Petrol and Diesel in South Africa

and the impact on air quality

November 2008

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1 Executive summary

The interaction between transport fuel (petrol and diesel), vehicles and the environment is complex, yet critical. It is important that this interaction is clearly understood within the specific context of the local environment to ensure the achievement of the desired outcome - namely cleaner air - without prejudice to the requirement for affordable transportation.

Air pollution continues to affect the quality of air that we breathe. The major sources of urban air pollution – motor vehicles, industry and domestic fuel use - are being addressed in a number of ways throughout the world.

This guide attempts to address some of the issues related to vehicle emissions, drawing on international experience, specifically that of Australia, New Zealand, Asia and Europe. The information gathered from the experience of these countries has been adapted for South African conditions in this guide, in order to provide appropriate contextualisation.

Key issues for consideration, as per the Asian [xi] and New Zealand [iv] cleaner fuels roadmaps, include the following:

- **The need for a systems approach**: Fuels and vehicles are part of an integrated system and need to be addressed simultaneously. The main emissions reduction benefits will be achieved through the coupling of cleaner fuels with advanced emission control devices.
- **Vehicle technology**: A cleaner fuel will not necessarily make a dirty vehicle clean.
- **Fuel quality regulation** needs to be combined with vehicle emissions standards, as the backbone of a country's roadmap for reducing pollution from vehicles.
- **Sulphur reduction is key**: Reducing sulphur levels in both petrol and diesel fuels is the primary fuel parameter that needs to be considered in developing a country's fuel roadmap. High sulphur levels impair the efficacy of exhaust after-treatment devices.
- **The importance of clean fuels**: Over the course of the past 30 years, pollution control experts around the world have come to realise that cleaner

fuels are a critical component of an effective clean air strategy. In recent years, this understanding of the critical role of fuels has grown and deepened and spread to most regions of the world. Fuel quality is now seen as not only necessary to eliminate or reduce certain pollutants (e.g. lead) directly, but also as a precondition for the introduction of many important pollution control technologies (e.g. diesel particulate filters).

One additional critical advantage of cleaner fuels that has emerged is its rapid impact on both new and existing vehicles. Thus, while tighter new vehicle standards can take ten or more years to be fully effective, the removal of lead in petrol in South Africa, for example, has had the effect of reducing lead emissions from all vehicles immediately. Certain fuel parameters will have a direct and "immediate" impact on improved air quality (such as sulphur reduction from 5500 to 500 ppm (m/m), and lead phase-out), while others may have little impact.

Further reductions in sulphur levels will require that the vehicle parc has the relevant emissions technology in place and that such technology is effectively inspected and maintained.

Motor vehicles, including both passenger cars and heavy-duty buses and trucks, continues to be the source of much urban air pollution. Key emissions from motor vehicles include carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_X), volatile organic compounds (VOC), and unburned hydrocarbons (HC). Carbon dioxide (CO_2) emissions are linked to climate change and hence need to be considered from a global perspective. Other non regulated emissions such as benzene and formaldehydes are also considered to be important from a health perspective.

Emissions of these pollutants depend predominantly on vehicle technology, the quality of fuels used and the maintenance levels of the vehicle parc. Reducing emissions from motor vehicles is dependent on the introduction of cleaner fuels, together with advanced emissions control technologies that require these cleaner fuels. A key first step has been the world-wide drive to eliminate lead in petrol and to reduce fuel sulphur content. To continue the process of reducing vehicle emissions, new technology will require further improvements to the enabling fuel quality.

This guide has been designed to provide relevant and current information for decision-makers on the means to improving air quality, with reference to motor vehicles. It attempts to discuss the interaction between fuels, vehicle technologies and the refining industry in South Africa, without attempting to draw specific conclusions for the South African roadmap. The guide does however provide suggestions for future consideration in this regard.

2 Contents

1 Executive summary **1**

2 Contents **3**

3 Abbreviations **9**

4 Introduction **13**

5 Regulations **15**

6 The South African fuel market and vehicle fleet **17**

6.1 Fuel Market 17
6.2 Where does South Africa's fuel come from? 18
6.3 Where is South Africa's fuel used? 23
6.4 Fuel Wholesalers 25
6.5 Regulatory vs. Internal Specifications 25
6.6 South African Vehicle parc 25
6.7 Vehicle Fleet Emissions 26
6.8 Registered Fleet 27
6.9 Where do our vehicles come from? 29
6.10 Fleet Age and Turnover 30
6.11 Emission Standards 31
6.12 Emissions Control Capability of the South African vehicle parc 31
6.13 Engine and Emission Control Technology 32
6.14 Off highway 33
6.15 Other Users – Commercial 33
6.16 Other Users – Retail 33
6.17 Agricultural Use 33
6.18 Summary 33

7 Consumer protection, environmental, health and safety considerations **35**

7.1 Consumer Protection 35
7.2 Consumer Issues [iv] 36
7.3 Fuel Quality Monitoring [iv] 36

7.4 Environment – Air Quality . . . 37
7.5 Sources of Air Emissions Arising from the Use of Petrol and Diesel in South Africa 39
7.6 Products of Combustion . . . 40
7.7 Displacement Losses from Distribution (Evaporative Losses) . . . 40
7.8 Evaporative Losses from Vehicles . . . 41
7.9 Global Climate Change [iv] . . . 41
7.10 Environment – Water Quality . . . 42
7.11 Health Effects [iv] . . . 43
7.12 Fuel Distribution Occupations [iv] . . . 43
7.13 Motor Trade Occupations [iv] . . . 44
7.14 Summary . . . 44

8 International scene . . . 45

8.1 Vehicle Emission Standards . . . 46
8.2 Fuel Quality and Emissions [iv] . . . 48
8.3 Fit-for-Purpose vs. Performance vs. Enabling Specifications [iv] . . . 48
8.4 Effects of petrol composition and properties on vehicle emissions . . . 50
8.5 Correlations between petrol quality and emissions . . . 50
8.6 Effects of diesel composition and properties on vehicle emissions [iv] . . . 51
8.7 Emissions: Vehicle Technology vs. Fuel Quality Effects . . . 52
8.8 Vehicle Technology . . . 52
8.9 Fuel Quality [iv] . . . 55
8.10 International Fuel Specifications . . . 55
8.11 Japan . . . 56
8.12 Australia . . . 57
8.13 New Zealand . . . 57
8.14 European Fuel Specifications . . . 58
8.15 World-Wide Fuel Charter [xiii] . . . 60
8.16 United States of America [iv] . . . 61
8.17 China and India . . . 63
8.18 Summary . . . 63

9 Properties of petrol . . . 64

9.1 Octane Number [iv] . . . 65
9.2 Colour [iv] . . . 69
9.3 Volatility and Distillation Parameters [iv] . . . 70
9.4 Residue and Existent Gum [iv] . . . 75
9.5 Copper Strip Corrosion [iv] . . . 76
9.6 Sulphur [iv] . . . 76

9.7 Oxidation Stability Induction Period [iv] . . . 79
9.8 Lead [iv] . . . 80
9.9 Total Aromatics [iv] . . . 81
9.10 Benzene [iv] . . . 84
9.11 Oxygenates [iv] . . . 85
9.12 Density [iv] . . . 94
9.13 Manganese [iv] . . . 95
9.14 Phosphorus [iv] . . . 96
9.15 Potassium [iv] . . . 97
9.16 Olefins [iv] . . . 98
9.17 Summary . . . 99

10 Properties of diesel . . . 100

10.1 Density [iv] . . . 100
10.2 Total Contaminants, Water Content, Appearance and Colour [iv] . . . 102
10.3 Cetane Number and Cetane Index [iv] . . . 104
10.4 Cold Flow Properties [iv] . . . 106
10.5 Viscosity [iv] . . . 108
10.6 Flash Point [iv] . . . 110
10.7 Sulphur [iv] . . . 111
10.8 Copper Strip Corrosion [iv] . . . 114
10.9 Ash [iv] . . . 115
10.10 Carbon Residue [iv] . . . 116
10.11 Distillation [iv] . . . 117
10.12 Oxidation Stability [iv] . . . 119
10.13 Lubricity [iv] . . . 120
10.14 Biodiesel / FAME . . . 121
10.15 Polycyclic Aromatic Hydrocarbons (PAH) [iv] . . . 122
10.16 Conductivity . . . 124
10.17 Summary . . . 124

11 Properties of Biofuels . . . 125

11.1 Fuel specifications . . . 125
11.2 Financial implications for RSA . . . 126
11.3 Security of petrol supply . . . 126
11.4 Quality control and product liability . . . 126
11.5 Blending of biofuels . . . 126
11.6 Technical aspects that need to be considered for biofuels implementation . . . 127
11.7 Biodiesel . . . 127

11.7.1 Ethanol . . . 128
11.8 Summary . . . 132

12 The requirement for regulation . . . 133
12.1 Why do we need Regulations? [iv] . . . 133
12.2 Fit for Purpose [iv] . . . 133
12.3 Test Methods [iv] . . . 133
12.4 Ensuring Fuel Consistency [iv] . . . 134
12.5 Pool Averaging [iv] . . . 134
12.6 Mandated Geographical Differences . . . 134
12.7 Additives [iv] . . . 135

13 Key issues . . . 136
13.1 Key Issues for the Fuel Supply Market . . . 136
13.2 Key Issues for Fuel Use . . . 137
13.3 Key Issues for Environment and Health [iv] . . . 138
13.4 Timing . . . 138

14 Appendices . . . 141
Appendix A – South African Specifications . . . 142
Appendix B – Internal combustion Engine Basic Operating Principles and Technology Trends [iv] . . . 144
Appendix C – New Zealand's Vehicle Emissions Control Strategy [iv] . . . 161
Appendix D – Air Contaminants [iv] . . . 165

15 Index . . . 177

16 References . . . 179

List of figures:

Figure 1 South African Refinery Locations 19
Figure 2 South African petroleum product depot map 20
Figure 3 Transnet Pipeline current and proposed pipeline network 22
Figure 4 Petrol usage in South Africa by Sector 23
Figure 5 Diesel usage in South Africa by Sector 24
Figure 6 Influences on Vehicle Emissions 27
Figure 7 Passenger car parc by age category 30
Figure 8 Fuel requirements by vehicle technology type in South Africa 32
Figure 9 Air Emissions Arising from the use of Petrol and Diesel 40
Figure 10 Discharges of Contaminants to Water Arising from the use of Petrol and Diesel in South Africa 42
Figure 11 Drivers of Fuel Quality 45
Figure 12 Timetable of international emissions legislations [xi] 48
Figure 13 Plot showing the relative reduction in emissions limits of the European emissions legislation for petrol vehicles [xii] 53
Figure 14 Plot showing the relative reduction in emissions limits of the European emissions legislation for diesel vehicles [xii] 54
Figure 15 EU Fuel Policy 59
Figure 16 Results of the RUFIT study to determine the optimum octane levels [xiv] 66
Figure 17 Typical Distillation Curve for Petrol [iv] 71
Figure 18 Contribution of different vehicle technologies to vehicle parc emissions 137
Figure 19 Predicted CO Emission Rates in New Zealand [iv] 162

List of tables:

Table 1.1 Consumption of petroleum products in South Africa in 2007 17
Table 1.2 Consumption of petroleum products in South Africa, 2000–2007 [i] 17
Table 2 South African vehicle population as at the end of 2007 28
Table 3 Typical Fuel specifications from vehicle source countries [xv] 30
Table 4 World-Wide Fuel Charter Fuel Categories 61
Table 5 Current South African and International Octane Specifications [xv] 68
Table 6 Current South African and International Colour Specifications [xv] 69
Table 7 Current South African and International Volatility Specifications [xv, xii] 73
Table 8 Current South African and International Gum & Residue Specifications [xv] 75
Table 9 Current South African and International Sulphur Specifications [xv] 77
Table 10 Current South African and International Oxidation Stability Specifications 79
Table 11 Current South African and International Lead Specifications [xv] 81
Table 12 Current South African and International Aromatic Specifications [xv] 83
Table 13 Current South African and International Benzene Specifications [xv] 84
Table 14 Key Blending Properties of most commonly used oxygenates 86
Table 15 Current South African and International Oxygen Specifications [xv] 88
Table 16 Current South African and International Density Specifications [xv] 94
Table 17 Current South African and International MMT Specifications [xv] 95
Table 18 Current South African and International Phosphorous Specifications [xv] 96
Table 19 Current South African and International Potassium Specifications [xv] 97
Table 20 Current South African and International Olefin Specifications [xv] 99
Table 21 Current South African and International Density Specifications [xv] 102
Table 22 Current South African and International Water & Total Contamination Specifications [xv] 103
Table 23 Current South African and International Cetane Specifications [xv] 105
Table 24 Current South African and International Cold Flow Specifications [xv] 108
Table 25 Current South African and International Viscosity Specifications [xv] 109
Table 26 Current South African and International Flash Point Specifications [xv] 110
Table 27 Current South African and International Sulphur Specifications [xv] 112
Table 28 Current South African and International Ash Specifications [xv] 115
Table 29 Current South African and International Carbon Residue Specifications [xv] 116
Table 30 Current South African and International Distillation Specifications [xv] 118
Table 31 Current South African and International Oxidation Stability Specifications [xv] 119
Table 32 Current South African and International Lubricity Specifications [xv] 120
Table 33 Current South African and International FAME Specifications [xv] 122
Table 34 Current South African and International PAH Specifications [xv] 123

3 Abbreviations

ACEA	European Automobile Manufacturers Association
ASTM	ASTM International
AQA	Air Quality Act
AQIRP	Air Quality Improvement and Research Program
CEF	Central Energy Fund
CBU	Completely built up (finished vehicle imported from overseas)
CFPP	Cold Filter Plugging Point
CI	Cetane Index
CN	Cetane Number
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conformity of Production
cSt	centistokes
DBL	Diurnal breathing losses
DEAT	Department of Environment and Tourism
DME	Department of Minerals and Energy
DPF	Diesel Particulate Filter
EC	European Commission
ECA	Environmental Capacity Analysis
EGR	Exhaust gas recirculation
EMA	Engine Manufacturers Association
EPA	Environmental Protection Agency
EPEFE	European Programmes on Emissions Fuels and Engine technologies
EU	European Union
GDi	Gasoline Direct Injection
IARC	International Agency for Research on Cancer
I&M	Inspection and maintenance
IP	The Institute of Petroleum, London
IP&WM	Integrated Pollution and Waste Management Policy
ISO	International Organisation for Standardisation
JAMA	Japan Automobile Manufacturers Association
LOAEL	Lowest Observable Adverse Effect Level
LPG	Liquefied petroleum gas (vehicle fuel)
LRP	Lead Replacement Petrol

LSD	Low Sulphur Diesel
MMT	Methylcyclopentadienyl managanese tricarbonyl (an octane enhancer)
MON	Motor Octane Number
MOT	Ministry of Transport
MTBE	Methyl tertiary butyl ether
NEMA	National Environmental Management Act
NMPP	New Multi Product Pipeline
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen (general term)
NOAEL	No Observed Adverse Effect Level
NRCS	National Regulator of Compulsory Specifications
O_3	Ozone
PAH	Polycyclic aromatic hydrocarbons
PM_{10}	Particulate matter of less that 10 μm diameter
$PM_{2.5}$	Particulate matter of less than 2.5 μm diameter
PPA	Petroleum Products Amendment Act
ppm	parts per million
RFG	Reformulated Gasoline
RON	Research Octane Number
RVP	Reid Vapour Pressure
SANS	South African National Standards
SABS	South African Bureau of Standards
SAPIA	South African Petroleum Industry Association
TWC	Three Way Catalyst
ULP	Unleaded Petrol
ULS	Ultra Low Sulphur
VOC	Volatile organic compound
VFEM	Vehicle Fleet Emissions Model
WES	Workplace Exposure Standard
WHO	World Health Organisation

Units of Measure

Barrel	159 litres
Bpsd	Barrels per stream day
cSt	centistokes, unit of kinematic viscosity; alternatively mm2 /sec
deg C	degrees centigrade
g	gram
g pb/l	grams of lead per litre
kPa	kilopascal (pressure)
mg	milligram, 10^{-3} grams
mins	Minutes
µg	microgram, 10^{-6} grams
ng	nanogram, 10^{-9} grams
kg/m^3	kilograms per cubic metre (unit of density)
kg/litre	kilograms per litre (unit of density)
g/m^3	grams per cubic metre, (unit of concentration) equivalent to mg/litre
mg/litre	milligrams per litre (unit of concentration) equivalent to ppm (m/v)
mg KOH/g	milligrams Potassium Hydroxide per gram
m/m	mass/mass (weight ratio)
m/v	mass/volume (weight volume ratio)
µm	micron, 10^{-6} m
ppm	parts per million
pS/m	Picosiemens per metre
v/v	volume/volume (volumetric ratio)

4 Introduction

This reference guide contains detailed discussion regarding diesel and petrol specifications with reference to international experience, specifically that of New Zealand, Australia and Asia. It also contains the background to these specifications, and the relevance for South Africa. It does not attempt to draw specific conclusions for the South African roadmap, but does however, provide suggestions for future consideration in this regard.

The parameters discussed concern fuel quality characteristics and components that might be considered appropriate for the South African vehicle parc and the country's unique climatic conditions. The discussion also covers fuel components that could be harmful to the environment or to the public health.

Specifications need to be continually reviewed to enable the introduction of cleaner, more efficient, vehicle technology, ultimately with a view to improving air quality. The overall specifications need to consider the entire vehicle population, which consists of old and new technologies.

The reference guide has two main objectives:

- To clarify the purpose of fuel specifications and regulations; and
- To clarify the need for such specifications and regulations over the medium to long term, and to learn from the experiences of other countries in this regard.

Petrol and diesel specifications were first regulated in 2006 in South Africa following the phase-out of lead, the introduction of benzene and aromatics specifications and the reduction in diesel sulphur.

Although emission-reduction enabling fuel has been available in South Africa since 1996, when unleaded petrol was introduced, new vehicle emissions have only been controlled for all new vehicle sales since the beginning of 2008. Sulphur reduction in diesel over the last decade also facilitated the introduction of newer technology in both on-road and non-road engines.

There have been further developments both domestically and internationally in fuel engine technologies and fuel production processes, while the understanding of the health and environmental issues surrounding petrol and diesel use has increased. With these developments in mind, a review of the enabling specifications is required to ensure that future specifications to be determined are "fit for purpose" for the South African conditions and the country as a whole.

Other jurisdictions, notably New Zealand, Europe, the United States of America, Australia and Japan, have adopted more stringent fuel specifications in recent years to achieve specific quality, safety, health and environmental outcomes. The reference guide provides summaries of relevant international experience in the area of fuel specification and examines the purpose of regulations introduced elsewhere.

Particular emphasis has been placed in this document on the following issues:

- Consumer, environmental, health and safety concerns and the most appropriate ways of addressing them.
- Whether the specifications create barriers to the development of new products and/or the adoption of new technology.
- International specification trends, and the reasons for adopting certain specifications in a specific region.
- The interdependence between fuel, vehicle technology and the environment.

Fuel specifications introduced in a number of regions in the world have been based on the European vehicle emissions and the respective enabling fuels, however they have often been modified to suit certain local conditions. Reference is made in this guide to New Zealand, Australia and Asia as they have followed this route.

