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3. INTERNATIONAL FUEL QUALITY STUDIES AND REGULATIONS

This chapter reviews fuel quality studies undertaken in Australia and overseas, enabling a comparison and appreciation of the fuel parameters which are important in determining air emission. While Chapter 2 focuses on issues related to motor vehicle emissions, including the policy setting and motor vehicle emission control technology, this section deals with issues related to fuel quality.

The relevant Australian Government policies are summarised to provide a background to the legislative setting in Australia. Several studies undertaken in Australia and overseas which examined the relationship between fuel quality parameters and motor vehicle emissions are then described. The section concludes with a summary of the international fuel quality regulations and specifications.

The structure of this chapter is as follows:

Section 3.1 provides an overview of the petrol and diesel fuel quality parameters included in the fuel quality studies. The fuel quality studies undertaken in Australia are reviewed in Sections 3.2, including;

- The Independent Inquiry into Urban Air Pollution in Australia;
- Review of Australian Design Rule ADR 37/01 and 70/00; and
- The fuel quality recommendations included in the report by the Motor Vehicle Environment Committee (MVEC), '*Review of Motor Vehicle Emission Standards*'.

Commonwealth and State Government policy initiatives related to fuel quality are also outlined in Section 3.2. The Australian government policy setting for fuel quality and motor vehicle emissions are summarised in Section 3.2.6 of this report. The Commonwealth Government policy related to ambient air quality is summarised in Section 2.1.2.

Section 3.3 describes major fuel quality studies undertaken overseas:

- The US / Auto Oil Air Quality Improvement Research Program (AQIRP); and
- The European Auto Oil Program and the European Programme on Emissions, Fuels and Engine Technologies.

Section 3.4 summarises the existing international fuel quality regulations and specifications.

3.1 Parameters Included In The Fuel Quality Studies

The fuel quality parameters which are included in the discussion of the fuel quality studies are discussed below (from *World Wide Fuel Charter, 1998*). Some of these parameters have an impact on air pollution and/or motor vehicle emissions, while others are related to motor vehicle performance.

3.1.1 Petrol Fuel Quality Parameters

Octane

Octane is a measure of a petrol's ability to resist auto-ignition, which can cause engine knock. There are two laboratory test methods to measure petrol octane numbers: one determines the Research Octane Number (RON) and the other, the Motor Octane Number (MON). RON correlates best with low speed, mild-knocking conditions and MON correlates with high-temperature knocking conditions and with part-throttle operation. RON values are typically higher than MON and the difference between these values is the sensitivity, which should not exceed 10.

Vehicles are designed and calibrated for a certain octane value. When a customer uses petrol with an octane level lower than that required, knocking may result, which could lead to severe engine damage. Engines equipped with knock sensors can handle lower octane levels by retarding the spark timing; however, fuel consumption and power suffer and at very low octane levels, knock may still occur. Using petrol with an octane rating higher than that required will not improve the vehicle's performance.

In older-model engines, lower octane provided the same anti-knock performance at high altitude, as higher octane at sea level. Since 1984, however, most vehicles have been equipped with sophisticated electronic control systems, which adjust to changes in air temperature and barometric pressure. These vehicles require the same octane levels at all altitudes. Thus, petrol octane levels should not be lower at higher altitudes.

Petrol research and motor octane number (RON and MON) can have an important influence on engine performance and durability when the engine's octane requirement is not satisfied. Most Euro-compliant engines are designed for 95 RON, with some designed for 98 RON. The introduction of Euro emission standards in Australia will therefore increase demand for 95 RON ULP, and may create a niche demand for 98 RON ULP.

Sulfur

Sulfur naturally occurs in crude oil. If the sulfur is not removed during the refining process it will contaminate vehicle fuel. Sulfur has a significant impact on vehicle emissions by reducing the efficiency of catalysts. Sulfur also adversely affects heated exhaust gas oxygen sensors. Reductions in sulfur will provide immediate reductions of emissions from all catalyst-equipped vehicles on the road.

Lead

Historically, lead alkyl additives have been used as inexpensive octane enhancers for petrol. Concerns over health effects associated with the use of this additive have resulted in many markets eliminating leaded petrol. While the phase-out of leaded petrol is supported, consideration must be given to the existing vehicle fleet as some older vehicles may require lead (or lead replacement additives) for engine protection.

Low-lead petrol at 0.05g/l is supported in leaded petrol markets. This reduces the risk of unleaded contamination and still provides adequate engine protection.

Unleaded petrol is necessary to support vehicle emission control technologies such as catalytic converters and oxygen sensors. As vehicle catalyst efficiencies are increased, tolerance to lead contamination decreases; even slight lead contamination can destroy a modern catalyst.

Oxygenates

Oxygenated organic compounds, such as MTBE and ethanol, are often added to petrol to increase octane, to extend petrol supplies, or to induce a lean shift in fuel/air stoichiometry to reduce carbon monoxide emissions. The “leaner” operation reduces carbon monoxide emissions, especially with carburetor equipped vehicles without electronic feedback-controlled fuel systems.

These emission benefits are not achieved as well in modern electronic feedback controlled vehicles because the lean air/fuel ratio effect only occurs during cold operation or during rapid acceleration. In fact, leaner fuel/air ratios caused by oxygenates can degrade “drivability” depending on the “leaness” of the engine’s base calibration using petrol without oxygenate. This over-leaning can also cause emissions to increase. Because ethanol has a higher heat of vapourisation than ethers, some of the drivability degradation of petrol / ethanol mixtures can be attributed to the additional heat needed to vapourise the petrol.

Olefins

Olefins are unsaturated hydrocarbons and, in many cases, are also good octane components of petrol. However, olefins in petrol can lead to deposit formation and increased emissions of reactive (ozone-forming) hydrocarbons and toxic compounds.

Olefins are thermally unstable and may lead to gum formation and deposits in an engine’s intake system. Furthermore, their evaporation into the atmosphere as chemically reactive species contributes to ozone formation and their combustion products form toxic dienes.

Aromatics

Aromatics are fuel molecules that contain at least one benzene ring. In general, aromatics are good octane components of petrol and high-energy density fuel molecules. Fuel aromatic content can increase engine deposits and increase tailpipe emissions.

Heavy aromatics, and other high molecular weight compounds, have been linked to engine deposit formation, particularly combustion chamber deposits. These deposits increase tailpipe emissions, including HC and NO_x.

Benzene

Benzene is a naturally occurring constituent of crude oil and is also a product of catalytic reforming, which produces high-octane petrol streams. It is a known human carcinogen.

The control of benzene levels in petrol is the most direct way to limit evaporative and exhaust emissions of benzene from automobiles. The control of benzene in petrol has been recognised by regulators in many countries as an effective way to reduce human exposure to benzene. These petrol recommendations recognise the increasing need for control of benzene concentration as emission standards become more stringent

Volatility

Sufficient volatility of petrol is critical to the operation of spark ignition engines with respect to both performance and emissions. Volatility is characterised by two measurements, vapour pressure and distillation.

Vapour Pressure

The vapour pressure of petrol should be controlled seasonally to allow for the differing volatility needs of vehicles at different temperatures. Lower vapour pressure is required at higher temperatures to reduce the possibility of hot fuel handling problems and to reduce evaporative emissions. Reid Vapour Pressure (RVP) is a measure of the volatility of fuels, especially petrol.

Distillation

Distillation of petrol yields either a set of 'T' points (eg. T50 is the temperature at which 50% of the petrol distils) or 'E' points (eg. E100 is the percentage of petrol distilled at 100 degrees). Excessively high T50 (low E100) can lead to poor starting and warm up performance at moderate ambient temperatures.

3.1.2 Diesel Fuel Quality Parameters

Cetane Number

Cetane number is a measure of the compression ignition behaviour of a fuel; it influences cold start-ability, exhaust emissions and combustion noise. Cetane index is the 'natural' cetane of the fuel, which is calculated based on measured fuel properties. The cetane number is measured on a test engine and reflects the effects of cetane improver additives. As shown below, natural cetane levels affect vehicle performance differently from cetane levels modified by additives. To avoid excessive additive dosage, a minimum difference between cetane index and cetane number must be maintained.

Density and Viscosity

The diesel fuel injection is controlled volumetrically or by timing of the solenoid valve. Variations in fuel density (and viscosity) result in variations in engine power and, consequently, in engine emissions and fuel consumption.

Influence of fuel density on emission control systems

Production diesel engines are set to a standard density, which determines the amount of fuel injected. The volumetric injection quantity is a control parameter for other emission control systems, such as exhaust gas recirculation (EGR). Variations in fuel density therefore result in non-optimal EGR-rates for a given load and speed point in the engine map and, as a consequence, influence the exhaust emissions.

Influence of fuel viscosity on injection system performance

Fuel quantity injected and injection timing is also dependent on fuel viscosity. High viscosity can reduce fuel flow rates, resulting in inadequate fueling. A very high viscosity may actually result in pump distortion. Low viscosity, on the other hand, will increase leakage from the pump elements, and in worse cases (low viscosity, high temperature) can result in total leakage. As viscosity is affected by ambient temperature, it is important to minimise the range between minimum and maximum viscosity limits to allow optimum engine performance.

Sulfur in Diesel

Diesel fuel sulfur contributes significantly to fine particulate matter (PM) emissions, through the formation of sulfates both in the exhaust stream and, later in the atmosphere. Sulfur can lead to corrosion and wear of engine systems. Furthermore the efficiency of some exhaust after-treatment systems is reduced as fuel sulfur content increases, while others are rendered permanently ineffective through sulfur poisoning.

Aromatics in Diesel

The aromatics content of diesel fuel influences flame temperature, and consequently, NO_x emissions during the combustion. Polyaromatics in the fuel affect the formation of particulates and emissions of polycyclic aromatic hydrocarbons (PAHs) from a diesel engine.

Distillation Characteristics

The distillation curve of diesel fuel indicates the amount of fuel which 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, characterised by the T90, T95 and final boiling points (FBP). (T90 is the temperature at which 90% of the fuel distills).

3.2 Review Of Fuel Quality Studies Undertaken In Australia And Australian Government Policies Relating To Fuel Quality

Recent studies undertaken in Australia which provide information on the relationship between fuel quality and motor vehicle emissions include:

- A report by the Australian Academy of Technological Sciences and Engineering (AATSE), *'Independent Inquiry into Urban Air Pollution in Australia'*, which identified a number of specific links between fuel characteristics and vehicle emissions;
- The current reviews of Australian Design Rule (ADR) 37 on light spark ignition (petrol) vehicles and ADR 70 on compression ignition (diesel) vehicles, which has highlighted issues with respect to fuel characteristics; and
- The fuel quality recommendations included in the report by the Motor Vehicle Environment Committee (MVEC), *'Review of Motor Vehicle Emission Standards'*.

The Commonwealth Government's *'A New Tax System'* legislation was passed by Parliament in June 1999. The legislation includes several commitments which will impact on future vehicle emissions and fuel standards, under the *'Measures for a Better Environment'* element of the *'Tax Package Agreement'*.

Recent Commonwealth Government policy statements have made reference to fuel quality and vehicle emission standards. The Prime Minister's statement on climate change in November 1997, *'Safeguarding the Future: Australia's Response to Climate Change'*, includes several commitments of relevance to this study. The National Greenhouse Strategy, including the Environmental Strategy for the motor vehicle industry, includes policy initiatives related to the phasing out of leaded petrol, as discussed in Section 2.1.2. State Government policy initiatives have also made reference to fuel quality standards, particularly in New South Wales, Victoria and Western Australia.

These major elements of these studies and policies are summarised below.

3.2.1 Review of Australian Design Rule ADR 37/01 and 70/00, 1996

Coffey Partners International Pty Ltd (Coffey) prepared a report entitled *'Parameter Projections for the Reviews of ADR 37/01 and ADR 70/00 by ACVEN'* in 1996. Coffey were commissioned by the Federal Office of Road Safety (FORS) to draw together existing data and projections on parameters relevant to the consideration of future emission controls for road vehicles in Australia. The information provided was used as input for policy development in the review of ADR 37/01 and ADR 70/00. The recommendations made by ACVEN for further work have largely been carried out within the joint NEPC/NRTC Motor Vehicle Environment Committee, as ACVEN was disbanded in 1997.

The information collated for the 1996 Coffey report, which is relevant to the Review of Fuel Quality Standards for Australian Transport includes:

- Fleet composition including vehicle types and age structure;
- Fuel properties, use and efficiency;
- Vehicle emissions including exhaust and evaporatives; and
- Air quality in Australian urban centres.

