The Road Map For Achieving Euro Standards in New Vehicles and Fuels To Improve Air Quality in Vietnam

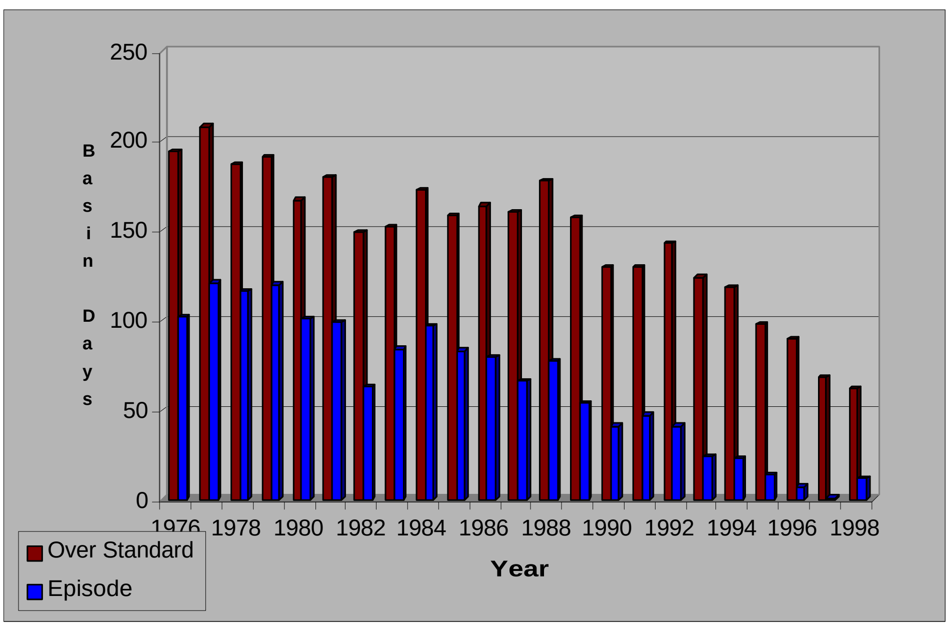
1. Introduction

Over the past fifty years, countries around the world have gradually imposed increasingly stringent emissions regulations on the motor vehicle and fuels industries with the result that new cars today emit but a small fraction per mile driven of what they did when the process began. While increasing numbers of vehicles have offset some of these gains, air pollution levels are decidedly down in most industrialized countries. Further, the clean vehicle technologies and fuels originally developed for the US or Europe or Japan in response to their standards are increasingly finding there way onto the roads of developing countries as well with the result that some air quality improvements also are occurring there. About 85% of all gasoline to be sold this year will be unleaded and almost 90% of all newly produced cars will contain a catalytic converter.

A. Great Progress Has Occurred Around The World

As we turned the corner into the new century, global vehicle emissions of non-methane hydrocarbons were about 67% lower than they would otherwise have been, carbon monoxide 56% lower and nitrogen oxides 18% lower. Focusing on Los Angeles, one of the most polluted cities in the world when this process began, the figure below illustrates that there has been continuous improvement in Air Quality over the past three decades.

B. More is Required



However, in spite of this progress, it is premature to declare victory. Most major industrialized countries continue to experience serious air pollution problems and even worse problems exist in the major cities in developing countries. Further, vehicle growth continues, maintaining the pressure to bring all vehicle emissions down to lower and lower levels, if not to zero, just to maintain the status quo.

Further new problems such as toxic emissions from diesel and other vehicles are emerging which will clearly require significant additional vehicle technology advances in coming years.

C. Vehicles Remain Dominant Pollution Source

Worldwide, cars, trucks, buses, and other motor vehicles continue to play a dominant role in causing air pollution. They are major sources of volatile organic compounds (VOCs) and nitrogen oxides, the precursors to both tropospheric ozone and acid rain; carbon monoxide (CO); toxic air pollutants such as diesel particulate; and chlorofluorocarbons (CFCs).

In the European Union as a whole, for example, on and off road vehicles are the largest sources of CO, NOx and non-methane hydrocarbons. Prior to the adoption of the Euro 3/4 requirements, forecasts indicated that vehicles would remain a major emissions source out to 2010.[1] In densely populated urban areas, vehicles can be a major source of exposure to particulates as well. For example, another study found that road vehicles account for 74% of nitrogen oxides and 94% of black smoke emissions in London. On their own, diesels account for 32% and 87% of total emissions (43% and 92% of vehicle emissions) for these two pollutants respectively. The European Commission also issued a Communication summarizing the results of the 4-year Auto-Oil II program, aimed at finding the most cost-effective ways to reduce emissions from road transport. It states that emissions from road transport of the traditional, regulated pollutants are expected to have fallen to 20% of their 1995 levels by 2020, leading to a marked improvement in air quality. However, it notes that some air quality problems such as particulate matter and ozone are a long way from being solved, so the report identifies particulate matter from diesel engines, dangerously high levels of localized nitrogen oxides and ozone as the major challenges for future policy.

The first scenarios showing the expected trends in emissions of air pollutants up to 2020 have now been released under the EU's Clean Air for Europe program (CAFE). One of the main items of the program is integrated assessment modeling, which is being used to develop scenarios for likely trends in emissions for the target years 2010, 2015 and 2020, from the base year 2000.

i. Emissions Trends

The first results of the EU computer modeling were revealed at a seminar in Brussels on 27 September.

Assuming full implementation of current air quality legislation, emissions of nitrogen oxides (NOx) will be reduced by about one-third by 2010 and by nearly half by 2020, while emissions of the coarse particulate fraction (PM10) will come down by about 40 per cent and those of the fine fraction (PM2.5) by 44 per cent.

[1] Recently adopted vehicles emissions standards and fuels requirements in the EU are summarized in Appendix A.

With regard to the oxides of nitrogen, on and off road vehicles will still contribute more than half the EU total in 2020. Vehicles will contribute more than one-quarter of the $PM_{2.5}$ in 2020.

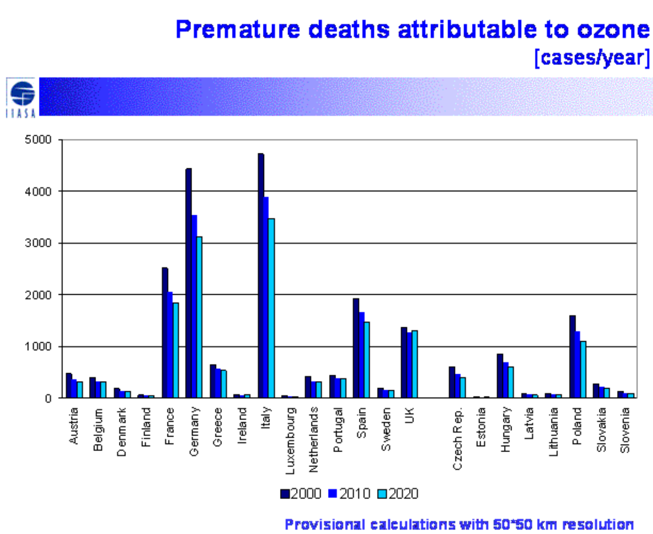
ii. Health and Environmental Impacts

The scenarios presented also included preliminary estimates of some health and environmental impacts expected to result from the projected levels of future emissions. For PM2.5 the RAINS model estimates changes in the loss of statistical life expectancy that can be attributed to changes in anthropogenic emissions. It should be noted that these calculations only refer to impact on the population over 30 years of age, thus underestimating the total impact.

Compared to the year 2000, when it is estimated that PM2.5 will result in an average shortening of life expectancy by approximately nine months in the EU25, the estimate comes down to less than six months by 2020. There is however a significant variation between countries, and even by 2020 some of them (notably Belgium and the Netherlands) will still have life expectancy losses of about nine months.

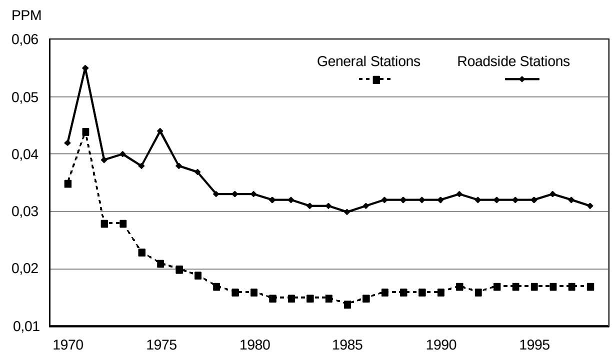
When it comes to the impact on health from ground-level ozone, the RAINS model estimates the number of premature deaths associated with ozone levels above a cut-off level of 35 parts per billion (ppb). Since there is medical evidence of health impacts even below 35 ppb, the use of this cut-off level results in an underestimation of the impact. The number of premature deaths estimated will also gradually decrease up to 2020 as a result of decreased emissions of the ozone precursors NOx and VOCs (see Figure below).