The reference document does not cover:

- **Alternative fuels**: Alternative fuels include LPG (Liquefied Petroleum Gas), CNG (Compressed Natural Gas) and E85 (85% ethanol; 15% petrol). The document does however consider the use of petrol/ethanol blends, discussed in Section 9.
- **Life-cycle energy analysis**: Changes to fuel specifications may require additional processing energy at refineries, which would increase emissions of CO_2. A full life-cycle analysis of the effect of the proposed changes on CO_2 emissions has not been conducted.
- **Traffic congestion**: The causes of traffic congestion and ways of managing congestion have not been discussed.
- **Road and fuel pricing policy**: This discussion does not extend to ways of financing any recommended changes in the specifications nor to concomitant road and fuel pricing policy and practice.
- **Costs**: The costs for refinery upgrades, inspection and maintance and vehicle technology have not been considered.

5 Regulations

The liquid fuels industry in South Africa has been regulated for a considerable period of time. Currently, there are licensing requirements and regulations pertaining to, *inter alia*:

- Importation of crude oil
- Importation and exportation of petrol and diesel
- Importation and export of intermediate blend stocks
- Refining of crude oil
- Extraction of coal and conversion to petrol and diesel
- The operation of pipelines, including tariff structures
- The operation of fuel depots and loading facilities
- Wholesaling of fuels, including the maximum wholesale price of diesel
- Retailing of fuels, including the pump price of petrol by grade and location
- Another reason we need Regulations on specs is to allow fungibility which in turn allows product exchange to take place and this in turn allows a more efficient way to serve the market.

Fuel quality specifications have previously been set through agreement between all the stakeholders, comprising the government, the oil industry, consumer bodies and the motor vehicle manufacturers. The Department of Minerals and Energy (DME) has the responsibility for managing changes to the specifications as required.

Specifications for petrol and diesel petroleum fuels were first promulgated in terms of the Petroleum Products Amendment Act (PPA), issued by the Department of Minerals and Energy (DME) on 23 June 2006*. The "Regulations Regarding Petroleum Products Specifications and Standards" defines the permitted petrol and diesel (including biodiesel) grades that can be legally marketed. It also makes provision for product specifications, inspection and testing,

* Refer to www.dme.gov.za

labelling on dispensing bowsers, and the requirement for purchase and sale records to be kept by licensees.

The purpose of the regulated standards for diesel and petrol supplied and sold in South Africa is to protect the interests of consumers and to provide minimum standards for performance, safety and environmental protection.

Regulatory guidance is necessary to allow for the required investment in the refining industry, in the best interest of the country.

6 The South African fuel market and vehicle fleet

This section considers South Africa's sources of petrol and diesel fuels, patterns of use and application. These factors are important when considering any future fuel specifications, bearing in mind the country's particular requirements and how best to meet them. This section also considers the characteristics of the South African vehicle parc.

6.1 Fuel Market

South Africa consumed approximately 11.5 billion litres of unleaded petrol and 10 billion litres of diesel during 2007.

Table 1.1: Consumption of petroleum products in South Africa in 2007

Product Volumes in millions of Litres	Q1	Q2	Q3	Q4	Total
PETROL	2878	2778	2908	2994	**11558**
DIESEL	2316	2314	2495	2632	**9757**
JET FUEL	615	575	581	621	**2392**
ILLUM PARAFFIN	155	187	190	165	**697**
FUEL OIL	104	113	124	129	**470**
BITUMEN	92	90	79	73	**334**
LPG	153	145	191	165	**654**
Sum of Above	6313	6202	6568	6779	25862

Petrol Consumption in South Africa has been fairly static over the last 5 years, with annual growth averaging approximately 1.6% and the proportion of premium grade, introduced in 2006, increasing slightly. There has been a fairly steady growth in diesel consumption, however, averaging approximately 8% over the last 5 years.

Table 1.2: Consumption of petroleum products in South Africa, 2000–2007 [i]

Product Volumes in millions of Litres	2000	2001	2002	2003	2004	2005	2006	2007
PETROL	10396	10340	10335	10667	10985	11165	11279	11558
DIESEL	6254	6488	6831	7263	7679	8115	8708	9757
JET FUEL	2020	1924	1967	2099	2076	2180	2269	2392
ILLUM PARAFFIN	857	786	745	769	797	761	738	697
FUEL OIL	555	555	536	528	569	489	476	470
BITUMEN	219	242	267	272	277	305	314	334
LPG	567	599	586	558	563	550	605	635
Sum of Above	20868	20934	21267	22156	22945.28	23565	24389	25843

6.2 Where does South Africa's fuel come from?

Refining, Production and Supply

Petrol and diesel supplied in South Africa comes from a number of sources:

- **Crude oil refined at the following refineries:**

Name	Crude throughput	Ownership
Chevref	100 000 bpsd	Chevron
Enref	125 000 bpsd	Engen
Natref	108 000 bpsd	Sasol / Total SA (64/36%)
Sapref	180 000 bpsd	Shell / BP (50/50%)

- **Coal and gas processed and refined at:**

Sasol Secunda	150 000 bpsd	Sasol
	(crude equivalent @ average yield)	

- **Gas processed and refined at:**

PetroSA	45 000 bpsd	Central Energy Fund (CEF)
	(crude equivalent @ average yield)	

- **Direct imports of finished product and fuel blending components into the following ports:**

  – Cape Town

  – Durban

  – Mossel Bay

  – Maputo

  Port Elizabeth and East London also receive product from local refineries.

Each product is as far as possible fungible (exchangeable), that is, product from any one refinery or import can be mixed with product from any other refinery or import, with the resulting mixture meeting the appropriate specification. This facilitates exchange agreements which allow for reduced infrastructural and logistic costs.

Four of the refineries are on the coast and two are inland. Approximately 60% of the demand is in the inland region. Product is currently conveyed inland via pipeline (operated by Transnet Pipelines), road and rail to a network of secondary depots, and by ship around the coast.

Figure 1: South African Refinery Locations

Sources of Crude Oil and blendstocks

Crude oil for the four crude refineries comes from various countries. Each refinery selects its optimum crude mixture based on its design and configuration, desired yield, crude cost and availability. Light crude oil is also imported as feedstock into the PetroSA refinery.

Some imported petrol blendstocks are required for refineries to meet octane requirements. These blendstocks are generally high octane components purchased from overseas refineries. As will be discussed later, changes to petrol specifications may limit or preclude the use of these blendstocks in future.

Typically, the current capacity for desulphurisation of diesel in the refining industry in South Africa is limited and is insufficient to allow each refinery to reach its maximum potential output whilst meeting the current legislated maximum sulphur levels of 500 ppm (m/m). As a result, a proportion of diesel or low sulphur diesel blendstock is currently imported.

A niche diesel grade is also marketed in limited areas at a level of 50 ppm (m/m) sulphur, as increasingly required by growing new passenger car technologies.

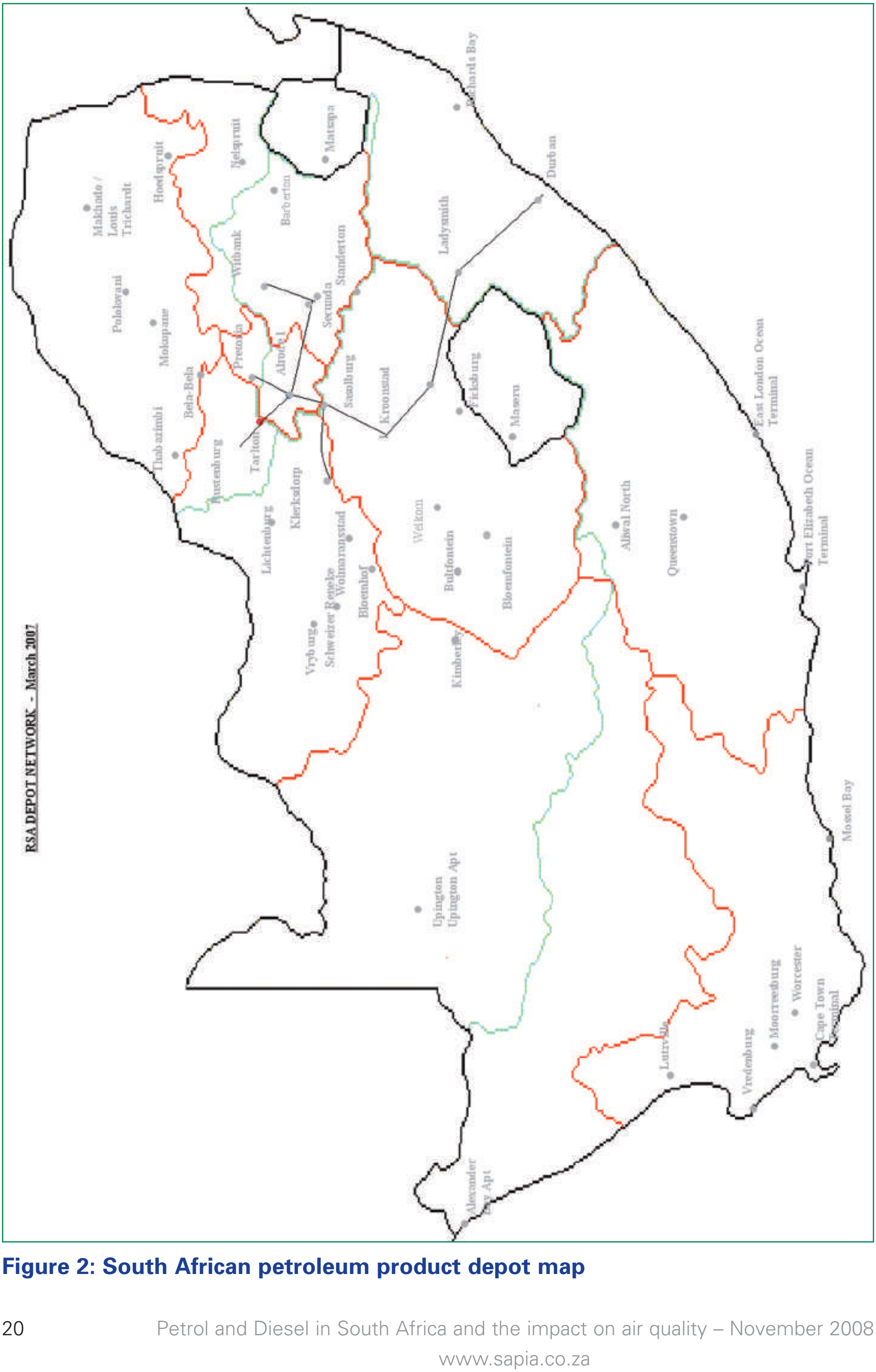

Figure 2: South African petroleum product depot map

This is sourced predominantly from the synthetic fuel manufactured in Secunda, while limited quantities are sourced from the other refineries and from imports.

The refining industry is currently constrained with regard to octane in petrol and distillate sulphur. As noted above, petrol blendstocks are already used to achieve the required octane rating within the regulated limits. Further reductions in appropriate enabling specifications, which will have an impact on air quality, will have certain volume and cost implications for the production of petrol.

Distribution of Product

There are four means to distribute product from the refineries and import terminals to regional centres, as indicated in Figure 2:

- By multi product pipeline (petrol, diesel and jet A1) from Durban;
- By coastal tanker from Durban, Cape Town and Mossel Bay to storage terminals at East London, Port Elizabeth, Mossel Bay and Cape Town;
- By road tanker from refineries and terminals;
- By railcar from refineries and terminals.

Transnet Pipeline

Transnet Pipeline (previously Petronet) was established in 1965 as a result of the inability of the South African rail network to cope with the demands of the inland fuel market. The first refined product pipeline was commissioned in November 1965 to carry refined product from Durban to Johannesburg.

Today, Transnet Pipeline operates, manages and maintains a network of 3 000 km of high-pressure gas pipelines. The network traverses 5 provinces, from KwaZulu-Natal to Gauteng. The pipelines range from 150 mm (6 inches) to 508 mm (20 inches) in diameter.

Transnet Pipeline is responsible for the transport of liquid fuels: petrols, diesel, jet fuel, crude oil and gas (methane rich gas). The total product throughput is approximately 16 billion litres per annum, and the gas throughput is 450 million cubic metres per annum.

The current pipeline is not sufficient to handle the high volume inland demand and a New Multi Product Pipeline (NMPP) is being built and is estimated to be completed by the third quarter of 2010.

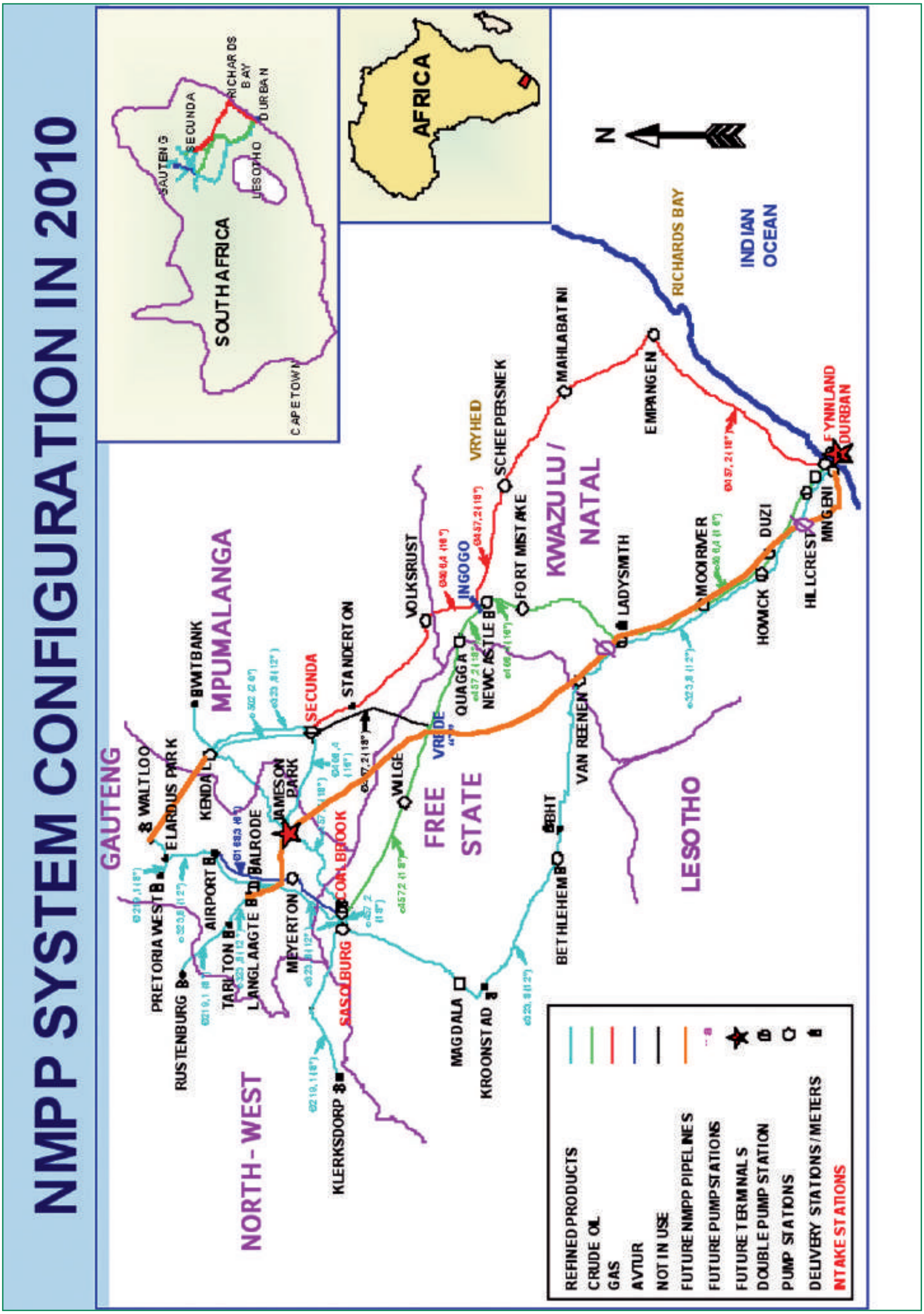

Figure 3: Transnet Pipeline current and proposed pipeline network

Imported fuel

The balance of diesel and petrol requirements not met by the local refining industry is imported directly, predominantly to the storage terminals in Durban.

6.3 Where is South Africa's fuel used?

Figure 4 and Figure 5 show South Africa's pattern of consumption of petrol and diesel, respectively, for the year 2007. 95% of petrol consumed was sold through retail outlets (petrol stations). By comparison, 51% of diesel consumed was used for transport but only 38% of this was sold through retail outlets (most of which was used for on-road transportation. Off-highway use of diesel is discussed in more detail in Section 6.4.)