The report includes some discussion of the impact of fuel characteristics on vehicle emissions, as summarised below:

Impact of aromatic concentration on vehicle emissions

The report states that:

“...tests conducted with benzene free petrol revealed that vehicle exhaust contained significant levels of benzene, the absolute value being dependent on the fuel’s aromatic fraction. In the case of benzene free petrol with 40% aromatics (by weight), 3.8% of exhaust hydrocarbons was found to be emitted as benzene.”

Reformulated Petrol

The results of a study undertaken by Bishop and Stedman (1990) showed that carbon monoxide (CO) emissions decreased by around 13 to 19% following an increase in petrol oxygen content from 0 to 2% (by weight).

The report also quotes dynamometer studies which indicate that:

“...an increase in oxygenates such as methyl tertiary butyl ether (MTBE) from 0 to 2% results in a reduction of CO emissions by 15 to 20%, reduction of hydrocarbon emissions by 8% and no significant change in nitrogen oxide (NO_x) emissions from light duty vehicles. (Hockhauser et. al., 1991; Gething, 1991 and Hoekman, 1992). An increase of 1 to 9% in NO_x emissions was found when fuel ethanol was increased from 0 to 3.5% (Reuter et. al., 1992).”

Alternative Fuels

The report included a summary of results from Radian (1992), which showed that, in comparison with petrol, reformulated petrol, LPG, CNG, M85 (85% methanol - 15% petrol blend), M100 (100% methanol) and E85 (85% ethanol - 15% petrol blend) have significantly less benzene and toluene emissions. Methanol and methanol-petrol blends, however, have higher 1,3-butadiene and formaldehyde emissions compared with petrol.

3.2.2 Independent Inquiry into Urban Air Pollution in Australia

An inquiry was commissioned by the Federal Minister for the Environment and was carried out by the Australian Academy of Technological Sciences and Engineering

(AATSE) in 1997, to determine the need for and to propose actions that would maintain or improve air quality in the future.

The objectives of this review included:

- Identification of current trends, scale and likely future sources of the major air pollutants which affect air quality;
- Identification and evaluation of management options for each of the identified pollutants; and
- Strategies and objectives for the reduction of air pollution in Australia.

The objective of identification and evaluation of management options for pollutants specifically addressed the emissions associated with motor vehicles, including the examination of:

- Tailpipe and evaporative emissions from new and in-service vehicles; and
- The composition of vehicle fuels (including alternative fuels).

The report states that Australia's vehicle fleet:

“...is the single greatest source of atmospheric pollutants. However, it is noted that ‘the introduction of unleaded petrol and of catalytic converters to minimise vehicle tailpipe emissions has had a marked effect on lead loading into airsheds as well as helping to contain the level of other pollutants.’”

The continuing growth of our cities and increased traffic congestion are noted as major pressures on urban air quality, with pollution incidents expected to increase with increases in vehicle kilometres travelled.

The basic policy options for dealing with pollution from motor vehicles are to reduce motor vehicle use and to clean up the vehicles. The report focused on the latter, providing three priority areas for measures directed towards the optimisation of the vehicle fleet:

- *Ensuring that motor vehicles are intrinsically low polluters when they are first brought into service;*
- *Ensuring that transport vehicles maintain compliance with realistic standards, based on those they had to meet when new; and*
- *Providing the cleanest, economically viable fuels to operate the vehicles.*

The report emphasises that initiatives should be implemented now to reduce this pressure on urban air quality from motor vehicles, stating that:

“Many initiatives, such as new emission standards for vehicles, will take seven or more years to have major effect. The decision to implement them needs to be taken now. A number, such as in-service maintenance of vehicles ensuring compliance with pertinent emission standards can have a much more immediate effect.”

Some of the recommended measures and options outlined in the AATSE report that are particularly relevant to the current Fuel Quality Study include:

- Australia should, without delay, move to adopt the current United Nations Economic Commission for Europe (UNECE) vehicle emission regulations for spark-ignition and diesel engines, as the basis for certifying all new vehicles sold in Australia;
- That emission limits based on ADR standards are set for the in-service life of vehicles, backed by effective inspection and maintenance programs in the major urban airsheds. Included in this recommendation is the proposed identification of a test for high polluting diesel vehicles. Diesel fuel quality is mentioned in this discussion, and it is stated that:

“...although there is some dispute as to the extent of the relationship, emissions of potentially carcinogenic fine particles are linked to levels of sulfur in diesel fuel.”

- Governments and industry should jointly explore the potential emissions benefits that could flow from:
 - Reducing the sulfur content of diesel fuel to levels comparable with those planned for Europe;
 - Assessing the likely benefits of mandating the use of detergent additives in diesel fuel to combat the build-up of detrimental deposits on fuel injectors;
 - A voluntary reduction of 9 kPa in petrol vapour pressure, currently being discussed between the oil industry and the NSW EPA for the Sydney airshed, should be strongly supported in view of its significant impact on evaporative VOC emissions. Similar reductions for other regions should be examined;
 - The use of CNG and LPG in all classes of vehicles should be encouraged through clear policies in the use of gaseous fuels and by increased investment in refuelling infrastructures and vehicles in both the private and public sectors; and
 - R&D and awareness programs which maintain Australia's stake in the implementation of future advanced vehicle technologies should be maintained.

3.2.3 The Prime Minister's Statement on Climate Change

The Prime Minister's statement on climate change in November 1997, '*Safeguarding the Future: Australia's Response to Climate Change*', includes a commitment to implement an Automotive Industry Environmental Strategy. The statement listed the elements of the strategy to include:

- Mandatory, model specific, fuel efficiency labelling;

- Harmonised noxious emission standards with international standards by 2006;
- A 15% fuel efficiency improvement target by 2010 over business as usual through negotiation; and
- Bringing forward the phase out of leaded petrol, taking equity considerations into account.

In addition, it is stated that the government will develop a basic network of compressed natural gas refuelling stations in selected metropolitan areas to encourage light commercial vehicles to switch to this more environmentally friendly fuel.

3.2.4 Fuel Quality Recommendations in MVEC's 'Review of Motor Vehicle Emission Standards'

MVEC's recommendations state that 'MVEC recognised that fuel characteristics will play an important role in the in-service delivery of the new emission standards, particularly Euro 3 and beyond'. The recommendations for fuel quality included in the MVEC report are as follows:

- *Voluntary reduction of the sulfur content of diesel fuel to 500 ppm in urban areas from 2000;*
- *Sulfur standard for road transport diesel set at 500 ppm from end 2002; and*
- *Sulfur standard for road transport diesel set at 50 ppm from 2006.*

The MVEC report stated that:

"...the adoption of tighter diesel emission standards will require a reduction in the sulfur content of diesel fuel, initially to 500ppm, and then to 50 ppm for the introduction of Euro 4 in 2006. The adoption of Euro 3 for petrol vehicles in 2005 will require changes to fuel parameters, based on the outcomes of the Fuel Quality Review and discussions with stakeholders. There is currently no mechanism for setting national fuel standards. This has been recognised by the National Environmental Protection Council (NEPC) and MVEC. The Commonwealth states that a mandatory 50ppm sulfur diesel standard may be introduced through a National Environment Protection Measure, equivalent legislative device or by use of the definition in the diesel fuel credit scheme."

3.2.5 State Government Policy Initiatives

State Government policy initiatives related to fuel quality and motor vehicle emissions are summarised below.

New South Wales

The NSW Government's Air Quality Management Plan, *Action for Air*, (NSW EPA 1998), indicated initiatives of relevance to the Review of Fuel Quality Requirements for Australian Transport, including:

- The reduction of petrol volatility in Sydney in summer. NSW has negotiated a Memorandum of Understanding with the Petroleum Industry for a phased reduction of petrol Reid vapour pressure (RVP) to 67 kPa for summer 1999/2000 and 62 kPa for summer 2000/2001);
- Assurance of cutting edge technology in the state bus fleet, including the specification of Euro 2 standards in all supply contracts from 1997, and the supply of 300 additional CNG-fuelled buses over the 5 years from 1997;
- Investigation of the merits of reducing sulfur in petrol;
- Support for the development of a diesel NEPM;
- Support for research to identify effective emission control strategies;
- Participation in the Western Sydney Natural Gas Vehicles Project, in partnership with Liverpool Council, NRMA Clean Air 2000, Planet Ark, and the Australian Gas Vehicles Association; and
- Development of a Cleaner Transport Fuels and Technology Strategy, in which the Premier's Department is working with AGL, the Australian Natural Gas Vehicles Council, the NRMA, Universities and the CSIRO.

Queensland

The South East Queensland Regional Air Quality Strategy (SEQRAQS) document was released in December 1999. SEQRAQS is a regional air quality strategy that was developed with community consultation and active involvement from State and Local Government, industry associations and community groups.

Studies undertaken in the development of the strategy found that motor vehicles contribute about 72% of all anthropogenic sources of air pollution in South East Queensland (excluding emissions from biogenic sources, controlled burning and natural events such as bushfires). The document includes strategies for improving air quality in the region, in areas including transport. The key strategy approaches in reducing overall transport emissions include:

- reduce new vehicle emissions and facilitate the adoption of new transport and emission control technologies;
- improve in-service emissions controls and performance; and
- improve fuel quality and increase use of low polluting fuels.

There is also one specific strategy to '*reduce vehicle emissions through fuel reformulation*'. The key actions for this strategy include:

- Negotiation with the AIP and other members of the industry for a 9kPa reduction in the vapour pressure of petrol as a means of reducing evaporative emissions from vehicles;

- Advocate the Commonwealth for an incentive scheme to be extended to the purchase and use of low sulfur fuels (ie those which maximise the emissions performance of Euro 2 and Euro 4 vehicles); and
- Monitor fuel supplies to ensure the availability of an adequate supply in south-east Queensland of low sulfur fuels (250 to 500 ppm). In the longer term, ensure the availability of very low sulfur fuels (less than 50 ppm).

The State of the Environment Queensland 1999 states that motor vehicles and power stations are the major sources of Queensland's air pollutants, with the Brisbane and Gladstone airsheds most affected. The introduction of unleaded petrol and lower lead content leaded fuel were found to have greatly reduced air pollution levels in Queensland, which are now consistently below national guidelines.

The Queensland Government announced new fuel quality regulations under the Environment Protection Act in February 2000. The regulations will require Queensland oil refiners to reduce sulfur levels in diesel fuel to 500 ppm by mid 2001 and remove lead from petrol by March 2001.

Western Australia

Fuel quality specifications have been regulated in Western Australian from December 1999, under the Environmental Protection (Diesel and Petrol) Regulations 1999, as part of Western Australia's Environment Protection Act 1986. The regulation specifies a 500ppm limit on the sulfur content of diesel from 1 January 2000. The following specifications (as maximum concentrations) have been set for petrol:

Specifications for Supplies in 2000 (maximum levels)

Hydrocarbons:	
Aromatics	48.0% v/v
Benzene	2.0% v/v
Oxygenates:	
Methyl tertiary-butyl ether (MTBE)	0.10% v/v
Lead:	13mg/L

Specifications for Supplies in 2002 (maximum levels)

Hydrocarbons:	
Aromatics	42.0% v/v
Benzene	1.0% v/v
Olefins	18.0% v/v
Oxygenates:	
Methyl tertiary-butyl ether (MTBE)	0.10% v/v
Lead:	5mg/L
Sulfur:	150 mg/kg.

The Report of the Select Committee on Perth's Air Quality (1998) included in its recommendations that:

“The State Government should develop a fuel formulation policy, specifying minimum fuel quality parameters (initially) for sulfur, vapour pressure and other constituents, for locally produced and imported petrol and diesel fuel.”

One of the main outcomes of the report was Government support for the development of an Air Quality Management Plan (AQMP) for Perth. This AQMP is due for release by the Western Australian Department of Environmental Protection in February 2000, and will include a review of the merits of more detailed fuel specification policies and regulatory mechanisms. Opportunities are also being explored for the early reduction of the benzene content and vapour pressure of petrol and the sulfur content of diesel fuel.

3.3 Review Of Fuel Quality Studies Undertaken Overseas

A number of overseas studies have been undertaken on fuel specifications. The recent Auto/Oil Quality Improvement Research Program (AQIRP) in the US showed a clear relationship between fuel specifications and emissions in petrol fuelled vehicles. A similar study in Europe, the European Auto-Oil Program (EPEFE) carried out by the European Motor Industry (represented by ACEA) and the European Oil Industry (represented by EUROPIA) identified the effect of changing specific fuel characteristics on emissions from diesel and petrol vehicles.