D. Motor Vehicle Also Important Elsewhere

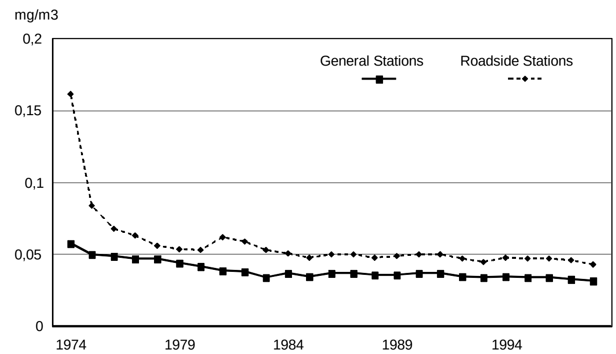


Motor vehicles are also major emissions sources in the United States and Japan. In the densely populated Northeastern United States where the air pollution problem is especially severe, the Environment Protection Agency (EPA) has projected that highway vehicles will account for approximately 38% of the total NOx inventory and 22% of the total VOC inventory in 2005, in spite of the introduction of tighter motor vehicle standards in the 1990 Clean Air Act. Further, when focusing on emissions in congested city centers, the

Nitrogen Dioxide Air Quality Trends In Japan



Suspended Particulate Matter Air Quality Trends In Japan



importance of vehicle emissions is even greater.
One recent study used a chemical mass balance technique to determine the source of the particulate in a midtown Manhattan street and concluded that diesel buses emitted more than 50%.

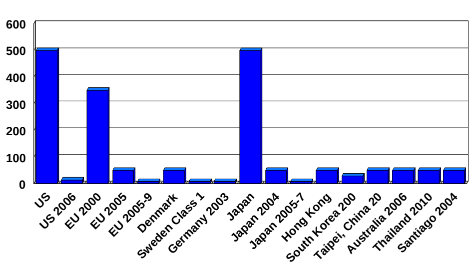
Japan has found that in spite of their strenuous efforts, particulate and NO_2 air quality levels have been approximately stable over the past 20 years and remain significantly higher in the vicinity of roadways than overall (see Figures above).

While not as well documented, it is increasingly clear that motor vehicles are also the major source of pollution problems in the developing world. Many citizens of Delhi, Bangkok, Jakarta, Manila, Sao Paulo, Mexico City etc. are literally choking to death on air pollution.

In every corner of the world, for every type of road vehicle, there is a clear trend toward lower and lower emissions levels. Over the next decade, this pattern will move toward similar controls on off road vehicles and fuels and will finally address the last holdouts – aircraft and marine vessels. Driving these trends are several factors:

- Continued growth in the production of vehicles (especially in China and other parts of Asia) and their concentration in urban areas where pollution levels remain unacceptably high,
- The growing accumulation of health studies which show adverse impacts at lower and lower levels and in the case of PM at virtually any level,
- Advances in vehicle technology and clean fuels which are making it possible to achieve lower and lower levels at reasonable costs.

Global Trends Toward Low Sulfur Diesel Fuel



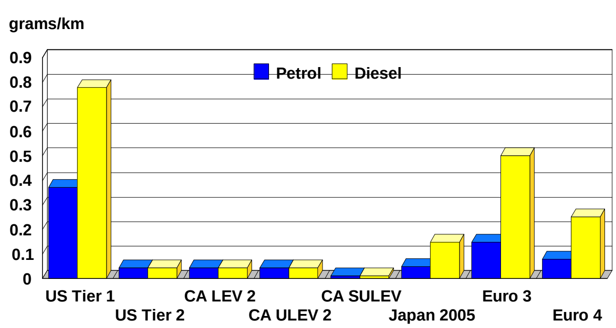
With regard to fuels, one can now foresee the possible elimination of lead from gasoline as African countries, the last large remaining dumping ground are coming to grips with this problem. Most African countries have committed to phase out the use of lead by 2005 or soon thereafter and progress toward this goal is occurring in many countries. Sulfur levels in both diesel and gasoline are falling rapidly throughout the OECD countries and low sulfur fuels are on the horizon in a number of developing countries as well. (A brief review of the major refinery processes is contained in Appendix B.)

Diesel technology is advancing rapidly and in addition to virtually saturating the heavy duty commercial vehicle market is increasingly penetrating the light duty sector. Diesel fueled light duty vehicles are gaining a foothold in countries such as China, Taiwan and South Korea where light duty diesels were previously banned. Diesel's superior fuel economy and relatively low carbon dioxide emissions are a principle reason for its increasing market share. With the exception of the US, however, light duty diesel standards remain more lenient than gasoline fueled vehicle standards, a situation which is expected to be corrected, at least in the EU and Japan, before the end of this decade.

E. Regulatory Developments

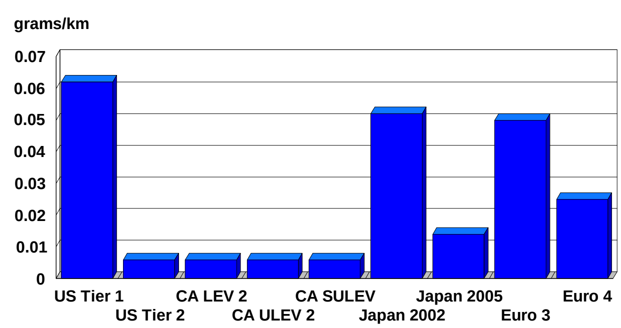
The three dominant regulatory programs in the world are the US (including California), the EU and Japan[2]. Each of them is currently in the process of phasing in tighter standards for both light and heavy duty vehicles. Illustrated below are the standards for NOx and PM for light and heavy duty vehicles and engines.

Light Duty Vehicle NOx Standards



Different Test Procedures in US, EU & Japan

Light Duty Diesel PM Standards

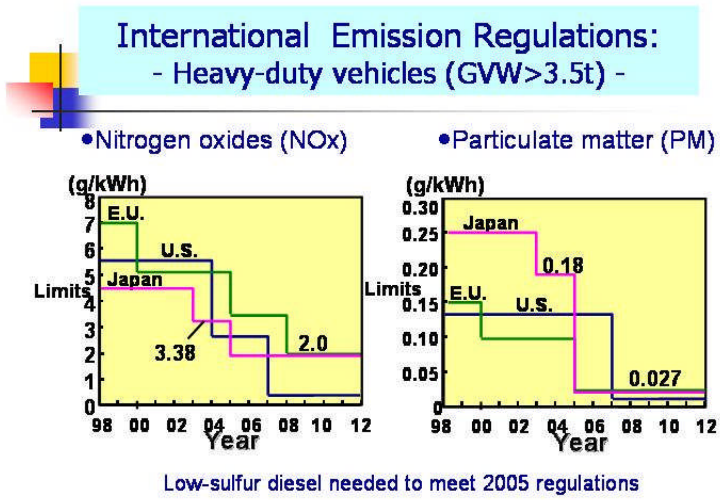


Different Test Procedures in US, EU & Japan

Major developments in the last few years include the following:

- The European Union has mandated the widespread availability of near zero sulfur levels in both gasoline and diesel fuel by 2005 and its universal use by 2009. It is in the process of implementing the already adopted Euro 4 standards for light duty vehicles and the Euro 4 and 5 standards for heavy duty vehicles with many cars already meeting

[2] Emissions regulations in every other country of the world are derivatives of one of these programs, especially the EU program.



Euro 4 requirements, well ahead of schedule. Finally it is already far along in developing so called Euro 5 standards for light duty vehicles and Euro 6 standards for heavy duty engines with proposals expected from the Commission during 2005. Almost certainly, these new standards will require PM filters on all new diesel vehicles. Whatever Euro 5 standards are adopted will likely go into effect earlier than the mandated date in many countries since several Member States will encourage early introduction through tax incentives.

- In the US, the Tier 2 and LEV 2 standards are gradually being phased in across the nation and California, respectively. The number of states opting in to the California requirements continues to grow with New Jersey and Rhode Island the most recent additions. In spite of a series of Court challenges and political battles, the 2007-10 heavy duty engine requirements and low sulfur fuel standards remain on track and are expected to go into effect on schedule. EPA has also adopted very stringent requirements for off road diesel engines and fuels which will require the same degree of controls for most categories as the on road standards.

- The California Air Resources Board (ARB) has voted to make significant modifications and upgrades to the state's zero emission vehicles (ZEV) regulations. The most important modification creates a new ZEV pathway, giving manufacturers a choice of two options for meeting their ZEV requirements.
  - Auto manufacturers can meet their ZEV obligations by meeting standards that are similar to the ZEV rule as it existed in 2001. This means using a formula allowing a vehicle mix of 2 percent pure ZEVs, 2 percent AT-PZEVs (vehicles earning advanced technology partial ZEV credits) and 6 percent PZEVs (extremely clean conventional vehicles). The ZEV obligation is based on the number of passenger cars and small trucks a manufacturer sells in California.
  - Or, manufacturers may chose a new alternative ZEV compliance strategy, meeting part of their ZEV requirement by producing their sales-weighted market share of approximately 250 fuel cell vehicles by 2008. The remainder of their ZEV requirements could be achieved by producing 4 percent AT-PZEVs and 6 percent PZEVs. The required number of fuel cell vehicles will increase to 2,500 from 2009-11, 25,000 from 2012-14 and 50,000 from 2015 through 2017. Automakers can substitute battery electric vehicles for up to 50 percent of their fuel cell vehicle requirements.

