the fuel tanks. For a light-duty vehicle, conversion costs of US$800-1,500 are typical. As with natural gas, the cost of conversion for high-use vehicles can typically be recovered through lower fuel costs within a few years.

Engine technology for LPG vehicles is very similar to that for natural gas vehicles, with the exception that LPG is seldom used in dual-fuel diesel applications, due to its poorer knock resistance.

LPG has many of the same emissions characteristics as natural gas. The fact that it is primarily propane (or a propane/butane mixture) rather than methane affects the composition of exhaust VOC emissions, but otherwise the two fuels are similar.

LPG is produced in the extraction of heavier liquids from natural gas, and as a byproduct in petroleum refining. Presently, LPG supply exceeds the demand in most petroleum-refining countries, so the price is low compared to other hydrocarbons. Wholesale prices for consumer-grade propane in the U.S. have ranged between $0.25 and $0.30 per gallon for several years, or about 30% less than the wholesale cost of diesel on an energy basis. Depending on the locale, however, the additional costs of storing and transporting LPG may more than offset this advantage.

3. **Methanol**{tc "autonum Methanol" \l 2}

Widely promoted in the U.S. as a "clean fuel," methanol in fact has many desirable combustion and emissions characteristics, including good lean combustion characteristics, and low flame temperature (leading to low NO_x emissions) and low photochemical reactivity. The major drawback of methanol as a fuel is its cost, and the volatility of pricing. While methanol prices have proven highly volatile in the past, there is little prospect for it to become price-competitive with conventional fuels unless world oil prices increase greatly.

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 NO_x emissions.

Light-duty vehicles using M85 tend to have emissions of NOx and CO similar to gasoline vehicles. The total mass of tailpipe non methane organic gas (NMOG) emissions tends to be similar to or somewhat higher than for gasoline vehicles, but the lower ozone reactivity of the NMOG results in similar or somewhat lower ozone impacts overall. Emissions of formaldehyde (a primary combustion product of methanol) tend to be significantly higher than those from gasoline or other alternative fuel vehicles, but emissions of other toxic air contaminants (especially benzene) tend to be lower. Formaldehyde emissions have been controlled successfully by catalytic converters, however.

Heavy-duty methanol engines are capable of much lower NOx and particulate emissions than similar heavy-duty bus diesel engines, while engine out NMOG, CO and formaldehyde emissions tend to be higher. These emissions have been controlled successfully by catalytic converters, however.

Methanol can be produced from natural gas, coal, or biomass. At current and foreseeable prices, the most economical feedstock for methanol production is natural gas, especially natural gas found in remote regions where it has no ready market. The current world market for methanol is as a commodity chemical, rather than a fuel, and world methanol production capacity is limited and projected to be tight at least through the 1990s. Methanol is a feedstock in the production of MTBE, and the anticipated huge increase in MTBE demand for reformulated gasoline will place strong pressure on price and supply for the foreseeable future.

The price of methanol on the world market has fluctuated dramatically in the last decade, from around $0.25/gallon in the early 1980's to $.60-.70 in the late 1980s. The lower price reflected the effect of a glut; while the higher value reflected a temporary shortage. Recent estimates of the long-term supply price of methanol for the next decade range from $0.43 to $0.59 per gallon. This would be equal to US$ 0.90 to 1.23 on an energy-equivalent basis (compared to present spot gasoline prices of the order of US$ 0.70 per gallon). In addition to new methanol supply capacity, any large-scale use of methanol for vehicle fuel would require substantial investments in fuel storage, transportation, and dispensing facilities, which would further increase the delivered cost of the fuel.

4. Ethanol{tc "□autonum□ Ethanol" \l 2}

Ethanol has attracted considerable attention as a motor fuel due to the success of the Brazilian Prooalcool program. Despite the technical success of this program, however, the high cost of producing ethanol (compared to hydrocarbon fuels) means that it continues to require heavy subsidies.

As the next higher of the alcohols in molecular weight, ethanol resembles methanol in most combustion and physical properties. The major difference is in the higher volumetric energy content of ethanol. Fuel grade ethanol, as produced in Brazil, is produced by distillation, and contains several volume percent of water. In addition, pure (anhydrous) ethanol is used as a blend stock for gasoline both in Brazil and in the U.S. By blending 22% anhydrous ethanol with gasoline to produce gasohol, Brazil has been able to eliminate completely the requirement for lead as an octane enhancer.

Emissions from ethanol fueled engines are not well characterized, but are believed to be high in unburned ethanol, acetaldehyde, and other aldehydes. These can be controlled with a catalytic converter. Uncontrolled NO_x emissions should be somewhat higher than for methanol, but still lower than for gasoline engines. Cold-starting of ethanol engines is not a serious problem in the warm Brazilian climate, but would be a concern in countries with cold winters.

Ethanol is produced primarily by fermentation of starch from grains or sugar from sugar cane. As a result, the production of ethanol for fuel is in direct competition with food production in most countries. The resulting high price of ethanol (ranging from $1.00 to $1.60 per gallon in the U.S. in the last few years - equivalent to US$ 1.56-2.5 per gallon of gasoline on an energy basis) has effectively ruled out its use as a motor fuel except where (as in Brazil and the U.S.) it is heavily subsidized. The Brazilian Prooalcool program to promote the use of fuel ethanol in motor vehicles in that country has attracted worldwide attention as the most successful example of an alternative fuel implementation program extant. Despite the availability of a large and inexpensive biomass resource, however, this program still depends on massive government subsidies for its viability.

5. Biodiesel{tc "autonum Biodiesel" \l 2}

Biodiesel is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel, and which can be used neat or blended with petroleum diesel in a diesel engine. Engines running on biodiesel instead of or blended with petroleum diesel tend to have lower black smoke and CO emissions, but higher NOx and possibly higher emissions of particulate matter. These differences are not very large, however. Other advantages of biodiesel include high cetane number, very low sulfur content, and the fact that it is a renewable resource. Disadvantages include high cost ($1.50 to $3.50 per gallon before taxes), reduced energy density (resulting in lower engine power output), and low flash point, which may make it hazardous to handle. The effects of biodiesel on engine performance and emissions over a long time in actual service are not well documented.

Although there are no published field test data on engine emissions, performance and durability for vehicles using blended or neat biodiesel, there are some reports in the literature on short-term effects measured in the laboratory. The general consensus of these studies is that blended or neat biodiesel has the potential to reduce diesel CO emissions (although these are already low), smoke opacity, and measured HC emissions. However, the studies show an increase in NOx emissions for biodiesel fuel when compared to diesel fuel at normal engine conditions. The higher NOx emissions from biodiesel-powered engines are partly due to the higher cetane number of biodiesel, which causes a shorter ignition delay and higher peak cylinder pressure. Some may also be due to the nitrogen content in the fuel. The reduction in smoke emissions is believed to be due to better combustion of the short chain hydrocarbons found in biodiesel, as well as the effects of the oxygen content. Other data have also shown that mixing oxygenates with diesel fuel helps to reduce smoke.

As for the HC emissions, research shows a reduction in HC emissions when biodiesel is used. However, the effect of the organic acids and/or oxygenated compounds found in biodiesel may affect the response of the flame ionization detector, thus understating the actual HC emissions. The behavior of these compounds with respect to adsorption and desorption on the surfaces of the gas sampling system is not known. Thus more studies are needed to understand the organic constituents in the exhaust gases from biodiesel-powered engines before firm conclusions can be drawn regarding the effects on HC emissions. There is controversy concerning the effect of biodiesel on particulate matter emissions.

The cost of biodiesel fuel is one of the principal barriers making it less attractive to substitute for diesel fuel. The cost for vegetable oils is about $2 to $3 per gallon. If the credit for glycerol, which is a by-product of the biodiesel transesterification process and a chemical feedstock for many industrial processes, is taken into account, the cost of converting vegetable oils to biodiesel is approximately $0.50 per gallon. Thus, the total cost for biodiesel fuel is about $2.50 to $3.50 per gallon. This is substantially higher than for conventional diesel, which presently costs about $0.75 per gallon before taxes. If waste vegetable oil is used, the cost of biodiesel is claimed to be reduced to about $1.50 per gallon. Since the heating value for biodiesel is less than that for diesel, more fuel must be burned to provide the same work output as diesel fuel. This adds further to the cost disadvantage of biodiesel.

6. **Hydrogen**{tc "autonum Hydrogen" \l 2}

While having the potential to be the cleanest burning motor fuel, hydrogen has many properties that make it difficult to use in motor vehicles. Hydrogen's potential for reducing exhaust emissions stems from the absence of carbon atoms in its molecular structure. Because of the absence of carbon, the only pollutant produced in the course of hydrogen combustion is NOx (of course, the lubricating oil may still contribute small amounts of HC, CO, and particulate matter). Hydrogen combustion also produces no direct emissions of CO_2. Indirect CO_2 emissions depend on the nature of the energy source used to produce the hydrogen. In the long term event of drastic measures to reduce carbon dioxide emissions (to help reduce the effects of global warming), the use of hydrogen fuel produced from renewable energy sources would be a possible solution.

Hydrogen can be stored on-board a vehicle as a compressed gas, as a liquid, or in chemical storage in the form of metal hydrides. Hydrogen can also be manufactured on-board the vehicle by reforming natural gas, methanol, or other fuels, or by the reaction of water with sponge iron.

7. **The Economics of Alternative Fuels**{tc "autonum The Economics of Alternative Fuels" \l 2}

The economics of alternative transport fuels depends on the cost of production and the additional cost of storage, distribution, and end-use. Production costs are a function of abundance or scarcity of the resources from which the fuel is produced, as well as the technology available to extract those resources. The additional costs of storage, distribution and end- vehicle-use are also important. Gasoline and diesel fuel made from heavy oils or natural gas require relatively minor changes to existing distribution and end-use systems, whereas CNG and alcohol fuels require larger modifications.

OECD estimates of the cost ranges (inclusive of production, distribution and end-use) of alternative fuels are shown in Table 4. These estimates were based on 1987 costs and technology. According to OECD's International Energy Agency, CNG and Very Heavy Oil (VHO) products could be economically competitive with conventional gasoline at 1987 prices. Methanol and synthetic gasoline made from natural gas were close to competitive, under optimistic assumptions about gas prices. Methanol from coal or biomass and ethanol from biomass were estimated to have a cost at least double that of gasoline (IEA, 1990).

A study by the World Bank (Moreno and Bailey, 1989) found that at crude oil prices of $10 per barrel or lower (in 1988 prices) alternative fuels were generally uncompetitive. Between $10 and $20 per barrel custom-built propane-fueled high mileage vehicles and retrofitted vehicles using CNG trickle-fill refueling (mostly applicable to captive vehicle fleets -- urban buses, taxis, and delivery trucks -- with a relatively high annual mileage but restricted range), become competitive. Between $20 and $30 per barrel, CNG fast fill and propane-fueled low mileage vehicles would be competitive. Methanol from natural gas becomes competitive above $50 per barrel while synthetic gasoline and diesel fuel do not become competitive until the price of crude oil reaches $70 per barrel. For CNG-fueled vehicles, the high cost of fuel transport in tube trailers suggests that CNG would become competitive at the crude oil prices indicated above only if filling stations are located near a natural gas pipeline or distribution network.

Table 4 Comparative costs of substitute fuels, 1987

Fuel	**Overall Cost (1987 US dollars per barrel-gasoline energy equivalent)**
Crude oil (assumed price)	$18
Conventional Gasoline	$27
Compressed Natural Gas	$20-46
Very Heavy Oil Products	$21-34
Methanol (from gas)	$30-67
Synthetic Gasoline (from gas)	$43-61
Diesel (from gas)	$69
Methanol (from coal)	$63-109
Methanol (from biomass)	$64-126
Ethanol (from biomass)	$66-101

Source: IEA, 1990.