As a result, in US and in the EU, fuel compositional changes have been driven by vehicle emission requirements and by engine emission control technologies. More recent emission control standards have been coupled with mandated quality and compositional requirements for market petrol and diesel fuel.

The AQIRP and EPEFE studies are discussed in more detail below.

3.3.1 US Auto/ Oil AQIRP Program

The Auto Oil/Air Quality Improvement Research Program (AQIRP) was established in 1989 by 14 oil companies and three domestic car makers, in anticipation of new laws in Washington and California, which could require cleaner burning fuels and lower emitting vehicles to help improve air quality.

AQIRP has made substantial progress in developing an information base on fuel and vehicle effects on emissions. A summary report, “Auto/Oil Air Quality Improvement Research Program Phase I Final Report”, was published in May 1993. It describes program findings from 1989 through 1992. The Program Final Report summarising Phases I and II, was published in January 1997 by the program's Coordinating Research Council.

The overall objective of AQIRP was to provide data to help legislators and regulators achieve the nation's clean air goals through a research program consisting of three components:

- Extensive programs of vehicle emission measurements;
- Air-quality modeling studies to predict the effects of the measured emissions on ozone formation; and
- Economic analysis of some of the fuel / vehicle systems.

AQIRP studies were designed to measure the effect of petrol fuel composition changes in various spark-ignition engines on both the amount and speciation of organic compounds emitted and the amounts of CO and NO_x emitted, and then to predict the impact of these changes on air quality. Diesel fuels were not included in the study.

Over the course of the six-year program, AQIRP conducted more than 5,000 emissions tests using over 90 fuel compositions in over 100 vehicles with spark-ignition engines. Two fleets were used for the emission tests for the Phase I study - a 'current' fleet, consisting of twenty 1989 model vehicles with new emission control technology, and an 'old' fleet of 14 1983-1985 vehicles, equipped primarily with carbureted engines. The Phase II tests included testing on 'California Tier 0' (1993 models), 'Federal Tier I (1994 models) and 'Advanced' (mid 1990's models).

The tests measured engine, tailpipe, evaporative and running-loss emissions, and quantified the concentrations of 153 different organic compounds plus oxides of nitrogen (NO_x) and carbon monoxide (CO). The data generated by these tests was used by AQIRP to develop an extensive database of fuel composition and vehicle effects on emissions.

The aim of the Phase I study was to determine some of the key components of petrol that affect vehicle emissions. Emissions were measured in vehicles of varying ages using petrols with different compositions of the following:

- total aromatic content;
- total olefin content;
- oxygenate type and content;
- sulfur content;
- Reid vapour pressure (RVP); and
- 90% distillation temperature.

Emissions were also measured from alternative fuels: CNG, methanol and ethanol blends with and without petrol.

The Phase II tests included further investigation of the distillation and sulfur effects found in Phase I.

The petrol fuel parameters tested in the Auto/Oil program and their impact on mass exhaust emissions (Phase I and II tests) are summarised in Table 3-1.

TABLE 3-1 IMPACT OF PETROL FUEL PARAMETERS ON EXHAUST EMISSIONS

Fuel Parameter Changed	Percent Change in Emissions			
	Hydrocarbons	Carbon Monoxide (CO)	Nitrogen Oxides (NO _x)	Air Toxics ¹
Reduce aromatics 45 to 20%	-6 (older fleet) +14 (current fleet)	0 (older fleet) -13 (current fleet)	-11 (older fleet) 0 (newer fleet)	-23 (older fleet) -28 (current fleet)
Add oxygenates 0 to 15%	-5	-11	0	Slight reduction in benzene; slight increase in aldehydes
Reduce olefins 20 to 5%	+6	0	-6	0 (total) -30 (butadiene)
Reduce heavy ends (T ₉₀) ¹ 360 to 280°F	-6 (older fleet) -22 (current fleet)	+14 (older fleet) 0 (current fleet)	0 (older fleet) +5 (current fleet)	0 (older fleet) -16 (current fleet)
Reduce T ₅₀ from 215 to 185°F	-5 to +10 (Federal Tier 1 and Advanced fleet)	-5 (Federal Tier 1 and advanced fleet)	+5 (current)	-10 (advanced fleet)
Reduce sulfur 450 to 50 ppm	-18 (current fleet)	-19 (current fleet)	-8 (current fleet)	-10
Reduce sulfur 320 to 35 ppm	-20 (Federal Tier 1)	-16 (Federal Tier 1)	-9 (Federal Tier 1)	-16 (Federal Tier 1)
Reduce RVP 9 to 8 psi	-4	-9	0	0

1: Includes benzene, 1,3-butadiene and acetaldehydes

2: T₉₀ = 90% distillation temperature

Older fleet - 1983-1985 model vehicles

Current fleet - 1989 model vehicles

California Tier 0 - 1993 model vehicles

Advanced - Mid 1990's model vehicles

The impact of changes in petrol fuel quality parameters on predicted ozone, as presented in the AQIRP report, are summarised in Table 3-2. It should be noted recognised that impacts on ozone concentration are strongly dependent on local factors and therefore cannot be readily applied to areas other than those considered in the AQIRP study.

TABLE 3-2 IMPACT OF CHANGES TO PETROL FUEL QUALITY PARAMETERS ON PREDICTED OZONE REDUCTION

Fuel Quality Parameter Changed	Impact on Predicted Ozone Reduction
Reduce aromatics 45 to 20%	No clear effect
Add oxygenates 0 to 15%	No clear effect
Reduce olefins 20 to 5%	Effective
Reduce heavy ends (T ₉₀) ¹ 360 to 280°F	Effective ¹
Reduce sulfur 450 to 50 ppm	Effective
Reduce RVP 9 to 8 psi	Effective

1: The Phase II results indicate that where distillation effects were significant, reducing T₉₀ from 325°F to 280°F reduced the light duty vehicle contribution to peak ozone by 4 to 6% and about 2% for T₅₀ reductions.

The effects of changing multiple parameters simultaneously were also noted in the AQIRP Phase I report (1993). Two of the main effects noted are summarised below:

- Interaction between aromatics and oxygenates - at low levels of aromatics, NO_x levels increased by about 5%;
- Reductions in T₉₀ reduced hydrocarbon emissions by a greater extent when the aromatics content was high.

The impact of changes in fuel quality parameters on fuel economy are summarised in Table 3-3.

TABLE 3-3 IMPACT OF CHANGES TO PETROL FUEL QUALITY PARAMETERS ON FUEL ECONOMY

Fuel Parameter Changed	Reduction in Fuel Economy (%)
Reduce aromatics 45 to 20%	1 to 3
Add oxygenates 0 to 15%	1 to 2
Reduce olefins 20 to 5%	less than 0.5
Reduce heavy ends (T ₉₀) ¹ 360 to 280°F	less than 1.5
Reduce sulfur 450 to 50 ppm	0
Reduce RVP 9 to 8 psi	0

The AQIRP report (1997) stated that the Phase I and II studies....

'confirmed that changes in automotive fuel could significantly reduce the contribution of both new and old cars and light-duty trucks to:

- *Ozone;*
- *Amounts of emission of regulated pollutants: - hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x);*
- *The reactivity of the emissions; and*
- *Toxic air pollutants (toxics).*

Program studies also confirmed that the changes in vehicle technology in the late 1980s substantially lowered regulated and toxic emissions, and ozone compared with technology used in the mid-1980s. Changes in technology since the late 1980s have brought additional, smaller, reductions. Additional changes in technology will provide still smaller absolute reductions'.

3.3.2 European Auto-Oil Program and EPEFE

Background and European Union legislation on vehicle emission standards

Despite the achievements of the vehicle emission standards set by the European Union in reducing the emissions of individual vehicles, it was considered that increased numbers of vehicles and increased vehicle-kilometres were likely to hinder the reduction of total emissions and attainment of future air quality objectives. It was also recognised that the emission reduction potential offered by further improvements in vehicle technology is limited and possibly very costly in comparison to other potential solutions. (The European Union's vehicle emission control standards and the introduction of emission Directives are discussed in Section 2.1.5).

The Commission organised a conference in October 1992 to discuss the issue of vehicle emission standards for the year 2000 and beyond. The conference concluded future emission standards should be based on an integrated approach and should aim to achieve air quality targets.

The EC Council and Parliament adopted this approach in the 1994 Directive¹. The main elements of the relevant Article of the Directive in outline are:

"In these proposals future proposals for emission standards to apply from 2000, the Commission shall take the following approach:

- *the measures shall be designed to produce effects to meet the requirements of the Community's air quality criteria and related objectives, and*
- *an assessment of the cost effectiveness of taking each measure shall be undertaken; in this global assessment full account shall be taken of the*

¹ Directive 94/12/EC

contributions that:

- *enhanced urban public transport,*
- *new propulsion technologies (e.g. electric propulsion),*
- *use of alternative fuels (e.g. biofuels), could make to improving air quality.*

The measures shall be reasonable in the light of the intended objectives.”

The proposals, taking account of the methodology outlined above and aimed at a substantial reduction of pollutant emissions from the vehicles covered by the Directive, were to include the following elements:

1. *Further improvements in the requirements of this Directive based on the assessment of:*

- *the potential of the traditional engine and post-combustion technology,*
- *possible improvements in the test procedure, e.g. cold-start, starting in low or wintry temperatures, durability (e.g. in the conformity tests), evaporative emissions,*
- *measures supporting strengthened inspection and maintenance requirements, including, for example, on-board diagnostic systems,*
- *the possibility of checking the emissions control performance of registered vehicles in use, and*
- *the need for:*
 - (i) *specific limits for HC and NO_x in addition to a cumulative limit, and measures to cover pollutants not yet regulated.*

2. *Complementary technical measures in the framework of specific Directives, including:*

- *improvements in fuel quality as far as vehicle emissions of dangerous substances, in particular benzene, are concerned,*
- *strengthening of the requirements of the inspection and maintenance programme.”*

Article 4 of the 1994 Directive² is the formal expression of the framework within which the Commission carried out its preparatory work for the development of legislative proposals directed at the reduction of emissions from road transport to be effective from the year 2000.

Objectives of the Auto Oil Programme

As noted in section 2.1.5, the European Auto / Oil program was initiated by the Commission to research and make recommendations for further emission reductions, following on from the 1994 Directive which brought in Euro 2 standards.

² Directive 94/12/EC

The objective of the Auto Oil programme was defined as:

“...to provide policy-makers with an objective assessment of the most cost-effective package of measures including vehicle technology, fuel quality, improved durability and non-technical measures, necessary to reduce emissions from the road transport sector to a level consistent with the attainment of the new air quality standards being developed for adoption across the European Union.”

The work programme was divided into a number of inter-related components as follows:

- (i) prediction of future air quality in the Community and, in the case where future air quality was predicted to fall below an acceptable standard, the identification of appropriate emission reduction targets for road transport;
- (ii) collation and, where necessary, the development of data concerning the potential of the various measures including engine technology, fuel quality, increased durability requirements and complementary measures, to reduce emissions from road transport;
- (iii) collation and, where necessary, the estimation of the costs of introducing those measures identified under (ii); and
- (iv) identification of the most cost-effective package of measures necessary to achieve the emission reduction targets identified in step (i) using the information produced in steps (ii) and (iii) above.

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE)

The EPEFE programme formed a component of the European Auto/Oil programme. The EPEFE report states that the programme was:

“...designed to extend the information on the relationships between fuel properties and engine technologies and to quantify the reduction in road traffic emissions that can be achieved by combining advanced fuels with the vehicle/engine technologies under development for the year 2000.”

The objectives of the EPEFE programme, as outlined in the report, were:

- To quantify further reductions in road traffic emissions, which would be expected to achieve agreed air quality objectives;
- To identify sets of measures - including improvements in fuel/vehicle technologies as well as other measures such as inspection and maintenance programmes, traffic control-which could achieve the emission reductions; and
- To evaluate the cost-effectiveness of the measures and to identify the most cost-effective.