- In other North American developments, Canada has adopted virtually identical standards for vehicles and fuels as the US on the same approximate schedule. Mexico has phased in Tier 1 light duty vehicle standards and is in discussion with industry regarding Tier 2. A key determinant of the outcome from these discussions as well as the prospects for significant tightening of the heavy duty requirements is whether fuel quality will be improved. PEMEX has developed a detailed plan to phase in fuels meeting US sulfur standards in almost the same timeframe as in the US and it is undergoing serious discussion at this time.

- Australia has recently harmonized its requirements with the EU and will largely be on a par with the EU by the end of the decade.

- China has already adopted Euro 2 standards for both light and heavy vehicles and will introduce Euro 3 standards in Beijing and Shanghai in 2005 and 2006, respectively. Euro 3 and Euro 4 standards have been drafted with the ultimate schedule for national introduction still under discussion but likely in 2007 and 2010, respectively.

- Thailand has decided to proceed to Euro 4 standards by the end of the decade. Agreement has been reached with the fuels industry to reduce sulfur levels in both diesel and gasoline to a maximum of 50 ppm by 2010 and discussions are ongoing regarding a possible reduction to 10 ppm maximum.

- South Korea will introduce ULEV standards for gasoline fuelled cars and Euro 4 standards for diesel cars by 2006. Maximum sulfur levels for gasoline and diesel will be reduced to a maximum of 50 ppm and 30 ppm, respectively, in the same timeframe. They intend to tighten emissions standards by an additional 50% by 2010.

- Taiwan will reduce the maximum sulfur levels in both gasoline and diesel to 50 ppm by 2007. At the same time, they will introduce Tier 2 light duty vehicle and 2004 US heavy duty vehicle standards; Euro 4 standards for both light and heavy duty diesels will be deemed equivalent.

- The Japanese Ministry of the Environment has begun drafting new regulations on tailpipe emissions that would require reducing nitrogen oxide emissions by as much as 90 percent by fiscal 2010 from the current levels. The Automobile Emission Gas Expert Committee, which advises the Central Environment Council, began drafting a new diesel vehicle emission standard that would reduce NOx by as much as 92 percent and particulate matter by 93 percent from the fiscal 2003 regulations.

- The New Zealand government, the last OECD country without emissions standards for new vehicles, has adopted a new rule that applies to new and used gasoline and diesel light vehicles that enter New Zealand from Jan. 1, 2004. Heavy vehicles must comply with the rule by Jan. 1, 2005. The rule requires vehicles imported into New Zealand to be built to the version of the emissions standard that was current in Australia, the United States, Japan, or Europe at the date the vehicle was manufactured.

- India has adopted Euro 2 standards for 2005 and Euro 3 by 2010. The major cities will be on a faster schedule, moving to Euro 4 by 2010. Currently, 11 cities are required to meet Euro II norms: New Delhi, Mumbai (Bombay), Kolkata (Calcutta), Bangalore, Chennai, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, and Agra. Under the new policy, vehicles in the 11 cities now operating under Euro II standards will be required to meet Euro III norms by April 1, 2005, and Euro IV standards by 2010.

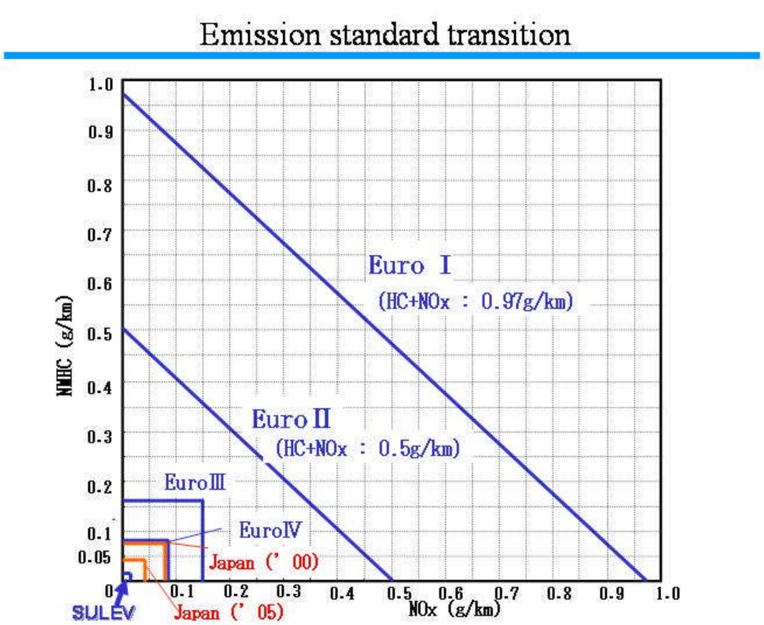
- Brazil will phase in US Tier 1 standards during the period from 2005-2007 jumping to Tier 2 in 2009. Diesel Cars will continue to be banned throughout the country. With regard to heavy duty trucks and buses, Euro 3 will be phased in during 2004-2006 and Euro 4 in 2009. Fuel quality remains under discussion with 50 ppm sulphur likely to be required in the major cities by 2009 or 2010.

2. International Best Practice

Based on all the developments around the world to date, one can point to a variety of Best Practices that have emerged. These will be summarized below.

A. Vehicle Emissions Standards are Approaching Zero

As illustrated below and discussed above, technologies and fuels are advancing sufficiently that new vehicle emissions standards are approaching levels which are somewhat difficult to measure. While these standards will be introduced initially in the highly industrialized countries, it is likely that many so-called developing countries will adopt similar requirements with only a short lag time.



In setting new vehicle standards, policymakers should be guided by the following best practice principles:

- New vehicle standards must be closely linked to fuel quality requirements as more advanced technologies are precluded by or diminished by certain fuel parameters such as lead in gasoline or high sulfur levels in gasoline or diesel.

- If the air pollution problem is serious, as it is in Vietnam's major cities, policymakers should strongly consider jumping forward to the most stringent standards possible after considering what quality of fuel could be made available.
- A short term and a longer-term plan for adopting vehicle and fuel standards should be adopted so that the vehicle and fuels industries have sufficient time to adapt. The longer-term goal for each country in Asia should be parity with European new vehicle and fuel standards by 2010 at the latest. Vehicles complying with 2010 US standards should also be acceptable.
- An active dialogue between the motor industry and oil industry to ensure that vehicle technologies and available fuels are closely linked should be strongly encouraged.
- As new vehicle standards are tightened, in use vehicle standards for those new models should also be tightened and these in turn should form the basis for routine vehicle inspections. Onboard Diagnostic Systems (OBD) which are linked to new vehicle standards can also play a critical role in controlling in use vehicle emissions.

B. New Gasoline Vehicle Technologies

With respect to best practice emissions technologies, catalytic converters have proven to be cost-effective means of reducing the emissions of CO, NO_x and hydrocarbons from gasoline vehicles and are now effectively mandatory in most industrial countries. Aside from catalytic converters, proven control technologies for gasoline vehicles include positive crankcase ventilation (recycling back exhaust gases that escape past the piston rings into the crankcase), canisters for controlling evaporative emissions, electronic ignition, computerized ignition timing, and fuel injection. Hydrocarbon losses during refueling can be controlled either by returning vapor from the vehicle to the service station tank or by using a larger carbon canister on the vehicle that traps the fuel vapors. On-board diagnostic systems which monitor emission control components are also beginning to be well established.

The newest vehicles, designed to meet stricter standards, come close to eliminating fuel-rich operation as very precise electronic control of air fuel and spark management systems continue to advance. Catalyst formulations and substrates also continue to advance including the introduction of much higher cell densities. Modern TWCs increasingly have the ability to store oxygen which allows for the efficient conversion of CO and HC during fuel-rich swings, including idle or acceleration periods. Increasingly strict emissions standards require extremely efficient catalysts over a long lifetime. Recent regulations in Europe and the U.S. require warmed-up catalysts to have over 98% HC control, even towards the end of the vehicle's lifetime (100,000 km in Europe and over 100,000 miles in the U.S.).

C. New Diesel Vehicle Technologies

Conventional diesel vehicles produce significant amounts of pollutant emissions - especially particulate matter (PM) and nitrogen oxides (NOx) - that cause a deterioration of air quality. In typical best practice diesel fuelled vehicles at present, these emissions are controlled primarily through improvements to the basic engine, rather than through the use of aftertreatment devices (other than diesel oxidation catalysts in limited applications.) These control techniques are usually limited by a NOx and PM tradeoff, where strategies to reduce one pollutant will result in an increase to the other.

NOx formation is directly dependent on the temperature. Increased combustion temperatures result in increased NOx. Therefore, best practice NOx control in an engine is accomplished by reducing peak combustion temperatures and the duration of these high temperatures in the combustion chamber. PM, on the other hand, is primarily the result of the incomplete combustion of diesel fuel. Best practice control technologies to reduce PM generally focus on improving combustion of the fuel, which results in higher combustion temperatures and NOx. Some best practice strategies currently used to control both diesel NOx and PM emissions include turbocharging, intercooling, combustion chamber design changes, injection timing retard, and high pressure fuel injection.

The turbocharger reduces both NOx and PM emissions by about 33%, compared to a naturally aspirated engine. The turbocharger boosts the pressure (and temperature) of the air entering the engine. This allows more fuel to be added to increase power output, while still inhibiting PM formation. The power to drive the turbocharger is extracted from the engine's exhaust stream. In effect, the turbocharger increases engine power and efficiency, which may translate to lower emissions.