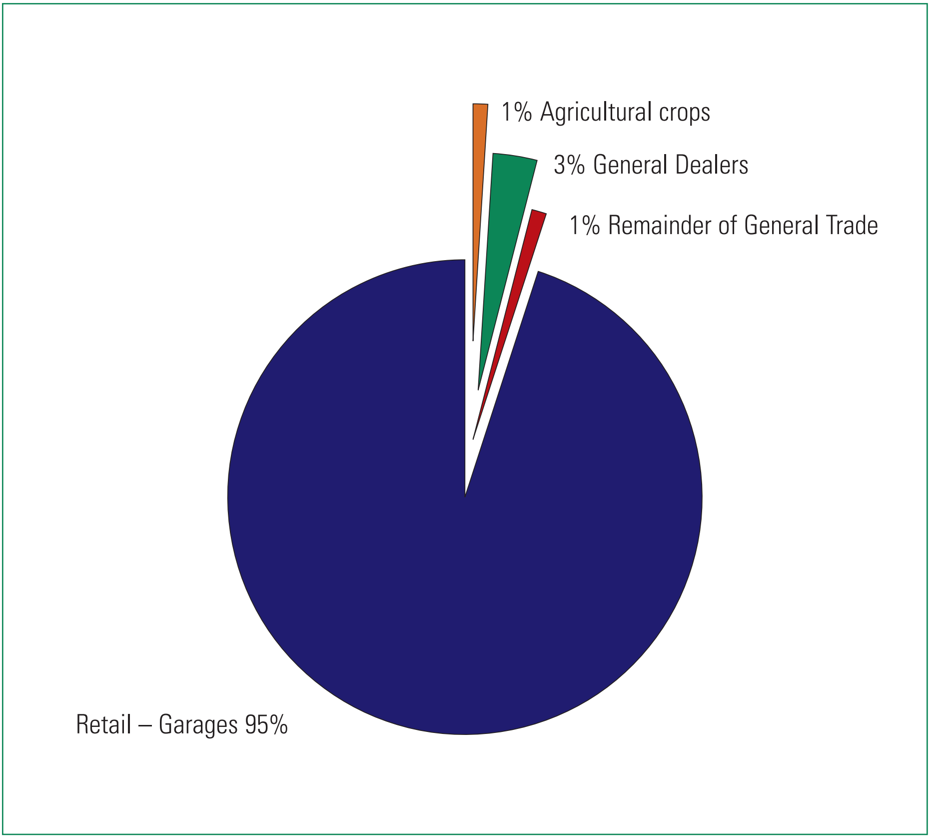

Figure 4: Petrol usage in South Africa by Sector

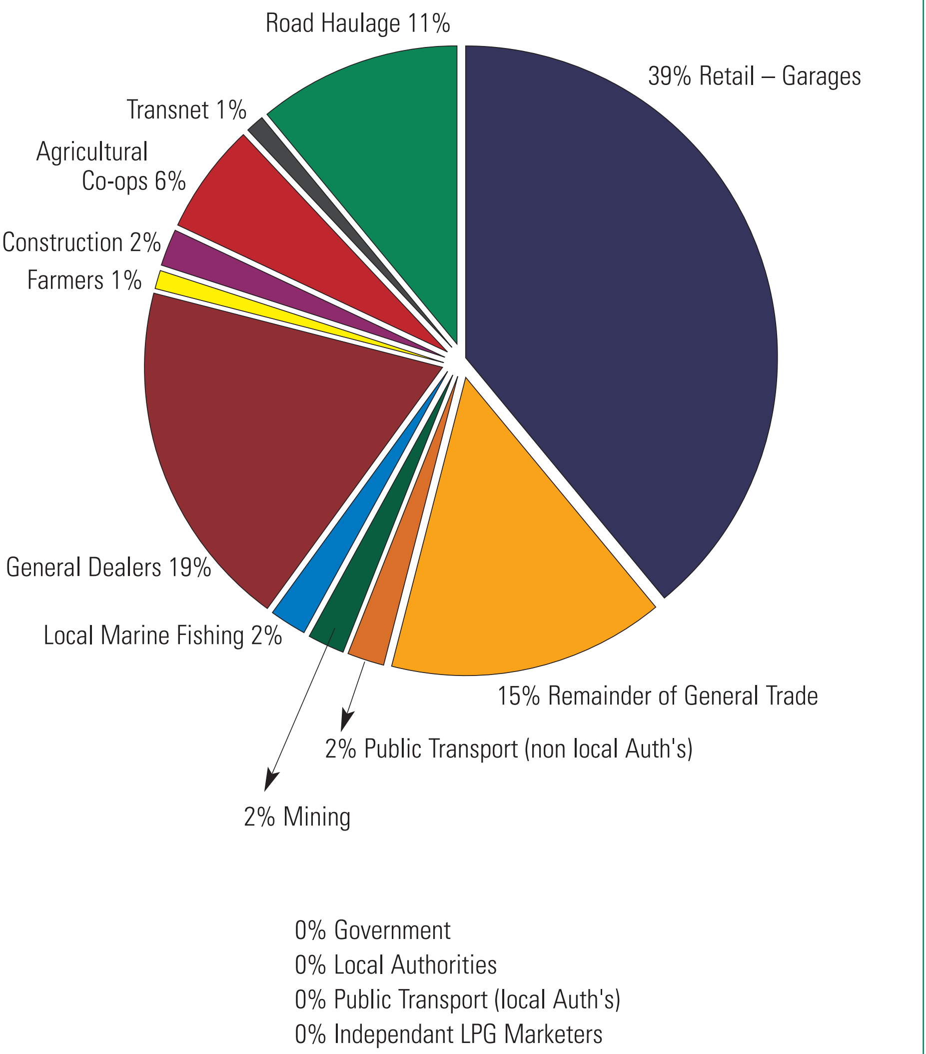

Figure 5: Diesel usage in South Africa by Sector

6.4 Fuel Wholesalers

"Majors"

The majors in the South African oil industry are BP, Chevron, Engen, PetroSA, Sasol, Shell and Total SA. They operate storage terminals and distribution facilities at the major ports and have distribution facilities throughout South Africa.

Competition in the fuels market has seen significant rationalisation of distribution infrastructure in the last few years. As all products are "fungible", hosting arrangements enable all companies to optimise shipping and use of terminal storage capacity and distribution infrastructure.

"New Entrants"

Until recently, there were relatively few non-refining wholesalers supplying petrol and diesel in South Africa. Today, however, there are a number that are registered with the Department of Minerals and Energy, including Afric Oil, Masana Petroleum Solutions and G2L.

6.5 Regulatory vs. Internal Specifications

All fuel is required to meet the regulated quality "ex nozzle", that is, at the point of sale or supply. Some minor changes occur with regard to fuel properties during storage and distribution and is inevitable. The fuel suppliers have therefore developed exchange specifications for refined product. These are more comprehensive and in some cases more stringent than the regulatory requirements.

These exchange specifications reflect more specific fit-for-purpose requirements (such as geographical variations) and allow some operating margin for quality changes between storage and sale.

6.6 South African Vehicle parc

South Africa's vehicle parc (fleet) is considered to be, on average, relatively old and therefore uses a wide range of vehicle and emission technologies. This is an important aspect to consider when comparing current fuel quality specifications with those applicable in other countries. Specifications in many other countries have generally been developed for vehicle parcs which are on average newer. Any changes to South African fuel specifications must therefore reflect the unique character of our vehicle parc.

From 1 January 2008 all new vehicles (both locally manufactured and imported) are required to meet or exceed "Euro 2" emissions levels. Over time, the "average" state of the vehicle parc's technology will improve as new vehicles feed into the vehicle parc and older vehicles are scrapped. Scrapping and renewal policies will determine the rate at which the improvement in the "average" technology level will continue to lag behind what can be considered "state-of-the-art".

6.7 Vehicle Fleet Emissions

In 1996, a South African Vehicle Emissions Strategy was initiated, involving a number of phases from establishing the contribution of vehicle emissions in South Africa to modelling. This was unfortunately not progressed past the testing phase.

However, vehicle emissions and modelling work has been conducted in other parts of the world, such as New Zealand where the Ministry of Transport is responsible for its Vehicle Fleet Emissions Control Strategy (VFECS). The purpose of this work was to characterise and quantify emissions from the New Zealand vehicle fleet, as a basis for evaluating policy options for emissions reduction. A summary of this work is provided in the Appendix C.

The VFECS work involved the development of a detailed vehicle fleet emissions model (VFEM) to characterise emission rates according to vehicle type, age, fuel and driving conditions, and to predict the likely impact of fleet changes and driving patterns over time. In addition to the VFEM, an Environmental Capacity Analysis (ECA) model was also developed to predict emissions rates at a localised geographical level, based on vehicle routes and traffic patterns, for use as a tool in local air quality management.

The study uncovered a number of factors that influence emission rates from vehicles, as illustrated in Figure 6. One of the key findings of the VFECS work was the significant impact that congestion and driving conditions have on vehicle emissions rates and the relatively smaller impact of vehicle and emissions control technology.

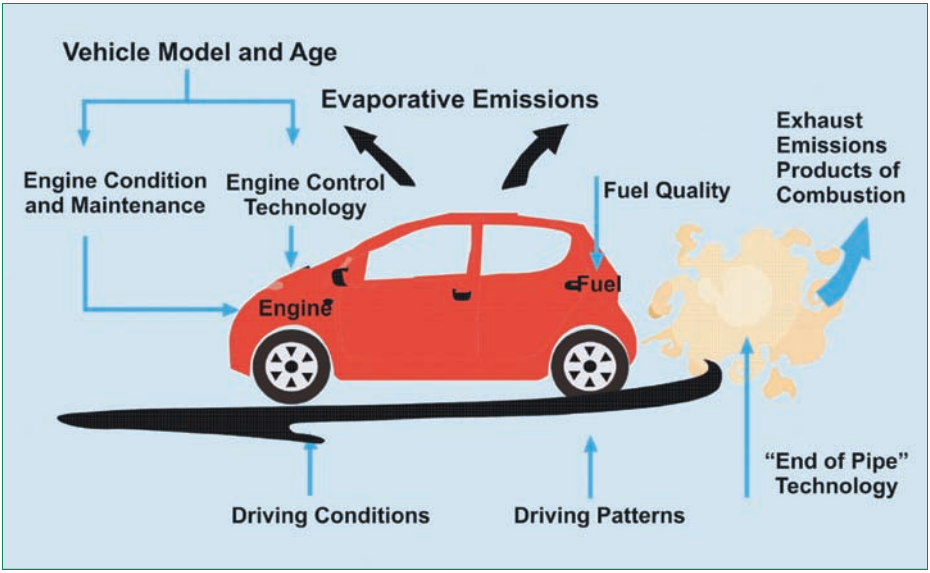

Figure 6: Influences on Vehicle Emissions

6.8 Registered Fleet

The following figures supplied by the National Department of Transport from the eNATIS vehicle registry data summarise the characteristics of the South African vehicle fleet, as at the end of 2007.

Table 2: South African vehicle population as at the end of 2007

Dec 2007	Vehicle population per province									
	GA	KZ	WC	EC	FS	MP	NW	LI	NC	RSA
Motorised Vehicles										
Motorcars	2,155,748	731,017	943,174	327,252	241,159	253,331	244,214	178,439	86,510	5,160,844
Minibuses	106,720	41,868	36,092	20,397	11,998	18,683	18,985	18,248	3,608	276,599
Buses	13,019	6,398	5,054	3,151	1,781	3,548	2,641	3,293	1,056	39,941
Motorcycles	124,311	31,370	63,437	19,665	19,718	18,726	17,162	10,420	7,237	312,046
LDV's - Bakkies	584,204	268,286	263,525	152,034	104,078	135,635	120,393	137,519	57,155	1,822,829
Trucks	113,427	47,645	34,476	23,715	18,373	22,474	16,925	17,808	8,112	302,955
Other & Unknown	32,385	28,532	29,008	11,500	35,795	21,078	23,307	11,810	6,468	199,883
Sub-Total	**3,129,814**	**1,155,116**	**1,374,766**	**557,714**	**432,902**	**473,475**	**443,627**	**377,537**	**170,146**	**8,115,097**
Towed Vehicles										
Caravans	42,147	8,813	16,732	6,025	8,172	9,310	7,769	5,084	3,026	107,078
Heavy Trailers	44,878	24,368	11,077	10,589	12,055	12,452	8,603	5,921	3,872	133,815
Light Trailers	262,897	66,788	107,140	42,555	53,707	45,591	46,521	28,407	21,272	674,878
Sub-Total	**349,922**	**99,969**	**134,949**	**59,169**	**73,934**	**67,353**	**62,893**	**39,412**	**28,170**	**915,771**
All other unknown	6,337	3,635	5,432	2,565	5,114	4,384	5,610	2,863	1,312	37,252
All Vehicles	**3,486,073**	**1,258,720**	**1,515,147**	**619,448**	**511,950**	**545,212**	**512,130**	**419,812**	**199,628**	**9,068,120**

Vehicle numbers and types

There were approximately 8.1 million registered motorised vehicles in 2007, an increase of 523,000 over the previous year. The total number included 302,995 trucks, 39,941 buses and 321,046 motorcycles and mopeds, with the balance (approximately 60% of the total) being motor cars.

It is believed that these figures significantly underestimate the actual fleet size, particularly in the agricultural sector where many vehicles are not registered for road use. On the other hand, it is acknowledged that there are a number of mostly older vehicles which remain registered but are in-active, and furthermore that older vehicles typically drive fewer kilometres per annum and thus consume proportionally less fuel.

Geographical distribution

At the end of 2007, approximately 40% of all vehicles were registered in the Gauteng area alone. The Gauteng area is situated at a relatively high altitude of between 1 200 m and 1 600 m. The octane and volatility requirements for petrol vehicles operating at these high altitudes are significantly influenced by the reduced air pressure. This is a somewhat unusual occurrence since almost all of the worlds vehicles are operated at much lower altitudes. Elsewhere in the world the major urban and industrialised areas are concentrated at the coast. Only two other major conurbations exist at similar altitudes, being the Denver area in Colorado US, and Mexico City in Mexico.

6.9 Where do our vehicles come from?

Vehicles sold in South Africa come from various countries, including South Africa itself, Europe, America, China, India, Japan, Australia and Korea. These vehicles are typically designed to European standards, but do not necessarily conform to the latest emission specifications.

The dominant fuel grade in the above-mentioned countries is summarised in Table 3 below.

Table 3: Typical Fuel specifications from vehicle source countries[xv]

Vehicle Origin	Petrol	Diesel
South Africa	R 95 Coast	500 ppm Sulphur
	R 93 Inland	50 ppm Sulphur Niche
Europe	R 95	50 ppm Sulphur
America	87/89/91 (R+M)/2	5000 / 500 / 15 ppm Sulphur
China	R90 / R93 / R97	500 / 350 / 50 ppm Sulphur
Australia	R 95	50 ppm Sulphur
India	R88 / R 91 / R93 / R95	500 / 350 ppm Sulphur
Japan	R 89 / R 96	10 ppm Sulphur

6.10 Fleet Age and Turnover

Predicting changes in the vehicle fleet age and make-up over time in South Africa, as a basis for assessing its future environmental performance, is difficult. It is, however, estimated that the average age of vehicles currently is approximately 11 years. The following chart shows the number of vehicles each year by age category since 1999.

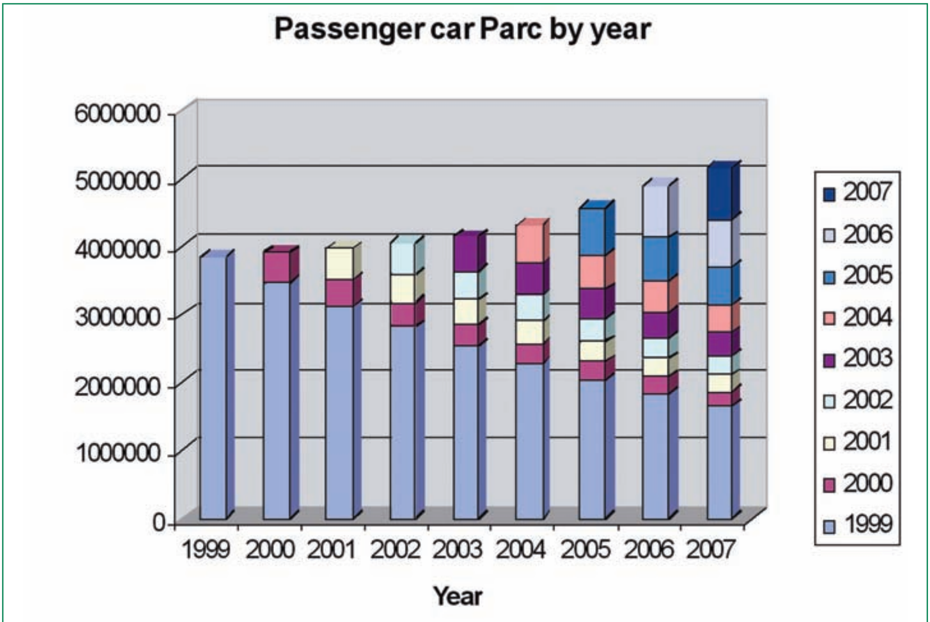

Figure 7: Passenger car parc by year

6.11 Emission Standards

While mandatory vehicle emission standards have been in place in many countries for a number of years, South Africa has only introduced emission specifications for new passenger car models approved for sale with effect from 2005, and for all new vehicle models (passenger cars, SUV's, LDV's and on-road trucks) with effect from 2006. As from 2008 all new vehicles sold need to comply with Euro 2 emissions specifications (as modified). This lags the introduction of enabling unleaded petrol, which has been marketed in South Africa since 1996.

6.12 Emissions Control Capability of the South African vehicle parc

Until recently a number of vehicles have been built specifically for the local market in South Africa, and these have been supplemented with imported vehicles and CBU (new Completely Built Up) units assembled locally. With the exception of a relatively small number, the emission requirements of the imported vehicles were minimal, and would generally have been well below that required in their country of origin or many other markets at the time.

The net effect is that the "potential" emissions control capability of the South African vehicle parc has lagged significantly behind many other countries. Previous vehicle design emission levels were not specified and the actual condition of catalytic converter devices, if installed, is unknown. In addition, it is known that a number of catalytic converters have been removed from vehicles.

This is concerning, as a catalytic converter treats the exhaust gas before it leaves the vehicle, removing about 90% of the pollutants. This is the main method of pollution control in petrol engines.

The concept of "potential" capability is important: simply because a vehicle is fitted with a catalytic converter on its exhaust does not mean that it is actually performing effectively. Emission standards typically set durability requirements, normally measured in kilometres or years, which indicate the period over which the vehicle should continue to be capable of meeting those standards. However, this is not the case in South Africa as the requirement was not included in the regulations.

Moreover, maintenance of emissions control equipment is not a priority when there is no monitoring of its performance or mandatory requirement for its effectiveness.

It is acknowledged, however, that even poorly functioning emissions control equipment is generally a lot more effective than none at all.

6.13 Engine and Emission Control Technology

For the purpose of the development of a vehicle emissions strategy, the parc should be categorised according to the type of engine and emissions control technology fitted. Four main vehicle technology configurations can be used for petrol and diesel vehicles. Please note that the data presented below, which indicates the incidence of each configuration relative to the South African car parc, is based on 2003 information. As certain penetration assumptions have been made, the data should be used with caution.

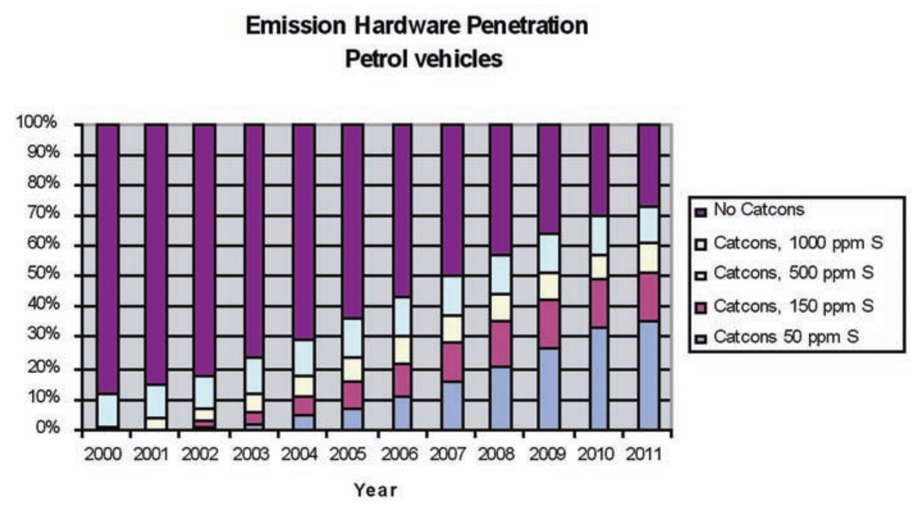

Figure 8: Fuel requirements by vehicle technology type in South Africa

The data indicates that, while emissions control technology in the vehicle parc will result in an improvement over time, this change is relatively slow and dependent on vehicle turnover.

As a general rule, model cycles for cars (that is the number of years between new models being introduced) tend to be shorter than for heavy commercial vehicles with the result that new light vehicle technology will tend to become available more quickly.

While the vehicle emissions strategy needs to consider the environmental performance of the vehicle fleet over the longer term, any changes to fuel specifications need also to take into account the shorter term impact on vehicle driveability. As an example, petrol engines with carburettors are much more sensitive to changes in fuel volatility than fuel injected engines. Future controls on volatility parameters need therefore to be taken into consideration, as a significant proportion of the petrol vehicle fleet will still have carburettors.