Table 5
Costs of Conventional and Alternative Fuels in the U.S.

Conventional and Alternative Fuel Costs	Gasoline[a]	Methanol[b]	Ethanol[c]	LPG[c]	CNG[d]	LNG[e]	Hydrogen[f]
Wholesale ($/gal[g])	0.51-0.68	0.32-0.42	1.29-1.45	0.25-0.45	0.25-0.50	0.40-0.55	0.25
Wholesale ($/therm[h])	0.41-0.54	0.56-0.74	1.70-1.91	0.29-0.53	0.26-0.52	0.53-0.72	0.85
Retail ($/gal)	0.97-1.32	0.80-0.92	n/a[i]	0.95-1.10	0.40-0.90	n/a	9.60-16.00
Retail ($/therm)	0.78-1.06	1.41-1.62	n/a	1.12-1.29	0.41-0.93	n/a	33.10-55.17

a Gasoline wholesale and retail prices - Oil & Gas Journal, December 21, 1992, page 114.
b Methanol wholesale prices - Oxy-Fuel News, October 5, 1992, page 9.
Methanol retail prices - current California retail prices.
c Ethanol and LPG wholesale prices - Oxy-Fuel News, October 5, 1992, pp. 8-9.
LPG retail prices - current California retail prices
d Wholesale and retail prices - Industry estimates
e LNG wholesale prices - Industry estimates
f Hydrogen retail prices are based on quotes from industrial gas suppliers.
g natural gas and hydrogen are priced in dollars per 100 ft^3
h Therm = 100,000 Btu
I n/a = not currently available at retail outlets

8. Factors Influencing Large Scale Use of Alternative Fuels{tc "autonum Factors Influencing Large Scale Use of Alternative Fuels" \l 2}

The introduction of alternative fuels requires changes in distribution, marketing and end-use systems. Irrespective of the economics, inadequate supply of fuel or unreliable distribution systems could adversely affect consumer acceptance of alternative transportation fuels. Experience with the use of ethanol in Brazil and CNG in New Zealand and elsewhere suggests that the main factors influencing large-scale introduction of CNG and alcohol fuels are price competitiveness, availability and cost of feedstock (e.g., sugarcane for ethanol, or natural gas for CNG), fuel safety and quality standards, reliable system of distribution, and technical quality of vehicles (driveability, durability, safety). The Brazil experience with ethanol and the New Zealand experience with CNG clearly show that it is possible to develop a large market for alternative fuels within a reasonable time frame if the financial incentives are favorable and efforts are made to overcome uncertainty on part of industry and consumers. In both instances, substantial subsidies had to be offered to private motorists to persuade them to convert to alternative fuels.

8. IMPLEMENTING A CLEAN FUELS PROGRAM{tc "autonum IMPLEMENTING A CLEAN FUELS PROGRAM"}

Implementing a clean fuels program can take many forms - strict government mandates, fiscal incentives, or some combinations of both. In addition, mandates can focus on fuel quality directly, vehicle fuel requirements and even fuel pump nozzles. Some of the more common approaches are summarized below.

1. Mandating Fuel Quality

Perhaps the simplest and most direct approach is to mandate that by a date certain all fuel or some grades of fuel must meet certain characteristics. For example, all stations can be required to provide at least one grade of unleaded petrol by a certain date. Refinements of this approach can limit this mandate to only those stations pumping a certain volume of fuels, so called high volume stations. Another approach would require all regular grade fuel of a certain octane to be unleaded while allowing the premium grade to remain leaded.

In Bangkok, for example, by 1996 all gasoline sold must be unleaded.

2. Mandating Vehicle Fuel Requirements

Another approach requires that all new vehicles from a certain date are only allowed to use fuels meeting certain characteristics, e.g., unleaded petrol. This approach has been implemented in Singapore where all new cars are required to be able to operate ion unleaded petrol. This assures that any concerns about valve seat recession and soft valve seats will not be a concern with these vehicles.

3. Mandating Fuel Pump Nozzle Characteristics

As noted earlier, vehicles equipped with catalytic converters require unleaded petrol to assure that these systems are not poisoned. To assure that these vehicles aren’t deliberately or inadvertently fueled with leaded petrol, especially in those circumstances where unleaded petrol may be priced cheaper than leaded, cars equipped with catalysts can be required to be equipped with filler inlet restrictors which will not allow normal leaded fuel nozzles to fit. Unleaded fuel, on the other hand, can be required to use more narrow nozzles which will fit these small diameter inlets. This is certainly not a fail safe approach but is directionally a positive step.

4. Adopting Clean Fuel Tax Incentives

Rather than directly mandating the introduction of unleaded petrol or low sulfur diesel fuel or in some cases in addition to mandating some such fuel many governments have introduced tax policies which assure that the desired fuel will cost less in the retail market than the alternative with the result that public demand assures its availability and use. This can be used in the absence of any sales mandate - perhaps, Hong Kong provides the most successful example, or as a complement to a mandate to accelerate the market penetration of the clean fuel.

Experience has shown that fuel pricing should be a key element of any strategy to encourage clean fuels. For example, in the US during the 1970's and early 1980's, leaded gasoline was consistently less expensive than unleaded. As a result, in spite of fuel nozzle size restrictions and vehicle fuel filler inlet restrictions, many people poised their catalytic converters by using leaded fuel.

9. COMPREHENSIVE PROGRAMS CAN WORK - THE EXPERIENCE IN THE UNITED STATES{tc "autonum COMPREHENSIVE PROGRAMS CAN WORK - THE EXPERIENCE IN THE UNITED STATES"}

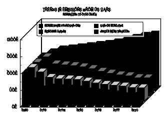
Since 1970, the United States has had an aggressive effort underway to reduce emissions from cars and improve air quality. This program has combined many elements including the introduction of leaded gasoline, tight standards for new vehicles, in-use vehicle inspection and maintenance efforts, and most recently the use of reformulated and low volatility gasoline. As a result, over the course of the past twenty five years, the emission rate for on-highway cars in the United States has declined dramatically. As newer vehicles equipped with advanced emissions controls have replaced older, higher polluting ones, there has been a clear downward trend in emissions of all three pollutants. This is especially encouraging in light of the continued rapid growth in vehicles and vehicle miles traveled by cars during this same period; in 1990 there were 50 million more cars on US highways than there were in 1970. Had emissions per mile not been reduced, passenger cars in 1990 would have emitted 65% more CO, HC and NOx than they did in 1970. In other words, as illustrated in Table 6, instead of passenger car CO having been reduced from 68 million metric tons to 27, these emissions would have climbed to 112 tons.

TABLE 6
EMISSIONS TRENDS IN THE US (1970 - 1990)
PASSENGER CARS (Tons Per Year)

	CARBON MONOXIDE	HYDROCARBONS	NITROGEN OXIDES
1970 ACTUAL	67.9	8.87	4.36
1990 ACTUAL	26.9	2.65	2.34
1990 POTENTIAL[53]	112.0	14.6	7.2

The Figure below illustrates the auto emissions reductions to date, 60% for CO, 70% for HC and 46% for NOX. Lead emissions from all highway vehicles have also been reduced dramatically; between 1970 and 1993, highway vehicle lead emissions declined from 171,960 short tons to 1,380.

[53] What would have occurred had pollution controls not been put on cars over this period.



The point of this example is to show that adoption of a strong motor vehicle pollution control program can be effective.

Cleaner Transportation Fuels Draft Final Report

Michael P. Walsh January 25, 1996

10. CONCLUSIONS AND RECOMMENDATIONS{tc "autonum CONCLUSIONS AND RECOMMENDATIONS"}

1. Current air quality levels in the many major Asian cities already reflect serious pollution. Because the vehicle populations in most of these cities continue to grow, frequently at annual rates in excess of 10 percent per year, one could expect even more serious pollution problems in the future unless aggressive control efforts are undertaken.

2. Substantial efforts have been and continue to be underway throughout many Asian countries to address their motor vehicle pollution problems. Several conclusions can be drawn from these efforts:

   Several comprehensive motor vehicle pollution control programs have been developed in the region.
   A wide variety of strategies are being implemented, tailored to the particular problems and capabilities in a particular country or city - one size does not fit all.
   In virtually every serious effort to reduce motor vehicle pollution, cleaner fuels - especially unleaded gasoline and lower sulfur diesel fuel - play a critical role.

3. A growing body of data on the adverse health effects of lead, especially in young children, indicates there may be no “safe” level. Reduced lead in gasoline has been shown to reduce the risk of behavioral problems, lowered IQ s and decreased ability to concentrate in exposed children.

4. Lead scavengers which accompany leaded gasoline have also been identified as human carcinogens; the elimination of lead in gasoline will therefore also reduce this cancer risk.

5. Studies in both Europe and the United States show that gasoline lead is responsible for about 90 percent of airborne lead and that 1 microgram per cubic meter of ambient lead will cause a 1-2 microgram per milliliter increase in blood lead levels. This is in addition to the lead burden which may be associated with food, drinking water and other sources.; this burden can be highly variable from country to country.

6. The availability of lead free gasoline can facilitate extensive reductions in the other major pollutants from motor vehicles, hydrocarbons, carbon monoxide and nitrogen oxides by allowing the use of catalytic converters.

7. Motor vehicle emissions of hydrocarbons, carbon monoxide and nitrogen oxides cause or contribute to a wide range of adverse impacts on public health and general well being including increased angina attacks in individuals suffering from angina pectoris, greater susceptibility to respiratory infection, more respiratory problems in school children, increased airway resistance in asthmatics, eye irritation, impaired crop growth, dead lakes and forest destruction.

8. The combination of lead free gasoline and catalysts can also facilitate very substantial reductions in other harmful pollutants such as aldehydes and polynuclear aromatic hydrocarbons (PAH s).

9. These emissions reductions can occur simultaneously with equally significant improvements in fuel economy and reductions in vehicle maintenance. Also, based on studies in Canada, reduced maintenance can save about 2.4 cents per liter with the use of unleaded gasoline compared to leaded gasoline.

10. The most direct strategy for eliminating lead in gasoline is to ban its use; several countries have adopted this strategy. In Asia, Thailand has been an aggressive proponent of this approach.

11. Tax policies which price unleaded fuel substantially below leaded fuel have also been found to be very effective in stimulating the sales of unleaded fuel. Hong Kong and Singapore stand out as Asian examples.

12. Countries concerned about the available supply of unleaded petrol may wish to maintain a higher price for unleaded compared to leaded but this strategy tends to increase the risk of poisoning of any catalyst equipped vehicles in the country and prolongs the use of lead with its concomitant health risks.

13. Beyond unleaded gasoline, hydrocarbons, CO and toxic emissions can be reduced from 10 to 30% through the reformulation of gasoline by modifying parameters such as volatility, oxygenates, sulfur levels and hydrocarbon mix. Care must be taken to assure that these modifications don't increase NOX emissions.

14. The use of oxygenates such as MTBE in cold temperature environments, while clearly bringing about significant reductions of CO, has raised concerns regarding adverse health effects in certain susceptible individuals. Studies to date by both the US EPA and several states have failed to identify a serious problem but additional studies are ongoing.

15. There is a clear worldwide trend toward lower and lower levels of sulfur in diesel fuel. At a minimum, this reduces the particulate emissions from diesel vehicles; recent European studies indicate that for every 100 PPM reduction in sulfur, there will be a .16% reduction in particulate from light duty vehicles and a 0.87% reduction from heavy duty vehicles.

16. Other diesel fuel properties such as volatility, aromatic content and additives can also have positive or negative effects on diesel vehicle emissions.