EPEFE Programme Design and Test Protocols

A literature review was undertaken prior to the commencement of the EPEFE programme, which was summarised in a report, *“Effect of Fuel Qualities and Related*

Vehicle Technologies on European Vehicle Emissions” (ACEA, EUROPIA and EC, 1995). The results of this literature review were presented in a paper prepared by the Department of Mechanical Engineering at Aristotle University, Thessaloniki, Greece, as summarised in the following tables:

Table 3-4: Effect of Improved Petrol on the Emissions of Non-Catalyst Light Duty Vehicles

Property	Change	Pb	CO	VOC exh	VOC evap	NO _x
Lead	0.15 to 0.08 g/L	-50%	0	0	0	0
Oxygenates	0 to 2.7% O ₂	0	-20 to -40%	-2 to -10%	0 to +10%	-2 to +2%
Aromatics	40 to 25%	0	0	-2 to -10%	0	-2 to -10%
Benzene	3 to 2%	0	0	0	0	0
Olefins	10 to 5%	0	-2 to +2%	+2 to +5%	-2 to 0%	-2 to -10%
Sulfur	300 to 100 ppm	0	0	0	0	0
RVP	70 to 60 kPa	0	0	-2 to +2%	-20%	0
E100	50 to 60%	0	0 to 2%	-2 to -10%	-2 to +2%	0
E150	85 to 90	0	0	-10 to -20%	0	+2 to +10%

Source: ACEA, EUROPEA and EC, 1995

Table 3-5: Effect of Petrol Properties on the Emissions of Catalyst Light Duty Vehicles

Property	Change	Pb	CO	VOC exh	VOC evap	NO _x
Lead	0.013 to 0.005 g/L	-2 to -10%	0 to -2%	0 to -2%	0	0 to -2%
Benzene	3 to 2%	0	0	0	0	0
RVP	70 to 60 kPa	0	0	0 to -2%	-2 to -10%	0

Source: ACEA, EUROPEA and EC, 1995

NOTE: The effects of changes to CO, VOC, NO_x and benzene on emissions of catalyst light duty vehicles were included in the report in the form of a series of regression equations.

The EPEFE final report states:

“...that the literature review ‘identified areas in which the changing effects of fuel qualities can be quantified, such as sulfur in diesel fuel, oxygenates and benzene content of petrol, as well as areas with knowledge gaps...EPEFE specifically addressed these gaps.’”

The programme assessed the effects of variations in the following fuel parameters³ on emission levels:

- Sulfur content, mid-range distillation (E100) and aromatic content of petrols; and
- Cetane number, polycyclic aromatic hydrocarbons (content), density and back-end distillation point (T95) of diesel.

The EPEFE programme also examined the impact of changes in vehicle technology and emission control systems on motor vehicle emissions. To achieve this, the

³ Fuel parameters are defined in Section 2.2.1.

engine / vehicle configurations were chosen to give the widest possible range of technology features used, from light passenger cars to heavy duty trucks.

The programme included the examination of 12 petrol test fuels in 16 vehicles, and 11 diesel fuels in 19 light duty and five heavy duty vehicles. More than 2000 emission tests were run and over 500,000 data items were produced.

The emission tests were run over the urban driving sequence (ECE cycle), from a cold start, and over the extra urban driving sequence (EUDC cycle), conducted when the catalyst was warmed up. The composite cycle measures emissions over both the ECE and EUDC cycle.

All light duty vehicles tested exceeded the requirements of the 1996 European emission standards, that is, Euro 2. Heavy duty engines exceeded the Euro 2 emission standards.

A wide range of exhaust emissions were investigated, including:

- Carbon monoxide, CO.
- Nitrogen oxides, NO_x
- Total hydrocarbons, HC
- Particulate matter quantity and composition
- Individual hydrocarbons and other organic species

Results of the EPEFE Study

The results of the EPEFE study for changes to petrol and diesel specifications are summarised in the following sections, extracted from the executive summary of the EPEFE report (European Programme on Emissions, Fuels and Engine Technologies).

Reduction of Aromatic Content and Increase E100 of Petrol

The results of the emissions testing undertaken as part of the EPEFE programme for fuel with reduced aromatic content and/or increased E100 are summarised below:

- Reducing aromatic content reduced HC and CO emissions but increased NO_x emissions over the full European driving cycle for constant E100;
- Increasing E100 also reduced HC emissions, increased NO_x emissions, while CO emissions were at their lowest value at E100 of 50% v/v, all for constant aromatics;
- Over the ECE cycle, HC emissions increased with increasing aromatic content. Over the EUDC cycle, when the engine is fully warm, the response of HC emissions to both aromatics and E100, while in the same direction as over the ECE cycle, was consistently lower;
- CO emissions increased linearly with increasing aromatics over the ECE, EUDC and full test cycle at constant E100;

- Increasing E100 at constant aromatics gave a non-linear CO emissions response over the ECE and the full test cycle, with the lowest emissions at E100 of 50% v/v. Over the EUDC cycle however, CO emissions decreased linearly;
- NO_x emissions showed different linear responses to increasing aromatics content over the two driving sequences of the test cycle. Over the ECE, NO_x increased with increasing aromatics, but over the EUDC, NO_x decreased with increasing aromatics. In this case, the EUDC effect was larger so that composite NO_x emissions also decreased with increasing aromatics. The reason for this effect is believed to be lower NO_x conversion efficiency over the catalyst with low aromatic fuels;
- CO₂ emissions decreased with reducing aromatics due to their effect on H/C ratio and hence the carbon content of the fuel;
- No clear effect of aromatics or E100 were found on calculated fuel consumption in the EPEFE programme;
- Benzene emissions decreased with decreased aromatic content. Benzene mass emissions generally also decreased with increasing E100 in line with total HC emissions, although at 20% v/v aromatics there was little effect.
- E100 or aromatics did not appear to influence 1,3-butadiene mass emissions in the exhaust gases; and
- Formaldehyde and acetaldehyde emissions showed a slight decrease with increasing aromatic content.

The impact of changes in petrol aromatic content on motor vehicle emissions from the EPEFE study are summarised in Table 3-6.

Table 3-6: Impact of Changes in Petrol Aromatic Content on Motor Vehicle Emissions from EPEFE Study

		Percent Change in Emissions		
		CO	HC	NO _x
Reduce Aromatic Content 50 to 20%	Including all results	-14.1 to -31.7	-8.7 to -31.7	-16.7 to +81.2
	Excluding EUDC cycle results	-14.1 to -18.5	Test cycle did not have significant impact on changes to emissions	-16.7 to +15.0

Sulfur in petrol

The effect of reducing fuel sulfur on regulated emissions was generally linear over the range studied.

Reducing sulfur content in petrols lowered HC, CO and NO_x emissions over the new European driving cycle consisting of an urban driving sequence (ECE) and an extra urban driving sequence (EUDC).

The relative effects of lowering the sulfur content were larger over the EUDC sequence than over the ECE sequence. Over the ECE sequence, the sulfur effect was significant only for CO emissions. This confirms that fuel sulfur affected catalyst

efficiency and had the greatest effect on a warmed up catalyst. The 4 km ECE driving sequence is run after an engine cold start and the vehicle must complete less than 1 km before the catalyst reaches its light-off temperature.

The relative distribution of HC species in the exhaust gases was unaffected by the fuel sulfur content. However, the absolute effect (g/km) for benzene and alkanes was:

- Benzene and C₃-C₁₂ alkanes were reduced upon sulfur reduction by an amount equivalent to the reduction measured for the total HC emissions.
- Methane and ethane were reduced by a larger amount.
- Three other toxics: 1,3-butadiene, formaldehyde and acetaldehyde were unaffected by changes in the petrol sulfur content.

The impact of changes in petrol sulfur concentration on light duty motor vehicle emissions, as indicated by the results of the EPEFE study, is summarised in Table 3-7.

Table 3-7: Impact of Changes in Petrol Sulfur Concentration on Motor Vehicle Emissions from EPEFE Study

		Percent Change in Emissions		
		CO	HC	NO _x
Sulfur 382 to 18 ppm	Composite cycle	-9.0	-8.6	-10.4
	EUDC cycle	-42.6	-52	-20.3

Note: Fuel effects have been described through regression equations. When these are linear it is possible to express these effects in both absolute values and percentages from a baseline petrol. (Sulfur = 382 ppm)

Changes to Diesel Fuel Parameters

The EPEFE programme assessed the impact of changes in diesel fuel parameters on emissions from light and heavy duty vehicles.

The parameters which were changed as part of the programme were Cetane number, polycyclic aromatic hydrocarbons (content), density and back-end distillation point (T95).

All comments concerning light duty (LD) diesel vehicles apply to the full European driving cycle, for heavy duty (HD) diesel engines the ECE R49 13 mode test cycle was used.

Density

Reducing density *decreased*:

- NO_x emissions in HD engines.
- PM emissions in LD vehicles. No significant effect was seen in HD engines.
- CO and HC emissions in LD vehicles.

- Benzene, 1,3-butadiene, formaldehyde and acetaldehyde in LD vehicles⁴.

Reducing density *increased*:

- NO_x emissions in LD vehicles.
- HC and CO emissions in HD engines

Poly-aromatics

Reducing poly-aromatics content *reduced*:

- NO_x emissions and PM emissions in both LD vehicles and HD engines
- HC emissions in HD engines
- Formaldehyde and acetaldehyde emissions in LD vehicles

Reducing poly-aromatics content *increased*:

- CO and HC emissions in LD vehicles.
- Benzene emissions in LD vehicles.

Cetane number

Increasing cetane number:

- Decreased NO_x emissions from HD engines only.
- Increased PM in LD vehicles with no significant effect from HD engines.
- Decreased benzene, 1,3-butadiene, formaldehyde and acetaldehyde emissions from LD vehicles.
- Decreased HC and CO emissions from both LD vehicles and HD engines.

ADO T95

Decreasing T95:

- Increased formaldehyde and acetaldehyde emissions from LD vehicles.
- Increased HC and CO emissions from HD engines.
- Increased NO_x emissions in LD vehicles
- Decreased PM emissions from LD vehicles.
- Decreased NO_x emissions from HD engines

The results for light duty vehicles are summarised in Table 3-8.

⁴ Emissions species could not be measured from HD engines

Table 3-8: Impact of Changes to Diesel Fuel Parameters on Motor Vehicle Emissions (Light Duty Vehicles) (from EPEFE Study)

Changes to Diesel Fuel Parameters	CO	HC	NO _x	PM	CO ₂
Density 855 to 828 g/L	-0.082 g/km -17.1 %	-0.018 g/km -18.9 %	+0.008 g/km +1.4 %	-0.012 g/km -19.4 %	-1.586 g/km -0.9 %
PAH 8 to 1%	+0.018 g/km +4.0 %	+0.005 g/km 5.5 %	-0.019 g/km -3.4 %	-0.003 g/km -5.2 %	-1.960 g/km -1.08 %
Cetane 50 to 58	-0.127 g/km -25.3 %	-0.026 g/km -26.3 %	-0.001 g/km -0.18 %	+0.003 g/km +5.2 %	-0.660 g/km -0.37 %
T-95 370 to 325 °C	-0.008 g/km -1.8 %	+0.003 g/km +3.4 %	+0.026 g/km +4.6 %	-0.004 g/km -6.9 %	+2.880 g/km +1.59 %

PAH: Polycyclic aromatic hydrocarbons

Note: Fuel effects have been described through regression equations. When these are linear it is possible to express these effects on both absolute values and percentage from a baseline.

The impact of changes in diesel fuel parameters on heavy duty motor vehicle emissions, as indicated by the results of the EPEFE study, is summarised in Table 3-9.

Table 3-9: Impact of Changes to Diesel Fuel Parameters on Motor Vehicle Emissions (Heavy Duty Vehicles) (from EPEFE Study)

Changes to Diesel Fuel Parameters	CO	HC	NO _x	PM	CO ₂
Density 855 to 828 g/L	+0.0297 g/km +5.0 %	+0.0332 g/km +14.25 %	-0.245 g/km -3.57 %	-0.002 g/km -1.59 %	+0.560 g/km +0.07 %
PAH 8 to 1 %	-0.0005 g/km -0.08 %	-0.0093 g/km -4.02 %	-0.1141 g/km -1.66 %	-0.0045 g/km -3.58 %	-4.947 g/km -0.60 %
Cetane 50 to 59	-0.061 g/km -10.26 %	-0.014 g/km -6.25 %	-0.039 g/km -0.57 %	0 0 %	-2.934 g/km -0.41 %
T-95 370 to 325 °C	+0.0392 g/km +6.54 %	+0.0306 g/km +13.22 %	-0.120 g/km -1.75 %	0 0 %	+3.073 g/km +0.42 %

PAH: Polycyclic aromatic hydrocarbons

Note: Fuel effects have been described through regression equations. When these are linear it is possible to express these effects on both absolute values and percentage from a baseline.