6.14 Off highway

As a result of the size of the open cast mining industry in South Africa, a considerable proportion of the diesel sold is for this market. The requirement of users and machines in this industry is often different to that applicable to passenger vehicles. In most parts of the world an off highway diesel that meets different specifications is available to provide an appropriate fuel for these operators. However, this is not the case in South Africa currently.

6.15 Other Users – Commercial

Many commercial operators in South Africa have their own storage and dispensing facilities for refuelling vehicles. Diesel is used for stationary engines such as small boilers and generators as well as for heavy machinery such as earthmoving equipment and mobile cranes. Again, in other parts of the world an appropriate fuel is available for these operators.

6.16 Other Users – Retail

Fuel for garden maintenance equipment is generally bought through service stations. Such equipment includes chainsaws, lawnmowers and weed-eaters. No figures are readily available but it is probable that usage for this purpose represents a very small percentage of the total volume of petrol sold (although to many individual users). It is noted, however, that recent Canadian studies[iv] suggest that two-stroke motors used for lawnmowers, chainsaws and small marine outboards are significant sources of exhaust emissions.

6.17 Agricultural Use

Agricultural use accounted for approximately 350 million litres of diesel in South Africa during 2007. As shown in Figure 5, these levels equate to some 6% of South Africa’s total diesel consumption. These figures are based on energy consumption data supplied by SAPIA and do not include fuel purchased through retail outlets.

6.18 Summary

The usage of petrol and diesel, vehicle technology, maintenance levels and age of the vehicle parc should be taken into account when determining the fuel specification requirements to enable cleaner ambient air quality. This is because of the interdependence and relationship between fuel quality and vehicle technology on the emission loading.

While it is essential that there should be vehicle emission standards in place, it will take considerable time and effort to ensure their efficacy.

7 Consumer protection, environmental, health and safety considerations

This section discusses the key considerations relating to consumer protection, the environment, and health and safety.

Section 7.1 describes the existing consumer protection framework in South Africa and makes some comparisons with the situation in New Zealand.

Sections 7.4 and 7.10 describe the environmental impacts arising from the use of petrol and diesel, and the controls in place to minimise those impacts.

Section 7.11 discusses the direct health impacts (both public and occupational exposure) arising from the use of petrol and diesel.

7.1 Consumer Protection

The Petroleum Products Amendments Act (PPA), introduced in 2006, regulated certain aspects of transport fuel specifications, with application to the South African National Standards (SANS). These ensure that the consumer has choice and is guaranteed a fit-for-purpose product, while certain environmental aspects are also addressed, as follows:

- Petrol and diesel must be supplied to regulated specifications.
- Suppliers must label fuel dispensers with the mandated label (grade and quality).
- The consumer has a right to request information about the product.
- The Department of Minerals and Energy has the right to sample the fuel and check that it meets the regulated specifications.

The regulations provide buyers of petrol and diesel with an additional layer of protection by ensuring that the fuel consumed anywhere in the country is considered to be "fit for purpose" at the point of sale.

The Automobile Association (AA) in South Africa also has a key role to play in ensuring that consumers are protected and that their views are heard, in addition to those of the new car and the fuel marketers. All over the world the AA evaluates issues that could have an impact on the motorist to determine if they are fair and appropriate, and lobbies government on behalf of vehicle users.

The Association also typically gives advice to fleet operators, provides policy advice and carries out technical and scientific studies on behalf of its members. The AA also has a specific interest in fuel quality and consistency, price and competition within the market.

7.2 Consumer Issues [iv]

Fit for Purpose

Fuel processing technology and the additives used in petrol and diesel to control fuel quality change with time. Fuel related problems resulting from changes in fuel properties that the specifications do not adequately cover occur from time to time and the specifications are consequently changed. The SANS committees meet regularly to discuss these issues and to implement solutions.

Niche and Branded Products

Niche and branded products that meet the current specifications but offer additional features have been available in South Africa for a number of years, but are becoming more prevalent. High performance European vehicle technology now available in South Africa is creating a demand for higher octane petrol, especially in the inland region, as well as a requirement for ultra low sulphur fuels (petrol and diesel).

These fuels are covered by the current legislation and thus comply with fit-for-purpose requirements.

7.3 Fuel Quality Monitoring [iv]

Fuel quality monitoring is a key element of consumer protection currently provided in terms of the Regulations. Monitoring is the role of the South African Bureau of Standards (SABS) and the Department of Minerals and Energy (DME). The Regulations set out the minimum requirements for each specified property as well as the test method that will be used to measure that property. They also set out the procedures to be used for sampling and for interpreting test results. The oil industry tests all batches of petrol and diesel prior to sale to ensure compliance with the specifications.

The SABS regulatory authority, or the newly formed National Regulator of Compulsory Specifications (NRCS) is required to sample service stations and report to the registered oil company on a regular basis. The frequency, however, is probably not statistically relevant by virtue of testing and sampling constraints.

The Fuel Quality Monitoring (FQM) Programme in New Zealand

New Zealand employs a sampling and testing programme for fuel quality which was initiated in 1989. A statistically based sampling scheme, designed in 1991, is based on factors such as the known failure rate and fuel consumption from each regional onshore bulk storage location. The FQM Programme is funded by a Petroleum Fuels Monitoring Levy on all fuel sold.

The annual sampling plan typically comprises approximately 100 service stations, with samples collected of each of the two grades of petrol and one of diesel (where available). The advantage of this system is that it monitors the quality of fuel that consumers receive, including any contamination introduced during transport or distribution. However, a drawback is that in the event of any non-compliant samples, the fuel will generally have been sold before the results become available.

Reports issued indicated that the number of non-compliant samples has been very low and almost all non-compliance has been of a minor nature (within testing error). To date there have been no prosecutions.

The oil industry itself tests its batches of petrol and diesel prior to sale to ensure compliance with the specifications. The test methods set down by the Regulations for measuring compliance are in turn used by the industry to assure itself of compliance.

7.4 Environment – Air Quality

In terms of ambient air quality (outdoor air pollution), urban areas which are considered to have poor air quality by world standards are referred to as "hot spots". Major causes of pollution levels include the prevalence of coal fired electricity generation plants, heavy industries and transport.

One such example that has been studied in South Africa is Cape Town which regularly exhibits a phenomenon locally referred to as "brown haze" - a thick brown coloured layer of pollution which stagnates over the low lying areas of the city on warm sunny days with low wind velocities, occurring more regularly in the winter months. This brown haze has been the subject of a number of studies. The first major source apportionment study, completed in 1997 [v], attributed the majority of the pollution to transport, with diesel particulates being the most dominant, followed by industrial emissions. The second, and arguably more thorough study [vi], supported the conclusion that vehicles contributed significantly to the brown haze but emphasised that industry and especially domestic combustion of sold fuel (mostly wood) also contributed to the phenomenon.

The brown haze phenomenon, while unsightly, is of minor concern from a health perspective as the bulk of the visible pollution is at altitudes above ground level (from 50 to 1300 m). Ground level pollutants of major concern include NO_x, hydrocarbons, CO, SO_x and primary particulate matter. The main sources of these pollutants are transport, heavy industry and coal fired electricity generation. Rapid urbanisation and the inevitable co-location of new and existing low income residential areas and the industries which provide employment result in increased human exposure to air pollution. The significant increase in urban traffic resulting from the unprecedented economic growth in South Africa over the past decade, evidenced by the increase in national annual fuel consumption, has meant that transport related emissions are the most important emerging air pollution issue.

Exacerbating the impact of the transport sector on air pollution is the status of the national vehicle parc. South Africa has only recently enacted legislation that will enable the control of emissions from vehicles (new vehicles). Up until 2008, there was no requirement for all new vehicles sold to meet any homologated maximum emissions limits. All new vehicles sold since January 2008 need to meet Euro 2 emissions limits as a minimum standard, and this is considered an important step in reducing the impact of the transport sector on air quality. Prior to this, some of the vehicles sold did conform to emissions limits even in the absence of legislation as these were either imported from markets with legislation, or were manufactured to conform as this was the only technical option for that model. However, the majority of vehicles sold, especially in the entry level of the market, did not conform. Thus, the current vehicle parc is dominated by vehicles that can be considered high emitters as they were not manufactured to conform to any emissions limits. Furthermore, there is currently no specific requirement to maintain these vehicles to any emissions limit.

By international standards the vehicle parc is relatively old and poorly maintained. Thus it can be expected that the time for the newer, emissions controlled vehicles to dominate the fleet will be longer than is the case in other markets. Unless there are specific interventions made, previous experience indicates that in general, the new emissions controlled vehicles will not be as well maintained as is common in the developed world. Poorly maintained vehicles are significantly worse polluters than well maintained ones, and this is especially true for emissions controlled vehicles with exhaust after-treatment. Thus much of the potential benefits of the new emissions legislation will be lost as these vehicles age.

It is generally accepted that the application of new vehicle technology and inspection and maintenance (I&M) has a profound effect on vehicle emissions and that this is much more significant than the effects of any changes to fuel specifications on their own. The application and durability of these vehicle technologies does however rely on fuel quality and thus some fuel specifications are considered "enabling", as without them the vehicle technology benefits would be unachievable. Other fuel quality related effects, while important, are much smaller in magnitude.

7.5 Sources of Air Emissions Arising from the Use of Petrol and Diesel in South Africa

Emissions can be generally grouped as either products of combustion or evaporative emissions. Figure 9 illustrates the following sources:

- Products of combustion.
- Evaporation during distribution (filling/loading operations and evaporation from thermal fluctuations).
- Evaporative losses from vehicles.

Evaporative losses can occur from both bulk storage sites and vehicles. In practice, one mechanism predominates in each case: displacement losses predominate in bulk distribution, where the tank size reduces thermal fluctuations while evaporative losses predominate from vehicles.

There are other sources that must be considered. Figure 9 provides a schematic illustration of the major sources of air emissions downstream of the refinery.

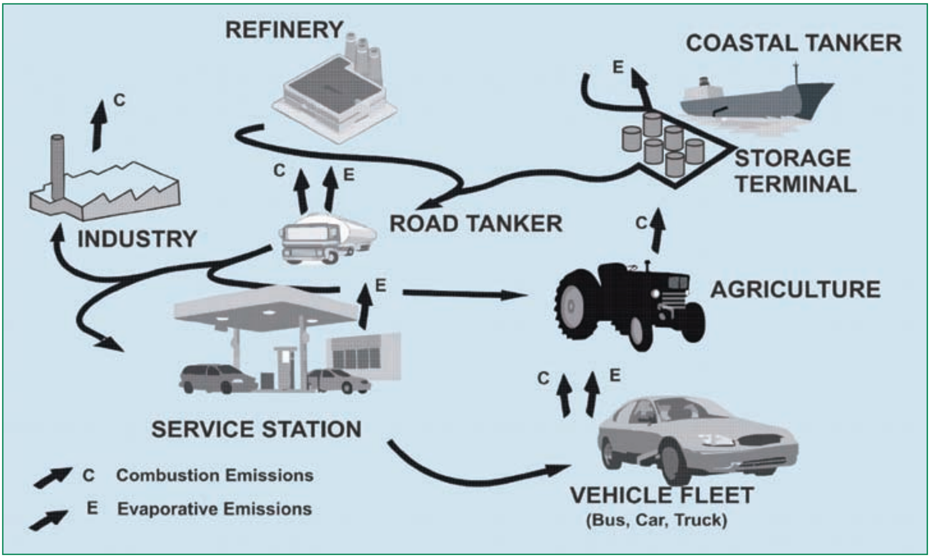

Figure 9: Air Emissions Arising from the use of Petrol and Diesel

7.6 Products of Combustion

Products of combustion are generally considered the major source of air emissions from the use of fuels. The majority of emissions from petrol and diesel engines are related to the vehicle parc. The mechanics of the combustion engine and the emissions that result are well understood. Appendices B, C and D of this guide provide an overview of "how engines work", the vehicle fleet and key air contaminants emitted by combustion.

Other sources of combustion products include stationary industrial sources (diesel-fired boilers, stand-by and peaking generators) and agriculture (farm machinery), all of which tend to use diesel fuel.

The effects of individual pollutants are described in Appendix D.

7.7 Displacement Losses from Distribution (Evaporative Losses)

When any storage vessel (large storage tank or vehicle fuel tank) is filled with petrol or diesel, air displaced from the vessel contains hydrocarbon vapour. In the absence of vapour recovery, this hydrocarbon vapour is emitted and pollutes ambient air. Vapour recovery, which can take various forms, attempts to mitigate these emissions and depending on the solution employed, can be very effective and reduce vapour emissions almost entirely. Different solutions are typically applied to different sectors of the distribution chain.

Vapour recovery has been partially implemented in South Africa, with complete vapour recovery being implemented at the refinery road tanker loading depots. As yet, there is no vapour recovery in the downstream logistics chain (tanker to forecourt tank and forecourt pump to vehicle tank).

7.8 Evaporative Losses from Vehicles

Evaporation can result from a number of factors that cause thermal fluctuations. The most significant is considered to be diurnal breathing losses (DBL) which occur as fuel is heated by rising ambient temperatures. Other evaporative losses from vehicles include hot soak losses (loss of vapour after vehicle shutdown caused by residual engine heat) and running losses [vii].

Modern vehicles use a number of strategies to control evaporative emissions, including electronic engine management systems, purge-flow controls, sealed petrol caps and carbon canisters. The latter are a key component and have only become legally required on all new vehicles sold in South Africa with effect from January 2008. The canister contains activated carbon which absorbs hydrocarbons evaporated from the fuel supply and engine, then "reclaims" these hydrocarbons by drawing air through the canister into the engine while the engine is running. Up to 95% of evaporative losses can be captured through the use of carbon canisters, which will significantly reduce total emissions from evaporative losses [vii]. There is concern that given the conditions in South Africa, especially related to high ambient temperatures and altitude effects, the carbon canisters applied in Europe, Japan and the US may be undersized for our market.

7.9 Global Climate Change [iv]

Climate change is a global problem. Carbon Dioxide (CO_2) is one of the major greenhouse gases, and is a normal by-product of the combustion of hydrocarbon fuels. Motor vehicles, electricity generation, the petrochemical, steel and dairy industries are typically the main sources of CO_2, which is a direct function of the fuel consumption. In addition, vehicle emissions contribute to other greenhouse gasses.

Changes to fuel specifications to decrease greenhouse gas emissions must also be considered on a full life-cycle basis. The energy used by a refinery to process fuel generates CO_2 and the benefits of the use of "cleaner fuels" may be offset by the higher energy requirements to produce them. This calls for a value judgment on the relative merits of a localised (refinery) discharge of a global pollutant versus the myriad of mobile emissions of both local and global pollutants.

7.10 Environment – Water Quality

Figure 10 provides a schematic illustration of the discharges to water, downstream of the refinery.

There are two primary routes:

- Discharges arising during distribution of petrol and diesel throughout South Africa. These include accidental spills and leaks.
- Emissions from vehicles in use, either directly onto a road surface, or into the atmosphere, from where they may be deposited on the roads or neighbouring environments. Once deposited, contaminants are subsequently mobilised during rainfall entrained in storm water runoff and enter aquatic environments.

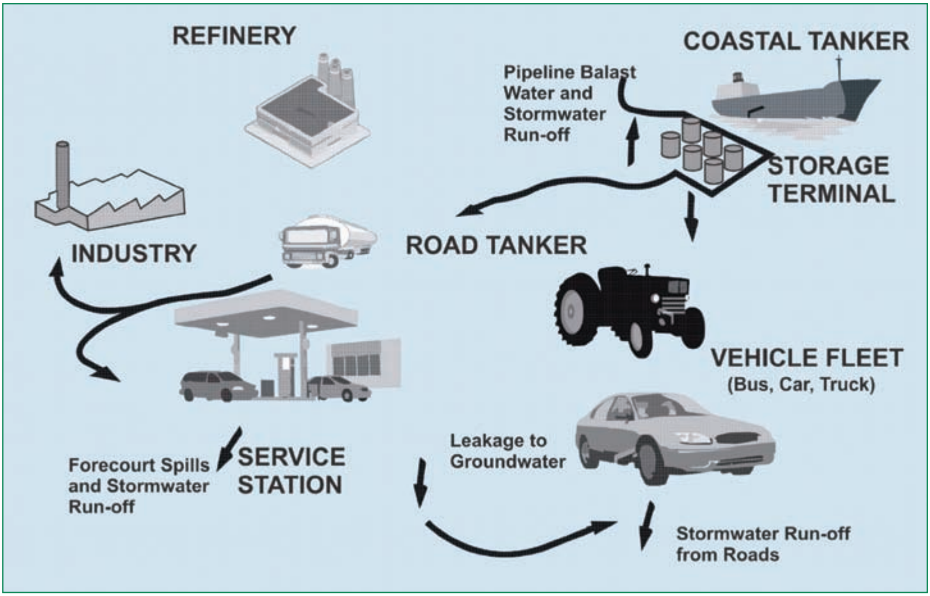

Figure 10: Discharges of Contaminants to Water Arising from the use of Petrol and Diesel in South Africa

Emissions from vehicles that may be deposited and subsequently entrained in storm water runoff come from a range of sources including tyre wear, brake pad wear and oil use, as well as combustion and evaporative sources. The latter are the only emissions that arise directly from petrol and/or diesel use.

Evaporative emissions or products of combustion primarily enter the environment in the gaseous phase. For Volatile Organic Compounds (VOC), atmospheric washout, which would result in contaminants being transported to the water phase is a possible, although minor, pathway. The more important contaminant in respect of potential storm water contamination is particulates, which are deposited on road surfaces. Particulates, particularly from diesel engines, have been shown in international studies to contain polycyclic aromatic hydrocarbons (PAHs), among other contaminants which present a health risk.

Oxygenates and its role as a water pollutant [iv]

The use in fuel of oxygenates (organic compounds containing carbon, hydrogen and oxygen) was made mandatory in the United States by federal law in 1990 on the grounds of their air quality benefits (reduced CO emissions). Methyl tertiary butyl ether (MTBE) is the most commonly used oxygenate and has been used in many parts of the world for a number of years as a petrol extender and octane booster. By comparison with alcohols, MTBE offers low water solubility, low reactivity and low volatility.

7.11 Health Effects [iv]

For the majority of the population, the primary route of exposure to petrol and diesel occurs via exposure to vapours, whether they be products of combustion or evaporation. Protection of human health is the primary basis for the derivation of the ambient air quality guidelines, and air quality and health effects are intrinsically linked. However, some sectors of the population do have regular, direct interaction with petrol and diesel, as a result of their occupation.

7.12 Fuel Distribution Occupations [iv]

Tanker drivers and forecourt attendants are occupationally exposed to petrol and diesel. In 1996, amid concerns over potential health effects of increased concentrations of aromatics, the retail oil companies in New Zealand commissioned a study to assess worker exposure to the VOC's present in petrol[viii]. Diesel has a much lower volatility than petrol; exposure to vapour from diesel is therefore considerably lower than that from petrol.

The study found that, in most cases, short term exposures for tanker drivers were well below the appropriate workplace exposure standard (WES). For service station forecourt attendants, the study found exposures to be very low, significantly below the WES. The monitoring indicated that, of the VOC's analysed, benzene was the most significant compound relative to the WES values.