The intercooling of the turbocharged air results in even greater NOx and PM reductions, by decreasing the temperature of the charged air after it has been heated by the turbocharger during compression. Cool air is denser than hot air and, therefore, this approach complements the turbocharger by further improving cylinder filling.

Combustion chamber design includes modifications to the shape of the chamber, location of the injection swirl, crevice volumes, and compression ratios. These can result in significant NOx and PM reductions by changing the conditions that occur during fuel combustion.

Injection timing retard is used to reduce the peak flame temperature and, thus, NOx emissions. However, timing retard typically lowers efficiency, resulting in increased fuel consumption and PM emissions. High pressure fuel injection can regain some of the efficiency loss by improving the atomization of the fuel spray and air utilization, resulting in more complete combustion.

In the 1990s, European manufacturers introduced oxidation catalysts on some of their truck engines and the majority of the urban bus engines to reduce PM emissions. Many diesel cars also contained oxidation catalysts. Flow through oxidation catalysts effectively oxidize gaseous hydrocarbons, as well as the soluble organic fraction of PM. A recent test program showed that oxidation catalysts reduced transient emissions of PM by 23 to 29% and hydrocarbons by 52 to 88%, using a lower sulfur fuel (368 parts per million sulfur). Testing with an even lower sulfur diesel fuel (54 parts per million sulfur) resulted in an additional 13% reduction in PM. The 1990s were also the period when the diesel engine best practice evolved into the electronic age.

Injection rate shaping is one way of tailoring the fuel injection event to reduce peak flame temperatures without impacts on fuel consumption. Injection rate shaping is possible because of electronic control and advances to the fuel injectors that work with the electronics. Approaches include using a pilot amount of fuel before the main injection event and splitting the main injection of fuel into two or more events. Injection rate shaping has been shown to simultaneously reduce NOx by 20 percent and PM by 50 percent, under certain operating conditions. Some fuel injection methods demonstrated to achieve effective rate shaping include the common rail, the mechanically actuated electronically controlled unit injector, and the hydraulically actuated, electronically controlled unit injector.

EGR has been researched extensively in recent years, especially as a means of complying with upcoming emission standards in the United States and Europe. EGR is the recirculation of a portion of the exhaust gas into the intake. It reduces NOx formation in the combustion chamber by diluting the air with inert mass (recirculated exhaust gas), which reduces peak flame temperatures when fuel is injected. Significant reductions of NOx emissions have been observed with the use of EGR. Laboratory studies have shown that EGR can reduce NOx by 40-50 percent at rated power, with minimal impact on PM, and by higher percentages at other loads, with some impacts on PM. These reductions rely on recirculating a large portion of the exhaust, with the amount depending on the speed and load of the engine.

For compliance with the very stringent emission standards which are emerging, NOx and PM aftertreatment devices will be necessary best practice to reduce emissions below levels achievable through engine modification strategies. A key reason for not previously using high efficiency aftertreatment devices is the lack of the in-use ultra-low sulfur fuel necessary to ensure the proper operation of aftertreatment devices and prevent sulfate formation. With the introduction of 10 or 15 parts per million sulfur diesel fuel, diesel engines equipped with aftertreatment devices and cooled EGR will be over 90 percent cleaner than today's engines. Diesel fuel with a maximum sulfur level of 10 ppm will be widely available across Europe by 2005 and will be used exclusively by 2009.

The best practice NOx aftertreatment devices under development include the lean NOx catalyst, the NOx adsorber, and selective catalytic reduction (SCR). Lean NOx catalysts (active systems with diesel fuel as the reductant) have been shown to provide up to 30 percent NOx reduction under certain operating conditions, although an increase in fuel consumption, for supplying the reductant, results.

NOx adsorbers operate by storing NOx under typical diesel engine operations ("lean" conditions). Before the NOx adsorbent becomes fully saturated, engine operating conditions and fueling rates are adjusted to produce a fuel-rich exhaust, which reduces the stored NOx into harmless N2. NOx adsorbers have been demonstrated to reduce NOx emissions by over 90 percent on ultra-low sulfur fuel, under many transient and steady-state conditions, with some fuel economy penalty. NOx adsorbers have a strong affinity for sulfur, which can deactivate the active catalyst sites and make the adsorbers less efficient over time. Improved NOx adsorber desulfurization systems, more sulfur resistant active catalyst layers, and other methods are currently being developed to maintain the NOx adsorber's high efficiency over the long useful life of the engine.

SCR has been used in stationary source applications for many years. It works by injecting ammonia or urea into the exhaust upstream of a catalyst to reduce NOx emissions. Studies have shown SCR can reduce NOx emissions by 20 to 35 percent over the transient FTP and by 15 to 99 percent over off-cycle tests. The main issues surrounding SCR usage are controlling the rate of urea introduced to maximize NOx reductions, without any "ammonia slip" through the catalyst, and ensuring that the urea is properly replenished throughout the vehicle life to ensure emission reductions.

A well-demonstrated best practice aftertreatment device for high-efficiency reduction of diesel PM is the diesel particulate filter (DPF). Over the last several years, test programs have focused on the emission reduction efficiency and durability of two types of DPFs, the catalyzed DPF and continuously regenerating DPF. In one program, using 54 parts per million sulfur fuel, the DPF reduced PM by 87 percent, to a level of 0.0008 g/bhp-hr, sufficient to comply with the US 2007 on-road truck and ARB's 2002 transit bus PM standards. Another program showed that heavy-duty trucks retrofitted with DPFs and using fuel with 2 parts per million sulfur emitted 91 to 99 percent less PM, compared to trucks using diesel fuel with 121 parts per million sulfur and with no exhaust aftertreatment devices.

In recent years, there has been concern over the reduction of not only PM mass emissions but also the number of particles, especially those of small size. Several studies have now shown that DPFs reduce the PM number count by 1 to 2 orders of magnitude as well as substantially reducing mass emissions.

The 2004 HD US standards lower NOx from present levels but retain the current PM standards. Therefore, manufacturers' approaches to complying with 2004 standards focus on improved fuel injection including rate shaping, combustion optimization, and in some cases exhaust gas recirculation (EGR) - possibly with variable rate turbocharging. According to the EPA, "engine manufacturers could meet the 2004 emission standards with engine control strategies". While there are other possible technologies that might be employed in 2007-10, the two that appear most likely are NOX adsorbers and catalyzed particulate filter systems.

According to the Clean Diesel Independent Review Panel, these technologies are making significant progress toward successful implementation in the 2007-2010 timeframe. The Panel found that Catalyzed Diesel Particulate Filters (CDPFs) are more mature than NOX adsorbers. According to the Panel, transit buses, school buses and other diesel vehicles are being retrofitted with CDPFs and other particulate filters throughout the US, and CDPFs are being used throughout Europe and elsewhere. Further, International Truck and Engine Company has already certified a CDPF-equipped medium-heavy-duty engine at the 2007 PM standard as well as the 2007 hydrocarbon standard. It should be noted, however, that these engines are limited to vehicle applications that fit the proper exhaust temperature profile and only use 15-ppm sulfur fuel.

In Europe on the other hand, many manufacturers expect to be able to achieve the EURO IV standards with oxidation catalysts and without the use of particle filters. Further NOx reductions will only be required in Europe in 2008. To achieve the Euro V standards, European manufacturers are focused on the use of SCR rather than NOx adsorbers and many are expected to use particle filters as well. One strategy being pursued would attempt to minimize engine out PM emissions and maximize fuel economy but with high engine out NOx; very efficient SCR would then be needed to meet the NOx standard. An alternative path would minimize engine out NOx and rely on very efficient particle filters to reduce PM. In the end it appears likely that some combination of these strategies will be needed.

Engine manufacturers design engines with a variety of factors in mind including costs, performance, fuel economy and emissions as well as other factors. Different engines, therefore, while complying with the same emissions standards (e.g., Euro 2) may utilize very different combinations of the above measures to achieve each engine's given market niche. Different manufacturers may also employ fundamentally different philosophies, believing for example that they have a competitive advantage with one technology versus another. Therefore in considering the discussion above, the important message is that there are a variety of technologies which have emerged and have been used by manufacturers to fulfill the emissions regulations of the market where the engine has been or will be sold.

D. Clean Fuels

In setting fuel quality standards, policymakers should be guided by the following best practice general principles:

- Implementing a successful systems approach to setting fuel standards will require institutional mechanisms that actively include a variety of stakeholders (government, private sector and civil society) and which allow for extensive consultation. In countries where such an institutional mechanism is not yet in place, it should be created.
- Because the environment and public health concerns are the driving force behind improvements in fuel quality the Environment Department should have a major role in setting fuel standards.
- All countries should develop a short and medium term strategy that identifies proposed standards to be adopted over the next several years so as to allow fuel providers and the vehicle industry sufficient time to adapt.
- The most important impediment to adopting state of the art new vehicle emission technology (equivalent to Euro III and IV) in Asia is the fuel quality, especially the level of lead and sulfur in gasoline and the level of sulfur in diesel. These parameters should receive highest priority in the development of medium and long-term strategies for fuel standards.
- In developing fuel standards, countries should attempt to work closely with neighboring countries and to harmonize standards where possible. This should not be used as an excuse for delaying or watering down requirements as harmonization does not mean that every country must follow the same time schedule.
- In order to implement stricter fuel standards and increase the acceptability of the associated costs to consumers, countries should institute more and better awareness campaigns. Such campaigns must emphasize the public health consequences of not improving fuel quality.
- Subsidies that favor fuels that result in high emissions should be eliminated and tax policies should be adopted which encourage the use of the cleanest fuels.