EPEFE Conclusions

The EPEFE report concludes that.....

'both fuels and engine technologies are important determinants of motor vehicle emission levels and that statistical relationships exist between fuel properties, engine technologies and exhaust emissions ... the relationships found between fuel properties / engine technologies / exhaust emissions are complex. Changes in a given fuel property may lower the emissions of one pollutant but may increase those of another. For example, decreasing petrol aromatic content lowers CO and HC emissions, but increases NO_x emissions. In some cases, engines in different vehicle categories, such as heavy duty and light duty vehicles, have different responses to changes in fuel properties.

Increasing cetane number in diesel fuels lowers NO_x emissions only on heavy duty and light duty DI engines, but not on light duty IDI engines. Thus, no simple options for reformulating petrol and ADO exist, however evaluations aimed at finding the most cost-effective combinations of improved vehicle technologies and improved fuel properties could provide the best overall set of combinations’.

3.3.3 Other Overseas Studies Relating Fuel Quality Specifications To Vehicle Emissions

The results of other fuel quality studies undertaken overseas are summarised below:

- A program was undertaken by the American Automobile Manufacturers Association in 1997 to quantify the increase in regulated emissions for low emission vehicles when the fuel sulfur level is increased above 40ppm. The study concluded that ‘the benefits of low emission vehicle (LEVs) hardware diminish as fuel sulfur increases above 40ppm. LEVs show a substantially larger detrimental effect due to fuel sulfur than Tier 1 or Tier 0 vehicles tested in AQIRP’. (Information provided by the Worldwide Fuel Charter Committee, September 1999).
- The United States EPA is considering setting new quality requirements for the fuel used in diesel engines, in an effort to reduce emissions which impact on human health, in particular, nitrogen oxides and particulate matter. An article posted on the Federal Register in May 1999 requests comments on potentially beneficial diesel fuel quality changes, with the emphasis on a reduction in the sulfur content of diesel fuel. The article quoted an industry / EPA workgroup, which evaluated the impact of changes in diesel fuel properties on NO_x and hydrocarbon emissions. The study used advanced technology heavy duty diesel engines – the engines depend on exhaust gas recirculation and optimization of engine design, but not on advanced after treatment. The results showed that state of the art heavy duty engines are mostly insensitive to changes in fuel density, aromatics content and cetane number.

The article also notes that....

‘sulfur reduction appears to be the only fuel change with the potential to enable new technologies needed to meet Tier 2 light duty or anticipated future heavy duty standards ... sulfur control is the most likely means of achieving cost-effective diesel fuel emissions reductions’.

It was noted, however, that more information is currently available on the impact of changes in diesel fuel parameters on emissions from heavy duty vehicles than light duty vehicles.

- Concawe report 90/54 documented a study on the influence of fuel sulfur content on particulate emissions from a range of light duty diesel vehicles and heavy duty diesel engines using European test procedures. The results for light duty vehicles are summarised below:

- A reduction in fuel sulfur content from 0.3% to 0.15% resulted in a 4.5% reduction in particulate emissions; and
- A reduction in fuel sulfur content from 0.3% to 0.05% lead to a 7% reduction in particulate emissions.

For heavy duty vehicles, the study was not able to establish a consistent trend of reducing particulate emissions with reducing fuel sulfur content. It was noted that this result contrasts with the literature.

- Concawe report 99/55 reviewed the interactions between fuel quality and vehicle technology, and concluded that they are mutually dependent. The report states that.....

'the results of EPEFE and other studies show clearly that effects of fuel quality changes alone on emissions from fixed technology engines are relatively small compared to the reductions achievable from changes to engine technology. Real benefits from changes to fuel quality arise when they are used to enable new technologies. Good examples are the introduction of unleaded petrol for catalyst cars, low sulfur diesel fuels for Euro 2 engines and development of detergent additives to prevent problems in fuel injected engines'.

3.4 International Fuel Standards

3.4.1 Overview of European Fuel Quality Regulations and Specifications

In 1988 the EU mandated the European Standards Organisation (CEN) to develop comprehensive specifications for unleaded petrols (premium and regular grades), diesel fuel and automotive LPG. They were then officially ratified by CEN in March 1993. Member States were required to adopt them as national standards by September 1993 and withdraw conflicting national standards by the same date. The specifications are given in Tables 3-10 and 3-11.

Following consideration of the Auto Oil programme, in 1996 the European Union (EU) Commission put forward proposals for changes in fuel quality, which required extensive revisions of the CEN petrol and diesel fuel specifications. In October 1998, the European Parliament and Council adopted Directive 98/70/EC on the quality of petrol and diesel fuels and amended the 1993 Directive, which produced the 1993 specifications below, i.e. EN228:1993 and EN 590:1993.

- Unleaded Petrol EN 228:1993

Apart from the octane requirements of the regular grade, all relevant characteristics and test methods are specified in this European Standard. Provisions are included for national bodies to select seasonal grades from the eight volatility classes during a defined period of the year for a defined region of its country.

- Diesel Fuel – EN 590:1993

EN 590:1993 standard specifies six CFPP grades for temperate climates and five different classes for arctic climates.

The 1998 Directive refers to the new fuel qualities as '*environmental specifications*' and requires them to be phased onto the market in two stages from 2000, when intermediate specifications, with higher benzene, total aromatics and sulfur in petrol than the second stage in force from 2005. In the case of diesel, the sulfur content may be 350 ppm in 2000, reducing to 50 ppm in 2005. In petrol for 2000, benzene will be 1.0% v/v maximum, aromatics will be 42.0% v/v.max and sulfur 150 mg/kg max. In 2005 aromatics will be 35.0% v/v max. and sulfur 50 mg/kg max.

European Petrol Specifications

Concawe report 6/97 (Concawe 1997), provides an excellent review of world vehicle regulations and fuel specifications for the period 1970 to 1996. The following material is largely drawn from that reference.

Lead content of petrol

From 1978 in the EU, the maximum lead content of leaded petrol was required to be within the range of 0.15 to 0.4 g/L. In practice, all countries were at 0.15 g/L maximum by 1985. In 1985 another Directive allowed unleaded petrol (0.013g/L maximum) to be marketed and, in addition, required the introduction of a premium unleaded grade of 95 RON/85 MON from October 1989.

Unleaded petrol (95 RON Europremium) is widely available in all West European countries and sales are growing. In 1994 over 64% of petrol sales in Europe were unleaded. Leaded regular has almost completely disappeared.

Reformulated petrols

Both Sweden and Finland have introduced reformulated petrol specifications with special requirements for volatility and composition.

An 'Environmental Classification' system for diesel fuel was introduced in Sweden in 1991. During 1993, a similar classification was developed for petrols, comprising four different classes. Class 4 is equivalent to CEN standard, and Class 3 to the current Swedish standard.

Aromatics and benzene

The 1985 EU Directive, which required the introduction of unleaded petrol, also specifies a maximum benzene level of 5% v/v. From October 1989 this also applied to leaded grades marketed in EU countries.

Oxygenates

In December 1985, the EU adopted a Directive on oxygenates in petrol. The Directive specifies that the following are acceptable for use as substitute fuel components:

- Mono-alcohols with an atmospheric boiling point lower than the final atmospheric boiling point laid down in the national petrol standards.
- Ethers, with molecules containing 5 or more carbon atoms, and with atmospheric boiling points lower than the final atmospheric boiling point laid down in the national petrol standards.

Table 3-10: European Union Unleaded Petrol Fuel Quality Specifications.

		EN228:1993	EU Directive 98/70/EC Environmental ULP from 2000 (Euro 3) ⁴	EU Directive 98/70/EC Environmental ULP from 2005 (Euro 5) ⁵
		Min / Max	Min / Max	Min / Max
Regular		(1)		
'95 RON	RON	95.0	95.0 / -	95.0 / -
	MON	85.0	85.0 / -	85.0 / -
'98 RON	RON	n.a		
	MON	n.a		
Oxidation stability	minutes	360	n.a	
Sulfur content	% m/m	n.a / 0.05	n.a / 0.015	n.a / 0.005
Lead content	g/L	n.a / 0.13	n.a / 0.005	
Oxygen content	% m/m	n.a	n.a / 2.7	
Olefins content	% v/v	n.a	n.a / 18.0	
Aromatics content	% v/v	n.a	n.a / 42.0	n.a / 35.0
Distillation: E100°C	% v/v	n.a	46.0/n.a	
	E150°C	% v/v	n.a	75.0/ n.a
Benzene	% v/v	n.a / 5.0	n.a / 2.7	
Volatility RVP	kPa	(2)	- / 60.0 summer period	
Oxygenates :		(3)	n.a	
- methanol, - stabilising agents to be added	% v/v	n.a	n.a	
- ethanol, - stabilising agents may be necessary	% v/v	n.a	n.a	
- isopropyl alcohol	% v/v	n.a	n.a	
- tertiary-butyl alcohol	% v/v	n.a	n.a	
- iso-butyl alcohol	% v/v	n.a	n.a	
- ethers with ≥ 5 carbon atoms	% v/v	n.a	n.a	
Other oxygenates	% v/v	n.a	n.a	
Density	kg/m ³	725-780	n.a	
Copper corrosion	merit	1	n.a	
Appearance		Clear and bright	n.a	
Fuel injector cleanliness	% flow loss	n.a	n.a	
Intake-valve sticking	pass/fail	n.a	n.a	

Notes:

(1) Must be specified in National standard.

(2) 8 volatility classes are specified with a relationship between RVP, E70 and VLI for the 8 classes.

(3) as per Directive 85/536/EEC

(4) Environmental ULP required in EU from 2000 is described in this report as Euro 3 specification.

(5) Environmental ULP required in EU from 2005 is described in this report as Euro 4 specification

European Diesel Fuel Specifications

Sulfur content

In March 1987, the EU's Council of Environment Ministers agreed to a Directive reducing the maximum sulfur content of all gas oils, except those used by shipping or for further processing, to 0.3% m/m and allowed Member States to set a stricter limit of 0.20% m/m in heavily polluted areas.

A single limit to be applied throughout the Union was adopted, requiring:

- A maximum limit of 0.2% m/m to be applied for all gas oils, including diesel fuel from 1 October 1994;
 - A maximum limit of 0.05% m/m for diesel fuel to be implemented by 1 October 1996; and
 - For all gas oils and aviation kerosene, further reductions in sulfur content below 0.2% m/m were to be considered.

European diesel fuel specifications

Table 3-11: European Union Diesel Fuel Quality Specifications.

All Grades	Specification EN590:1993	EU Directive 98/70/EC Environmental Qualities	
		for 2000 (Euro 3)	for 2005 (Euro 4)
Flash Point °C (min)	55		
Ash % m/m	max 0.01		
Water mg/kg	max 200		
Particulates mg/L	max 24		
PAH % m/m		max 11	
Copper corrosion 3hr at 50°C	max 1		
Oxidation stability g/m ³	max 25		
Sulfur % m/m	max 0.2 (1)		
Sulfur mg/kg		max 350	max 50
Carbon residue (10% bottoms) % m/m	max 0.3		
Temperature climate grades (Grades A to F)			
Density at 15°C	820-860	max 845	
Viscosity at 40°C	2.00-4.50		
Cetane number (min)	49	51	
Cetane index (min)	46		
Distillation (°C):			
10% v rec. at	report		
50% v rec. at	report		
65% v rec at	min 250		
85% v rec at	max 350		
95% v rec at	max 370	max 350	

(1) Sulfur limit will be reduced towards 0.05% m/m maximum, in line with EU directives or national standards.

Arctic grades are also part of EN 590:93.

European Specifications for Alternative Fuels

Vegetable Oil Methyl Esters (Biodiesel)

DG VII put forward a draft proposal for a Council Directive for a specification for vegetable oil methyl esters (biodiesels). The proposal was presented in the framework of EU's ALTENER Programme for the promotion of alternative fuels. Within this programme the EU has the objective of securing a 5% market share of total motor fuel consumption for biofuels, of which it is expected that biodiesel will form the major share.

3.4.2 Overview Of United States Fuel Quality Regulations And Specifications

ASTM D4814-94 Petrol Specification

A new specification was issued in 1988 to cover petrol and its blends with oxygenates such as alcohols and ethers. This specification, which was further revised in 1993 and 1994, is not a legal requirement except in a few states, which have adopted it as such. It can consequently be overruled by US Federal legislation.