A similar study was undertaken in South Africa in 2002 and very similar results were obtained. The main findings were that both the tanker drivers and forecourt attendants had benzene exposures well below the South African Occupational Exposure Limits.

7.13 Motor Trade Occupations [iv]

New Zealand also conducted a similar study to that carried out for the fuel distribution occupations amongst people engaged in motor vehicle trade occupations, commissioned by the Motor Trade Association[x]. Occupational exposure monitoring was carried out at selected garages to assess individual exposure to hydrocarbon vapours from petrol and other solvents. The results indicated that full-shift routine exposures to hydrocarbons were significantly lower than the WES and did not present risk to the health of workers[x]. Short-term monitoring during specific tasks was also undertaken. These results indicated that exposure was elevated, but exposure during tasks involving petrol did not exceed the WES; the highest exposure occurred during interior car grooming using a hydrocarbon-based cleaner[x].

7.14 Summary

Regulation is required to ensure not only fit for purpose fuel specifications are met, but for consumer protection as well. This should cover the environmental and health impacts that transport fuels have on the environment from combustion, production and handling in a pragmatic manner. These regulations should be set taking all the emission sources into account, the vehicle parc technology, age and maintenance.

This approach would ensure that the best benefit is achieved in a region, at the lowest cost.

8 International scene

This section discusses vehicle emission standards and the relationships between fuel quality and vehicle emissions. The current fuel quality specifications used internationally and their relevance to South Africa are also discussed. Specifications for individual properties of petrol and diesel are compared and discussed in more detail in Sections 10 and 11 respectively.

In recent years, changes to fuel quality specifications in the USA, Europe, Japan, Australia and elsewhere have been largely driven by air quality targets, which in turn have led to regulated vehicle emission limits and, more recently, fuel efficiency requirements. Vehicle technology and fuel specifications have been developing in response to these requirements. The relationship between these key drivers is illustrated in Figure 11.

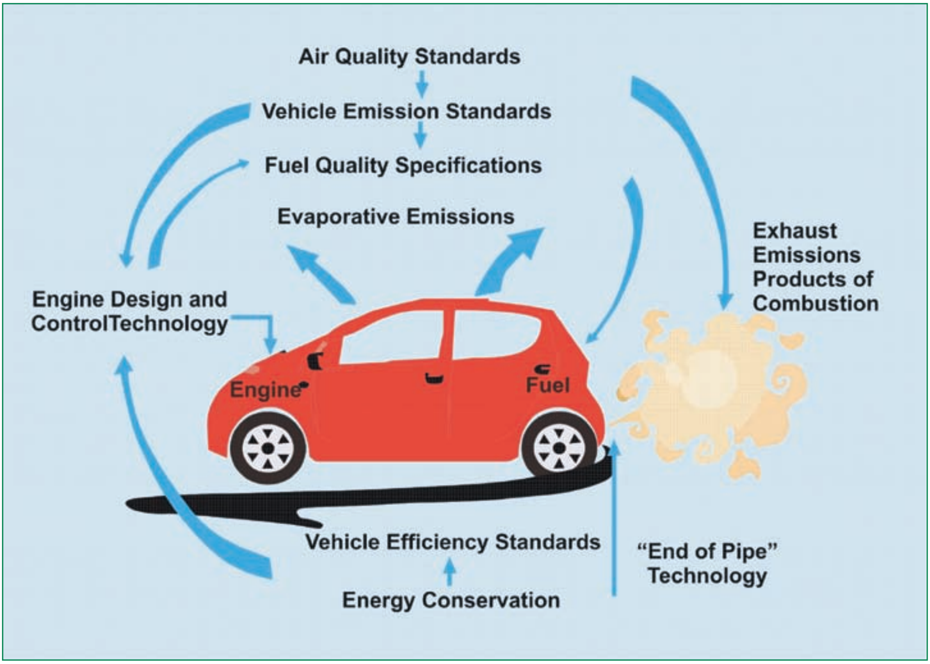

Figure 11: Drivers of Fuel Quality

8.1 Vehicle Emission Standards

The first controls on vehicle exhaust emissions were introduced in the USA and Japan in the 1960s, in response to concerns about the impact of increased vehicle use on urban air quality. Since then, legislators in all the world's main vehicle markets have developed tailpipe and evaporative emission standards and set progressively more stringent limits on regulated emissions, such as CO, NO_x, hydrocarbons, visible smoke and particulates. The term "regulated emissions" is frequently used to refer to the tailpipe emissions controlled by these regulations which are:

- Spark ignition vehicles using petrol (or similar fuels): hydrocarbons, CO and NO_x
- Compression ignition vehicles using diesel (or similar fuels): hydrocarbons, CO, NO_x and particulates.

These emissions are measured in units of mass per vehicle distance travelled (g/km in regions using the metric system and/or following the European legislation and g/mile in the US and territories following the US Environmental Protection Agency (EPA) legislation).

Emission standards prescribe limits for the regulated exhaust components as well as the test conditions and test procedures under which these limits apply. These standards define test cycles to be used for engine and vehicle certification and are intended to simulate a range of, and reflect the transient nature of, actual vehicle operating conditions. Performance requirements relating to durability are now also stipulated. As noted, these standards have driven the development of engine and emissions control technology and also fuel quality specifications.

In practice, these test cycles can be quite different to actual driving cycles, so that even for the most sophisticated test cycle, actual on-road emissions may differ significantly from those derived from test cycles. In addition, the different vehicle manufacturing countries have developed their own standards and associated test cycles, in response to the nature of their own particular air quality problems and through dialogue with their own manufacturers, so that direct comparisons between countries cannot easily be made.

South Africa has elected to follow the European vehicle emissions legislation although in a somewhat lagged fashion. The process of regulation places emissions requirements in the normal vehicle homologation process. Each territory or country will require vehicle models to be homologated prior to the release of that model for general sale. Typically, the vehicle manufacturer or importer will have to provide to the regulator proof that the vehicle model meets all of the homologation criteria by providing test reports from accredited testing authorities. In order to ensure continued compliance of the vehicle model throughout its life time, the regulations may require, for some of the requirements, that "conformity of production" (COP) tests be performed on a regular basis by the manufacturer, who must provide statistical evidence that production units remain compliant. The regulator further reserves the right to test vehicles from time to time to ensure compliance. Homologation requirements are mostly related to safety critical items such as brakes, lighting, restraint systems and crashworthiness.

The current South African regulations do not require that manufacturers comply with the Conformity of Production requirements, although amendments to bring the legislation in line should be completed soon and are expected to be in place by early 2009.

It is quite common for new legislation to be implemented in a stepped process whereby with effect from a certain date, all new homologations need to meet the new requirements while models already in production can continue to meet the old requirements. At some future date, typically 2 years, the new requirements are applicable to all models, requiring the vehicles already in production to be re-homologated to the new standards. This is the approach taken in South Africa where the Euro 2 requirements have been applied with effect from January 2006 for new homologations and January 2008 for all new vehicles sold. The stated agenda of the regulators is to align with the latest European legislation at some point in the future, although the timetable for this is not yet agreed.

Even though emissions legislation is relatively recent in South Africa, a number of vehicles sold in years prior to the implementation were at an emissions compliance level equivalent to or higher than Euro 2, and currently many new vehicles sold meet the most stringent emissions legislation in the world. This is because many of the cars sold in South Africa are fully imported from regulated markets in quantities too small to justify any specification differences in terms of emissions compliance. Therefore the current South African vehicle fleet incorporates a wide range of engine and emission control technologies.

In comparison to the developed countries and some developing countries, South Africa has lagged quite considerably in the enforcement of vehicle emissions legislation. A timetable giving the implementation of legislation in a select group of countries is provided below in Figure 12.

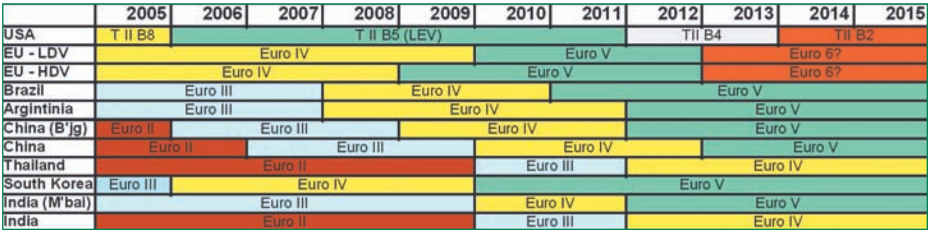

Figure 12: Timetable of international emissions legislations† xi

8.2 Fuel Quality and Emissions iv

A number of overseas studies have been undertaken on fuel specifications in recent years. The US Auto/Oil Quality Improvement Research Programme (AQIRP) was initiated in 1989 and completed in 1997. The programme, established by 14 oil companies and three domestic car manufacturers, identified clear relationships between fuel specifications and emissions for petrol vehicles. A similar study in Europe, the European Auto/Oil Programme, initiated by the European Commission in 1994, looked at the effect of specific fuel characteristics on emissions from both diesel and petrol vehicles. The objective of both programmes was to provide data to assist legislators and policy makers in developing and assessing measures to reduce emissions and improve air quality. The key findings of these studies in relation to both petrol and diesel, are summarised below.

8.3 Fit-for-Purpose vs. Performance vs. Enabling Specifications iv

Generally speaking fuel specifications can be broken into three broad categories, albeit with some overlap. These can be classified as follows:

- Fit-for-purpose specifications set quality standards to ensure trouble free operation and safe handling. An example would be contaminants.
- Performance specifications ensure acceptable performance. An example would be petrol octane.
- Enabling specifications are required to enable certain engine or exhaust after-treatment technologies. An example would be ultra low sulphur fuels (less than 50 ppm (m/m)) which are required for certain exhaust catalyst technologies.

† Note that this indicates the first application of emissions legislation which may apply only to new homologations with a lag (typically 2 years) until applicable to all new vehicles.

It is important to be certain of the purpose of any given specification when setting levels. Fuel specifications should be established in order to achieve a specific objective, bearing in mind that different local conditions can significantly impact the outcome of a particular specification change. The most obvious example is differences in vehicle parc in terms of technology, emissions level, age and condition. Furthermore, different regions can have very different objectives which will also impact the route taken in terms of fuel specifications.

In terms of air quality, given that a fuel is fit-for-purpose, both performance and enabling specifications can be used to reduce vehicle emissions and improve urban air quality. However, the mechanisms are quite different. Performance specifications can have an immediate impact since the entire fleet can benefit from the specifications. The impact of enabling specifications on the other hand can take longer to exhibit since it is dependant on new vehicle technologies that are introduced. The overall growth of the new vehicle population in relation to the overall vehicle parc is generally small and therefore the total emissions will be reduced slowly. Typically, the overall reductions in emissions attainable from fuel performance specifications, although significant in their own right, are much less than that achievable through improved vehicle technology especially when coming off of a low technology base such as applies to South Africa's current vehicle parc (see Section 8.7).

Unlike enabling specifications, when considering performance specifications it is often possible to meet the air quality objectives through pool averaging (controlling the specification parameter on a rolling average basis), and this flexibility can be beneficial to the refinery operations. Furthermore, performance specifications can be significantly relaxed in areas where there are no air quality concerns without jeopardising the improvements in the areas where these concerns exist. This provides the refinery industry with an outlet for fuels with less onerous specifications and thus reduces the overall severity of refinery processes and decreases security of supply concerns. Such outlets for this alternative specification fuels could include so-called off-highway fuels intended for use in the mining industry (notwithstanding the underground mining fuel specifications) and railways etc. This kind of approach, including differentiated vehicle emissions specifications, has been applied in some developing countries as an interim measure: for example Beijing and Mumbai have both applied at times more stringent vehicle emissions limits than China and India as a whole (see Figure 12) and both countries have regionally differentiated fuel specifications.

8.4 Effects of petrol composition and properties on vehicle emissions

- **Sulphur:**

  Sulphur content in petrol affects the performance of catalysts, but can recover somewhat after using higher sulphur fuel. Advanced catalyst formulations being developed for Euro 4 compliance are particularly sensitive and can only be used with very low sulphur fuel (less than 50 ppm (m/m)). Euro 5 technologies typically require "sulphur free" fuel (<10 ppm (m/m)).

- **Fuel parameters:**

  Volatility and aromatics content affect engine emissions, but do not directly affect emissions control technology.

- **Volatility:**

  Reducing the volatility of petrol through reduced Reid Vapour Pressure (RVP) and/or lower distillation temperatures has an impact on VOC emissions.

- **Oxygenates:**

  Addition of oxygenates reduces CO emissions, but can increase permeation and VOC emissions, depending on the oxygenate type used.

- **Aromatics:**

  Reduction of aromatics content reduces emissions of air toxics, hydrocarbons and CO from the vehicle parc.

There is a down side however: some of these changes may affect the energy content of the fuel and so increase fuel consumption.

8.5 Correlations between petrol quality and emissions

Various correlations have been developed for predicting toxic and other emissions as a function of fuel quality, based on the results of the AQIRP, European Programmes on Emissions Fuels and Engine technologies (EPEFE) and other studies. These are generally expressed as mass emission rates of individual components per kilometre, and presented as functions of fuel composition or other properties. It is important to note that the data on which these correlations are based is generated from vehicle emissions testing and standard drive cycles and may not be particularly representative of actual driving conditions. Internationally, it has been identified that driving patterns and congestion have a major impact on actual emission rates.

While the emission rates for vehicles fitted with catalytic converters have generally been expressed as functions of multiple fuel quality variables, the data for older vehicles without catalytic converters has been presented as percentage changes to individual parameters in isolation and, it is noted, the results were not always clear cut.

The computer models developed using the correlations are designed to predict vehicle emissions (tailpipe and evaporative) and do not predict the resultant air quality. However, they do provide a good basis for comparing the likely effects of changes to certain fuel parameters.

The goal of the United States' Environmental Protection Agency's (EPA) reformulated gasoline (RFG) programme has been to achieve vehicle emissions reductions relative to 1990 levels. The EPA has developed a complex model based on fuel quality/emissions relationships to provide a means of measuring these reductions through fuel quality changes, while allowing some flexibility for refiners as to how they achieve this through control of fuel properties. Fuel characteristics modelled include sulphur, benzene, olefin, total aromatics and oxygenate content, as well as distillation parameters and RVP. The EPA model considers both evaporative and exhaust emissions and generates an Air Toxics Index (ATI) as well as emission rates for benzene, aldehydes, butadienes and polyaromatic matter [iv].

The air toxics model approach has been used internationally in the past as a basis for setting specifications. By using these models, it has been shown that using pool averages and caps rather than fixed limits for certain petrol parameters can be used successfully to meet the desired air quality targets.

8.6 Effects of diesel composition and properties on vehicle emissions [iv]

There is a clear correlation between certain diesel properties and regulated emissions, but drawing general conclusions is somewhat difficult by virtue of such factors as inter-correlation of different fuel properties, different engine technologies or engine test cycles.

- Sulphur increases particulate emissions in both light duty and heavy duty diesels. It also degrades the performance of nearly all emissions control equipment. In particular, de-NO_x catalysts and continuously regenerating particulate traps require very low sulphur levels.

- In heavy duty diesel engines, increasing cetane number reduces HC, CO and NO_x emissions. Reducing fuel density reduces NO_x and PM but increases HC and CO emissions.
- Light duty diesels show different fuel sensitivity to heavy duty diesels.

The characteristics of light and heavy duty diesel engines are discussed in Appendix B.

8.7 Emissions: Vehicle Technology vs. Fuel Quality Effects

The aim of this sub-section is to attempt to quantify the emission benefits from advancements in vehicle technology and the effects that fuel quality can have on vehicle emissions. This is very difficult to do with any precision as a result of many factors, including changes over time in the various driving cycles used for the legislative process. Furthermore, emissions responses to any given variable change (vehicle technology or fuel quality) can be significantly different depending on the driving mode, vehicle condition and various other factors. Another very important aspect to note is that fuel quality changes often have directionally different emissions responses depending on the vehicle technology employed. Thus published results need to be considered only in the context of the specific vehicles used. Given these caveats, an indication of the relative magnitudes of the different effects is presented below.

8.8 Vehicle Technology

The development of improved vehicle technology to reduce emissions has its origins in the 1960's when California and other cities in the United States realised that their worsening air quality was largely caused by automobiles and traffic. Initial advances were made with improved existing technology, which included improvements to combustion chambers, carburettors and ignition systems. Once legislation became more stringent from the late 1980's to mid 1990's, the automotive manufacturers had to rely on exhaust after-treatment for petrol vehicles, starting with oxidation catalysts and later moving to Three Way Catalysts (TWC). Significant technological advances in injection systems, turbocharging and Exhaust Gas Recirculation (EGR) were required for diesel engines. With the latest emissions legislation, petrol engines have required advanced TWC's and after-treatment in the form of oxidation catalysts, NO_x adorbers and particulate traps have become necessary for diesel engines.

All of these developments were driven by significant step changes in the emissions legislation. A convenient way to visualise the relative improvements in vehicle emissions is to plot the emissions limits of the various stages of the legislation. Plotted on XY axes, each step forms a rectangle which can be considered the envelope within which all vehicles made in compliance with that legislation must fall. As the limits become tighter, the rectangles become smaller. For petrol vehicles the appropriate axes are CO vs. ($HC + NO_X$), while for diesel vehicle these are PM vs. ($HC + NO_x$). Plots for various stages of European legislation, which is most relevant to South Africa, are provided below.