With regard to gasoline, the following best practice policies are recommended:

- The addition of lead to gasoline should be eliminated as rapidly as possible.

- In order to maximize the performance of current catalyst technology, sulfur concentrations in gasoline should be reduced to a maximum of 500 parts per million (ppm) as soon as new vehicle standards requiring catalysts are introduced. If the longer term target is 50 PPM or less (see below), consideration should be given to going directly to this level in one step which would reduce the overall cost.
- Emerging advanced catalyst technologies that are capable of achieving very low emissions will require a maximum of 50 ppm or less and a plan for introducing such fuel quality should be adopted at the early stages of development of a long term vehicle pollution control strategy.
- Gasoline vapor pressure should be reduced to a maximum of 60 kilopascals whenever temperatures in excess of 20° C are anticipated to occur. In tropical or semi-tropical countries, this is of course all the time.
- Benzene content should be reduced to a maximum of 1 percent by volume.
- To the extent that the long-term vehicle emissions standards strategy is to adopt European step 4 (so called Euro 4) standards for light duty vehicles, the European gasoline standards should be adopted in the same timeframe.

With regard to diesel fuel, the following best practice policies are recommended:

- To introduce Euro 2 standards, the maximum sulfur content should be reduced to 500 PPM; for Euro 3 vehicles, the maximum should be no more than 350 PPM; for Euro 4 vehicles, 50 PPM is required. Maximum emissions reductions from Euro 4 or more advanced systems will be achieved with a maximum of 10-PPM sulfur. A plan for introducing such low sulfur fuels should be adopted at the early stages of development of a long-term vehicle pollution control strategy.
- While interim improvements in diesel fuel quality will be beneficial to air quality, it is most efficient and cost effective for a refinery to go directly to lowest desired sulfur level rather than to do so with several interim steps.
- When low sulfur diesel fuel is introduced, strong consideration should be given to **retrofitting existing vehicles** with oxidation catalysts (500 PPM maximum sulfur) or diesel PM filters (50 PPM Maximum) which can achieve significant and rapid PM reductions.
- An effective means of encouraging the rapid introduction of low sulfur fuels beyond traditional command and control regulations is to adopt a tax policy that results in higher sulfur fuels costing more at the pump than lower sulfur fuels. Hong Kong has successfully implemented such a strategy.
- While less critical, other diesel fuel properties such as cetane number, density, distillation and polyaromatic content can also have positive or negative impacts on emissions and should be carefully evaluated.
- To the extent that the long term vehicle emissions standards strategy is to adopt European step 4 (so called Euro 4) standards for light duty vehicles and step 5 (so called Euro 5) standards for heavy duty vehicles, the European diesel fuel standards should be adopted in the same timeframe.

Reviews of the impact of various gasoline and diesel fuel properties on emissions from Asian vehicles are summarized in Appendices C and D, respectively.

Considering the current stage of development and emissions reduction potential of alternative fuels, the following best practice policies are recommended:

- Where compressed natural gas is readily available in a given locality, and where very low sulfur diesel (50 PPM or less) is not readily and reliably available, strong consideration should be given to replacing diesel buses with CNG buses. Other centrally fuelled fleets such as refuse trucks or local delivery trucks are also attractive candidates for replacement. (As noted above, where 50-PPM S or less diesel fuel is available, or is mandated to be made available within a reasonable time period (maximum 3 years or less) particulate filter retrofits should be considered as a possibly lower cost option.)

- Where compressed natural gas or LPG is readily available in a given locality, strong consideration should be given to replacing other high polluting vehicle types such as two stroke engined autorikshaws with CNG or LPG. Conversions to both LPG and CNG have been well established as a viable technology. In terms of PM and HC emissions reductions, the most successful strategy for three wheelers is to replace the existing petrol fuelled, two stroke engine with a CNG or LPG fuelled 4 stroke engine.
- There are several obstacles to the widespread use of natural gas and LPG fuelled vehicles including the absence of transportation and storage infrastructure, additional cost (primarily of the fuel storage tanks), loss of cargo space, increased refueling time, and lower driving range. Therefore, economic incentives in the form of lower taxes on fuels or other incentives should be considered as a means to stimulate the introduction and acceptance of these fuels
- Where LPG is readily available, and where ULSD is not readily and reliably available, strong consideration should be given to replacing diesel or petrol taxicabs with LPG.
- **Conversion of existing diesel vehicles** to natural gas is difficult and problematical and very often results in higher actual NOx emissions. Therefore, for diesel vehicles, **replacement** should be considered rather than conversion.
- Conversion of existing gasoline fuelled vehicles to CNG or LPG is not very difficult and if done well can result in emissions reductions. Therefore such conversions should be considered wherever such fuels are available in a given location.
- An inherent advantage of gaseous fuels is the assurance that adulteration will not be a problem. They are also inherently low in PM. These factors should be carefully taken into account when considering whether or not to switch vehicles to these fuels.

E. In Use Compliance With Standards

New vehicle standards are not intended to apply only when the vehicle comes off the assembly line but rather are intended to define the vehicle manufacturers' responsibilities over a reasonable period of actual in use driving. For example, the current EU requirements provide that the vehicle manufacturer is responsible for assuring that vehicles meet standards in use for 80,000 kilometers. In the US, they apply for 160,000 km. If substantial numbers of vehicles, which are properly cared for and driven, fail to meet their new vehicle standards in use over the defined period, using best practices they should be subject to a recall program whereby, at the manufacturers' costs, defective vehicles will be repaired. Further, defective parts for individual vehicles are covered by a warranty.

To trigger these recall or Conformity of Production programs, individual member states in the EU and the EPA in the US carry out in use testing programs using the same test procedures as the Type Approval or certification programs.

The United States has required the introduction of best practice onboard diagnostic or OBD systems since 1996 and they are required in Europe with the introduction of vehicles meeting Euro 3 requirements. As new vehicle standards in Asia are tightened to these levels, OBD systems can identify failures to vehicle owners as well as to in use vehicle inspectors. In the meantime, in order to assure that vehicles in use are properly cared for, many countries adopt in use standards based on short tests that are much less expensive to operate than typical Type Approval tests. These in use programs will be the subjects of the next section.

F. Inspection and Maintenance Requirements

Combustion powered vehicles naturally tend to deteriorate with age and usage, and as a result emission levels can rise significantly. Good maintenance is required to keep emissions levels at or near design levels. Such maintenance is not always performed or performed properly. Targeted I/M programs, however, can identify problem vehicles and assure their repair, thereby contributing substantially to lower emissions and improved air quality. In introducing best practice I/M programs, certain overriding principles have emerged which should guide policymakers in developing and implementing such programs:

- I/M program designs should be comprehensive and address a variety of important aspects from inception, including:
  - There must be a well thought out public awareness program that explains the public health need for the program, the potential benefits and how the program works.
  - Roadside apprehension or remote sensing programs to intercept vehicles that slip through the system or have problems in between periodic tests must be included.
  - The different pollutants of concern from diesel-fuelled vehicles (PM, smoke and NOx) and gasoline (petrol) fuelled vehicles (CO, HC and NOx) should be carefully accounted for in program design.
  - An effective enforcement mechanism to assure motorist participation in the program is essential for success. In areas where motor vehicle registration requirements are routinely and effectively enforced, registration-based I/M enforcement systems have been very effective.
  - Policies should be developed to prevent, root out and penalize any corruption that might creep into the system.
  - Sufficient flexibility should be built in to allow variations in frequency of inspections for vehicles with differing mileage accumulation rates and with more or less durable emission control systems.
  - Quality assurance including covert and overt auditing and quality control
  - The service industry must have sufficient equipment to properly repair vehicles. In addition, adequate training must be made available so that the mechanics and technicians are sufficiently skilled. Also careful attention must be paid to assuring that the service industry has sufficient lead-time to properly equip itself.
  - One mechanism for resolving disputes or difficulties with individual vehicles is the introduction of referee stations, where owners can get a second opinion and advice about appropriate repairs. Policymakers should carefully consider provision of one or more referee stations in the overall design of the program.
- So as not to overwhelm the service sector or create a strong political backlash, I/M stringency should be gradually phased in so that only the worst 15% to 20% of the vehicle fleet fails with periodic tightening of the in use standards as the service industry and maintenance practices adapt.

Appendix A: Recent EU Emissions Standards

Emission Limits For Passenger Cars

Emission Limits for Petrol Cars (g/km) [a]

PETROL	As from [b]:	CO	HC	NO_x
EURO I*	1/7/1992	4.05	0.66	0.49
EURO II*	1/1/1996	3.28	0.34	0.25
EURO III	1/1/2000	2.30	0.20	0.15
EURO IV	1/1/2005	1.00	0.10	0.08

* As measured on new test cycle for application in year 2000.

Emission Limits for Diesel Cars (g/km) [a]

DIESEL	As from [b]:	CO	HC	NO_x	PM
EURO I*	1/7/1992	2.88	0.20	0.78	0.14
EURO II*	1/1/1996	1.06	0.19	0.73	0.10
EURO III	1/1/2000	0.64	0.06	0.50	0.05
EURO IV	1/1/2005	0.50	0.05	0.25	0.025

* As measured on new test cycle for application in year 2000.