The specification still contains reference to the lead content and recommended octane level of leaded petrols. With regard to volatility, six vapour pressure/distillation classes and five vapour lock protection classes are specified.

EPA regulations require a grade with a minimum antiknock index $[(RON + MON)/2]$ of 87 to be sold.

ASTM Specifications for Diesel Fuel and Automotive LPG

ASTM 0975-94 covers specifications for two grades of 0.05 %m/m automotive gas oil. It also has a specification (D1835) for automotive LPG, which also requires a propane content of 85% min.

United States Petrol Specifications

Lead Content

The EPA imposed a drastic reduction in the permitted lead level in petrol, from 1.1 g/USgal to 0.5 g/USgal (0.13 g/L) in 1985 and then to 0.1 g/USgal (0.026 g/L) from January 1986. This was considered to be the lowest lead level that would allow continued operation of older engines. Sales of leaded petrol were banned in California from January 1992. Elsewhere in the United States sales of leaded regular declined to around 1.5% by 1993, and leaded petrol was finally banned from January 1995. This date coincided with the requirement for reformulated petrol to be sold in specified areas which did not meet ambient ozone targets.

Volatility

Since 1989 the EPA has imposed maximum limits on petrol vapour pressure during the summer months varying between 9.5 and 10.5 lb. RVP for different states. Since

May 1992 these limits have been replaced by the more stringent Phase 2 limits. These are simplified into north and south zones with maximum RVPs of 9.0 psi (62.1 kPa) (May to September) and 78 psi (53.8 kPa) (June to September) respectively. A permanent waiver of 1 psi (7 kPa) is allowed for ethanol blends.

RVP will be further restricted from 1 January 1995, in those areas where legislation requires "reformulated petrols", to 8.1 psi (55.8 kPa) and 7.2 psi (49.6 kPa) respectively. From 1996, an even lower limit of 7.0 psi (48.2 kPa) will be required in California for "Phase 2 reformulated petrols".

Sulfur content

Standard petrol sulfur content is specified at max 1000 ppm. Federal US Phase II Reformulated petrol is required not to exceed a refiner's 1990 average sulfur content (statutory baseline of 338 ppm. The sulfur level for Californian Phase 2 petrol is limited to a maximum of 40 ppm.

Benzene and total aromatics content

In the USA benzene content was limited to 1% v/v maximum (or 0.95% v/v period average, with a 1.3% v/v absolute maximum) from 1 January 1995 by Implementation of the regulations requiring *reformulate'* petrol. Total aromatics are indirectly controlled by the requirement to demonstrate a 15% reduction in the emissions of air toxics.

In California, the *Phase 2 Reformulated Petrol* required from March 1996 also has a 1% v/v benzene limit (or 0.85% average, with an absolute maximum of 1.2% v/v). Total aromatics are also limited to 25% v/v (or 22% v/v average, absolute maximum of 30% v/v).

Reformulated Petrols

Federal States

The US Clean Air Act includes a requirement for *Reformulated Petrol* to be sold in major cities which fail to meet ambient ozone standards. Other areas with similar problems can also opt into the program. The EPA announced the final rule for the reformulated petrol program on 15 December 1993.

The program is being implemented in two phases. Phase I of the program began on 1 January 1995 and Phase II begins on 1 January 2000. The EPA expects the Phase I program to achieve a 15 to 17 per cent reduction in both volatile organic compounds (VOC) and in toxic emissions from motor vehicles compared with 1990. The Phase II program will achieve a 25 to 29 per cent reduction in VOC, a 20 to 22 per cent reduction in toxic emissions and a 5 to 7 per cent NO_x reduction. All reductions are relative to the average 1990 US baseline quality.

All reformulated petrol must contain a minimum of 2.0% m/m oxygen, a maximum of 1.0% v/v benzene and must not contain heavy metals. Sulfur, T90E and olefins

contents are not reduced, but may not be higher than a refiners' 1990 average. In addition, they must meet certain VOC, air toxics and NO_x emissions performance requirements, judged against qualities produced in 1990. Emissions performance will be calculated on the basis of empirical models.

From January 1998, refiners will be required to use a complex model for Certification. The complex model is a set of equations correlating a petrol's properties to its emissions characteristics. Refiners can comply with the standards either on a batch (per gallon) basis or on a quarterly average basis. Average limits are more severe overall, but have more latitude on a per gallon basis.

The complex emissions model uses formulae to calculate total VOCs, air toxics and NO_x reductions. The exhaust VOC formulae use regression equations based on the RVP, distillation parameters (E200 and E300, in °F) and sulfur, oxygen, aromatics and olefins contents within specified ranges, together with weighting factors based on the emissions characteristics of old and new technology vehicles. These weighting factors may be changed in future years to match the characteristics of the car population.

Oxygenates

The use of new components in unleaded petrol must be approved by the EPA, who must ensure that they will not adversely affect emission control systems.

In the case of oxygenates, the EPA has ruled that aliphatic alcohols and glycols, ethers and polyethers may be added to the fuel, provided that the amount of oxygen in the finished fuel does not exceed 2.7% m/m. However, note should be taken of new limits set out in the Clean Air Act Amendments. Methanol is excluded from this approval.

A number of specific proposals have been granted waivers allowing their use as follows:

- Gasohol consisting of petrol with 10% v/v ethanol is permitted. This contains 3.5% m/m oxygen. (1979).
- A mixture of TBA and methanol up to a maximum concentration of 3.7% m/m oxygen, provided that methanol does not form more than 50% of the mixture. (1981).
- Methanol up to 5.0% v/v plus at least 2.5% v/v co-solvent (ethanol, propanols or butanols) plus a corrosion inhibitor, with maximum oxygen content of 3.7% m/m. (1985).

Deposit control additives

The 1990 Clean Air Act Amendments required that from January 1995, all petrols in the US must contain additives to prevent the accumulation of deposits in engines and fuel supply systems.

United States Diesel Fuel Specifications

Sulfur Content

In the US a sulfur limit of 0.05% m/m has been adopted by the EPA and made effective from 1 October 1993 for on-highway diesel fuel. The California Air Resources Board (CARB) adopted a new diesel fuel specification of 0.05% m/m sulfur and 10% v/v aromatics applying from October 1993. The intention is to provide fuel quality that will ensure low emissions, and other fuels are allowed, provided the supplier can demonstrate equivalent emissions to a reference fuel from engine test data. The current specification for the reference fuel is shown below.

Table 3-12: Californian diesel reference fuel specification

Property	Limit
Sulfur % m/m (max)	0.05
Aromatics % v/v (max)	10
Polycyclic aromatics, % m/m (max)	1.4
Nitrogen, ppm (max)	10
Natural Cetane Number (min)	48
API gravity	33-39
Viscosity at 40°C, mm ² /s	2.0-4.1
Flash Point, °F (min)	130
Distillation °F (°C)	
Initial boiling point	550-610°F (290-320 °C)
10% boiling point	340-420 °F (170-215 °C)
50% boiling point	400-490 °F (205-255 °C)
90% boiling point	470-560 °F (245-295 °C)
Final boiling point	580-660 °F (305-350 °C)

United States Alternative Fuels Specifications

The final version of the Clean Air Act Amendments does not contain a mandate for the introduction of alternative fuels. Instead it describes performance criteria for 'clean alternative fuels' which may include 'methanol and ethanol, reformulated petrol, natural gas, LPG, electricity and any other fuel which permits vehicles to attain legislated emission standards'.

With the exception of the specification for LPG, there are no official ASTM specifications for alternative fuels.

Natural gas

Variations in gaseous fuel composition can affect the level of pollutant emissions by affecting the air-fuel ratio. There is a good linear correlation between air-fuel ratio and the Wobbe index or number of a gas ($W = H / \sqrt{\rho}$, where H is the volumetric heating value and ρ is the specific gravity). Reasonable variations in Wobbe index

have little effect on emissions from light-duty vehicles using modern engine technology with three-way catalysts and closed-loop feedback control.

Liquefied petroleum gas

The effects of varying LPG composition on the exhaust hydrocarbon species and reactivity have not been documented. However, according to the Carter reactivity scale (used by the California Air Resources Board), olefins such as propene and butenes are much more reactive in contributing to ozone formation than paraffins such as propane and the butanes. It has been argued that increasing the olefin content of LPG will result in increased ozone-forming potential in the exhaust. In order to reduce the possibility of emissions increases due to variation in LPG composition, the California Air Resources Board therefore requires that LPG sold for automotive use in California comply with the HD-S standard in the ASTM D 1835. Due to concerns about supply availability, the maximum 5% propene content required by the HD-S specification was been delayed until January 1997. In the intervening period, LPG containing up to 10% propene was permitted.

3.4.3 Fuel Quality Regulations and Specifications in Asia

Petrol – Main Trends in Selected Countries

Indonesia

A leaded 88 octane "premium" is the only grade available but 10%v MTBE can be added at service stations to produce a 91.5 RON "Premix".

Japan

Unleaded regular petrol was introduced in 1975 and the market became totally unleaded in 1987. Following an amendment to the air pollution laws in April 1995, from April 1996 petrol specifications were required to include mandatory limits on sulfur (0.01 %m/m), benzene (5.0% v/v), methanol (nil) and MTBE (7%v/v max). There were no specification limits on aromatics in 1996. Content or olefins content and typical values range from 25-47 %v/v and below 33%v/v respectively. Sulfur contents average around 35 ppm, well below the 100ppm limit.

Singapore

Singapore has a leaded premium, with a lead content of 0.15 g/L max, and unleaded superpremium and regular grades. The government is likely to reduce the benzene content of petrol to below 3 %v/v by 2000.

South Korea

South Korea has had unleaded grades since 1986/7 and became totally unleaded in 1993. The premium and regular unleaded grades have specified limits of 50.0 %v/v aromatics, 5.0 %v/v benzene and a requirement for the addition of a minimum of 0.75 %m/m oxygen as oxygenates.

Diesel fuel – Main Trends in Selected Countries

Sulfur Content

There is no specific legislation in Asian countries imposing compositional constraints on automotive diesel fuels. However, the former relatively high sulfur levels are gradually being reduced. In India, it was proposed to reduce sulfur contents from 1.0% m/m to 0.50% m/m by 1998 and to 0.25% m/m by 2000. Oil suppliers were asked to make their best endeavour to reduce sulfur levels before 1998. The Japanese petroleum industry reduced the sulfur content of Japanese diesel fuel to 0.20% m/m from October 1992. In Malaysia, sulfur content was scheduled to be reduced from 0.5% m/m to 0.2 % m/m by 1997 and to 0.05% by 2000. The sulfur content of automotive diesel fuel in Singapore was reduced from 0.5% m/m to 0.3% in July 1996. Taiwan reduced the sulfur content of diesel fuel from 0.5% m/m to 0.3% in July 1993. The Ministry of Commerce of Thailand issued a specification for diesel fuels in January 1993 giving a phased reduction of sulfur for diesel fuel used in cities from the level of ASTM 0.5 %m/m max current at that time to 0.25% from 1.01.96 and 0.05% from 1.01.2000.

3.4.4 Worldwide Fuel Charter

Following the publishing of the US AQIRP's final report and the European EPEFE report, a group of four international automotive manufacturing associations, in December 1998, produced a set of recommendations for petrol and diesel fuel specifications, which they titled a "World-Wide Fuel Charter".

The purpose of the Charter is to make a major contribution to the process of achieving a harmonisation of worldwide automotive petrol and diesel fuel specifications. Harmonised and sufficiently advanced specifications will contribute to reduced air pollution by themselves, as demonstrated in the AQIRP and EPEFE programs. Further, such specifications will enable the necessary quality requirements of advanced IC engine and emissions control technologies to be met. Without consistent and sufficiently high quality fuel specifications, the engine manufacturers maintain that automotive transport vehicles will not be able to achieve the emissions and other performance characteristics now expected of them.

The group of four international automotive manufacturing associations are the:

- American Automobile Manufacturers Association; the AMMA
- European Automobile Manufacturers Association; the ACEA
- Engine Manufacturers Association; the EMA
- Japan Automobile Manufacturers Association; the JAMA

The transmittal letter attached to the Charter document, signed by the CEO's of the four Associations, include the paragraph:

"Representatives from American, European and Japanese automotive manufacturers developed the attached fuel specifications, which are expected

to be applied world-wide. Consistent fuel quality world-wide is necessary to market high-quality automotive products matching world-wide customer performance and environmental needs.”