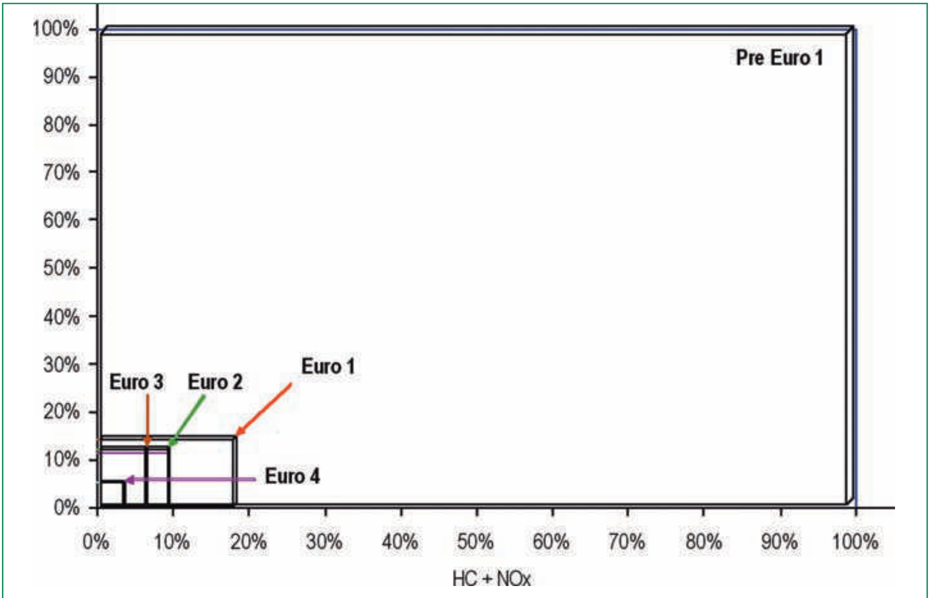

Figure 13: Plot showing the relative reduction in emissions limits of the European emissions legislation for petrol vehicles [#] [xii]

[#] Pre Euro 1 refers to ECE T83/00

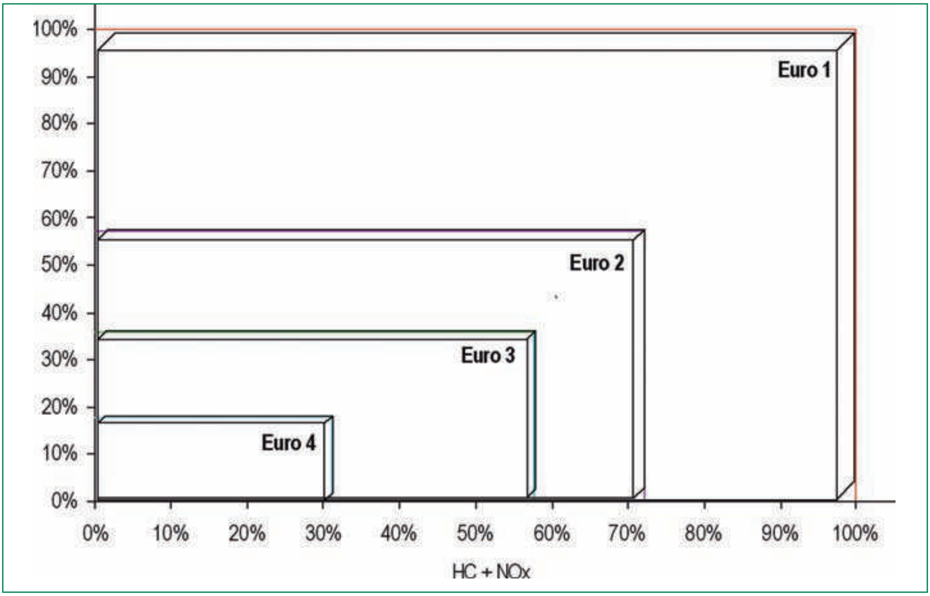

Figure 14: Plot showing the relative reduction in emissions limits of the European emissions legislation for diesel vehicles [xii]

It is worth noting the following points:

- Petrol vehicles were regulated prior to the institution of the Euro 1 legislation, but diesel passenger vehicles were not; for this reason the diesel figure does not indicate the initial improvement from Pre Euro 1 to Euro 1
- Changes to the legislative driving cycle have occurred over time:

  Pre Euro 1 – consisted only of an "urban" driving cycle, max speed of 50 km/hr

  Euro 1 and 2 – same "urban" cycle, plus "extra urban" cycle with max speed of 120 km/hr

  Euro 3 and 4 – same as Euro 1 and 2 except initial unmeasured 40 seconds of idle deleted
- The envelopes can be considered as "worst case" scenarios – most manufacturers would be conservative and actual vehicles would be significantly inside these rectangles.

As can be seen in the above figures, vehicle technology has enabled massive improvements in the emissions of vehicles over the past few decades.

State-of-the-art vehicles are probably at least 95% better than they were only 20 years ago in terms of the regulated pollutants.

8.9 Fuel Quality [iv]

As indicated above, there have been a number of large scale research projects undertaken by consortiums of automotive manufacturers and oil companies to investigate the impact of fuel quality parameters on vehicle emissions. A large number of smaller scale research projects have also been reported in the literature. Useful improvements in emissions are achievable from fuel quality parameters which are considered "performance" parameters, as opposed to "enabling" specifications. Examples of these effects are provided in the section above, however in general the magnitude of these effects is modest, typically having the ability to impact emissions by less than 30%, with most effects being of the order of 10%. Considering that in South Africa these improvements will be from an already low base for vehicles with emissions controls, the overall impact may be quite small. On the other hand, "enabling" para-meters are important to ensure that the vehicle technology can be applied in the market and thus the large improvements from these technologies can be attained.

8.10 International Fuel Specifications

This section looks at a number of fuel quality specifications currently in existence and their relevance in setting new standards for South Africa. These are as follows:

Japan – Source of a significant portion of the vehicle fleet

Australia – European specifications were used as the basis for the implementation of localised regulations to suit the local conditions and environment.

New Zealand – Lessons can be learned from New Zealand's implementation emission legislation and fuel specifications.

Europe – Euro 2, 3 and 4 enabling fuel specifications are de-facto international standards and a benchmark for fuel quality worldwide. South Africa has elected to follow the European model of vehicle emissions legislation. Europe is a significant source of vehicles in the national fleet.

The World-Wide Fuel Charter – The international automotive industries preferred fuel standards.

United States – There are a range of specifications in place across the United States; California, however, is acknowledged to have the most stringent vehicle emission fuel quality standards in the world.

China – As the leading developing country in terms of scale and pace of development, China is an interesting example of a country grappling with the demands of exceptional growth, poor air quality, aspirations of being a leading nation and a low base in terms of infrastructure (refineries, roads, vehicle manufacturing etc).

India – India faces very similar issues to China.

In all instances, specifications have not developed in isolation but result from ambient air quality and vehicle emission standards in the respective jurisdictions in which they apply, which in turn have developed in response to particular air quality problems.

Comparisons of these international specifications for petrol and diesel with the current South African specifications is made on a property-by-property basis in Sections 10 and 11 respectively.

8.11 Japan

Petrol

The current Japanese standard for motor gasoline (petrol), JIS K2202:2008, includes mandatory limits on sulphur (10 ppm (m/m) max.), benzene (1% max. by volume) and Ethers (5 C atoms or more) (7% max. by volume). Prior to January 2000, the benzene limit was 5% maximum by volume and sulphur limits were 100 ppm (m/m) and 50 ppm (m/m) since 2005. There are currently no limits on aromatics or olefins. Two grades of petrol are specified in the standard, No.1 (96 RON min.) and No.2 (89 RON min.). Petrol must not contain methanol, lead or kerosene.

Diesel

The Japanese standard for diesel fuel for diesel engines (primarily for automotive use) is JIS K2204:2004. Prior to 1992, the allowable sulphur content of diesel was 2000 ppm (m/m). This was reduced to 500 ppm (m/m) in 1997 and is currently 50 ppm (m/m). Five cold weather classes are specified, according to pour point.

Relevance to South Africa

Japanese vehicles make up a significant portion of the South African vehicle parc and new vehicle sales.

8.12 Australia

Prior to 2000, Australia had no national mandatory controls governing fuel quality. Fuel properties affecting performance, health and the environment had variously been regulated at state and national level. However, Australia enjoyed vehicle emission standards for a number of years prior to national fuel specifications.

The Australian Government set national environmental standards for petrol and diesel quality in 2000 and revised them in 2005 and 2008.

The standards focus primarily on air quality i.e. those fuel parameters with health and environmental implications. In summary, they harmonise:

- Petrol standards with EN228:1993 (Euro 2) in 2002 and EN228:1999 (Euro 3) in 2005;
- Diesel standards with EN590:1993 (Euro 2) in 2002 and EN590:1999 (Euro 3) in 2006 (except for sulphur in diesel which harmonises with EN590:2004 (Euro 4) in 2006).

Where standards were already better than these, they were locked in and some flexibility was allowed in the transitional period (2002 – 2006).

Relevance to South Africa

European specifications were used as the basis for the implementation of localised regulations that suited the local conditions and environment.

8.13 New Zealand

Specifications for petroleum fuels were first promulgated in the Ministry of Energy (Petroleum Product Specifications) Regulations 1988, which came into effect on 1 January 1989. The basic structure of the regulations is still the same, with only a few changes over the last 12 years:

1994 – Changes to E70 limits following cold starting problems encountered with one particular shipment of imported fuel (which met the limits then applicable).

1994 – Amendments to require regular unleaded petrol to be supplied from 1 July 1995 and to phase out the supply of premium leaded petrol during 1996.

1995 – Replacement of the 1988 Regulations with the Petroleum Products Specifications Regulations 1995. This consolidated changes associated with the introduction of premium unleaded petrol (PULP) together with minor changes for regular grade petrol and for diesel.

1996 – Limits and test methods established for total aromatics levels in PULP, following difficulties which arose with the introduction of this grade (again related to fuel that met the limits then applicable).

1998 – Replacement of the 1995 Regulations with the Petroleum Products Specifications Regulations 1998 which came into force in October 1998, and are still current. Limits on total aromatics for both grades of petrol were harmonised and specific colour requirements for petrol were removed.

With effect from 2006, benzene, sulphur, and olefin limits in all petrol grades were reduced to 1 vol%, 150 ppm and 18 vol%, respectively. In diesel, cetane number was increased to 51 whereas sulphur and T95 limits were reduced to 50 ppm and 360°C respectively. As was the case in Australia, a polyaromatics limit of 11 wt% was introduced. Also, the minimum viscosity limit in diesel was increased from 1.5 to 2 cSt. The maximum viscosity limit remains at 4.5 cSt.

In May 2005, the Ministry released a discussion paper on "Review of Permitted Sulphur Levels Beyond 2006 under the Petroleum Products Specifications Regulations," which proposed that sulphur limits be reduced to max 50 ppm in petrol with effect from 2008, with an ultimate requirement of max 10 ppm sulphur petrol possibly around 2010, and that sulphur for diesel be reduced to max 10 ppm with effect from 2009.

Relevance to South Africa

New Zealand took a pragmatic approach in determining the causes, identifying solutions and then implementing them across the value chain. Although they based the decisions on the European legislation, they did not follow these blindly.

8.14 European Fuel Specifications

The current European fuel specifications have developed out of European Union directives on vehicle emissions, commencing with passenger cars in 1992, and subsequently extending to heavy duty vehicles and light commercial vehicles by 1997 (see Figure 15). These emission standards have become known as Euro 1, 2, 3, 4 and 5. Euro 6 standards are not completely finalised for all vehicle categories.

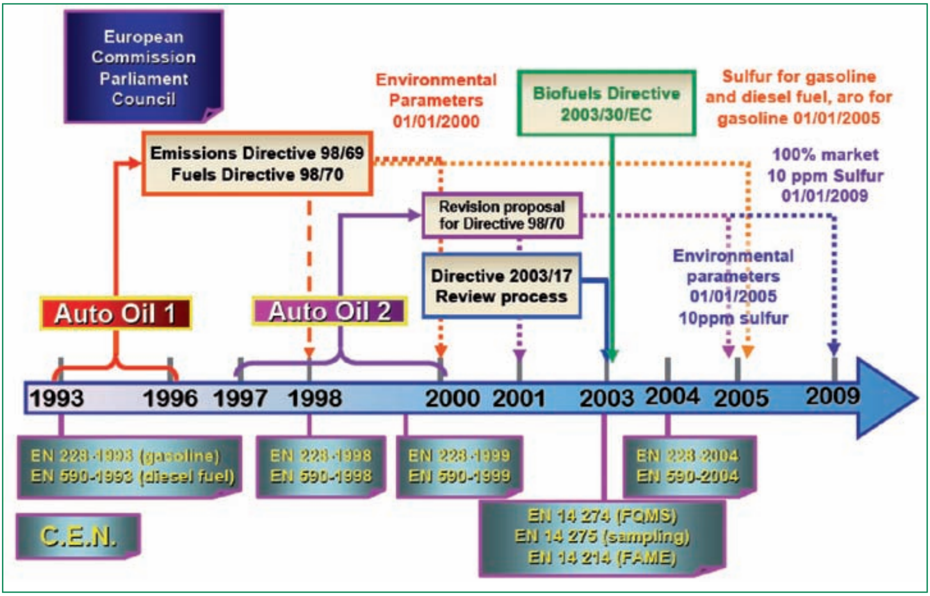

Figure 15: EU Fuel Policy

In developing these standards, the relationship between emissions and fuel quality was recognised and has resulted in the development of European-wide specifications for diesel and unleaded petrol. The current European standards for fuel are EN 228:2004 and EN 590:2004 respectively. They cover environmental, health and driveability requirements. While these apply equally to all member countries of the European Union, they also allow for volatility specifications (for petrol) and cold flow properties (for diesel) to be set on a national basis.

The various levels of fuel specifications have also become known as Euro 1, 2, 3 and 4, although this has the potential to generate confusion with the vehicle emissions standards of the same name. While the naming intentionally coincides in terms of the timing of the introduction of the two sets of standards, the naming convention leads to the misconception that Euro X vehicles require Euro X fuels in order to meet the emissions targets. This is clearly not the case in terms of all of the fuel specifications. Some of the fuel specifications which would be considered to be "enabling" would certainly be necessary to ensure that the vehicle technology applied remains effective at reducing emissions. Some of the other parameters (not considered enabling parameters) specified in the standards may be incorporated with the specific intention of reducing vehicle emissions. Deviations from these parameters would not necessarily detract from the achievement of substantial improvements as a result of the application of vehicle technologies required to meet the vehicle emissions standards. As noted elsewhere in this document, vehicle technology effects are typically significantly larger in terms of emissions relative to fuel performance specifications.

Relevance to South Africa

- European standards are effectively a true international standard with respect to international harmonisation of fuel quality, as they apply across national borders.
- These standards incorporate environmental, health and operability parameters.
- European sourced vehicles make up a significant portion of the South African vehicle parc and new vehicle sales.
- The standards were designed to achieve an improvement in air quality for Europe and hence should be treated as such when applying them in other regions of the world where conditions are different.

8.15 World-Wide Fuel Charter [xiii]

The World-Wide Fuel Charter (WWFC) [xiii] is a set of recommendations for unleaded petrol and diesel specifications, produced by a group of four international automotive manufacturing associations. The purpose was to promote a greater understanding of the fuel quality requirements of motor vehicle technologies and to harmonise fuel quality world-wide in accordance with these requirements. The original Charter was published in 1998 and the latest revision is dated September 2006.

The four associations that were involved in the development of the charter are:

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

Four categories of specification were developed for diesel and petrol, reflecting different levels of engine and emissions technology required by international vehicle markets.

Table 4: World-Wide Fuel Charter Fuel Categories [xiii]

Category	General Description
1	Fuel quality based largely on engine performance considerations – minimal or no emissions control
2	Stringent requirements for emissions control – equivalent to Euro 1 and 2, US Tier 1 and 2
3	Markets with advanced requirements for emission control - Euro 3, US/California LEV or ULEV
4	Markets with further afvanced requirements for emission control to enable sophisticated NO_x and particulate matter after-treatment technologies - Euro 4 and 5, US/California LEV-II

Although the charter did include limited oil company input, it clearly represents the international automotive industry's perspective.

Relevance to South Africa

- Current South African fuel quality is better than Category 1 but not on par with all of the specifications of Category 2.
- The specifications have a slant towards engine and emissions control technology and specify a number of parameters that are probably not necessary in a regulatory specification.
- The specifications reflect new vehicles only and do not take into account a country's vehicle parc as a whole.

8.16 United States of America [iv]

Fuel quality in the United States is regulated at both state and federal level. The State of California has the most stringent requirements in the world with respect to vehicle emissions, and as a consequence, fuel quality. Since 1990, the EPA has been working to implement the use of cleaner fuels on a national basis through the Clean Air Act.

Petrol

In 1995, Phase 1 of the reformulated gasoline (RFG) programme was introduced (RFG1), requiring the use of RFG in key metropolitan areas with major air quality problems, particularly related to ozone. In reformulated gasoline, the components are regulated to achieve cleaner burning and lower vehicle emissions, by imposing limits on, for example, volatility parameters, aromatics and oxygen content. Phase 2 of the programme (RFG2), requiring more stringent limits, was introduced from January 2000. California has had its own specifications for reformulated gasoline (CaRFG2) and a third phase (CaRFG3) was introduced in September 2000.

The focus of the RFG programme has been on reducing emissions of VOC's, air toxics and NO_x in order to achieve emissions targets relative to a 1990 baseline. All RFG produced by refiners is required to be certified, with the emissions performance of the fuel being determined using a complex air toxics model developed by the Environmental Protection Agency (EPA). The use of pool averaging allows some flexibility in meeting targets for individual components and properties.

The specification of a minimum oxygen content in petrol as a means of reducing CO emissions was first introduced under the Clean Air Act in 1990, much earlier than the RFG programme. This legislation effectively made the use of oxygenates mandatory in a limited number of cities with high levels of carbon monoxide.

As a result of this move, MTBE, the most popular oxygenate, has been widely used in the United States for a number of years. However, in response to recent concerns about groundwater contamination from leaking tanks, the use of MTBE and other oxygenates (except ethanol) was banned in California. Other states have followed suit.

Diesel

EPA standards for diesel fuel for on-road use came into effect in 1993. These included a limit of 500 ppm (m/m) sulphur, a minimum Cetane Number of 46 and total aromatics limit of 35% maximum by volume. Exemptions to the sulphur limit apply in certain states, and there is currently no sulphur limit on diesel for non-road use. In California, more stringent standards were adopted, with a similar sulphur limit and a 10% maximum by volume limit on total aromatics. The Californian standard applies to both on-road and off-road use, but excludes marine and locomotive use and allows some flexibility for alternative specifications.

In 1999, the EPA gave notice of its intention to set a more stringent standard for diesel fuel in line with efforts to implement Tier 2 vehicle emission standards. The Bush administration confirmed its intention to proceed with the further reduction in diesel sulphur levels to 15 ppm (m/m) with effect from 2006, in conjunction with more stringent controls on emissions control equipment for heavy diesel vehicles.

Relevance to South Africa

- Californian requirements, being the most stringent in the world, effectively fix the "green" boundary of the fuel quality spectrum, thereby providing a benchmark as to what can actually be achieved given the resources.
- The USA is consequently a leader in vehicle emissions control and fuel efficiency technology.

8.17 China and India

Current fuel specifications from these countries are included in section 9 and 10 as these countries are faced with many of the same challenges facing South Africa.

8.18 Summary

By way of summary, one of the conclusions drawn in the EPEFE study highlights the wide spread in emissions levels related to the vehicle technologies evaluated (spanning the year 2000 European vehicle park and thus including pre Euro 1, Euro 1, Euro 2 and Euro 3). This variance was wider than the variations arising from fuel parameter variations (which included very wide parameter swings outside of what would be considered practical). For petrol vehicles, the total spread in terms of vehicle technologies evaluated, for the various emissions evaluated, ranged from 49.5% to 84.6%, while that for the fuel parameters was typically less than 20%, and most less than 10%, with some effects (caused by parameters outside of the practical range) as high as 42.1%. Similar results are seen for diesel vehicles, with vehicle technology effects generating a spread of between 56.7% and 89.1% and fuel effects having a spread of only 9.3% to 28.3%.

While fuel quality parameters are an important aspect in terms of combating vehicle emissions, the impacts from improved vehicle technologies are significantly larger.

Significant lessons can also be learnt from the approaches taken from other countries who have built on the experience of Europe, but implemented modified specifications, taking the climatic and environmental conditions into account.

9 Properties of petrol

This section examines the main properties that determine petrol quality. These include:

- Properties specified in the current regulations;
- Other properties currently not specified.

Each is examined under the following headings (as applicable)[iv]:

1. Property

- What is it?
- Why is it important (its effect on engine performance)?
- How is it controlled?

2. Comparison of current South African and international specifications

3. Why regulate?

- Why does this property need to be regulated?