Notes:

a) "Euro 3 and 4" (Directive 98/69/EC): Standards also apply to light commercial vehicles (<1305 kg).
b) The above dates refer to new vehicle types; dates for new vehicles are 1 year later.

Emission Limits for Light Commercial Vehicles (Classes N1, N2 and N3)

Light Commercial Vehicles N1 Class (<1350 kg) Emission Limits (g/km).

N1	As from:	Fuel Type:	CO	HC	NO_x	HC + NO_x	PM
EURO I*	1/10/1994	All	2.72	-	-	0.97	0.14
EURO II*	1/1/1998	Petrol	2.2	-	-	0.5	-
		Diesel	1.0	-	-	0.60	0.1
EURO III	1/1/2001	Petrol	2.3	0.2	0.15	-	-
		Diesel	0.64	-	0.5	0.56	0.05
EURO IV	1/1/2006	Petrol	1	0.1	0.08	-	-
		Diesel	0.5	-	0.25	0.3	0.025

* For Euro I and II the weight classes were N1 (<1250 kg), N2 (1250-1700 kg) and N3 (>1700 kg)

Light Commercial Vehicles N2 Class (1305-1760 kg) Emission Limits (g/km).

N2	As from:	Fuel Type:	CO	HC	NO_x	HC + NO_x	PM
EURO I*	1/10/1994	All	5.17	-	-	1.4	0.19
EURO II*	1/1/1998	Petrol	4	-	-	0.65	-
		Diesel	1.2	-	-	1.1	0.15
EURO III	1/1/2002	Petrol	4.17	0.25	0.18	-	-
		Diesel	0.8	-	0.65	0.72	0.07
EURO IV	1/1/2006	Petrol	1.81	0.13	0.1	-	-
		Diesel	0.63	-	0.33	0.39	0.04

* For Euro I and II the weight classes were N1 (<1250 kg), N2 (1250-1700 kg) and N3 (>1700 kg)

Light Commercial Vehicles N3 Class (>1760 kg) Emission Limits (g/km).

N3	As from:	Fuel Type:	CO	HC	NO_x	HC + NO_x	PM
EURO I*	1/10/1994	All	6.9	-	-	1.7	0.25
EURO II*	1/1/1998	Petrol	5	-	-	0.8	-
		Diesel	1.35	-	-	1.3	0.2
EURO III	1/1/2002	Petrol	5.22	0.29	0.21	-	-
		Diesel	0.95	-	0.78	0.86	0.1
EURO IV	1/1/2006	Petrol	2.27	0.16	0.11	-	-
		Diesel	0.74	-	0.39	0.46	0.06

* For Euro I and II the weight classes were N1 (<1250 kg), N2 (1250-1700 kg) and N3 (>1700 kg)

Emissions Limits for Heavy Duty Vehicles

Emission Limits for Heavy Duty Vehicles. (G/kWh)

	As from:	Test cycle	CO	Total HC	Non-Methane HC	NO_x	Particulate Matter
EURO I	1/10/1993	13-mode	4.5	1.10	-	8	0.612 <85 kW 0.36 >85 kW
EURO II	1/10/1996	13-mode	4.0	1.10	-	7	0.15 (a)
EURO III	1/1/2000	ESC (c)	2.1	0.66	-	5	0.10 0.13 (b)
		ETC (d)	5.5	0.78	1.6	5	0.16 0.21 (b)
EURO IV	1/10/2005	ESC (c)	1.5	0.46	-	3.5	0.02
		ETC (d)	4.0	0.55	1.1	3.5	0.03
EURO V	1/10/200	ESC (c)	1.5	0.46	-	2	0.02

	8	ETC [d]	4.0	0.55	1.1	2	0.03

Notes:

(a) Until 30/11/1998 the particulate limit for engines <700 cc per cylinder and with a rated power speed of more than 3000 rpm was 0.25 g/kWh
(b) For engines <750 cc per cylinder and with a rated power speed greater than 3000 rpm
(c) Measured on the European Standard Cycle (ESC)
(d) Measured on the European Transient Cycle (ETC)

"Euro I and II": Directive 91/542/EEC; "Euro III, IV and V": Council position December 1998 and agreed with the European Parliament.

Relevant Fuel Specification Limits:

Relevant Petrol and Diesel Fuel Specification Limits

PETROL	2000	2005
RVP summer	60	-
Aromatics	42	35
Benzene	1	-
Olefins	18	-
Oxygen	2,7	-
Sulphur	150	50

DIESEL	2000	2005
CETANE # (MIN)	51	-
Density 15°C	845	-
Distillation 95°C	360	-
Polyaromatics	11	-
Sulphur	350	50

3. Appendix B: Brief Description of Refinery Processes

A. Atmospheric Crude Distillation Unit

The crude blend is heated and flashed into the crude distillation tower for fractionation into Light Hydrocarbons, Naphtha, Jet Fuel, Gas Oil and Atmospheric Residue. Kerosene and Gas Oil are drawn from the tower and sent to side strippers where volatile components are removed. The gas Oil component can go either to fuel blending (diesel fuel or other distillate products) or to hydro-treating for sulphur reduction. This Gas Oil is commonly called Straight-run Gas Oil.
The Gas Oil plus Kerosene yields of a crude distillation unit range typically between 20% and 50%, depending on the crude processed. Typical yields for some commonly used crude oils are:

Crude Type	**Gas Oil plus Kerosene Yields, wt%**
Arabian Light	33.1
Nigerian (Forcados)	47.2
Brent	35.5
Maya	23.1

B. Thermal Cracking

Conventional thermal cracking is now virtually obsolete, since there are several other superior cracking processes available. However some units are still in operation. The process requires the feed (generally heavy fuel oil and/or heavy gas oils) to be heated to around 500 deg.C at a pressure of up to 70 bars. Then it is passed into a soaking chamber, where the cracking reactions take place. The gas oil yields are about 30% (up to 60% is naphtha) of a fairly high sulphur and low cetane product.

C. Coking

This is a severe form of thermal cracking designed to convert residual products, such as heavy fuel oils, into gas, naphtha, gas oils and coke. It is a particularly valuable conversion process, when the market for heavy fuel oil is not attractive, compared to the markets for naphtha and gas oils. Light gas oil from this unit is usually stabilized in a hydro-treating unit. The heavy gas oil is often used as a feed for catalytic crackers or for hydro-crackers.

D. Visbreaking

It is a low severity form of thermal cracking, originally developed to reduce the viscosity of residual fuel oils, thereby minimizing the amount of higher value distillates needed as fuel oil fluxants. Nowadays it is most often used as a cheap process for converting some of the excess fuel oil into the more profitable distillate. In principle, the process is similar to the conventional thermal cracking, using temperatures up to about 500 deg.C, but lower pressures of about 20 bars. The yield of gas oil can vary between 15% and 25%, when using atmospheric residuum as feed. The visbreaker gas oil has usually high sulphur content.

E. Fluid Catalytic Cracking (FCC)

This is the most important and widely used process for converting heavy refinery streams into lighter products, and it is the most popular method of increasing the ratio of light to heavy products from crude oil. It has superseded conventional thermal cracking because of its higher yields, better product quality (particularly for gasoline blending components) and superior economics. The gas oils produced through this process (usually called cycle oils) are poor diesel fuel blending components, because of their high sulphur content and particularly for their very low cetane numbers.

F. Distillate Hydro-treating

Gas oil streams from the Atmospheric Crude Oil Distillation Unit, the various conversion units, and cycle oil from the FCC Unit can all be desulphurized by hydrogen treatment in Distillate Hydro-treating Units. There are many variations of this process, but they all use hydrogen, albeit at different pressures and with different catalysts. By far the largest fraction of distillate hydro-treating capacity world wide operates at low to medium hydrogen pressure, i.e. below 60 bars. At this level of pressures, hydro desulphurization units can reduce the sulphur level of straight-run distillates from Middle East crude oils down to 1,000 to 2,500 ppm, while the sulphur level of thermally cracked distillates (including visbreaker distillates) can be reduced to values ranging from 3,000 to 5,500 ppm.

High Pressure Hydro-treating units, operating with hydrogen pressures above 60 to 70 bars, can reduce the sulphur content of the treated gas oil down to about 200 ppm. The capital and operating costs of the high pressure units are significantly higher.

G. Hydro-cracking

The mechanism of hydro-cracking is similar to that of catalytic cracking, but with hydrogenation superimposed. A dual-function catalyst is needed which performs satisfactorily both cracking and hydrogenation reactions. Hydro-cracking is used mainly to produce low boiling fractions from heavier feed stocks, such as heavy gas oils, waxy distillates, etc. The degree of cracking depends greatly on the feed stock, and, in general, the heavier the feed the more middle distillate is produced.

The hydrogen requirement of these units is extremely high, so that, in general, it is necessary to have a hydrogen production plant as part of the hydro-cracker complex. The yields and product quality achieved depend on the feed and the severity of operation. However, in most cases, the units are run to maximize middle distillate production. In these cases, the distillate yields can be as high as 60% to 70%, the other products being saturated LPG, naphtha and Kerosene. The distillate produced by these units is characterized by a very low sulphur content (typically 10 ppm or even lower) and overall high quality.