17. In addition to the adoption of mandatory limits, it has been shown that tax policies can be very effective in encouraging the introduction and use of low polluting diesel fuels.

18. Alternative fuels including methanol (made from natural gas, coal or biomass) ethanol (made from grain), vegetable oils, compressed natural gas (CNG) mainly composed of methane, liquefied petroleum gas (LPG) composed of propane, butane, electricity, hydrogen, synthetic liquid fuels derived from hydrogenation of coal, and various fuel blends such as gasohol, have drawn increasing attention during the last decade. The motives for this substitution include conservation of oil products and energy security, as well as the reduction or elimination of pollutant emissions.

19. Some alternative fuels such as natural gas do offer the potential for large, cost-effective reductions in pollutant emissions in specific cases. Care is necessary in evaluating the air-quality claims for alternative fuels, however - in many cases, the same or even greater emission reduction could be obtained with a conventional fuel, through the use of a more advanced emission control system. Which approach is the more cost-effective will depend on the relative costs of the conventional and the alternative fuel.

11. APPENDIX A: ADVERSE EFFECTS FROM VEHICLE RELATED POLLUTION{tc "autonum APPENDIX A: ADVERSE EFFECTS FROM VEHICLE RELATED POLLUTION"}

Cars, trucks, motorcycles, scooters and buses emit significant quantities of carbon monoxide, hydrocarbons, nitrogen oxides and fine particles. Where leaded gasoline is used, it is also a significant source of lead in urban air. As a result of these emissions many major cities around the world are severely polluted. This section will review some of the consequences of these pollutants.

1. Lead{tc "autonum Lead" \l 2}

There has been an explosion of knowledge during the last two decades with regard to the adverse health impact of long term exposures to low levels of ambient lead.[54] In response to this growing body of data, most industrialized countries and several developing countries have introduced unleaded gasoline and several have or will soon prohibit the use of leaded gasoline entirely.

The toxic properties of lead at high concentrations have been known since ancient times as lead has been mined and smelted for more than 40 centuries. Precautions in its use have been widespread for centuries but it has only been recently that its adverse impacts at very low levels have been fully appreciated. The seminal work in this area is the 1979 report by Dr. Herbert Needleman and his colleagues which showed that children with high levels of lead accumulated in their baby teeth experienced more behavioral problems, lower IQ s and decreased ability to concentrate.[55] More recent evidence indicates that it is not only the length and severity of exposure to lead which results in the health damage but the age at which exposure occurs. This is especially important because “Of all the persons in the community, the newborn child is the most prone to injury from overexposure to lead for several reasons, and the damage that may be caused then will have the greatest long-term social and economic consequences.”[56]

Another series of health studies in the UK confirmed these findings. [57] They add further evidence that lead contributes to behavioral problems, lower IQ s and decreased ability to concentrate. Even after taking up to 15 social factors into account, a 3 IQ number deficit was consistently found. While not necessarily statistically significant in any individual study (which is largely influenced by the size of the sample among other factors), the body of data consistently shows the effects.

In addition, the studies of Dr. Winneke in Germany offer further evidence that “neuropsychological effects are causally related to very low blood lead levels.”[58] The effects are not necessarily the dominant ones in any particular instance but they are real, a matter of concern and preventable.

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[54]“Lead Exposure And Human Health: Recent Data On An Ancient Problem”, Needleman, Technology Review, March/April 1980
“Air Quality Criteria For Lead”, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., December 1977

[55] “Deficits In Psychological And Classroom Performance Of Children With Elevated Dentine Lead Levels”, Needleman, et al, The New England Journal Of Medicine, Vol. 300, Number 13, March 29, 1979.

[56] “Exposure to Lead In Childhood: The Persisting Effects”, Moore, Nature Vol. 283, 24 January 1980

[57]“The Relationship Between Blood Lead Concentrations, Intelligence and Attainment in a School Population: a Pilot Study”, Yule, Lansdown, Millar and Urbanowicz, Devel., Med. Child. Neurol. 1981, 23, 567-576.

[58] Comments at Conference, Lead In Petrol, Winneke, May 1983

Several comprehensive studies of the health issue have been conducted and their major conclusions are summarized below:

1. In 1980, the US National Academy of Sciences completed an extensive study of “Lead in The Human Environment.”[59] A major finding of this study is “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.” The Academy then recommended that “A serious effort should be made to reduce the baseline level of exposure to lead for the general population of the United States.”

2. In August of 1982, as part of its review of the existing lead program, the U.S. Environmental Protection Agency (EPA) reanalyzed the issue and summarized the results in this way: “ The majority of the comments emphatically rejected the proposition that lead was no longer a public health problem. Sixty-four comments were received from the professional health community and academia. Sixty of these opposed any loosening of the lead standard, and many suggested that tighter controls would be desirable. Thirty-two comments were received from local and state governments. All of these supported retention of the current standard to protect the citizen s health. Most of the commenters pointed to previous studies, as well as their own experiences, to demonstrate that lead has an adverse effect on people at very low dosages, and that the more the problem is studied the lower the “acceptable level” of lead becomes. They concluded that protection of public health and welfare demands that all reasonable steps be taken to eliminate lead from the environment.”[60] In October of 1982, EPA decided as a result of this review to reduce the amount of lead in gasoline even further.

3. In April of 1983, The U.S. Court of Appeals completed it's review of the EPA decision to lower the gasoline lead levels.[61] In its opinion the Court noted, “there is compelling evidence that gasoline lead is a major cause of lead poisoning in young children.” In making this assessment, the Court found that “recent studies suggest that the recognized danger point of 30 micrograms per deciliter is too high and that lead reduces intelligence at blood lead levels as low as 10 - 15 micrograms per deciliter ... Other studies have correlated blood lead levels of 10 - 15 micrograms per deciliter with altered brain activity." The Court concluded that "the demonstrated connection between gasoline lead and blood lead, the demonstrated health effects of blood lead levels of 30 micrograms per deciliter or above, and the significant risk of adverse health effects from blood lead levels as low as 10 - 15 micrograms per deciliter, would justify EPA in banning lead from gasoline entirely."

4. Finally, also in April of 1983, in the Untied Kingdom, the Royal Commission on Environmental Pollution concluded that “the safety margin between the blood lead concentrations in the general population and those at which adverse effects have been proven is too small... it would be prudent to take steps to increase the safety margin of the population as a whole.” They continued, “that measures should be taken to reduce the anthropogenic dispersal of lead wherever possible...”[62]

Based on the growing body of data showing adverse effects from lead, in 1985 the US EPA reduced the maximum allowable lead content in leaded gasoline to 0.1 grams per gallon. As part of that rulemaking, EPA uncovered evidence linking lead in the blood and high blood pressure.[63]

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[59] “Lead In The Human Environment”, National Academy of Sciences, Washington, D.C., 1980

[60] Federal Register, Vol 47, No. 167, Friday, August 27, 1982

[61] United States Court of Appeals, No. 82-2282, Small Refiner Lead Phase-Down Task Force, et. al. v. U.S. EPA, April 22, 1983

[62] “Lead In The Environment”, Ninth Report, Royal Commission on Environmental Pollution, April 1983

[63] Schwartz, J., H. Pitcher, R. Levin, B. Ostro, and A.L. Nichols. 1985. Costs and Benefits of Reducing Lead in Gasoline: Final Regulatory Impact Analysis, Report No. EPA-230-05-85-006, U.S. EPA, Washington, D.C.

A subsequent study, in which 249 children were monitored from birth to two years of age, 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.[64]

Most recently, British researchers reviewed every epidemiologic study on lead and IQ published since 1979 that had over 100 children and measured IQ as a function of blood or tooth lead levels. Based on a meta-analysis of all the data, they concluded that a doubling of body lead burden from 10 to 20 g/dl in blood levels was associated with a mean fall of about 1 to 2 IQ points.[65]

In summary, the available evidence indicates that "there is no known physiological function served by lead in mammalian metabolism. As far as cells are concerned, each molecule of lead has the potential to disrupt the chemical basis of normal cellular function. For nerve cells, this interference is particularly destructive because communications between cells in the brain depends upon precisely controlled movements of such molecules such as calcium, sodium, potassium and chloride. Lead can interfere, on a molecule by molecule basis, with these essential elements."[66]

2. Lead Scavengers{tc "autonum Lead Scavengers" \l 2}

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

Ultimately, a significant portion of these additives are emitted from vehicles. This is important because, unfortunately, these lead scavengers, most notably ethylene dibromide, have been found to be carcinogenic in animals and have been identified as potential human carcinogens by the National Cancer Institute.[67] Therefore, their removal along with the removal of lead may result in significant benefits to health.

3. Carbon Monoxide (CO){tc "autonum Carbon Monoxide (CO)" \l 2}

Carbon monoxide -- an odorless, invisible gas created when fuels containing carbon are burned incompletely -- poses a serious threat to human health. Persons afflicted with heart disease and fetuses are especially at risk. 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 amount of oxygen. Numerous studies in humans and animals have demonstrated that those individuals with weak hearts are placed under additional strain by the presence of excess CO in the blood. In particular, clinical health studies have shown a decrease in time to onset of angina pain in those individuals suffering from angina pectoris and exposed to elevated levels of ambient CO.[68]

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[64] Needleman, 1989.

[65] Pocock S.J., et al, "Environmental Lead and Children's Intelligence: A Systematic Review of the Epidemiological Evidence", BMJ 1994, November 5; 309: 1189-97.

[66] "Lead Poisoning", Dr. Ellen Silbergeld, Toxic Substance Control Newsletter, Autumn 1982

[67] "Automotive Emissions of Ethylene Dibromide", Sigsby, et al, Society of Automotive Engineers, #820786

[68] "Effect of Carbon Monoxide On Exercise Performance In Chronic Obstructive pulmonary Disease", Aronow, et. al., Am. J. Med., 1977, "Health Effects of Exposure To Low Levels of Regulated Air Pollutants, A Critical Review", Ferris, Journal of The Air Pollution Control Association, May 1978

4. Nitrogen Oxides (NOX){tc "autonum Nitrogen Oxides (NOX)" \l 2}

As a class of compounds, the oxides of nitrogen are involved in a host of environmental concerns impacting adversely on human health and welfare. Nitrogen dioxide (NO_2) has been linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function.[69] It has been shown that even short term exposures to NO_2 have resulted in a wide ranging group of respiratory problems in school children - cough, runny nose and sore throat are among the most common.[70] Further, in France, in an ingenious experiment, Dr. Orehek has shown that asthmatics are especially sensitive to even one hour exposures.[71] A small group of asthmatics were initially exposed to carbachol, a bronchoconstrictor representative of urban pollen, and then to NO_2; adverse effects such as increased airway resistance were experienced by some of the individuals at levels as low as 0.1 parts per million for 1 hour.

The oxides of nitrogen also participate in the formation of the family of compounds known as photochemical oxidants and in acid deposition. Finally, as a result of secondary transformations in the atmosphere, NOX emissions are converted to nitrates thereby increasing the accumulation of particulate in the air.[72]

5. Photochemical Oxidants (Ozone){tc "autonum Photochemical Oxidants (Ozone)" \l 2}

The most widespread air pollution problem in areas with temperate climates is ozone, one of the photochemical oxidants which results from the reaction of nitrogen oxides and hydrocarbons in the presence of sunlight. Motor vehicles are a major source of both of these precursor pollutants. Ozone causes eye irritation, cough and chest discomfort, headache, upper respiratory illness, increased asthma attacks and reduced pulmonary function.[73]

It has also been demonstrated in numerous studies that photochemical pollutants seriously impair the growth of certain crops. For example, the Congressional Research Service of the U.S. Library of Congress found that “the short-run or immediate impacts of ozone are evident in annual crop yield decreases estimated at \$1.9 to \$4.3 billion.”[74]

6. Particulate (PM){tc "autonum Particulate (PM)" \l 2}

A series of studies released in the last few years indicate that particulate may be the most serious urban air pollution problem. By correlating daily weather, air pollutants and mortality in six US cities, scientists have discovered that non accidental death rates tend to rise and fall in near lockstep with daily levels of particulates -- but not with other

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69 “Air Quality Criteria For Nitrogen Oxides”, Draft, U.S. Environmental Protection Agency, June 1980, “Health Effects of Exposure To Low Levels of Regulated Air Pollutants, A Critical Review”, Ferris, Journal of The Air Pollution Control Association, May 1978

70 “The University Of Akron Study on Air Pollution and Human Health Effects”, Mostardi et al, Archives of Environmental Health, September/October 1981.