The AMMA, ACEA, EMA and JAMA assert that the implementation of the Charter’s fuel specification recommendations will:

- *“Reduce the impact of motor vehicles on environment through reduced vehicle fleet emissions;*
- *Consistently satisfy customer performance expectations; and*
- *Minimise vehicle equipment complexities with optimised fuels for each emissions control category, which will reduce customer costs (purchase and operation) and increase satisfaction.”*

In developing the charter, three different categories of fuel quality were established for both unleaded petrol and diesel fuel. These were defined as:

Category 1:

Markets with no or minimal requirements for emission controls; based primarily on fundamental vehicle/engine performance concerns.

Category 2:

Markets with stringent requirements for emission control or other market demands. *For example, markets requiring US Tier 0 or Tier 1, EU-Stage 1 and 2, or equivalent emission levels.*

Category 3:

Markets with advanced requirements for emissions control or other market demands. *For example, markets requiring US California Low Emission Vehicles (LEV), Ultra Low Emission Vehicles (ULEV) and EU-Stage 3/4, or equivalent emission levels.*

The Charter’s fuel quality recommendations are for ‘the properties of the finished fuel as provided to the end user’. It is also stated that ‘where national requirements are more severe than [the Charter’s] recommendations, national limits have to be met’.

The fuel quality recommendations in the World Wide Fuel Charter are reproduced in the following sections. Category 2 and 3 of the specifications are those closest to those which are likely to be adopted in Australia. The Category 1 specifications are of value in indicating the Charter specifications to meet the engine and vehicle performance requirements when engine emissions are not controlled.

It should be noted that a draft update to the Worldwide Fuel Charter was released late in 1999. The update to the Charter was produced in response to the increasingly stringent vehicle emission standards and requirements for reductions in fuel consumption. In particular, automotive manufacturers have concluded that additional substantial reductions in fuel sulfur levels will be required to achieve new vehicle emission standards.

The Worldwide Fuel Charter: Specifications for Petrol

Category 1 Unleaded petrol

Markets with no or minimal requirements for emissions control; based primarily on fundamental vehicle/engine performance concerns.

Table 3-13: World Wide Fuel Charter Specifications for Category 1 Unleaded Petrol

PROPERTIES	UNITS	LIMIT	
		Minimum	Maximum
'91 RON' (1) Research Octane Number	-	91.0	--
		82.0	--
'95 RON' (1) Research Octane Number	-	95.0	--
		85.0	--
'98 RON' (1) Research Octane Number	-	98.0	--
		88.0	--
Oxidation stability	minutes	360	--
Sulfur content	%m/m	--	0.10 (2)
Lead content	g/l	--	0.013 (3)
Manganese content	g/l	--	(3)
Oxygen content	% in/in	--	2.7 (4)
Aromatics	%v/v	--	50.0
Benzene content	%v/v	--	5.0
Volatility		See volatility tables, Section 4.2	
Unwashed gums	Mg/100ml	--	70
Washed gums	Mg/100ml	--	5
Density	kg/m ³	715	780
Copper corrosion	merit	Class I	
Appearance		Clear and bright	
Carburettor cleanliness	merit	8.0 (5)	--
Fuel injector cleanliness	% flow loss	--	10 (5)
Intake valve cleanliness I	merit	9.0 (5)	--

- (1) Adequate labeling of pumps must be defined and used; fuel should be dispensed through nozzles meeting SAE J285, 'Recommended Practice Petrol Dispenser Nozzle Spouts'. Three octane grades defined for maximum market flexibility. Availability of all three not needed.
- (2) Lower sulfur content preferred for catalyst-equipped vehicles. Limit of 0.10 %m/in may be referred to as 1000 ppm.
- (3) No intentional addition.
- (4) Where oxygenates are used, ethers are preferred. Where up to 10% of volume ethanol (meeting ASTM D 4806 and a pH of 7 - 9) is permitted by pre-existing regulations, the blended fuel must meet all other Category I requirements. Higher (C > 2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.
- (5) Compliance to this requirement can be demonstrated by the use of proper detergent additives in comparable-base petrols.

Category 2 Unleaded Petrol

For markets with stringent requirements for emission control or “other market demands”

Table 3-14: World Wide Fuel Charter Specifications for Category 2 Unleaded Petrol

PROPERTIES	UNITS	LIMITS	
		Minimum	Maximum
'91 RON' (1) Research Octane Number		91.0	
	Motor Octane Number	82.5	
'95 RON' (1) Research Octane Number		95.0	
	Motor Octane Number	85.0	
'98 RON' (1) Research Octane Number		98.0	
	Motor Octane Number	88.0	
Oxidation stability	minutes	480	
Sulfur content	% m/m		0.02 (2)
Lead content	g/l		Non-detectable (3)
Phosphorus content	g/l		Non-detectable (3)
Manganese content			Non-detectable (3)
Silicon	g/kg		Non-detectable (3)
Oxygen content	% m/m		2.7 (4)
Olefins content	% v/v		20.0
Aromatics content	% v/v		40.0
Benzene content	%v/v		2.5
Volatility		See following volatility tables	
Sediment	mg/L		1
Unwashed gums	mg/100mL		70
Washed gums	mg/100mL		5
Density	kg/m ³	715	770
Copper corrosion	merit		Class I
Appearance			Clear and bright
Fuel injector cleanliness	% flow loss		5
Intake-valve sticking	pass/fail		Pass

(1) Adequate labeling of pumps must be defined and used; fuel should be dispensed through nozzles meeting SAE J285, 'Recommended Practice Petrol Dispenser Nozzle Spouts'. Three octane grades defined for maximum market flexibility. Availability of all three not needed.

(2) Limit of 0.02 %m/m commonly referred to as 200 ppm.

(3) At or below detection limit of test method used. No intentional addition.

(4) Where oxygenates are used, ethers are preferred. Where up to 10% of volume ethanol (meeting ASTM D 4806 and a pH of 7-9) is permitted by pre-existing regulations, the blended fuel must meet all other Category 2 requirements. Higher (C>2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.

Category 3 Unleaded Petrol

For markets with advanced requirements for emissions control “or other market demands”.

Table 3-15: World Wide Fuel Charter Specifications for Category 3 Unleaded Petrol

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
'91 RON' (1) Research Octane Number	-	91.0	--
	Motor Octane Number	82.5	--
'95 RON' (1) Research Octane Number	-	95.0	--
	Motor Octane Number	85.0	--
'98 RON' (1) Research Octane Number	-	98.0	--
	Motor Octane Number	88.0	--
	Motor Octane Number	88.0	--
Oxidation stability	minutes	480	--
Sulfur content	% m/m	--	0.003 (2)
Lead content	g/L	Non-detectable (3)	
Phosphorus content	g/L	Non-detectable (3)	
Manganese content .	g/L	Non-detectable (3)	
Silicon	g/kg	Non-detectable (3)	
Oxygen content	% m/m	--	2.7 (4)
Olefins content	% v/v	--	10.0
Aromatics content	% v/v	--	35.0
Benzene content	%v/v	--	1.0
Volatility	See following volatility tables		
Sediment	mg/L	--	1.0
Unwashed gums	mg/100 mL	--	30
Washed gums	mg/100mL	--	5
Density	kg/m ³	715	770
Copper corrosion	merit	Class I	
Appearance	Clear and bright		
Fuel injector cleanliness II	% flow loss	--	5
Intake-valve sticking	pass/fail	Pass	
Intake valve cleanliness			
Method I (CEC F-05-A-93), or	avg. mg/valve	--	30
Method 2 (ASTM D 5500), or	avg. mg/valve	--	50
Method 3 (ASTM D 6201)	avg. mg/valve	--	50

(1) Adequate labelling of pumps must be defined and used; fuel should be dispensed through nozzles meeting SAE J285, 'Recommended Practice Petrol Dispenser Nozzle Spouts'. Three octane grades defined for maximum market flexibility. Availability of all three not needed.

(2) Limit of 0.003 %m/m commonly referred to as 30 ppm.

(3) At or below detection limit of test method used. No intentional addition.

(4) Where oxygenates are used, ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and a pH of 7-9) is permitted by pre-existing regulations, the blended fuel must meet all other Category 3 requirements. Higher (C>2) alcohols are limited to 0.1% maximum by volume. Methanol is not permitted.

Table 3-16: Volatility classes of harmonised specifications for petrol, Categories 2 and 3

Class*	A	B	C	D	E
Temp.Range, °C	> 15	5 to 15	-5 to +5	-5 to -15	<-15
VapourPressure, kPa	45-60	55-70	65-80	75-90	85-105
T10, °C	65	60	55	50	45
T50, °C	77-100	77-100	77-100	77-100	77-100
T90, °C	130-175	130-175	130-175	130-175	130-175
EP, °C max.	195	195	195	195	195
E70,%	15-45	20-45	25-45	25-47	25-47
E100,%	50-65	50-65	50-65	55-70	55-70
E180,%min	90	90	90	90	90
D.I.,max	570	565	560	555	550

* Where 'Class' is based on the minimum expected ambient temperatures of the market.

Class will vary by season

D.I.(Driveability Index) = (1.5 x T10) + (3 x T50) +T90 + (11 x oxy.wt%)

NOTE: E 100 is the percentage of a petrol distilled at 100°C. Excessively high T50 - low E100 - can lead to poor starting and warm-up performance at moderate ambient temperatures. Control of the "Drivability Index" (DI), derived from T10, T50, T90, and oxygen content can also be used to assure good cold start and warm-up performance

The technical background for recommendations on harmonised petrol specifications.

Further technical detail on the recommendations for harmonised petrol specifications in the World Wide Fuel Charter (WWFC) are provided in the following sections.

Octane

The Fuel Charter specifies three octane grades in each petrol Category, but states that.....

'it is not intended to require all three grades in all markets. One or more of the octane grades should be made available consistent with market requirements'.

Sulfur

The WWFC quoted the results of the AQIRP and EPEFE studies on the impact of the sulfur of fuel on exhaust emissions, and noted that.....

'the hydrocarbon reductions in the US AQIRP study indicate a steeper reduction when sulfur is reduced from about 100 ppm to 50 ppm. This suggests the importance of a very low sulfur limit for advanced technology vehicles'.

The Charter also discusses the impact of high sulfur fuels on catalyst efficiency and the resultant impact on the feasibility of on-board diagnostic systems: 'there is some concern that the loss of catalyst efficiency resulting from high sulfur fuels will cause some catalyst monitors to indicate a problem code resulting in the illumination of a malfunction indicator'. In addition, low sulfur petrol is necessary for the introduction of lean-burn, fuel efficient catalyst technology.

A category 4 specification has been added to the February 2000 draft of the World Wide Fuel Charter, which applies to markets with further advanced requirements for emission control, to enable sophisticated NO_x technologies. This category provides for sulfur free (less than 5ppm to 10ppm) petrol.

Lead

The Associations responsible for developing the Charter, assert that a petrol supply that is completely lead-free is essential in the longer term.

Oxygenates

A maximum limit for oxygen content of 2.7% was specified for all three categories. The Charter notes that *'where oxygenates are used, ethers are preferred'*, and notes that this was developed on the basis of emissions benefits, vehicle performance and pre-existing regulations. Specifications are also provided for the addition of ethanol as an oxygenate, including a specification to control pH and prevent the degradation of fuel systems.

Olefins

The ozone specification on the Charter were based on the results of research undertaken as part of the US Auto/Oil program. The Charter states that...

'the research concluded that reducing total olefin emissions from 20% to 5% would significantly decrease ozone-forming potential in three critical cities: Los Angeles, Dallas-Fort Worth, and New York. The research also showed that the same reduction in petrol olefin level would reduce the light-duty vehicle contribution to peak ozone by 13% to 25% in future years for the 3 cities. About 70% of this effect would be due to reducing low molecular weight olefins'.

The specification for olefin content in the Charter is 20% v/v for Category 2, and 10% v/v for Category 3.

Aromatics

The levels of aromatics specified in Categories 1, 2 and 3 are 50% v/v, 40% v/v and 35% v/v respectively. The reduction in the levels of aromatics specified has been prompted by the results of the US AQIRP and European EPEFE programmes, which have shown that lower levels of aromatics in petrol significantly reduce toxic benzene emissions in exhaust from vehicles, as well as reducing CO₂ emissions.

The Worldwide Fuel Charter: specifications for diesel fuel (ADO)

Category I

For markets with no or minimal requirements for emissions control; based primarily on fundamental vehicle/engine performance concerns.