4. Appendix C: Impact of Diesel Fuel Composition on Asian Vehicle Emissions[3]

The following tables summarize the impacts of various diesel fuel qualities on emissions from light and heavy duty diesel vehicles, respectively.

Impact of Fuels on Light Duty Diesel Vehicles

<table>
<tr><th>Diesel Fuel Characteristic</th><th>Pre-Euro</th><th>Euro 1</th><th>Euro 2</th><th>Euro 3</th><th>Euro 4</th><th>Euro 5[4]</th><th>Comments</th></tr>
<tr><td>Sulfur↑</td><td colspan="2">SO_2, PM↑</td><td colspan="2">If ox cat, SO_3, SO_2, PM↑</td><td colspan="2">If Filter, 50 ppm maximum, 10-15 ppm better</td><td>If NOx adsorber used requires near zero sulfur (<10 ppm)
With low S, use lubricity additives</td></tr>
<tr><td>Cetane↑</td><td colspan="6">Lower CO, HC, benzene, 1,3 butadiene, formaldehyde & acetaldehyde</td><td>Higher white smoke with low cetane fuels</td></tr>
<tr><td>Density↓</td><td colspan="6">PM, HC, CO, formaldehyde, acetaldehyde & benzene↓, NOx↑</td><td></td></tr>
<tr><td>Volatility (T95 from 370 to 325 C)</td><td colspan="6">NOx, HC increase, PM, CO decrease</td><td></td></tr>
<tr><td>Polyaromatics↓</td><td colspan="6">NOx, PM, formaldehyde & acetaldehyde↓ but HC, benzene & CO ↑</td><td>some studies show that total aromatics are important</td></tr>
</table>

Impact of Fuels on Heavy Duty Diesel Vehicles

<table>
<tr><th>Diesel</th><th>Pre-Euro</th><th>Euro 1</th><th>Euro 2</th><th>Euro 3</th><th>Euro 4</th><th>Euro 5[5]</th><th>Comments</th></tr>
<tr><td>Sulfur↑</td><td colspan="2">SO_2, PM↑</td><td colspan="2">If ox cat, SO_3, SO_2, PM↑</td><td colspan="2">If Filter, 50 ppm maximum, 10-15 ppm better</td><td>If NOx adsorber used requires near zero sulfur (<10 ppm)
With low S, use lubricity additives</td></tr>
<tr><td>Cetane↑</td><td colspan="6">Lower CO, HC, benzene, 1,3 butadiene, formaldehyde & acetaldehyde</td><td>Higher white smoke with low cetane fuels</td></tr>
</table>

[3] Most Asian countries have linked their vehicle emissions control programs to the EU or ECE requirements so much of the discussion that follows will relate fuels parameters to different technologies meeting EU standards.

[4] Euro 5 emissions standards for light duty diesel vehicles have not yet been adopted by the EU. However, the EU Commission has indicated that it will propose these standards during 2005 and they will likely become mandatory during the period from 2008-2010. It seems likely that these standards will mandate the use of PM filters on all light duty diesel vehicles.

[5] The EU Commission has also indicated that it will propose Euro 6 emissions standards for heavy duty engines during 2005, likely mandating the use of PM filters on all heavy duty diesel vehicles from 2010 or 2012.

Density↓	HC, CO ↑, NOx↓	
Volatility (T95 from 370 to 325 C)	Slightly lower NOx but increased HC	Too much heavy ends increases smoke and PM
Polyaromatics↓	NOx, PM, HC ↓	Some studies show that total aromatics are important

Higher **sulfur** content will tend to increase sulfur dioxide (SO_2) and PM emissions from all vehicle categories, from the least controlled to the most controlled. Sulfur dioxide is an acidic irritant that also leads to acid rain and the formation of sulfate particulate matter. As vehicle emissions standards are tightened to Euro 2 and Euro 3 levels, oxidation catalysts will tend to be introduced to reduce PM emissions but these systems will also tend to convert some of the SO_2 into more hazardous SO_3 emissions which when combined with water vapor leads to sulfuric acid mist (H_2SO_4). Further tightening of vehicle emissions standards will tend to require the introduction of PM filters on many vehicles and while these systems can largely eliminate PM emissions they tend to be very sensitive to sulfur levels in fuel. It is generally recommended that maximum sulfur levels with these systems be reduced to 50 ppm or less; many of these systems give optimum performance with fuels having sulfur levels in the range of 10 to 15 ppm or less. NOx control systems for diesel vehicles are still evolving with the two major candidates for Euro 4 and Euro 5 vehicles being Selective Catalytic Reduction (SCR) Systems which are not especially sensitive to sulfur levels in fuel[6] and NOx adsorber systems which are extremely sensitive to sulfur and require levels in the range of 10 to 15 ppm or less.

Cetane number is a measure of auto-ignition quality. High cetane number fuels enable an engine to be started more easily at lower air temperatures, reduce white smoke exhaust, and reduce diesel knock. An increase in cetane number generally results in a decrease in carbon monoxide and hydrocarbon emissions, nitrogen oxides emissions (most notably in heavy duty engines), as well as benzene, 1,3 butadiene, formaldehyde and acetaldehyde emissions from light duty engines. For diesel vehicles equipped with oxidation catalysts or catalyzed PM filters, emissions of CO, HC and the toxics, benzene, 1,3 butadiene, formaldehyde and acetaldehyde, will tend to be less sensitive to cetane number. While one major study (the EU EPEFE[7] study) found that particle emissions increased from light duty vehicles as the cetane number increased (no significant effect was seen in heavy duty engines) other research has suggested that an increase in cetane number can lead to lowered particle emissions.

Density relates to the energy content of fuel; the higher the density of the fuel the higher its energy content per unit volume. Too high a fuel density for the engine calibration has the effect of over-fuelling, increasing black smoke and other gaseous emissions. The European EPEFE study found that:

[6] While SCR systems are not particularly sensitive to sulfur levels, they tend to be combined with an oxidation catalyst to reduce ammonia slip and these oxidation catalysts are sensitive to sulfur levels. They will also tend to increase sulfate emissions levels.
[7] European Program on Emissions, Fuels and Engine technologies

- For light duty vehicles, reducing fuel density decreased emissions of particles, hydrocarbons, carbon monoxide, formaldehyde, acetaldehyde and benzene; increased emissions of NOx; but had no impact on the composition of the particle load.

- For heavy duty vehicles, reducing fuel density decreased emissions of NOx; increased emissions of hydrocarbons and carbon monoxide; but had no impact on particle emissions or the composition of the particle load.

CONCAWE investigations have shown that changes to engine calibration can considerably reduce the impact of changes in density (and viscosity) on emissions. Density effects could therefore be compensated for by changes in engine calibration.

The **distillation** curve of diesel fuel indicates the amount of fuel that will boil off at a given temperature. The curve can be divided into three parts: the light end, which affects startability; the region around the 50% evaporated point, which is linked to other fuel parameters such as viscosity and density; and the heavy end, characterized by the T90,[8] T95 and final boiling points. Investigations have shown that too much 'heavy ends' in the fuel's distillation curve can result in heavier combustion chamber deposits and increased tailpipe emissions of soot, smoke and particulate matter. The effect of T95 on vehicle emissions was examined in the EPEFE study which indicated that exhaust gas emissions from heavy duty diesel engines were not significantly influenced by T95-variations between 375°C and 320°C. However, a tendency for lower NOx and higher hydrocarbon emissions with lower T95 was observed.

Polyaromatic hydrocarbons (PAHs) are increasingly attracting special attention because many are known human carcinogens. Testing for the EU EPEFE study showed that:

- For light duty vehicles reducing polyaromatics decreased NOx, particles, formaldehyde and acetaldehyde emissions, but increased hydrocarbon, benzene and carbon monoxide emissions.
- for heavy duty vehicles, reducing polyaromatics decreased NOx, particles and hydrocarbon emissions

[8] The temperature at which 90% of the fuel will evaporate.

5. Appendix D: Impact of Gasoline Composition on Asian Vehicle Emissions.

The following tables summarize the impacts of various diesel fuel qualities on emissions from light duty gasoline vehicles.

Impact of Gasoline Composition on Emissions from Light Duty Vehicles

Gasoline	No Catalyst	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Comments
Lead ↑	Pb, HC↑	CO, HC, NOx all increase dramatically as catalyst destroyed					
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NOx all increase ~15-20% SO_2 and SO_3 increase					MIL light may come on incorrectly
Olefins ↑	Increased 1,3 butadiene, increased HC reactivity, NOx, small increases in HC for Euro 3 and cleaner						Potential deposit buildup
Aromatics ↑	Increased benzene in exhaust						Deposits on intake valves and combustion chamber tend to increase
	potential increases in HC, NOx	HC↑, NOx↓, CO↑		HC, NOx, CO ↑			
Benzene ↑	Increased benzene exhaust and evaporative emissions						
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NOx increase(when above 2% oxygen content), Higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Concerns over Water Contamination
Distillation Characteristics T50, T90↑	Probably HC↑	HC↑					
MMT ↑	Increased Manganese Emissions			Possible Catalyst Plugging	Likely Catalyst Plugging		O_2 sensor and OBD may be damaged, MIL light may come on incorrectly
RVP ↑	Increased evaporative HC Emissions						Most critical parameter for Asian countries because of high ambient

			Temperatures
Deposit control additives ↑		Potential HC, NOx emissions benefits	Help to reduce deposits on fuel injectors, carburetors, intake valves, combustion chamber

Lead additives have been blended with gasoline, primarily to boost octane levels, since the 1920s but there is now a clear worldwide trend to eliminate their use and most Asian countries have done so. Lead emissions from all vehicles using leaded gasoline increase in direct proportion to the amount of lead consumed. This lead is toxic and has long been recognized as posing a serious health risk especially for children. In addition, vehicles using leaded gasoline cannot use a catalytic converter (required to comply with Euro 1 emissions standards or tighter) and therefore have much higher levels of CO, HC and NOx emissions.