71 “Effect of Short-Term, Low-Level Nitrogen Dioxide Exposure on Bronchial Sensitivity of Asthmatic Patients”, Orehek, et. al., The Journal of Clinical Investigations, Volume 57, February 1976.

72 Atmospheric nitrate is essentially secondary, formed from reactions involving oxides of nitrogen to form nitric acid.

73 “Air Quality Criteria For Ozone And Other Photochemical Oxidants”, U.S. Environmental Protection Agency, April 1978.

74 “Air Pollution Impacts On Agriculture And Forestry”, Biniek, Congressional Research Service, Library of Congress, May 1982

pollutants.[75] 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 suggested to the researchers that as many as 60,000 US residents per year may die from breathing particulates at or below legally allowed levels.[76]

More recently, another study has emerged showing a strong linkage between particulate air pollution and mortality.[77] The study is distinctive in that it used a prospective cohort design that allowed for direct control of other individual risk factors such as cigarette smoking, diet, etc. In addition, the study was larger and represented a larger geographic area than any other study to date.

Air pollution data from 151 US metropolitan areas were linked with individual risk factors in 552,138 adults who resided in these areas when they were enrolled in this study in 1982. Deaths were ascertained through 1989. Sulfates and fine particulate air pollution were associated with a difference of approximately 15 to 17% between mortality risks in the most polluted cities and in the least polluted cities. Even in cities that meet the US Federal clean air standards, the risk of death is 2 to 8 percent higher than in the cleanest cities.

Certain particles appear to be especially hazardous. For example, diesel particles, because of their chemical composition and extremely small size, have raised special health and environmental concerns. 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. Much 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.

A comprehensive assessment of the available health information on diesel particulate was carried out by the International Agency For Research on Cancer (IARC) in June 1988 and concluded that diesel particulate is probably carcinogenic to humans.[78]

Studies conducted at the Fraunhofer Institute 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, recently verified this conclusion. These "results, and recent findings from other laboratories, suggest that (1) the small respirable soot particles in diesel exhaust are primarily responsible for lung cancer developing in rats exposed to high concentrations of diesel emissions, and (2) at high particle concentrations, the mutagenic compounds adsorbed onto the soot play a lesser role, if any, in tumor development in this species."[79] This is quite significant as it indicates that it is important to control the particles themselves and not just the organic material sitting on the surface of the carbon.

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[75]"An Association Between Air Pollution And Mortality In Six U.S. Cities", Dockery, et. al., The New England Journal of Medicine, December 9, 1993.

[76] "Air Pollution and Daily Mortality in Philadelphia", Dr. Joel Schwartz, presented at the 1991 meeting of the American Lung Association, Anaheim, CA, May 1991.

[77] Pope at al, 1995.

[78] The term `carcinogen' is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors.

[79] "Pulmonary Toxicity of Inhaled Diesel Exhaust and Carbon Black in Chronically Exposed Rats", Mauderly, et al, Health Effects Institute Research Report Number 68, October 1994.

In a subsequent analysis, the HEI raised questions about this conclusion.[80] The authors argue that because the rats were exposed to very high concentrations over their full lifetimes, the observed effects are more likely the result of the impairment of the rat's ability to clear particles from its lungs, leading to inflammation and rapid cell proliferation. They note that similar effects did not occur in hamsters and results were mixed with mice.

While further studies are carried out to determine which element in diesel particles is most hazardous, the prudent course of action seems to be to reduce both the organics and the particulate mass.

To put the concerns with diesel NOX and particulate into perspective, one recent study attempted to quantify the health benefits associated with reducing diesel particulate and nitrogen oxides.[81] Based on a careful review of the available health information, the authors concluded that reducing one gram per mile of particulate or NOX, over a 100,000 mile vehicle lifetime would produce benefits of $11,432 and $ 1175, respectively. Focusing specifically on the 1992 heavy duty vehicle fleet in Los Angeles, the authors conclude that a 50% reduction in NOX and PM-10 emissions, would be worth $9,200 and $13,500 per vehicle, respectively. A 90% reduction would have a value of $16,600 and $24,300 per vehicle respectively. It is important to emphasize that these amounts reflect the value of the health benefits alone. Earlier studies have indicated that the economic benefits of reduced soiling and improved visibility are also quite significant.

1. **Physics And Chemistry of Particulate**[82]{tc "autonum Physics And Chemistry of Particulate Excerpted from US EPA Draft PM Criteria Document, April 1995. " \l 3}

Atmospheric particles originate from a variety of sources and possess a range of morphological, chemical, physical, and thermodynamic properties. Examples include combustion-generated particles such as diesel soot or fly ash, photochemically produced particles such as those found in urban haze, salt particles formed from sea spray, and soil-like particles from resuspended dust. Some particles are liquid, some are solid; others contain a solid core surrounded by liquid. Atmospheric particles contain inorganic ions and elements, elemental carbon, organic compounds, and crustal compounds. Some atmospheric particles are hygroscopic and contain particle-bound water. The organic fraction is especially complex. Hundreds of organic compounds have been identified in atmospheric aerosols, including alkanes, alkanoic and carboxylic acids, polycyclic aromatic hydrocarbons, and nitrated organic compounds.

Particle diameters span more than four orders of magnitude, from a few nanometers to one hundred micrometers. Combustion-generated particles, such as those from power

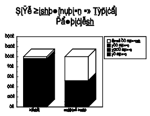
[80]HEI, 1995

[81]"On The Costs of Air Pollution From Motor Vehicles", Small, A. and Kazimi, C. , Department of Economics, UC Irvine, forthcoming in The Journal of Transport Economics, January 1995.

[82]Excerpted from US EPA Draft PM Criteria Document, April 1995.

generation, from automobiles, and in tobacco smoke, can be as small as 0.01 μm and as large as 1 μm. Particles produced in the atmosphere by photochemical processes range in diameter from 0.05 to 2 μm. Fly ash produced by coal combustion ranges from 0.1 to 50 μm or more. Wind-blown dust, pollens, plant fragments, and cement dusts are generally above 2 μm in diameter.

Recent measurements of the size distributions of primary particles confirm U.S. Environmental Protection Agency conclusions that most fugitive dust emissions are in particles larger than 2.5 m and that the majority of emissions from combustion sources are in sizes smaller than 2.5 m. As illustrated below diesel truck emissions are almost all less than 1.0 m in size; particles in this size range are especially hazardous because when breathed in, they are able to penetrate to the deepest part of the lung where the critical gas exchange takes place.



2. Sources of Suspended Particles{tc "□autonum□ Sources of Suspended Particles" \l 3}

The ambient atmosphere contains both primary and secondary particles; the former are emitted directly by sources, and the latter are formed from gases (SO_2, NOX, NH_3, VOCs). Fugitive dust is a primary pollutant. Major sources of particle emissions are classified as major point sources, mobile sources, and area sources; these are anthropogenic. Natural sources also contribute to ambient concentrations.

Fugitive dust is a major contribution to PM_{10} at nearly all sampling sites, although the average fugitive dust source contribution is highly variable among sampling sites within the same areas, and is highly variable between seasons.

Primary motor vehicle exhaust in the US makes up as much as 40% of average PM_{10} at many sampling sites. Vegetative burning outdoor and residential wood burning are significant sources in residential areas. Fugitive dust from paved and unpaved roads, agricultural operations, construction, and soil erosion constitute ~90% of nationwide primary emissions in most countries. Fugitive dust consists of geological material that is suspended into the atmosphere by natural wind and by anthropogenic activities from sources such as paved and unpaved roads, construction and demolition of buildings and roads, storage piles, wind erosion, and agricultural tilling.

Mobile sources are major emitters of primary particles, oxides of nitrogen, and volatile organic compounds. They are also minor emitters of sulfur dioxide and ammonia. On-road motor vehicles using gasoline-and diesel-fueled engines are by far the largest component of mobile source emissions in most countries, and the emissions estimation methods are most highly developed for these vehicles. Motor vehicle exhaust contains high concentrations of organic and elemental carbon, but their ratios are much different from those found in wood combustion with the abundance of elemental carbon being nearly equal to the organic carbon abundance.

7. Other Toxics {tc "□autonum□ Other Toxics " \l 2}

The 1990 Clean Air Act (CAA) directed the US EPA to complete a study of emissions of toxic air pollutants associated with motor vehicles and motor vehicle fuels. The study found that in 1990, the aggregate risk is 720 cancer cases in the US. For all years, 1,3-butadiene is responsible for the majority of the cancer incidence, ranging from 58 to 72 percent of the total motor vehicle toxics risk. This is due to the high unit risk of 1,3-butadiene. Gasoline and diesel particulate matter, which are considered to represent motor vehicle polycyclic organic matter (POM), are roughly equal contributors to the risk. The combined risk from gasoline and diesel particulate matter ranges from 16 to 28 percent of the total, depending on the year examined. Benzene is responsible for roughly 10 percent of the total for all years. The aldehydes, predominately formaldehyde, are responsible for roughly 4 percent of the total for all years.

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 are responsible for almost 60% of the air pollution related cancer cases in the US per year.

12. APPENDIX B: GASOLINE FUELED VEHICLE CONTROLS{tc "autonum APPENDIX B

Great progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the gasoline fueled vehicle emissions which cause or contribute to many of the above adverse effects. However, in order to utilize the best of these technologies, the catalytic converter, it is necessary to fuel vehicles exclusively on unleaded gasoline since lead tends to "poison" existing converter systems. The following section reviews the technologies available for reducing gasoline vehicle emissions and the important role that catalysts have come to play.

Before emission controls were mandated, fumes from the engine crankcase were vented directly into the atmosphere. Crankcase emission controls involved closing the crankcase vent port, and were introduced on new automobiles in the early 1960s. Control of these emissions is no longer considered a significant technical issue.

Evaporative emissions of hydrocarbons result from distillation of fuel in the carburetor float bowl and evaporation of fuel in the gas tank. The control of these emissions generally requires feeding the HC vapors back into the engine to be burned along with the rest of the 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 control problem is the one related to vehicle exhaust emissions. Fortunately, much progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the exhaust pollutants. These involve the physics of combustion, changes in engine design, and exhaust treatment devices.

1. Combustion and Emissions{tc "autonum Combustion and Emissions" \l 2}

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 so are the concentrations of nitrogen oxides in the exhaust.

Carbon monoxide also 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 unit of fuel, the lower the carbon monoxide emission rate.

Finally, <u>lead compounds</u> (and their associated scavengers) are exhausted by an automobile almost directly in proportion to the amount of fuel used by a vehicle and the concentration of lead in it.

2. **Engine Design Parameters**{tc "autonum Engine Design Parameters" \l 2}

Certain engine design parameters are capable of inducing significant changes in emissions. Most notable among these are air/fuel ratio and mixture preparation, ignition timing, and combustion chamber design and compression ratio.

1. **Air/Fuel Ratio and Mixture Preparation**{tc "autonum Air/Fuel Ratio and Mixture Preparation" \l 3}

The air/fuel ratio has a significant 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 with increasing air/fuel ratio, 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.