Table 3-17: World Wide Fuel Charter Specifications for Category 1 Diesel Fuel

PROPERTIES	UNITS	LIMIT Minimum	LIMIT Maximum
Cetane Number (1)		48(2)	-
Cetane Index (1)		45(3)	
Density @ 1 Soc	kg/in ³	820 (4)	860
Viscosity@40C	mm ² /s	2.0 (5)	4.5
Sulfur content	% m/m		0.50 (6)
T95	°C	--	370
Flash point	°C	55 (7)	-
Carbon residue	% rn/rn	--	0.30
CFPP (8) or LTFT or CP	c	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	-	
Oxidation stability	g/m ³	--	25
Copper corrosion	merit	--	Class I
Ash content	% m/m	--	0.01
Appearance		Clear and bright	
Lubricity(HFRR scardia.@60C)	micron	--	400

(1): Compliance with either cetane index or cetane number is allowed.

(2): The minimum limit can be relaxed to 45 when ambient temperatures are below -30°C.

(3): The minimum limit can be relaxed to 42 when ambient temperatures are below -30°C.

(4): The minimum limit can be relaxed to 800 kg/m³ when ambient temperatures are below -30°C.

(5): The minimum limit can be relaxed to 1.5 mm²/s when ambient temperatures are below -3°C and to 1.3 mm²/s when ambient temperatures are below -4°C.

(6): Limit of 0.50 %m/m may be referred to as 5000 ppm.

(7): The minimum limit can be relaxed to 38°C when ambient temperatures are below -30°C.

(8): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

Category 2 Diesel fuel

For markets with stringent emissions control standards “or other market demands”.

Table 3-18: World Wide Fuel Charter Specifications for Category 2 Diesel Fuel

Properties	Units	Limit	
		Min.	Max.
Cetane Number	--	53 (1)	
Cetane Index		50	
Density @ 15 °C	kg/in ³	820 (3)	850
Viscosity@40 °C	mm ² /s	2.0 (4)	4.0
Sulfur content	% m/m	--	0.030 (5)
Total aromatics content	% m/m	--	25
Polyaromatics content (di+tri+)	% m/m	--	5
T90 (6)	°C	--	340
T95 (6)	°C	--	355
Final Boiling Point	°C	--	365
Flash point	°C	55	-
Carbon residue. .	% m/m	--	0.30
CFPP (7) or LTFT or CP	°C	-	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	200
Oxidation stability	g/m ³	--	25
Biological growth			'Zero' content
Vegetable Derived Esters	% m/m		See Footnote (8)
Total acid number	mg KOH/g	--	0.08
Corrosion performance			Light rusting or less
Copper corrosion	merit		Class I
Ash content	% m/m		0.01
Particulates	mg/L	--	24
Injector cleanliness	% air flow loss	--	85
Lubricity (HFRR scar dia @ 60 °C	micron	--	400

- (1) The minimum limit can be relaxed to 48 when ambient temperatures are below -30⁰ C.
- (2) The minimum limit can be relaxed to 45 when ambient temperatures are below -30⁰ C.
- (3) The minimum limit can be relaxed to 800 kg/in³ when ambient temperatures are below -30⁰ C. For environmental purposes, a minimum of 815 kg/in³ can be adopted.
- (4) The minimum limit can be relaxed to 1.5 mm²/s when ambient temperatures are below -30 C, and to 1.3 mm²/s when ambient temperatures are below -40⁰ C.
- (5) Limit of 0.030 %m/m commonly referred to as 300 ppm.
- (6) Compliance either with T90 or T95 is required, not both.
- (7) If compliance is demonstrated by meeting CFPP, then it must be no more than 10⁰C less than cloud point.
- (8) Up to 5% vegetable derived esters (VDE), conforming to DIN VS 1606 or equivalent standard, can be used where it is allowed under pre-existing regulations. Where VDE is used, it is recommended that fueling pumps are marked

Category 3 Diesel Fuel

Markets with advanced requirements for emissions controls “or other market demands”.

Table 3-19: World Wide Fuel Charter Specifications for Category 3 Diesel Fuel

PROPERTIES	UNITS	LIMITS	
		Min.	Max.
Cetane Number		55(1)	-
Cetane Index	-	52 (2)	-
Density at 15°C	kg/in ³	820 (3)	840
Viscosity at 40°C	mm ² /s	2.0 (4)	4.0
Sulfur content	% m/m		0.003 (5)
Total aromatic content	% m/m	--	15
Polyaromatic content (di+tri+)	% m/m	--	2.0
T90 (6)	°C	--	320
T95 (6)	°C	--	340
Final Boiling Point	°C	--	350
Flash point	°C	55	-
Carbon residue	% m/m	--	0.20
CFPP (7) or LTFT or CP	°C		Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg		200
Oxidation stability	g/m ³	--	25
Foam volume	mL		100
Foam vanishing time	sec.	--	15
Biological growth			'Zero' content
Vegetable Derived Esters	% rn/rn		Non-detectable
Total acid number	mg KOH/g		0.08
Corrosion performance			Light rusting or less
Copper corrosion	merit		Class I
Ash content	% m/m		0.01
Particulates	mg/L		24
Injector cleanliness	% air flow loss		85
Lubricity (HFRR scardia. at 60°C)	micron		400

(1): The minimum limit can be relaxed to 50 when ambient temperatures are below -30°C.

(2): The minimum limit can be relaxed to 47 when ambient temperatures are below -30°C.

(3) The minimum limit can be relaxed to 800 kg/m³ when ambient temperatures are below -30°C.

(4) For environmental purposes, a minimum of 8 15 kg/rn³ can be adopted.

The minimum limit can be relaxed to 1.5 mm²/s when ambient temperatures are below -30°, and to 1.3 mm²/s when ambient temperatures are below -4°C.

(5): Limit of 0.003 %m/m commonly referred to as 30 ppm.

(6): Compliance either with T90 or T95 is required, not both.

Technical background for recommendations on harmonised specifications for diesel fuel (ADO).

Cetane number and index

The Charter specifies Cetane numbers for Categories 1, 2 and 3 of 48, 53 and 55. It states that 'increasing cetane number will decrease engine crank time (the time before the engine reaches 'starter off') at a given engine speed'.

The results of the EPEFE study are also quoted, which found that increases in the cetane number reduced NO_x emissions for heavy duty engines and reduced hydrocarbon and CO emissions for light duty engines. The EPEFE results also indicated that increased cetane number reduced fuel consumption and combustion noise.

Density and viscosity

The Charter states that 'variations in fuel density (and viscosity) result in variations in engine power and, consequently, in engine emissions and fuel consumption. The EPEFE found that fuel density also influences injection timing of mechanically controlled injection equipment, which has effects on emissions and fuel consumption. Therefore, in order to optimise engine performance and tailpipe emissions, both minimum and maximum density limits must be defined in a fairly narrow range'. Studies have indicated that reduced density in diesel fuels will reduce emissions of particulate matter from all diesel vehicles, and NO_x emissions from heavy duty vehicles.

The specifications for maximum density in diesel fuels for Categories 1, 2 and 3 are 860kg/in³, 850kg/in³ and 840kg/in³.

Sulfur

The specifications for sulfur content in diesel fuels reduce dramatically from Category 1 to 3, with the specified levels 500ppm for Category 1, 300ppm for Category 2 and 30 ppm for Category 3. As for petrol, the February 2000 draft of the World Wide Fuel Charter includes a Category 4 for markets with further advanced requirements for emission control to enable sophisticated NO_x and particulate after treatment technologies. This category calls for sulfur free (5ppm to 10ppm maximum) diesel.

The Charter includes a discussion on the impact of sulfur in diesel on particulate emissions. It is noted that the predictive equations formulated by the European Auto Oil programme assessed percentage reduction of particulates, and did not take into account the absolute particulate level or the fuel consumption.

The Charter states that:

"...a correction factor has been developed by European heavy-duty manufacturers to better reflect the relationship between PM emissions and fuel sulfur levels. This correction suggests that the real benefit from sulfur

reductions will be more significant for heavy-duty trucks. Reductions in fuel sulfur will also provide particulate emissions reductions in all engines, regardless of emissions calibration. Testing performed on heavy duty vehicles using the Japanese diesel 13 mode cycle have shown significant PM emission reductions can be achieved both with and without catalytic converters. The testing showed that PM emissions from a truck without a catalytic converter, running on 400 ppm sulfur fuel, were about double the emissions when it was operating on fuel with 2 ppm sulfur. (JSAE No. 981-25)."

Effect of sulfur on diesel after-treatment

The Charter includes the following discussion in the effect of sulfur on diesel catalyst systems:

Future regulations will require lower NO_x and particulate emissions in combination with lower fuel consumption and CO₂ emissions. De-NO_x catalyst systems, which can remove NO_x emissions from the diesel's oxygen-rich exhaust, could be the solution to break the trade-off between NO_x, PM and fuel consumption. However, these systems are very sensitive to fuel sulfur content. The level of sulfur in diesel fuel (and petrol) is an important factor in the performance of De-NO_x systems, and the catalyst performance is better with lower sulfur fuel.

The NO_x reducing after-treatment technology, NO_x adsorption, is poisoned and rendered ineffective by the presence of sulfur. This technology can be up to 90% efficient for NO_x removal, if operated on sulfur-free fuel.

In catalytic oxidizers, depending on the catalyst formulation, the presence of sulfur can lead to increased particulate emissions or result in a reduction of catalyst effectiveness.

Aromatics

The specification for maximum aromatic content becomes progressively lower for Categories 1, 2 and 3. The aim of this specification was to reduce NO_x emissions.

The specified maximum polyaromatic content was also progressively decreased from Categories 1 to 3 to reduce emissions of particulates and PAHs.

3.5 Summary of the Relationship Between Fuel Quality Parameters and Motor Vehicle Emissions Based on Fuel Quality Studies

3.5.1 Key Fuel Parameters for Noxious Motor Vehicle Emissions

Petrol

Sulfur content is the critical petrol parameter, primarily due to its effect on catalyst performance and durability. Advanced catalyst formulations being developed for Euro3/4 compliance and compatibility with developing engine technologies, are especially sensitive and can only be used with very low sulfur fuel.

Lowering the volatility of petrol, as measured by a reduction in vapour pressure or a lower distillation temperature, has been shown to have a significant impact on evaporative VOC emissions.

The relationship between the lead content of petrol and the lead content of motor vehicle emissions in the fuel quality studies is clear.

The addition of oxygenates was found to lower carbon monoxide emissions. A reduction in the aromatics content of petrol reduced emissions of air toxics, hydrocarbons and carbon monoxide, and a reduction in olefins content lead to a significant reduction in emissions of butadiene.

Diesel

There is a clear correlation between some fuel properties and regulated diesel emissions. Drawing general conclusions is, however, difficult due to such factors as inter-correlation of different fuel properties, different engine technologies, or engine test cycles.

In heavy-duty engines increasing the cetane number lowers HC, CO, and NO_x emissions, while reducing fuel density lowers NO_x and PM but increases HC and CO. Light-duty engines show different fuel sensitivity than the heavy-duty engines.

Sulfur increases PM in both classes of engines. Sulfur is also known to interfere with several diesel emission control strategies, especially in relation to particulate emissions reductions. The influence of sulfur on the effectiveness and durability of the key diesel emission reduction technologies are discussed in Chapter 2.

The combustion of engine lubrication oil, although not strictly a fuel issue, is also relevant because diesel engines typically burn significant quantities of oil. Some of the products of combustion, notably phosphorous, zinc, and calcium oxide accumulate on the surface or within catalysts or particulate traps. These oil-derived poisons can result in an irreversible catalyst/trap deactivation.

3.5.2 Key Fuel Parameters for Fuel Consumption

The AQIRP study found that the petrol fuel quality parameters which reduced fuel economy were:

- A reduction in the olefin content from 20% to 5%;
- A reduction in heavy ends (T_{90}) from 360° to 280° ;
- A reduction in sulfur content from 450 to 50 ppm; and
- The addition of oxygenates (0 to 15%).

The studies undertaken in Europe and the United States have confirmed that advanced fuel specifications alone can contribute to reduced air pollution. In addition, they:

“...enable the necessary quality requirements of advanced internal combustion engine and emission control technologies to be met. Without consistent and sufficiently high quality fuel specifications, the engine manufacturers maintain that automotive transport vehicles will not be able to achieve the emissions and other performance characteristics now expected of them”(World Wide Fuel Charter, 1998).