Sulfur dioxide emissions increase from all categories of gasoline fueled vehicles in direct proportion to the amount of **sulfur** in fuel. Sulfur dioxide is an acidic irritant that also leads to acid rain and the formation of sulfate particulate matter. Its greatest impact, however, is in vehicles equipped with catalytic converter technology, required for compliance with Euro 1 or tighter vehicle emissions standards. Testing of catalysts has demonstrated reductions in efficiency resulting from higher sulfur levels across a full range of air/fuel ratios. The effect is greater in percentage for lower emission vehicles (Euro 3, 4 and 5) than for less controlled vehicles (Euro 1 or 2). The durability of catalysts is also impacted by sulfur levels in fuels as active catalyst sites tend to get coated with sulfur compounds. Studies have also shown that sulfur adversely affects heated exhaust gas oxygen sensors; slows the lean-to-rich transition, thereby introducing an unintended rich bias into the emission calibration; and may affect the durability of advanced on-board diagnostic (OBD) systems.

The lean-burn gasoline engine with direct fuel injection which is emerging makes possible a 15% decrease in fuel consumption compared with conventional gasoline engines thereby reducing greenhouse emissions. In Europe, there is a clear recognition that to be able to comply with future ‘severe emissions limit values’, the use of NOx accumulator DeNOx catalytic converters will be necessary. Even low levels of sulfur in fuel lead to deterioration in the accumulation capacity of this catalytic converter and make more frequent regeneration intervals necessary, which causes an increase in fuel consumption. A reduction of the fuel sulfur content from 50 to 10 ppm lowers the frequency of the regeneration intervals, and decreases fuel consumption; with sulfur levels above 50 ppm, DeNOx catalysts are not feasible.

The EU EPEFE study found that reducing sulfur from 382 to 18 ppm reduced exhaust emissions of HC, CO and NOx (the effects were generally linear at around 8-10% in urban driving and 20 to 50% in high speed driving). In the case of air toxins, benzene and C3-12 alkanes were in line with overall hydrocarbon reductions, with larger reductions (around 18%) for methane and ethane.

Gasoline **volatility** is an indication of how readily a fuel evaporates and is characterized by two measurements – vapor pressure and distillation. High gasoline **vapor pressure** causes high evaporative hydrocarbon emissions which can comprise a large part of total hydrocarbon emissions. Their release may occur during the delivery and transfer of gasoline to storage, vehicle refueling, the diurnal breathing of vehicle fuel tanks (as they heat up and cool down with normal daily temperature variations), and the fugitive losses that occur from carburetors and other equipment during normal vehicle operation. Reductions in fuel volatility will significantly reduce evaporative emissions from vehicles. A reduction in vapor pressure is one of the more cost effective of the fuel-related approaches available to reduce hydrocarbon emissions.

Vapor pressure is most effectively managed on a regional and seasonal basis to allow for the different volatility needs of gasoline at different temperatures. The reduction of evaporative emissions is most effectively achieved when RVP is controlled when ambient temperatures are high – i.e. the summer period. Any associated cold weather driveability-related problems can be addressed by either restricting limits to the summer period, or by shortening the summer period and/or setting regional volatility limits to take into account both climatic and seasonal temperature profiles.

Distillation is a second method for measuring the volatility of gasoline. The EPEFE study found that increasing E100 in gasoline (the percentage of gasoline evaporated at 100°C) reduces emissions of hydrocarbons but increases NOx emissions. Increasing E100 from 35% to 50% by volume showed a decrease in mass emissions of both formaldehyde and acetaldehyde but increasing E100 from 50 % to 65 % by volume showed no clear effect.

Olefins are good high octane components of gasoline but they can lead to the build up of engine deposits and increased emissions of highly reactive ozone-forming hydrocarbons and toxic compounds. They tend to be chemically more reactive than other hydrocarbon types. A study by the US Auto/Oil program concluded that reducing total olefins from 20% to 5% would significantly decrease ozone-forming potential. Reduction of low molecular weight olefins accounts for about 70% of the ozone reduction effect. In addition, 1,3-butadiene, a known carcinogen, is formed during the combustion of olefin compounds in gasoline and is therefore reduced by lowering the olefin fraction in gasoline.

Aromatics are hydrocarbon fuel molecules based on the ringed six-carbon benzene series or related organic groups. Combustion of aromatics can lead to the formation of benzene in exhaust gas, a human carcinogen that can cause leukemia in exposed persons. Lowering aromatic levels in gasoline significantly reduces toxic benzene emissions from vehicle exhausts. In the EU EPEFE study, benzene emissions were found to vary between 3.6% and 7.65 % of total volatile organic compounds for fuel aromatic contents ranging from 19.5% to 51.1% by volume.

Benzene is a six-carbon, colorless aromatic that occurs naturally in gasoline and is also a product of catalytic reforming used to boost octane levels. Benzene in gasoline leads to both evaporative and exhaust emissions of benzene.

Oxygen is added to gasoline to improve combustion, to limit emissions of ozone precursors and carbon monoxide, and/or to raise octane levels. The principal oxygenates which are used today are ethanol and MTBE. Where ethanol is used, evaporative HC emissions can increase significantly if the RVP of the fuel is allowed to increase. Increases in NOx exhaust emissions can occur with either oxygenate when the oxygen content is higher than 2 weight %. (There is some debate regarding the NOx effect for newer technology vehicles.) The magnitude of the reductions in HC exhaust emissions depends upon the vehicle technology; while older (pre Euro 1) vehicles would experience some reductions in exhaust emissions, newer vehicles (Euro 1 and newer) with oxygen sensors and adaptive learning systems will experience little or no effects. HC emissions during storage and transportation depend upon the presence or absence of Stage I and Stage II vapor recovery systems. Carbon monoxide emissions can decrease by around 10% following an increase in gasoline oxygen content from 0 to 2% (by weight).

Certain other **additives** which are put into gasoline can also affect vehicle emissions. Methylcyclopentadienyl manganese tricarbonyl (**MMT**) when added to gasoline will increase manganese emissions from all categories of vehicles. Vehicle manufacturers have expressed concerns regarding catalyst plugging and oxygen sensor damage with MMT use which could lead to higher in use vehicle emissions especially at higher mileage. The impact seems greatest with vehicles meeting tight emissions standards and using high cell density catalyst substrates.

Deposit control additives can reduce the build up of deposits on various engine components including fuel injectors and carburetors thereby maintaining low emissions from vehicles.

Two and Three Wheeled Vehicles

Many countries and cities throughout Asia have much higher proportions of two and three wheeled vehicles than anywhere else in the world. While emissions from these vehicles are expected to be influenced by fuel characteristics, there has been very little study focused on the impacts of specific fuel parameters on these vehicles. However, based on the limited available data and the combustion similarities between these and other internal combustion engines, these impacts are estimated to be as shown in the table below.

Impact of Gasoline Composition on Emissions from Motorcycles

Gasoline	No Catalyst	India 2005	Euro 3	India 2008	Taipei,China Stage 4	Comments
Lead ↑	Pb, HC↑	CO, HC, NOx all increase dramatically as catalyst destroyed				
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NOx all increase SO_2 and SO_3 increase				
Olefins ↑	Increased 1,3 butadiene, HC reactivity and NOx					Potential deposit buildup
Aromatics ↑	Increased benzene exhaust					
Benzene ↑	Increased benzene exhaust and evaporative emissions					
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NOx increase	Minimal effect with oxygen sensor equipped vehicles				Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit

			issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC	Minimal effect with ox. sensor equipped vehicles	Concerns over Water Contamination small fuel economy penalty
Distillation characteristics T50, T90 ↑	Probably HC↑	HC↑	Not as quantifiable as in passenger cars
MMT ↑	Increased Manganese Emissions	Possible Catalyst Plugging	With low cell density, catalyst plugging risk seems small but there are concerns regarding deposits on spark plugs and in the combustion chamber
RVP ↑	Increased evaporative HC Emissions		
Deposit control additives ↑		potential emissions benefits	Help to reduce deposits on fuel injectors, carburetors

Most two and three wheeled vehicles currently used throughout the region are not equipped with catalytic converters to control emissions. Therefore it would seem that the impact of the various fuels parameters will be similar to those from pre Euro 1 cars. Some catalysts are starting to enter the fleet as emissions standards are being tightened, especially in India, Taipei,China and Europe. These vehicles are anticipated to be impacted by sulfur and lead in a manner similar to Euro 1 and 2 gasoline fueled cars. For two and three wheeled vehicles equipped with 2-stroke engines, the amount and quality of the lubricating oil is probably more important than fuel quality.