2. **Ignition Timing**{tc "autonum Ignition Timing" \l 3}

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 allowing 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 are reduced.

3. **Compression Ratio and Combustion Chambers**{tc "autonum Compression R

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 chambers 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 influence 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.

3. Emission Control Technologies{tc "autonum Emission Control Technologies" \l 2}

Tighter emission standards have required more specific attention to the treatment of vehicle exhaust emissions. Commonly used technologies to control exhaust emissions include recirculation of exhaust gases, electronic control of engine performance, exhaust after-treatment devices, and advanced combustion techniques.

With the current state of the art, engine modification alone cannot reduce emissions to the same extent as with a three-way catalyst. Compared to a carburetted engine, an electronically controlled engine equipped with a 3-way catalyst can reduce CO emissions from a mean rate of 7.5 g per km to 1.5 g per km; HC emissions from 1.5 g per km to 0.25 g per km; and NOx from 2.0 g per km to 0.25 g per km. Electronic fuel injection and ignition systems (EFI) without a catalytic converter are effective in reducing CO and HC emissions but have only a minor effect on NOx emissions.[83]

1. Exhaust Gas Recirculation (EGR){tc "autonum Exhaust Gas Recirculation (EGR)" \l 3}

Recirculating a portion of the exhaust gas back into the incoming air/fuel mixture is frequently used as a technique for lowering NOx. The dilution of the incoming charge reduces peak cycle temperature by slowing flame speed and absorbing some heat of combustion.

Charge dilution of homogeneous-charge engines by excess air and/or by exhaust gas recirculation (EGR) has been used for many years. The use of excess air alone results in relatively small NOx reductions, in the order of 35-40%. When EGR is incorporated, substantially higher NOx reductions have been demonstrated. Excessive dilution, however, can result in increased HC emissions, driveability problems or fuel economy losses.

Fuel consumption can be modified 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.

[83]ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

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.

2. Electronics {tc "autonum Electronics " \l 3}

With so many interrelated engine design and operating variables playing an increasingly important role in the modern engine, the control system has become increasingly important. Modifications in spark timing must be closely coordinated with air/fuel ratio changes and amount 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 more selective depending on engine load or speed have been found beneficial in preventing adverse impacts.

To meet these requirements, electronics have begun to replace more traditional mechanical controls. The conventional combination of carburettor and distributed ignition systems can now be replaced by electronic fuel injection (EFI) and ignition to provide more precise control.[84] Furthermore, electronic control of ignition timing has been shown to optimize timing under all engine conditions and has the added advantage of reduced maintenance and improved durability compared with mechanical systems. When both ignition timing and EGR are electronically controlled, it has been demonstrated that NOx emissions can be reduced with no fuel economy penalty and in some cases with an improvement.

3. Exhaust After-Treatment Devices{tc "autonum Exhaust After-Treatment Devices" \l 3}

The use of catalytic converters and thermal reactors, generically known as exhaust after-treatment devices, becomes necessary in order to achieve a quantum reduction in exhaust emissions, beyond those feasible with engine design modifications. The catalyst comprises a ceramic support, a washcoat (usually aluminum oxide) to provide a very large surface area, and a surface layer of precious metals (platinum, rhodium, and palladium are most commonly used) to perform the catalytic function. The catalyst is housed in a metal container forming part of the vehicle exhaust system. For effective operation, the catalyst temperature must exceed the light-off value (about 300 C), which takes one to three minutes to achieve in typical urban driving conditions.[85] The cost of a catalytic converter and its accompanying equipment ranges from US$250 to US$750 per automobile (1981 prices) equivalent to a 4 - 20% increase in the cost of the vehicle.[86] Small inexpensive vehicles bear the brunt of the cost increase in relative terms. These devices can reduce HC emissions by an average of 87%, CO by 85% and NOx by 62% over the life of a vehicle.[87]

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 to carbon dioxide and water vapor. Starting with the 1975 model year automobile, catalysts have been placed on upwards of 80% of all new cars sold in the United States. In 1981, they

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[84]ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

[85]ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

[86]OECD [1988a]. Transport and Environment, Paris.

[87]French, H.F. [1990]. "You are what you breathe." World Watch, Vol. 3, No. 3, Washington, D.C.

were placed on 100% 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.

Three-way Catalysts: So called because of their ability to lower HC, CO and NOx levels simultaneously, they were first introduced in the United States in 1977 by Volvo and subsequently became widely used when the U.S. NOx standard was made more stringent (1.0 grams per mile) in 1981. For three-way catalysts 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, throttle body fuel injection, and 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.

Thermal Reactors: They are well insulated vessels with internal baffling to allow several passes of the exhaust gas to maintain high temperature and extend the residence time. They thus promote oxidation of CO and HC emitted from the engine. To maintain 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.

4. **Lean Burn**{tc "autonum Lean Burn" \l 3}

At one point, it was believed that combustion advances, especially lean burn, might ultimately allow the catalyst to be eliminated. Recent experience, however, indicates that low HC and NOx levels are not attainable across the range of normal driving conditions through the use of advanced combustion technology alone. At least an oxidation catalyst is needed to control HC emissions. Also, under higher speeds and 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 also equipped with catalytic converters.

4. **Emission Control and Energy Conservation** {tc "autonum Emission Control and Energy Conservation " \l 2}

Many technologies which exist today and which could be placed on automobiles to improve fuel economy -- e.g., advanced air/fuel management systems such as fuel injection, electronic controls of spark timing, advanced choke systems, improved transmissions -- can also result in significant exhaust emissions benefits. In fact, some of the advances in fuel efficient vehicle power plants were made as a direct result of increasingly tighter emission control requirements. Furthermore, it is likely that in the absence of tight emission requirements these advanced technologies would not have been placed on automobiles. In many cases, once these technologies have been introduced, fuel economy has been even better than when emission requirements were less stringent.

Lead has been added to gasoline as it is an inexpensive way to increase octane values for improved vehicle fuel efficiency. In fact, a halt to the addition of lead to gasoline does entail a small (less than 1% in the United States) fuel penalty at the refinery. However, the greatest potential impact and the one that has generated the most serious debate is the impact on vehicle fuel efficiency - does it improve or deteriorate?

Attainment of the emission standards through 1987 in the United States has been accompanied by improvements in fuel economy, from a sales weighted fleet average of 14.9 miles per gallon (mpg) in 1967 to 27.3 mpg in 1987, an increase of 83%. Correcting for vehicle weight reductions, the improvements compared to pre-controlled cars are still about 47%. The introduction of unleaded fuel and catalytic converters in 1975 coincided with very substantial fuel economy gains. At a minimum, this demonstrates that tight emission standards are quite compatible with substantial fuel economy gains because unleaded gasoline provides design freedom to automotive engineers.

As vehicle technology is pushed harder and harder to achieve low pollution levels, whether it be in Europe, North America or the Pacific Rim, common elements are emerging. First, in every case, the least polluting vehicles is equipped with catalytic converters. As these systems are poisoned by lead and by phosphorous in most engine oils, they inevitably foster the introduction of unleaded gasoline and cleaner engine oils, with the result that overall lead pollution is also reduced. Further, to optimize the effectiveness of these systems, better air/fuel and spark management systems have evolved leading to a much greater use of both electronics and fuel injection. These advances, in turn, increase the prospects of better fuel efficiency and lower CO_2 emissions.

5. Cost of Exhaust Emission Controls{tc "autonum Cost of Exhaust Emission Controls" \l 2}

Implementing tighter emission control standards has three cost implications:

the increased cost of the vehicle, including the cost of additional or more advanced components;

the increased or reduced cost of vehicle maintenance; and

the cost of additional or less fuel if emission control measures impact on fuel consumption (either up or down).

Estimated increase in the cost of vehicles and changes in fuel consumption for various low-emission engine and exhaust treatment configurations are given below.[88]

The costs to consumers of various emission control technologies

Technologies	Price increase (%)	Fuel Consumption increase (%)
Lean burn engine with carburetor and conventional ignition	1.0	-2
Pulsair and EGR	4.5	+3

[88]ECMT [1990]. Transport Policy and the Environment. European Conference of Ministers of Transport. OECD, Paris.

Lean burn engine with carburetor and programmed ignition	2.0	+1
Recalibrated conventional engine with EFI	8.0	+2
Lean burn engine and EFI	9.0	-7
Lean burn engine oxidation catalyst	4.5	-3
Open loop 3-way catalyst carburettor	4.1	+2
Lean burn engine - closed loop - EFI variable intake system-oxidation catalyst	15.0	-7
Closed loop - EFI - 3-way catalyst	13.0	+3

Baseline = small vehicle, 1.4 litre conventional carburettor engine meeting ECE 15/04 standard.

In the United States, a cost model was developed by U.S. EPA to arrive at estimates of the initial cost paid by consumers to comply with the U.S. emission standards. The cost estimates were based on an analysis of the retail price equivalent of each component in the emission control systems used in gasoline-fuelled vehicles. The list of emission control components on each car was obtained from the Application for Certification submitted to the U.S. EPA by automobile manufacturers. Prices and price estimates were obtained from three sources: a study conducted for U.S. EPA, a price survey of dealer parts departments, and direct request to the manufacturers for parts price information. Based on the above, new automobile price increases as a function of increasingly tighter U.S. emissions standards were estimated and are summarized below. All emissions standards have been converted to the U.S. 1975 test procedure (CV5-75) along with the U.S. compliance programme.

Progression of U.S. emission standards for automobiles (in grams per mile)[89]

Model Year	HC/CO/NOx	Initial cost increase (in 1981 US$)
1968-69	5.9/50.8/N.R.[a]	30
1970-71	3.9/33.3/N.R.	50
1972	3.0/28.8/N.R.	70
1973-74	3.0/28.0/3.1	100
1975-76	1.5/15.0/3.1	150
1977-79	1.5/15.0/2.0	175
1980	0.41/7.0/2.0	225
1981	0.41/3.4/1.0	350
1990 (proposed	0.25/3.4/0.4 (by 1995/96)	n.a.
legislation)	0.125/3.4/0.2 (by 2003)	n.a.

89 OECD [1988a]. Transport and Environment, Paris.
USEPA [1988]. Mobile Source Emission Standards Summary. Office of Air and Radiation, United States Environment Protection Agency, Washington, D.C.

[a] N. R. = not required.
n. a. = not available.

An international workgroup has been formed under the auspices of the Convention on Long Range Transboundary Air Pollution to discuss methods for researching VOC emissions and control strategies. As part of the development of a UN ECE protocol to deal with these emissions, a technical annex dealing with mobile sources was drafted at a meeting in Switzerland on April 6, 1990. A major conclusion is that closed loop three way catalyst technology is cleaner and more efficient than either engine modifications or lean settings with open loop catalysts.

Technology Option	Emission Level	Cost	Fuel Consumption
Uncontrolled	400	-	<100
Engine Modifications	100	Base	100
Lean Setting w/ox. Cat	50	150-200	100
Closed Loop TWC	10	250-400	95
Advanced Closed Loop	6	350-600	90

Recognizing that there is no universal consensus regarding the cost and fuel economy impacts of emission regulations, a fair conclusion would seem to be that technology exists which can lower emissions by an order of magnitude at a cost of approximately 3 to 5% of the overall cost of a vehicle with no pollution controls and with improved fuel economy.

6. Technological Advances on the Horizon{tc "autonum Technological Advances on the Horizon" \l 2}

The technology to reduce vehicle emissions continues to evolve and develop. Lower trace lead levels in unleaded gasoline and more advanced emission control components, particularly more durable catalysts, better air fuel management systems, and electronics will be key elements of future control. California (USA), still plagued by severe smog conditions in Los Angeles, continues its worldwide leadership in extending the pollution control requirements.