It is noted that for some properties of petrol, there is a high degree of interdependence – for example, volatility and distillation parameters, composition and density are all inter-related with the result that it is not possible to change one in isolation without affecting the others. In refinery operations, where each crude oil produces a range of fuels, changing the properties of one product will also have flow on effects for other products – for example, changes required to meet new specifications for petrol may have an impact on production of diesel or other products. One important aspect of the interrelatedness of properties, which needs to be considered when setting specifications, relates to the restrictions imposed by one specification on the meeting of other specifications. The obvious example of this is the RON / aromatics / olefin / oxygenates relationship. Aromatics, olefins and oxygenates are all good octane components. Limits to the inclusion of these components, while still requiring a high octane specification for local fuels, would be extremely onerous on the refining industry and in the extreme case may be impossible of achievement. This is due to the refining technology and constraints in the marketplace. Therefore a broader view needs to be taken when considering the implications of any changes to specified quality properties.

Appendix B contains a description of how spark-ignition engines work, and the fuel characteristics that are relevant to petrol engine performance.

PROPERTIES CURRENTLY SPECIFIED

9.1 Octane Number [iv]

What is it?

Octane Number is a measure of petrol's resistance to auto-ignition. Auto-ignition in petrol engines can be classified into two types:

- **Knock**, caused by spontaneous combustion of a portion of unburnt air-fuel mixture ahead of the advancing flame front; and
- **Surface ignition (pre-ignition or post-ignition)**, where ignition is initiated by any hot surface in the combustion chamber rather than spark discharge at the spark plug.

Both processes result in uncontrolled combustion which, if severe, can cause major engine damage. Knock is generally the more common form of abnormal combustion. A significant defining feature of knock is that it is able to be controlled by ignition timing.

The higher the octane number of a petrol, the greater its resistance to knock. Iso-octane (octane number 100) and n-heptane (0) are used as the reference points for octane number. An octane number of 91 means that the fuel, when tested in a specified engine and procedure, has the same anti-knock quality as a mixture of 91% iso-octane and 9% n-heptane by volume.

There are two common measures of octane:

- **Research Octane Number (RON)** is an indicator of the fuel's anti-knock performance at lower engine speed and typical acceleration conditions.
- **Motor Octane Number (MON)** reflects the anti-knock performance of a fuel under high engine speed and higher load conditions.

The difference between them (i.e. RON – MON) is called the **sensitivity** and reflects the effect of severity of operation.

Why is it important?

Spark ignition engines are designed for a certain octane rating, corresponding to the compression ratio. Using a fuel of a lower rating may result in knocking, as a result of compression ignition occurring before spark ignition. In many modern engines, the spark occurs before the end of the compression stroke, to maximise the length of the power stroke, which requires the fuel to be resistant to compression ignition.

Many modern vehicles are designed with knock sensors which can retard the spark timing to accommodate conditions that would cause knocking. However, compensating for a low octane fuel by this mechanism results in loss of performance and efficiency. Using a petrol with a higher octane rating than specified will generally not improve engine performance. The manufacture of high octane fuels is both more expensive and less efficient than the manufacture of lower octane fuels and when a vehicle uses a fuel of higher octane than it actually requires, it can be said to be "wasting" octane.

The fuel sensitivity (the difference between the RON and MON values) can also be important in determining the overall fuel performance. Values are typically near to 10.

In the 1970s, the EU undertook a study known as RUFIT (Rational Use of Fuel in Transport) to identify the optimal octane value for crude derived unleaded petrol. The study established the optimum octane, with reference to what the refinery processes could produce to redress the octane deficit of lead removal and what the engine needed, taking fuel consumption into account. This octane optimum was found to be 94.5 RON which was subsequently rounded up to 95 RON. A new study is being undertaken in Japan to re-check the refinery/auto balance for modern spark ignition engines and the latest refinery technology, and reduce CO_2 emissions. Indications are that the optimal octane may be higher than 95 (possibly around 97), although it is too early to draw any conclusions.

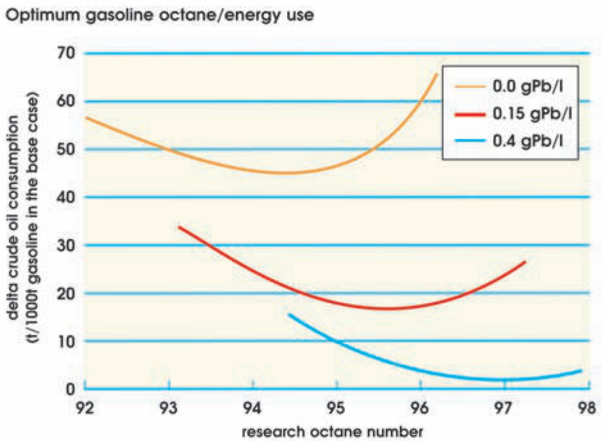

Figure 16: Results of the RUFIT study to determine the optimum octane levels [xiv]

How is octane controlled?

Branched chain hydrocarbons, olefins and aromatics are high octane components of petrol and their presence tends to improve its anti-knock performance. These compounds have differing sensitivities and so their use will affect the balance between RON and MON. Octane enhancing additives (organo-metallic compounds such as lead alkyls and MMT) can be used to improve the octane number of petrol. High octane blending components (oxygenates such as ethers and ethanol) can also be used.

By virtue of the different refining technologies and situations in South Africa, different routes are required to meet the current and future fuel specifications. Some of these include:

- The formation of branched chain hydrocarbons is achieved through alkylation and isomerisation during refining of the petrol fraction. Not all the refineries have this capability, and some need to import.
- There is a trend worldwide to reduce the amount of aromatics and olefins in petrol because of the effects of some of their products of combustion on air quality. These are discussed in more detail in Sections 10.9 and 10.16 respectively. The use of lead alkyls has now been phased out because of the adverse environmental effects of lead discharged from vehicle exhausts and the fact the exhaust catalytic converters are poisoned by this compound.
- Similarly, other organo-metallic compounds (such as MMT) are not favoured by the automotive industry as octane enhancers because of their alleged effects on engine components and catalysts.
- Oxygenates such as ethers and ethanol have a strong affinity for water and can migrate from fuel spills into ground water. Oxygenates are discussed in more detail in Section 10.11.

Because of these constraints, the South African Refining industry has limited capacity for reducing the benzene and total aromatics content of petrol, with its current configuration and balance of feedstocks. This will have implications for other properties when a specification review is considered.

Current South African and International Specifications

Most petrol specifications state a minimum limit only for both RON and MON. International specifications for octane number are already closely aligned as shown below.

In the United States, an Anti-knock Index (AKI) is commonly used, which is the average of RON and MON i.e. (RON + MON)/2. The US EPA regulations require a minimum anti-knock index of 87. The value of AKI for South Africa's 91 grade is 86, for 93 Grade is 88 and for 95 grade is 90.

Table 5: Current South African and International Octane Specifications [xv]

Grade	Regular		Premium		98 RON	
Specification (min)	RON	MON	RON	MON	RON	MON
South Africa [1]	**93 / 91**	**83 / 81**	**95**	**85**		
EN228:1993 (Euro 2)	91[2]	81[2]	95	85		
EN228:1999 (Euro3)	91[2]	81[2]	95	85		
EN228:2004 (Euro4)	91[2]	81[2]	95	85		
US[4]	(87[3])		(89[3])		(91[3])	
US : CARB[4]	(87[3])		(89[3])		(91[3])	
Japan	89	-	96	-		
New Zealand	91	82	95	85		
Australia	91	81	95	85		
India (Metro)	91	81	95	85		
India (Nationwide)	88	(84[3])	93	(88[3])		
China (Beijing)	90	85	93	88	97	Report
China (Nationwide)	90	85	93	88	97	Report
Worldwide Fuel Charter	91	82.5[5]	95	85	98	88

[1] Currently only 95 RON is marketed at the coast. 93 RON is dominant in inland market with some 95 RON being sold (no 91 RON).

[2] Applicable where regular grades are available

[3] Antinock index (RON + MON)/2

[4] Industry standard indicated, regulated at state level

[5] Category 2, 3 and 4 only, Category 1 is 82.0

Why regulate?

The primary reason for continued regulation is to ensure that the consumer is able to buy petrol of known and consistent octane number. Matching the fuel with the octane requirement of the vehicle will ensure that no engine damage occurs.

9.2 Colour [iv]

What is it?

Petrol is normally colourless and a dye is sometimes added (usually at the refinery) to provide any required colour. Generally, colours are used to differentiate between grades during pipeline distribution. This dye does not affect vehicle performance.

Table 6: Current South African and International Colour Specifications [xv]

Specification	Colour
Units	-
South Africa	**allowed [1]**
EN228:1993 (Euro 2)	-
EN228:1999 (Euro3)	-
EN228:2004 (Euro4)	-
US	-
US : CARB	-
Japan	specified
New Zealand	required [2]
Australia	-
India (Metro)	specified
India (Nationwide)	specified
China (Beijing)	-
China (Nationwide)	-
Worldwide Fuel Charter	-

[1] The petrol can also contain small quantities of harmless colouring materials to give it a distinctive appearance

[2] Not to be mistaken for harmless substance

Previously, different petrol grades in South Africa were required to contain dyes to indicate the grade of fuel. This was intended to provide an easy method to verify the fuel grade.

Why regulate?

Normally the consumer will not see the fuel that is being put into a vehicle, but the colour does allow the grade of petrol to be easily determined when it is sampled and for it to be readily distinguishable from diesel, which has no added colour.

9.3 Volatility and Distillation Parameters [iv]

What are they?

These properties characterise the volatility of the petrol, that is, its tendency to vaporise. This is critical to engine performance, particularly starting, as well as vapour emissions from the fuel distribution system. As petrol is a mixture of a large number of different hydrocarbons, the boiling point is a temperature range rather than a single value, and therefore four main measures of volatility are commonly used in Europe.

E70, E100, E150 and E180

These are the percentages by volume of petrol that evaporate when it is heated to 70°C, 100°C, 150°C and 180°C respectively. E70 is a measure of cold running performance. The distillation properties can alternatively be expressed as temperatures corresponding to different volumes, for example T10, T50 and T90. These are the temperatures at which 10%, 50% and 90% by volume of the petrol has evaporated, as is the case in South Africa.

Distillation End Point

This is the temperature beyond which all the volatile components have boiled off, leaving only a residue (see Section 10.4). These properties are illustrated in Figure 17 which shows a typical distillation curve for petrol.

Reid Vapour Pressure (RVP)

The vapour pressure is another measure of the volatility of the fuel and relates principally to the lighter components in the fuel such as butane. To measure the true vapour pressure is relatively complicated, and therefore a simpler parameter, Reid Vapour Pressure, is used and is referenced to a standard temperature (37.8°C or 100°F).

Flexible Volatility Index (FVI)

This is a parameter calculated from the RVP and the measured value of E70, and is an indicator of the hot running performance (the tendency for vapour lock).

$$FVI = RVP + (0.7 \times E70)$$

Vapour Lock Index (VLI) is used in European specifications and is essentially the same as FVI, though it differs by a factor of 10.

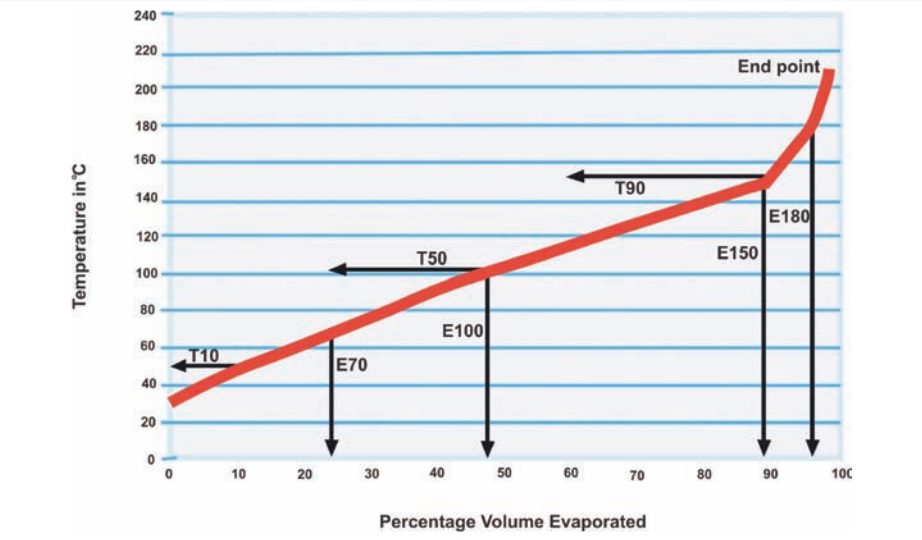

Figure 17: Typical Distillation Curve for Petrol [iv]

Another indicator of volatility is the Driveability Index or Distillation Index (DI) which is calculated from T10, T50 and T90 and also allows for the effects of oxygenates. The formula is:

$$DI = (1.5 \times T10) + (3 \times T50) + T90 + (11 \times \%O_2\ w/w)$$

DI is a measure of cold driveability. 'T' numbers have traditionally been used in the USA, Japan and Australia although the USEPA is moving away from these in favour of % evaporation properties (E70 etc.) which behave linearly when blending different batches.

Why are they important?

Fuel must contain enough volatile components (light ends) to enable easy starting and acceptable driveability when an engine is cold, but not so much that it begins to vaporise in the fuel lines when the engine is hot (this is known as vapour lock and impedes fuel flow). The fuel must also not be so volatile that evaporation from the fuel tank is excessive – both for environmental and health reasons. The volatility of the fuel, and hence its performance, is affected by the ambient air conditions (temperature and pressure) and therefore these factors need to be taken into consideration. Thus, volatility must reflect not only the general performance requirements of spark-ignition engines, but also the range of climatic conditions in which they must operate, with the result that direct comparisons with other countries are not necessarily valid.

At the high end of the distillation curve, the least volatile (heaviest) components are important in contributing to deposit formation and exhaust emissions. These compounds may not fully vaporise before entering the combustion chamber, particularly under cold running operation. This can cause oil dilution and increased cylinder wear, and may lead to combustion chamber and inlet system deposits and spark plug fouling. Exhaust hydrocarbon emissions are also influenced to a small extent by the heavy compounds; reducing the fuel's T90 value leads to small reductions in hydrocarbon emissions, particularly under cold running conditions. The evaporative emission of VOC's is also reduced with decreased T90. These effects are generally fairly small.

The heavier compounds in petrol are generally those with the highest energy content and density, so their reduction will tend to reduce the energy content per litre of fuel slightly, thereby increasing fuel consumption.

How are these properties controlled?

- **RVP** is usually controlled during refining by adjusting the proportion of butane, the most volatile component, and other components, in the final blend. Reducing RVP reduces evaporative losses and the international trend is towards lower maximum RVP limits.
- **End Point** is reduced by altering the cut point between the petrol fractions and heavier products during refining.

The other distillation properties are not usually controlled directly but reflect the composition of the petrol.

Current South African and International Specifications

The following table compares the current South African requirements with a range of volatility specifications used internationally. It is important to note that the values of these volatility properties must be set to suit the climatic conditions in which the fuel is used. The European specifications define volatility classes on the basis of climate, which each EU country is able to assign on a seasonal basis. The World-Wide Fuels Charter volatility classes are based on minimum expected ambient temperatures.

Why regulate?

Performance

By virtue of the differences in the South African vehicle parc and climatic conditions, altitude and latitude specific parameters have been established

Table 7: Current South African and International Volatility specifications [xv, xii]

Specification	E70		E100		E180	End Point	RVP	FVI
	Vol % min	Vol % max	Vol % min	Vol % max	Vol % min	°C max	kPa max	kPa max
South Africa	T10, T50 T90 Specified					**215**	**45 - 75**	**89 - 100(1)**
Northern Europe	20 - 22	48 - 50	46	71	75 (E150)	210	45 - 70	125
Southern Europe						210	45 - 70	125
US	-	-	-	-			controlled at state level	
US : CARB	-	-	-	-			controlled at state level	
Japan	T10, T50 T90 Specified					220	48 - 78	
New Zealand	25	45	45	67	90	220	-	77.5 - 115
Australia	-	-	-	-		210	controlled at state level	
India (Metro)							0.720 - 0.775	
India (Nationwide)							0.710 - 0.770	
China (Beijing)							0.720 - 0.775	
China (Nationwide)							-	-
Worldwide Fuel Charter	20 - 25	45 - 47	50 - 55	65 - 70	90	195	55 - 70	

(1) inland and coastal arease differ

over the years to ensure that petrol is fit for purpose relative to local conditions. As a result there are 2 different classes of products for the coastal and inland region. As the vehicle parc changes it is believed that these altitude differences may not be an issue from the perspective of vehicle performance or the environment, and, as a result, it will be possible to minimise the logistics by reducing the number of grades manufactured and distributed.

The current specifications for FVI (100 max coastal and 89 inland) reflect the allowable seasonal variation.

Engines with carburettors are more susceptible to vapour lock than those with fuel injection systems. As carburetted engines currently make up a significant proportion of the South Africa petrol vehicle fleet, and were sold up until December 2007, it is likely that the maximum limit on FVI will need to be retained.

Lowering (reducing) of the end point will reduce smoke emissions as a result of reduced high molecular weight aromatics. Changing the distillation end point to 210°C will align with the Euro standard.

Evaporative Emissions

In order to reduce evaporative losses and resulting hydrocarbon emissions from vehicles and during bulk storage and distribution, there have been moves in many countries to reduce the allowable vapour pressure. It is noted, however, that the evolution of biofuels is challenging this view. By virtue of the tight FVI limits in South Africa the RVP is constrained and hence typically limited.

RVP reduction is achieved by reducing the lighter ends (components that evaporate easily), such as butanes, which affect cold starting. Lower volatility fuels are less of a problem in fuel-injected engines, which are fitted to all new vehicles, but can cause problems with carburetted engines in older vehicles which make up a significant proportion of the South African fleet.

Therefore RVP limits should not be set too low.

Harmonisation with other specifications

Volatility requirements reflected in international standards cover a range of climatic conditions and care needs to be taken when identifying suitable values for use in South Africa. It would be appropriate for South Africa to adopt the European specifications and align with Southern Europe volatility classes. However the benefits need to be determined in light of the current vehicle parc, altitude and climatic conditions.

9.4 Residue and Existent Gum [iv]

What is this?

Residue is the percentage volume remaining after the distillation end point is reached and represents the proportion of non-volatile components in the fuel. This material, primarily waxes and gums, may form deposits in engine fuel inlet systems. The residue is determined as part of the standard distillation test using ASTM D 86.

The residue is washed in a solvent before drying and weighing to determine the amount of gum present – the "Existent Gum." The test method is ASTM D 381.

These properties are a function of the petrol composition and distillation characteristics. Actual engine fuel inlet system deposit formation can be effectively controlled with the use of suitable additives and thus these parameters do not always indicate the actual tendency of the fuel to form engine deposits.

Current South African and International Specifications

The current specification requires a maximum of 2% by volume residue after distillation which is almost universal in international petrol specifications. The specification for gum is 4 mg per 100 mls, which is slightly better than both the European standards and the Worldwide Fuel Charter.