The level of tailpipe hydrocarbon emissions from modern vehicles is primarily a function of the engine-out emissions and the overall conversion efficiency of the catalyst, both of which are highly dependent on proper function of the fuel and ignition systems. A fairly comprehensive system has evolved. A significant portion of the HC and CO emissions are generated during cold-start, when the fuel system is operating in a rich mode and the catalyst has not yet reached its lightoff temperature. There are many technological improvements, which are currently becoming widespread or are on the horizon, that make more stringent control of HC and CO feasible. These advances are expected to not only reduce the emission levels that can be achieved in the certification of new vehicles, but also to reduce the deterioration of vehicle emissions in customer service.

First is the trend toward increased use of fuel injection. Fuel injection has several distinct advantages over carburetion as a fuel control system -- more precise control of fuel metering, better compatibility with digital electronics, better fuel economy, and better cold-start function. Fuel metering precision is important in maintaining a stoichiometric air/fuel ratio for efficient three-way catalyst operation. Efficient catalyst operation, in turn, can reduce the need for dual-bed catalysts, air injection, and EGR. Better driveability from fuel injection has been a motivating force for the trend to convert engines from carburetion to fuel injection. In fact, it has been projected that the percentage of new California light-duty vehicles with fuel-injection will reach 95% by the early 1990's, with 70% being multi-point. Because of the inherently better fuel control provided by fuel-injection systems, this trend is highly consistent with more stringent emissions standards.

Fuel injection's compatibility with onboard electronic controls enhances fuel metering precision, and also gives manufacturers the ability to integrate fuel control and emissions control systems into an overall engine management system. This permits early detection and diagnosis of malfunctions, automatic compensation for altitude, and to some degree, adjustments for normal wear. Carburetor choke valves, long considered a target for maladjustment and tampering, are replaced by more reliable cold-start enrichment systems in fuel-injected vehicles.

Closed-loop feedback systems are critical to maintain good fuel control, although when they fail emissions can increase significantly. In fact, the CARB in-use surveillance data show that failure of components in the closed-loop system frequently has been associated with high emissions. The CARB's new requirement for onboard diagnostics will enable the system to alert the driver when something is wrong with the emission control system and will help the mechanic to identify the malfunctioning component.

Second, improvements to the fuel control and ignition systems, such as increasing the ability to maintain a stoichiometric air/fuel ratio under all operating conditions and minimizing the occurrence of spark plug misfire, will result in better overall catalyst conversion efficiency and less opportunity for catastrophic failure. These improvements, therefore, have a twofold effect: 1) limiting the extra engine-out emissions that would be generated by malfunctions, and 2) helping to keep the catalyst in good working condition.

Finally, there are alternative catalyst configurations that could and likely will be used in the future to meet lower emission standards. It is likely that dual-bed catalysts will be phased out over time, but a warm-up catalyst (preceding the TWC) could be used for cold-start hydrocarbon control. To avert thermal damage and lower the catalyst deterioration rate, this small catalyst could be bypassed at all times other than during cold-start. Warm-up air injection could also be used with a single-bed TWC for cold-start hydrocarbon control. As hydrocarbon standards are lowered, preheated catalysts will likely become a more important element of the pollution control system of many cars.

7. Special Concerns With Two & Three Wheeled Vehicles{tc "□autonum□ Special Conce

Two- and three-wheeled vehicles, such as motorcycles and auto rickshaws constitute a large portion of motorized vehicles in developing countries, particularly in East and South Asia. While they are responsible for a relatively small fraction of the total vehicle kilometers of travel (VKT) in most countries they may make a substantial contribution to air pollution from mobile sources, in particular motorcycles/auto rickshaws with two-stroke engines running on a mixture of gasoline and lubricating oil. For example, it has been estimated that uncontrolled motorcycles in industrialized countries emit 22 times as much hydrocarbons and 10 times as much carbon monoxide as automobiles controlled to U.S. 1978 levels.[90] In Taiwan, HC emissions from two-stroke engine motorcycles were 13 times higher than the emissions from new four-stroke motorcycles and over 10 times higher than the emissions from in-use passenger cars. The CO emissions from two-stroke motorcycle engines were similar to those from four-stroke engines.[91]

Technologies available to control emissions from two- and three-wheeled vehicles are similar to those available for other Otto cycle powered engines. Reducing the content of lubricating oil in the fuel is one possible approach. Refining the fairly simple type of carburetors used would help significantly reduce HC, CO, and smoke emissions. Even catalytic converters are technologically feasible for these engines.[92]

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[90]OECD [1988a]. Transport and Environment, Paris.

[91]Shen, S-H., and Huang, K-H. [1989]. "Taiwan Air Pollution Control Programme -- Impact of and Control Strategies for Transportation - Induced Air Pollution." Bureau of Air Quality Protection and Noise Control, Environmental Protection Agency, Taiwan.

[92]OECD [1988a]. Transport and Environment, Paris.

Many modern engines use a separated lubrication system, which brings about overall leaner fuel/oil ratios and is therefore favorable for smoke reduction. Since 1986 Mopeds with catalysts have been available in Switzerland and in Austria, and since 1992 motorcycles in Taiwan have been similarly equipped.

It is a fair conclusion to state today that the historical problems of high smoke and unburned hydrocarbons from two stroke technology are no longer technologically necessary. New technology promises to resolve these concerns. As examples, direct cylinder electronic fuel injection, electronic computer control, and catalytic exhaust conversion are now commonplace solutions. In addition, modern, advanced two stroke engines such as those under development from the Orbital company indicate that these engines can even be cleaner and more fuel efficient than four strokes.

8. **Additional Health Benefits From Catalysts**{tc "autonum Additional Health Benefits From Catalysts" \l 2}

In addition to the significant improvements in carbon monoxide, hydrocarbon and nitrogen oxide emissions, the catalyst has several additional advantages which it is worth briefly summarizing.[93]

1. **Aldehydes**{tc "autonum Aldehydes" \l 3}

These are the most prevalent oxygenated organic species in gasoline engine exhaust and tend to be highly photochemically reactive and to contribute directly to eye irritation. As illustrated below, the available data shows that these compounds are effectively reduced by catalysts.

Aldehyde Emissions From Passenger Cars

Vehicle Type	Aldehydes (grams per mile)
Average of 10 non-catalyst gasoline cars	0.141
Average of 3 catalyst gasoline cars	0.023

It is worth noting that one particular aldehyde, formaldehyde, has been found to be carcinogenic in animal tests.

2. **Reactive Hydrocarbons**{tc "autonum Reactive Hydrocarbons" \l 3}

Exhaust hydrocarbons standards are generally written in terms of total hydrocarbons. Certain of these hydrocarbons such as methane are of less environmental concern because they are chemically stable and tend not to

[93] "Automotive Hydrocarbon Emission Patterns in the Measurement of Nonmethane Hydrocarbon Emission Rates", Black and High, SAE #770144.
"Effect of Catalytic Emission Control on Exhaust Hydrocarbon Composition and Reactivity", Jackson, SAE # 780624.
"Unregulated Emissions From A PROCO Engine Powered Vehicle", McKee et al., SAE # 780592.
"Measurement of Unregulated Emissions from General Motors Light Duty Vehicles", Cadle, Nebel and Williams, SAE # 790694.
"Automotive Emissions of Polynuclear Aromatic Hydrocarbons", Gross, SAE # 740564.

participate in the reactions leading to photochemical smog.[94] However, since catalytic converters tend to selectively oxidize the more reactive hydrocarbons more easily than methane, a greater proportion of the hydrocarbon species which participate in the photochemical reactions leading to smog will be reduced by catalysts.

3. Polynuclear Aromatic Hydrocarbons (PAH s){tc "□autonum□ Polynuclear Aromatic Hydrocarbons (PAH s)" \l 3}

Emissions of this class of hydrocarbons are of particular interest because of the well established direct carcinogenic effects of certain specific PAH compounds which have been detected in vehicle exhaust. Most notable among the polynuclear aromatics is benzo(a)pryene (BaP), a five ring aromatic that has been shown in a variety of experiments to be an animal carcinogen.

Listed below are BaP emissions data from passenger cars with various types of control technology.

Vehicle Type;	Emissions (Micrograms per mile)
Pre-emissions control	12.04
1968 emissions controlled	2.77
1970 emissions controlled	1.62
Catalyst equipped	0.08

These data show that PAH emissions from gasoline powered cars are reduced substantially by controls designed to reduce hydrocarbons and carbon monoxide but that catalytic converters can almost eliminate them. In fact, the catalyst equipped vehicles reduce BaP by over 99 percent from pre-controlled levels and by about 96 percent from 1970 levels with first generation emissions controls. There is every reason to conclude that the catalyst has the same impact on other multi-ring aromatics which are likely to be in gasoline vehicle exhaust. This was verified in a study conducted several years ago which measured various polycyclic aromatic hydrocarbons both with and without a catalyst.

Polycyclic Aromatic; Hydrocarbon	Without; Catalyst	With; Catalyst	Percent Reduction
phenanthrene	1.85	0.16	91%
anthracene	0.61	0.04	93%
fluoranthrene	2.27	0.23	90%
phrene	2.91	1.50	48%
perylene	1.21	0.40	67%
benzo(a)pryene	0.94	0.17	82%
benzo(e)pryene	2.76	0.41	85%
dibenzopyrenes	0.28	0.23	18%

[94]While not a direct health concern in the urban environment, methane is one of the gases which is accumulating in the upper atmosphere which is an important potential greenhouse gas.

coronene	0.41	0.27	34%

The data show that polynuclear aromatic hydrocarbons are removed by catalysts and in most cases the removal rate is substantial.

13. APPENDIX C: DIESEL FUELED VEHICLE CONTROLS{tc "□autonum□ APPENDIX C: DIESEL FUELED VEHICLE CONTROLS"}

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 hydrocarbon (HC) and particulate (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 substantially lower or raise emissions. The following sections will review the status of each of the technology areas; Chapter VIII will summarize the fuel impacts.

Except for particulate matter, exhaust emissions (particularly HC and CO) from diesel engines are quite low compared to gasoline engines. Thus much of the attention on diesel exhaust emissions has focused on particulate and NOx emissions. The particulate matter from diesel exhaust consists of soot, condensed hydrocarbons, sulphur-based compounds, and other oil-derived material. Smoke represents the immediately visible portion of particulate emissions and its opacity depends on the number and size of carbon particles present. The main cause of black smoke is poor maintenance of air filters or fuel injectors. Fuel quality can also affect smoke emissions, the main factors being fuel density, aromatic content and certain distillation characteristics [T. J. Russell, 1989, ECMT, 1990].

Most of the techniques for reducing particulate and HC emissions from diesel engines improve the combustion efficiency and are fuel efficient but result in higher NOx levels in the exhaust. Common approaches to emission control require a series of diesel engine modifications, including fuel injection, electronic engine controls, combustion chamber modifications, air handling characteristics, reduced oil consumption, turbocharging, injection retard, exhaust gas recirculation, and reduced heat rejection [ECMT 1990].

Efficient combustion through improved mixing of air and fuel results in low emissions of hydrocarbons and smoke. Electronic control of fuelling levels and timing combined with high pressure fuel injection systems can be quite beneficial in this respect. Turbocharging increases NOx emissions but reduces particulates. Charge cooling (cooling the intake air after the turbocharges) directly reduces NOx emissions by reducing peak cycle temperatures and pressures. Injection retard is the most effective way of reducing NOx emissions but it increases fuel consumption and smoke and HC emissions, particularly under light loading. EGR can significantly reduce NOx but may double particulate emissions. Effective control of lubricating oil through engine design to prevent it from entering the engine piston rings, valve guides or turbochargers has been shown to reduce HC emissions by about 50% [ECMT 1990].

In order to achieve low levels of particulate emissions, manufacturers also have turned to the development of exhaust treatment devices, that is, devices added to clean up the exhaust after it leaves the engine. Several types of devices are being evaluated. First, a flow-through catalytic converter designed to operate on low sulfur fuel could reduce the soluble organic fraction (SOF) of particulates by as much as 90% and may also reduce the carbon portion. Second, and probably the most promising of these aftertreatment devices is the trap oxidizer control system. Trap oxidizer systems have demonstrated particulate control efficiencies in some instances of over 90%.

1. ENGINE MODIFICATIONS{tc "autonum ENGINE MODIFICATIONS" \l 2}

1. Air Motion and Combustion Chamber Design {tc "autonum Air Motion an

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 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.

2. Combustion Systems {tc "autonum Combustion Systems " \l 3}

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 than DI engines but with recent developments in DI engine emission controls, this is no longer the case. Disadvantages of the IDI engine are 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.

3. DI Combustion Chamber Design {tc "autonum DI Combustion Chamber Design " \l 3}

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.

<u>Crevice volume</u> The crevice volume is that part of the compression volume which lies outside the combustion chamber. This includes the clearance between the top of the piston and the cylinder head, and the "top land"--the space between the side of the piston and the cylinder wall above the top compression ring. The smaller the crevice volume, the larger the combustion chamber volume can be for a given compression ratio, thus, effectively increasing the amount of air available for combustion.

The major approaches to reducing the crevice volume are to reduce the clearance between the piston and cylinder head through tighter production tolerances, and moving the top compression ring toward the top of the piston. This increases the working temperature of the top ring, and poses mechanical design problems for the piston top and cooling system as well. These problems have been addressed through redesign and the use of more expensive materials. The higher piston ring temperature may also make additional demands on the oil.

<u>Combustion chamber shape</u> For high swirl DI engines, a reentrant combustion chamber shape (in which the lip of the combustion chamber protrudes beyond the walls of the bowl) provides a substantial improvement in performance and emissions over the previous straight sided bowl designs. Researchers at AVL found that the use of a reentrant bowl gave a 20 percent reduction in PM emissions from those measured with a straight sided bowl at the same compression ratio. NOx emissions were increased 3 percent, but the reentrant bowl combustion chamber has also been found more tolerant of retarded injection timing than the straight sided bowl.

Because of the superiority of the reentrant bowl design for high swirl engines, nearly all manufacturers of such engines are developing or already using this approach. Similar improvements in the performance of low swirl DI engines may also be possible through modifications to combustion chamber geometry, but there is much less unanimity as to what the optimal shape may be.

<u>Intake air swirl</u> Optimal matching of intake air swirl ratio with combustion chamber shape and other variables is critical for emissions control in high swirl engines. The swirl ratio is the ratio of the rotational speed of the air charge in the cylinder to the rotational speed of the engine, which is determined by the design of the air intake port. The selection of a fixed swirl ratio involves some tradeoffs between low speed and high speed performance. At low speeds, a higher swirl ratio provides better mixing, permitting more fuel to be injected and thus greater torque output at the same smoke level. However, this can result in too high a swirl ratio at higher speeds, impairing the airflow to the cylinder. Too high a swirl ratio can also increase HC emissions, especially at light loads.

Attaining an optimal swirl ratio is more difficult in smaller engines, as these experience a wider range of engine speeds than do heavy engines. One solution to this problem is to vary the swirl ratio as a function of engine speed. A two position variable swirl system has been developed and applied to some diesel engines in Japan. This system is being considered for engines used in the US as well. Test data using this system show a noticeable reduction in PM and NOx emissions due to optimization of the swirl ratio at different speeds.

4. Fuel injection {tc "autonum Fuel injection " \l 3}

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 fuel injection system normally consists of a low pressure pump to transfer fuel from the tank to the engine, one or more high pressure fuel pumps to create the pressure pulses that actually send the fuel into the cylinder, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel metering system. These determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

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. Systems offering electronic control of these quantities, as well as fuel injection rate, have been introduced. 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. 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.

1. Injection System Types {tc "autonum Injection System Types " \l 4}

Fuel injection systems used in heavy duty diesel vehicles can be divided into two basic types. The most common type consists of a single fuel pump (typically mounted at the side of the engine) which is driven by gears from the crankshaft, and connected to individual injection nozzles at the top of each cylinder by special high pressure fuel lines. These pump line nozzle (PLN) injection systems can be further divided into two subclasses: "distributor" fuel pumps, in which a single pumping element is mechanically switched to connect to the high pressure fuel lines for each cylinder in turn; and "in line" pumps having one pumping element per cylinder, each connected to its own high pressure fuel line. The latter type is much more common in heavy duty trucks.
The most common alternative to the pump line nozzle injection systems are systems using unit injectors, in which the individual fuel metering and pumping element for each cylinder is combined in the same unit with the injection nozzle at the top of the cylinder. The pumping elements in a unit injector system are generally driven by the engine camshaft.

Worldwide, many more engines are made with pump line nozzle injection systems than with unit injectors. This is primarily due to the higher cost of unit injector systems. Presently, three US engine manufacturers (accounting for more than half of US heavy heavy duty engine production) produce unit injector equipped truck engines. Due to the absence of high pressure fuel lines, however, unit injectors are capable of higher injection pressures than pump line nozzle systems. With improvements in electronic control, these systems offer better fuel economy at low emission levels than the pump line nozzle systems. For this reason, many heavy duty engine models sold in the US will be equipped with unit injectors for the 1991 model year.

Fuel injection pressure and injection rate -- 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.

The injection pressures achievable in pump line nozzle fuel injection systems are limited by the mechanical strength of the pumps and fuel lines, as well as by pressure wave effects, to about 800 bar. Improvements in system design to minimize pressure wave effects, and increases in the size and mechanical strength of the lines and pumping elements have increased the injection pressures achievable in pump line nozzle systems substantially from those achievable a few years ago.

The pumping elements in all current fuel injection systems are driven through a fixed mechanical linkage from the engine crankshaft. This means that the pumping rate, and thus the injection pressure, are strong functions of engine speed. At high speeds, the pumping element moves rapidly, and injection pressures and injection rates are high. At lower speeds, however, the injection rate is proportionately lower, and injection pressure drops off rapidly. This can result in poor atomization and mixing at low speeds, and is a major cause of high smoke emissions during lugdown. Increasing the pumping rate to provide adequate pressure at low speeds is impractical, as this would exceed the system pressure limits at high speed.

A new type of in line injection pump has recently been developed which provides a partial solution to this problem. The cam driving the pumping elements in this pump has a non-uniform rise rate, so that pumping rate at any given time is a function of the cam angle. By electronically adjusting a spill sleeve, it is possible to select the portion of the cam's rotation during which fuel is injected, and thus to vary the injection rate. Injection timing varies at the same time, but the system is designed so that desired injection rate and injection timing correspond fairly well. Ishida and coworkers obtained a 25 percent reduction in PM emissions and a 10 percent reduction in HC using this system, with virtually no increase in NOx. The same approach could easily be applied to a unit injector system, using an electronically controlled spill valve.

Another approach to increasing injection pressure at low engine speeds is the use of electro-hydraulic actuators for injection instead of mechanically driven pumping elements. Through appropriate design and control schemes, such systems can control and maintain fuel injection pressures nearly independently of engine speed. A number of such systems have been described in the technical literature, but, to date, none has actually been implemented on commercial engines. It is expected that such systems will be introduced in the US in 1991, however.

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

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

Low sac/sacless nozzles -- The nozzle sac is a small internal space in the tip of the injection nozzle. The nozzle orifices open into the sac, so that fuel flowing past the needle valve first enters the sac, and then sprays out the orifices. The small amount of fuel remaining in the sac tends to burn or evaporate late in the combustion cycle, resulting in significant PM and HC emissions. The sac volume can be minimized or even eliminated by redesigning the injector nozzle. One manufacturer reported nearly a 30 percent reduction in PM emissions through elimination of the nozzle sac. It is also possible to retain some of the sac while designing the injector nozzle so that the tip of the needle valve covers the injection orifices when it is closed. This valve covers orifice or VCO injector design is used in some production engines, and in many engines being developed for compliance with the US 1991 emissions standards.

5. Engine Control Systems {tc "autonum Engine Control Systems " \l 3}

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.

1. Mechanical Controls {tc "autonum Mechanical Controls " \l 4}

Most current diesel engines still rely on mechanical engine control systems. The basic functions of these systems include basic fuel metering, engine speed governing, maximum power limitation, torque curve "shaping", limiting smoke emissions during transient acceleration, and (sometimes) limited control of fuel injection timing. Engine speed governing is accomplished through a spring and flyweight system which progressively (and quickly) reduces the maximum fuel quantity as engine speed exceeds the rated value. The maximum fuel quantity itself is generally set through a simple mechanical stop on the rack controlling injection quantity. More sophisticated systems allow some "shaping" of the torque curve to change the maximum fuel quantity as a function of engine speed.

Acceleration smoke limiters are needed to prevent excessive black smoke emissions during transient acceleration of turbo charged engines. Most are designed to limit the maximum fuel quantity injected as a function of turbocharger boost, so that full engine power is developed only after the turbocharger comes up to speed.

Many pump line nozzle fuel injection systems incorporate mechanical injection timing controls. Since the injection pump is driven by a special shaft geared to the crankshaft, injection timing can be adjusted within a limited range by varying the phase angle between the two shafts, using a sliding spline coupling. A mechanical or hydraulic linkage slides the coupling back and forth in response to engine speed and/or load signals.

In mechanical unit injector systems, the injectors are driven by a direct mechanical linkage from the camshaft, making it very difficult to vary the injection timing. Cummins, in its California engines, has introduced a mechanical timing control which operates by moving the injector cam followers back and forth with respect to the cam. Although effective in limiting light load HC and PM emissions under the stringent California NOx standards, these systems have proven very troublesome and unpopular among users.

2. Electronic Controls {tc "autonum Electronic Controls " \l 4}

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

Other electronic control features, such as cruise control, upshift indication, and communication with an electronically controlled transmission will also help to reduce fuel consumption, and will thus likely reduce in use emissions. Since the effect of these technologies is to reduce the amount of engine work necessary per mile, rather than the amount of pollution per unit of work, their effects will not be reflected in dynamometer emissions test results, however.

6. Turbocharging and Intercooling {tc "autonum Turbocharging and Intercooling " \l 3}

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.

1. Turbocharger refinements {tc "autonum Turbocharger refinements " \l 4}

Turbochargers for heavy duty diesel engines are already highly developed, but efforts to improve their performance continue. The major areas of emphasis are improved matching of turbocharger response characteristics to engine requirements, improved transient response, and higher efficiencies. Engine/turbocharger matching is especially critical, because of the inherent conflict between the response characteristics of the two types of machines. Engine boost pressure requirements are greatest near the maximum torque speed, and most turbochargers are matched to give near optimal performance at that point. At higher speeds, however, the exhaust flowrate is greater, and the turbine power output is correspondingly higher. Boost pressure under these circumstances can exceed the engine's design limits, and the excessive turbine backpressure increases fuel consumption. Thus, some compromise between adequate low speed boost and excessive high speed boost must be made.

2. Variable geometry turbochargers {tc "autonum Variable geo

Because of the inherent mismatch between engine response characteristics and those of a fixed geometry turbocharger, a number of engine manufacturers are considering the use of variable geometry turbines instead. In these systems, the turbine nozzles can be adjusted to vary the turbine pressure drop and power level in order to match the engine's boost pressure requirements. Thus, high boost pressures can be achieved at low engine speeds, without wasteful overboosting at high speed. The result is a substantial improvement in low speed torque, transient response, and fuel economy, and a reduction in smoke, NOx, and PM emissions.

Prototype variable geometry turbochargers (VGT) have been available for some time, but they have not been used in production vehicles up to this point The major reasons for this are their cost (which could be 50% more than a comparable fixed geometry turbocharger), reliability concerns, and the need for a sophisticated electronic control system to manage them. With the forthcoming deployment of electronic engine controls on virtually all vehicles in the US, these latter arguments have lost much of their force, and the fuel economy and performance advantages of the VGT are great enough to outweigh the costs in many applications. As a result, variable geometry turbo chargers should be available on a number of production heavy duty diesel engines in the relatively near future.

3. Other types of superchargers

A number of alternative forms of supercharging have been considered, with a view to overcoming the mismatch between turbocharger and engine response characteristics. The two leading candidates at present are the Sulzer Comprex (tm) gas dynamic supercharger, and mechanically assisted turbochargers such as the "three wheel" turbocharger developed by General Motors. The major advantages of these systems are superior low speed performance and improved transient response. These advantages would be expected to yield some improvement in PM emissions, as well as driveability and torque rise.

4. Intercoolers {tc "autonum Intercoolers " \l 4}

Presently, most intercoolers rely on the engine cooling water as a heat sink, since this minimizes the components required. The relatively high temperature of this water (about 90` C) limits the benefits available, however. For this reason, an increasing number of heavy duty diesel engines are being equipped with low temperature charge air cooling systems.

The most common type of low temperature charge air cooler rejects heat directly to the atmosphere through an air to air heat exchanger mounted on the truck chassis in front of the radiator. Although bulky and expensive, these charge air coolers are able to achieve the lowest charge air temperatures -- in many cases, only ten or 15 degrees C above ambient. An alternative approach is low temperature air to water intercooling, which has been pursued by Cummins Engine in the U.S.. Cummins has chosen to retain the basic water air intercooler, but with drastically reduced radiator flowrates to reduce the water temperature coming from the radiator. This water is then passed through the intercooler before it is used for cooling the rest of the engine.

7. Intake manifold tuning {tc "autonum Intake manifold tuning " \l 3}

Tuned intake manifolds have been used for many years to enhance airflow rates on high performance gasoline engines, and are being considered for some heavy duty diesel engines. A tuned manifold provides improved airflow and volumetric efficiency at speeds near its resonant frequency, at the cost of reduced volumetric efficiency at other speeds. At least one medium heavy duty manufacturer is considering a variable resonance manifold, in order to improve airflow characteristics at both low and high speeds.

8. Lubricating Oil Control{tc "autonum Lubricating Oil Control" \l 3}

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.

Advances in piston/cylinder tribology could potentially eliminate or greatly reduce oil consumption in the cylinder. Areas such as boundary lubrication and development of low friction ceramic coatings are presently the subjects of much research. The potential for transforming this research into durable and reliable engines on the road remains to be demonstrated, however.

2. Aftertreatment Systems {tc "autonum Aftertreatment Systems " \l 2}

In order to achieve very low levels of particulate emissions, manufacturers also have turned to the development of exhaust control devices, that is, devices added to clean up the exhaust after it leaves the engine. Several types of devices are available. First, a flow-through oxidation catalytic converter installed on a vehicle designed to operate on low sulfur fuel can reduce the soluble organic fraction (SOF) of the particulate by as much as 90 percent and may reduce the carbon portion somewhat. Second, a trap oxidizer control system can achieve up to, and in some cases greater than, a 90 percent reduction in particulate. Catalyst and trap technology can be combined to provide even greater control.

Further, a great deal of work continues on the development of NOx aftertreatment systems and positive results are beginning to emerge.

1. **Catalytic converters** {tc "autonum Catalytic converters " \l 3}

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 existing emissions standards.

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. In addition, the catalytic converter has little impact on fuel economy or safety, and it will probably not require replacement. Also,, 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 potential 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.

Fortunately, Europe, the US and Japan have already decided to reduce the sulfur content of diesel fuel, thereby making catalyst technology viable.

The idea behind an oxidation catalyst is that it causes chemical reactions without being changed or consumed. An oxidation catalytic converter consists of a stainless steel canister that typically contains a honeycomb-like structure called a substrate. There are no moving parts, just acres of interior surfaces on the substrate coated with catalytic metals such as platinum or palladium. It is called an oxidizing catalyst because it transforms the pollutant, in this case the SOF, into harmless gases by means of oxidation. The oxidation catalyst has been optimized such that engine durability and reliability are unaffected and no fuel penalties will occur.

Oxidation catalysts have demonstrated the ability to control a significant portion of the SOF in the particulate. For example, one study reported that oxidation catalysts could reduce the SOF of the particulate by 90 percent under certain operating conditions, and could reduce total particulate emissions by 40 to 50 percent. Destruction of the SOF is important since this part of the particulate emissions contains numerous chemical pollutants that are of particular concern to health experts. Another benefit of the oxidation catalyst is that it also controls gaseous hydrocarbon and CO emissions in the exhaust with up to an 80% to 90% efficiency. Finally, use of a catalyst will noticeably reduce the odor of diesel exhaust.

2. Trap Oxidizers or Filters {tc "□autonum□ Trap Oxidizers or Filters " \l 3}

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.

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 should 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. Ongoing studies in South Korea continue to show high promise.

Some trap systems, to protect the filter from overheating and possibly being damaged, incorporate a by-pass for exhaust gases which is triggered and used only when exhaust temperatures reach critical levels. The period during which the by-pass is operated is very short and relatively infrequent. Systems are also designed with dual filters in which one filter collects while the other is being regenerated.

Development work with traps is focusing on further optimizing regeneration systems which are simple, reliable and reasonable priced and demonstrating durability of the trap system in the real world operation.

3. NOx Reduction Techniques{tc "autonum NOx Reduction Techniques" \l 3}

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.

A report prepared by Acurex under contract with CARB, entitled "Technical Feasibility of Reducing NOx and Particulate Emissions From Heavy-Duty Engines," concludes that NOx can potentially be reduced to as low as 2.5 g/BHP-hr. The 2.5 g/BHP-hr standard would require the use of a combination of some or all of the following emission control approaches: very high pressure fuel injection, variable geometry turbocharging, air-to-air aftercooling, optimized combustion, electronic unit injections with minimized sac volumes, rate shaping, exhaust gas recirculation and sophisticated electronic control of all engine systems. Such controls would create substantial increases in costs and fuel consumption. Most of the devices described in the Acurex report are in relatively early stages of development and would require extensive changes in heavy-duty diesel-powered engines compared to today's designs.

4. Status of Aftertreatment Applications{tc "autonum Status of Aftertreatment Applications" \l 3}

In Europe, over 500,000 diesel automobiles annually are being equipped with catalysts; virtually all new diesel cars sold in Germany, Austria and France come equipped. The public demand for clean diesels and tax incentives are spurring the use of these devices. "Oxidation catalysts can lower CO, HC and particulate emissions considerably, and also improve the odor of diesel exhaust"[95] As a result, it is expected that virtually all new diesel light duty

[95]"Automotive Diesel Engines & the future", Ricardo, 1994.

vehicles sold in Europe will be equipped with at least an oxidation catalyst by 1997, after the Step 2 light duty vehicle standards are introduced.

In the US, a number of engine manufacturers have offered catalyst equipped trucks in 1994 capable of meeting the 0.1 particulate standard. Indeed, catalysts are being used on a significant number of 1994 model year heavy-duty (trucks in the 8500-33,000 lbs. GVWR range) to help manufacturers meet the tougher particulate standard. Also, engine manufacturers are will use catalysts to meet the 0.07 bus standard and may be able to meet the 0.05 standard on some bus engines. Recently, 200 school buses with Caterpillar 3116 engines were equipped with catalysts as part of a demonstration program sponsored by the State of California. Catalysts will also be an available option for urban bus engines rebuilt under EPA's bus rebuild requirements.

Application of NOx reduction catalysts. "DeNOx catalysts, currently at the prototype stage, offer the potential for considerably lower NOx emissions; they may begin to be applied to some vehicle models over the next few years."[96]

By the year 2000 further significant improvements will need to be made to all passenger car diesel engines in order to attain the standards currently being discussed, 0.04 g/km particulate and 0.5 g/km HC + NOx. "To achieve [these levels], both engine types, the ID and the DI, must be equipped with sophisticated emission control systems which include:

Electronically controlled injection system
Injection rate shaping (at least for the DI)
Multi valve technology
Turbocharging
Intercooling
Controlled EGR
Oxidation Catalyst"[97]

"Hydrocarbon levels of less than 0.03 g/km over the European emissions cycle are possible with a well optimized catalyst equipped diesel car, which is comparable with the requirements of the California Low Emissions Vehicle (LEV) standards."[98]

For heavy duty vehicles, "To comply with the European Stage III standards all engines are likely to feature 4 valve per cylinder combustion systems and very high pressure injection systems, with injection pressure in excess of 1500 bar. These engines will also incorporate new technologies for NOx reduction, such as the use of pilot injection or EGR. If EGR is employed significant problems associated with engine durability will need to be overcome. However, these engines will offer the possibility of achieving zero visible smoke under all operating conditions.

To achieve standards projected beyond the year 2000 there is already significant research and development on NOx reduction (DeNOx) catalysts. Development of particulate traps and regeneration technology is also underway; if successful this will enable further significant reductions in exhaust particulate emissions."[99]

Engine manufacturers throughout the world are subjecting trap systems to a full range of evaluation. In addition, devices have been or are being evaluated by other parties interested in diesel particulate control.

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[96] "Automotive Diesel Engines & the future", Ricardo, 1994.

[97] "Vehicle Engine Development Trends under Future Boundary Conditions", F. Pischinger, SAE # 945001, Fisita 94.

[98] "Automotive Diesel Engines & the future", Ricardo, 1994.

[99] "Automotive Diesel Engines & the future", Ricardo, 1994.

Trap oxidizers are not only being developed for new vehicles, but also as a control device that can be retrofitted on existing trucks and buses. In fact, traps already have been retrofitted on urban buses and on fire trucks in a number of cities around the world.

3. Effect on Fuel Consumption and Costs{tc "autonum Effect on Fuel Consumption and Costs" \l 2}

Fuel economy of diesel-fueled vehicles is likely to suffer significantly as a result of stringent exhaust emission limits, with an overall increase in operating costs of about 2%. The techniques available for reducing NOx emissions (primarily ignition retard and EGR) will lead to poor economy while other engine improvements such as increased use of turbocharging and charge cooling, and better control of injection rates and timing may offset some of the fuel efficiency losses.

Additional equipment (for example, charge coolers or particulate traps) needed to comply with exhaust emission requirements are likely to increase vehicle costs. The use of more advanced equipment (such as electronic fuel injection systems or variable geometry turbo chargers) will increase costs initially but the costs would go down when such equipment becomes standard. Vehicle maintenance costs are not likely to increase except for particulate traps which have not yet been shown to be durable. Table C-1 shows estimated cost increases for individual engine modifications likely to be needed to meet future emissions standards.

Table C-1: Cost of diesel engine exhaust emissions control technology

Technology	Estimated extra cost as (excluding development costs)
Baseline engine, no emissions control equipment. Developed for performance only	Nil
Injection timing retard	Nil
Low sac volume/valve covering orifice nozzle	Minimal
Turbocharging	3 - 5%
Charge cooling	5 - 7%
Improved high pressure fuel injection	13 - 15%
High pressure fuel injection with electronic control	14 - 16%
Variable geometry turbocharging (assuming it is already	

applied to the engine)	**1 - 3%**
Particulate trap	**4 - 25%**

Source: [ECMT 1990]