Table 8: Current South African and International Gum & Residue Specifications [xv]

Specification	Existent Gum [1]	Residue
Units	mg/100 ml (max)	% vol (max)
South Africa	**4**	**2.0**
EN228:1993 (Euro 2)	5	2.0
EN228:1999 (Euro3)	5	2.0
EN228:2004 (Euro4)	5	2.0
US	5	2.0
US : CARB	5	2.0
Japan	5[2]	2.0
New Zealand	5	2.0
Australia	5	-
India (Metro)	5	2.0
India (Nationwide)	4	2.0
China (Beijing)	5	2.0
China (Nationwide)	5	2.0
Worldwide Fuel Charter	5	n/a

[1] Also referred to as "Washed Gum"

[2] Also contains 20 mg/100 ml (max) Unwashed Gum specification

9.5 Copper Strip Corrosion [iv]

What is it?

Corrosiveness in petrol is usually caused by free sulphur or sulphur compounds which combine with water from combustion to form acids. The test procedure uses a strip of polished copper which is immersed in a sample of the fuel and heated to a specified temperature for a specified time. The degree of corrosion is measured by comparing the staining with a reference sample. The test method is ASTM D 130.

Current South African and International Specifications

The South African specifications are currently in line with the European specifications, the Worldwide Fuel Charter and specifications from all of the countries considered.

Why regulate?

Some measure of the corrosivity of petrol needs to be retained to provide protection for fuel tanks, dispenser pumps and vehicle engine and fuel system components.

9.6 Sulphur [iv]

What is it?

Sulphur occurs naturally in crude oils and must be removed to an acceptable level during the refining process as it promotes corrosion and affects the performance of vehicle emissions control equipment.

Why is it important?

Sulphur does not affect engine performance directly but reduces the efficiency of catalytic converters. There is no performance or emissions effect on older vehicles not fitted with catalysts, however all vehicles with operating catalysts will show some emissions reduction with reduced fuel sulphur levels, although the magnitude of the effect will vary according to technology employed, vehicle and catalyst condition and driving mode. Reduced sulphur levels therefore have the potential to reduce emissions from the existing vehicle fleet as well as to be an enabler for the introduction of cleaner vehicle technologies.

Some of the advanced exhaust after-treatment technologies utilised to meet Euro 4 and Euro 5 emissions standards require 50 ppm (m/m) or lower sulphur levels in order for the efficiency of the devices to be maintained at optimal levels. The existing fleet of emissions controlled vehicles in South Africa, as well as the significant majority of new vehicles sold, is mostly of a technology level lower than Euro 4 and these vehicles will gain the majority of the reduced sulphur benefit at levels higher than 50 ppm (m/m), with 150 ppm (m/m) being commonly proposed for these vehicle technologies.

Current South African and International Specifications

The Sasol synthetic fuel process produces fuel products with very low sulphur contents, typically below the "sulphur free" threshold of 10 ppm (m/m). The conventional crude oil refineries in South Africa are more constrained in their ability to produce low sulphur fuels.

South African fuel specifications currently allow two distinct fuel grades, namely metal free unleaded petrol (ULP) which may not contain metal additives, and unleaded petrol containing metal (commonly referred to as Lead Replacement Petrol or LRP). These two fuel grades have different sulphur specifications. The LRP grade is not intended for use in vehicles with catalysts and is typically dispensed through a large diameter nozzle which will not fit vehicles manufactured since 2001 and thus there is no significant benefit to reducing the sulphur content of this grade of fuel.

Table 9: Current South African and International Sulphur Specifications [xv]

Grade	Metal Free	Metal Containing
Specification	Sulphur	
Units	ppm (max)	
South Africa	**500**	**1500**
EN228:1993 (Euro 2, 1995)	500	-
EN228:1999 (Euro3)	150	-
EN228:2004 (Euro4)	50/10 [1]	-
US	80/30 [2]	
US : CARB	30	
Japan	10	
New Zealand	50	-
Australia	150/50 [3]	
India (Metro)	150	
India (Nationwide)	500	
China (Beijing)	50	
China (Nationwide)	500	
Worldwide Fuel Charter	1000/150/30/10 [4]	-

[1] 10 ppm "Sulphur Free" fuel to be available on a balanced geographical basis

[2] 80 ppm Cap with 30 ppm average

[3] Regular / Premium

[4] Category 1/2/3/4

Why regulate?

Sulphur in petrol degrades the efficiency of exhaust catalysts and by limiting sulphur levels reduced vehicle emissions will result from vehicles equipped with catalysts. All vehicles sold since January this year (2008) are fitted with catalysts and a significant number of vehicles sold in the last number of years have catalysts, thus some benefit will occur in the existing fleet. It is however probable that the current actual levels of sulphur in much of the fuel available in South Africa already low enough and hence may necessarily benefit from tighter sulphur specifications.

The state of the art exhaust after-treatment currently offered on Euro 4 and Euro 5 compliant vehicles require significantly reduced sulphur levels for durable and efficient operation. Availability of a fuel grade of sufficiently low sulphur content is therefore considered an enabling specification for the introduction of these vehicle technologies. The number of vehicles that truly need this fuel is extremely small and will grow slowly over time. However, it is important to have the fuel available for these vehicles at the right time for an incremental improvement in air quality to be achieved.

9.7 Oxidation Stability Induction Period [iv]

What is it?

This oxidation stability test (ASTM D525) is a measure of the stability of the petrol during long term storage. Oxidation results in the formation of gums, deposits and sludges.

In the test the sample is heated in a sealed vessel with oxygen and the time before it starts to absorb the oxygen (i.e. oxidise) and form gum is then measured and used to determine the induction period. The induction period measured does not equate to the safe storage time. A figure of 360 minutes minimum usually ensures a satisfactory level of stability for normal storage and distribution purposes, which corresponds to the current South African specification.

Petrol containing sufficient straight-run naphtha (fuel component) contains naturally occurring anti-oxidants. However, some petrols require dosing with antioxidants to control oxidation.

Table 10: Current South African and International Oxidation Stability Specifications

Specification Units	Oxidation Stability minutes (min)
South Africa	**360**
EN228:1993 (Euro 2)	360
EN228:1999 (Euro3)	360
EN228:2004 (Euro4)	360
US	240
US : CARB	240
Japan	240
New Zealand	360
Australia	360
India (Metro)	360
India (Nationwide)	-
China (Beijing)	480
China (Nationwide)	480
Worldwide Fuel Charter	360/480/480/480 [1]

[1] Category 1/2/3/4

9.8 Lead [iv]

What is it and why is it important?

Previously, lead was added to petrol in the form of compounds such as tetra-ethyl lead (TEL) to improve the octane rating. While it does not affect engine performance as such, lead contamination accumulates in catalytic converters and poisons the catalyst. This effect is cumulative and irreversible. No reference has been found to the minimum level of lead required to avoid damage to catalysts but a standard of 5 mg/litre has become a common international standard for unleaded petrol.

Concerns over effects on human health have resulted in the phasing out of petrol additives containing lead in many countries. As lead affects the performance of catalysts in vehicle emission control systems its withdrawal has been necessary to enable the introduction of catalyst technology in petrol vehicles. Lead free petrol has been available in South Africa since 1996 and all petrol sold has been lead-free since 2006.

The current test method specified is IP 224.

Current South African and International Specifications

The current South African specifications set a maximum level of 13 mg/litre to allow for some level of minor contamination, although the test procedure used can detect levels as low as 0.3 mg/litre. The actual lead levels in South Africa are very low and the tanks and systems were flushed quickly after lead phase out in January 2006. Any lead detected will generally be a result of contamination during transport in ships' tanks which have previously been used for leaded fuels, although this is reducing as lead is phased out around the world.

Table 11: Current South African and International Lead Specifications [xv]

Specification Units	Lead mg/l (max)
South Africa	**13**
EN228:1993 (Euro 2)	13
EN228:1999 (Euro3)	5
EN228:2004 (Euro4)	5
US	13[1]
US : CARB	13[1]
Japan	1
New Zealand	5
Australia	5
India (Metro)	5
India (Nationwide)	13
China (Beijing)	5
China (Nationwide)	5
Worldwide Fuel Charter	not detectable [2]

[1] No intentional addition. Allowed in aircraft, racing cars, and off-road farm & marine engines.

[2] No test method defined. No intentional addition.

9.9 Total Aromatics [iv]

What are they?

Aromatics are hydrocarbons with a molecular structure based on cyclic carbon (benzene) rings. Benzene itself is the simplest aromatic compound (discussed separately below) but others common in petrol include toluene and xylene. Some, particularly benzene, are known to be carcinogenic. Aromatics containing multiple benzene rings are known as polycyclic aromatic hydrocarbons or PAHs (also referred to as PCAs). Many PAHs detected in exhaust emissions display some mutagenic and carcinogenic activity.

Aromatics occur naturally in crude oil. They are also produced as part of the catalytic cracking and reforming processes used in refining and are used to increase the octane rating of petrol.

Why are they important?

Aromatics are high octane constituents of petrol, and therefore any reductions in levels need to be made up with some other high octane constituents or octane improving additives. With the move to the wider use of unleaded petrol, refiners have tended to increase the level of aromatics to meet octane requirements, particularly for premium grades.

As they are solvents, at high concentrations aromatics can affect some of the elastomers used in seals and gaskets in pumps and fuel lines, particularly on older vehicles. However, sudden large reductions in aromatic levels or low levels can also cause loss of elasticity or shrinkage in some elastomers "acclimatised" to higher levels. This can also be a problem in diesel fuels.

The heavy compounds, particularly PAHs, can be more difficult to combust; this may lead to combustion chamber and inlet system deposits and spark plug fouling. Exhaust hydrocarbon (HC) emissions are also influenced to a small extent by these heavy compounds; reducing the fuels aromatics content (manifesting as a reduced T90) leads to small reductions in the HC emissions, particularly under cold running conditions.

The main drive to reduce aromatics is the reduction of human exposure to toxics in ambient air. The total aromatic, and especially benzene, content of the fuel leads directly to reduced toxic emissions. This has led to some juris-dictions imposing maximum pool average and overall cap limits on aromatics and benzene emissions. This achieves the overall reduction in terms of human exposure while providing the refinery industry some flexibility in its operations. By way of example, New Zealand has implemented a 42% average with a 45% cap on aromatics and the US EPA has proposed a 2011 limit of 0.62% annual average on benzene while CARB allows California refiners to opt to have a 35% total aromatics cap as long as their annual average does not exceed 22% or to have a fixed 25% cap on all petrol produced.

Current South African and International Specifications

Total aromatics levels in South African petrol currently average around 45% by volume, with a maximum regulated level of 50%.

Why regulate?

The control of aromatics levels in petrol is the most direct way of limiting evaporative losses and exhaust emissions of these compounds, thereby reducing human exposure to them. Consequently, in recent years international standards have focused on progressively reducing allowable aromatics levels. Attention originally focused on benzene because of its carcinogenic properties and higher volatility.

Table 12: Current South African and International Aromatic Specifications [xv]

Specification	Aromatics
Units	% vol (max)
South Africa	**50**
EN228:1993 (Euro 2)	n/a
EN228:1999 (Euro3)	42
EN228:2004 (Euro4)	35
US	- [1]
US : CARB	35 [2]
Japan	-
New Zealand	45 [3]
Australia	45 [4]
India (Metro)	42
India (Nationwide)	-
China (Beijing)	-
China (Nationwide)	40 [5]
Worldwide Fuel Charter	50/40/35/35 [6]

[1] Controlled by predictive model calculated toxic emissions.

[2] Cap limit, also controlled by predictive model calculated toxic emissions controls.

[3] 42% average

[4] Average over 6 months

[5] 42% in RON 97

[6] Category 1/2/3/4

As previously noted, sudden changes in aromatics levels can affect elastomers in engines and too low a level may also cause shrinkage in seals in older vehicles in the vehicle parc which have always operated on a variety of fuels from relatively low to relatively higher levels. It is noted that Japan, a major source of our vehicles, has no aromatics limit.

A lower limit for aromatics could be imposed for the lower octane grades of petrol which would in effect reduce the overall human exposure levels while not over constraining the refinery total output. This would of course only apply if differentiated octane grades have sufficient market penetration, a situation which is currently not the case in South Africa. However, it is not international practice to impose different limits for regular and premium grades, although China allows a slight relaxation for their premium RON 97 grade.

The benefits of an early reduction in aromatics levels are less obvious than reductions in benzene. Unless oxygenates such as ethers or ethanol are used, it will be extremely difficult to meet the octane requirements for petrol produced if aromatics levels are restricted.

9.10 Benzene [iv]

What is it and why is it important?

Benzene is the simplest aromatic compound and the one that has received most attention by virtue of its known carcinogenic properties.

Vehicles emit benzene through evaporation from their fuel systems and through exhaust emissions. International practice in recent years has been to set lower limits on benzene in petrol in response to health and air quality concerns.

The benzene content does not directly affect engine performance, but like other aromatics, it is a good source of octane.

Current South African and International Specifications

Benzene levels in South African petrol have risen slightly in the last 2 - 3 years and currently average around 3%, still below the specified maximum of 5%. This value was set in the original specifications in 2006 and has remained unchanged since then.

Table 13: Current South African and International Benzene Specifications [xv]

Specification Units	Benzene % vol (max)
South Africa	**5**
EN228:1993 (Euro 2)	5
EN228:1999 (Euro3)	1
EN228:2004 (Euro4)	1
US	1 [1]
US : CARB	1.1 [2]
Japan	1
New Zealand	1
Australia	1
India (Metro)	1
India (Nationwide)	3
China (Beijing)	1
China (Nationwide)	2.5
Worldwide Fuel Charter	5/2.5/1/1 [3]

[1] Also controlled by predictive model calculated toxic emissions.

[2] Cap limit, also controlled by predictive model calculated toxic emissions controls.

[3] Category 1/2/3/4

Why regulate?

Benzene levels have historically been regulated to control both evaporative emissions and exhaust emissions.

While for many other air contaminants, such as particulates, exposure comes from a number of different sources, for most people, motor vehicles are the primary route of exposure to benzene.

- **Controlling evaporative losses**

  The evaporation of volatile components from petrol can be reduced by minimising the concentration of those components in the fuel and by minimising the exposure of the fuel to air. Reduction of benzene levels achieves the first objective; modern vehicle fuel systems design (including absorption traps on fuel tank breathers and fuel injection systems instead of carburettors) achieves the second.

- **Vehicle exhaust emissions**

  Benzene emissions in vehicle exhausts arise from benzene in unburned fuel, and from pyrolysis and partial combustion of heavier aromatics and possibly some other hydrocarbons, therefore a reduction in total aromatics also reduces benzene levels in exhaust from vehicles. 3-way catalytic converters are the most effective way to reduce benzene in exhaust emissions. Other newer measures to further reduce hydrocarbon emissions, such as better control of the air-fuel ratio, improved catalysts and reductions in the light-off time (how quickly the catalyst heats up and starts to operate effectively) will also reduce benzene concentrations in exhausts.

9.11 Oxygenates [iv]

What are they?

Oxygenates are organic compounds containing carbon, oxygen and hydrogen. They can be added to petrol as a blending component and to increase octane. Their use in petrol effectively increases the available oxygen for combustion which has the effect of reducing CO formation and hydrocarbon emissions. The two main groups are alcohols (such as ethanol and methanol) and ethers (such as methyl tertiary-butyl ether (MTBE) or ethyl tertiary-butyl ether (ETBE)). Blends containing up to 20% ether and 9,5% ethanol are allowable in the inland region, while 15% ether and 7.5% ethanol is allowable at the coast.

The key properties of the most commonly used oxygenates, when blended at a level of 5% in petrol, are found in the table below:

Table 14: Key Blending Properties of most commonly used oxygenates

Substance	Blending Motor Octane Number	Blending Research Octane Number	Blending Reid Vapour Pressure (kPa)	Boiling Point (°C)	Water Tolerance
Ethers					
MTBE	101	118	55	55	Excellent
ETBE	102	118	28	72	Excellent
Alcohols					
Methanol	92	125	522	65	Very Poor
Ethanol	96	130	222	78	Very Poor
TBA	95	105	62	71	Poor
Petrol	82-88	92-98	70-100	26-230	

Why are they important?

- **Driveability**

  The use of oxygenates can induce a "lean shift" in the fuel/air stoichiometry (air / fuel ratio) thereby reducing CO in vehicle exhaust emissions (CO occurs when there is insufficient oxygen for complete combustion to CO_2). This tends to benefit mostly older carburetted engines as modern electronic engine management systems monitor the oxygen content of the exhaust gases and adjust the air/fuel ratio accordingly.

  Oxygenates in petrol can cause over-leaning depending on how the engine management system is calibrated, leading to driveability problems and increasing emissions of NO_x. For MTBE, the effect is quite small – 15% MTBE results in a change in the stoichiometric air/fuel ratio of only 2%. Ethanol requires more heat to vaporise than ethers and this can also affect the driveability of petrol/ethanol mixtures.

- **Volatility**

  Blending oxygenates into petrol can increase the vapour pressure of the fuel and significantly modify the volatility and distillation characteristics, resulting in increases in evaporative emissions. Methanol has the most dramatic impact - small amounts (in the order of 2%) can cause 35% increases in vapour pressure. Ethanol can also have significant effects on vapour pressure, whereas for ether, the effect is much smaller (around 8 numbers at 2-3% concentrations).

- **Exhaust emissions**

  Particulate Matter (PM) emissions from petrol engines, while already low compared with diesel engines, can be reduced by up to 50% with the addition of oxygenates to petrol.

- **Octane enhancement**

  Oxygenates are good sources of octane but also have high sensitivities (see Section 10.1) which can limit their application for octane enhancement. Ether does not appear to affect high speed octane performance, while methanol may do so. Generally, the effects will vary with the base fuel and specific vehicles, however ether appears to be more effective in providing octane enhancement.

Current South African and International Specifications

Many new specifications allow oxygenates to be added but place a limit on the overall oxygen content of the final blend. A limit of 2.7% max by mass is common, which is equivalent to around 7.5% by volume ethanol and 15% by volume ether. A number of countries allow exemptions and/or place limits on specific types of alcohols and ethers.

The use of oxygenates was made mandatory by Federal law in the United States in 1990 on the grounds of its air quality benefits (primarily reduced CO emissions). Because of its lower volatility and cost, MTBE has generally been more attractive as an oxygenate than alcohols or other ethers, and its use increased significantly in the United States with the subsequent introduction of the reformulated petrol (RFG) programme. It is also used widely in Europe and parts of Asia. However MTBE has a strong affinity for water and has been found at low levels in groundwater both in the USA and the United Kingdom. As a result, California banned the use of MTBE and other ethers in petrol with effect from the end of 2002 and other states have followed.

Table 15: Current South African and International Oxygen Specifications [xv]

Grade	Coastal	Inland	All Gasoline	All Gasoline							
Specification	Oxygen [1]			Mehtanol	Ethanol [1]	Iso-Propyl Alcohol	n-Propyl Alcohol	Iso-Butyl Alcohol	Tert-butyl Alcohol	Ethers (≥ 5 C)	Others
Units	% wt (max)			%vol (max)							
South Africa	**2.8**	**3.7**	**-**	**trace [2]**	**allowed [2]**	**allowed [2]**	**allowed [2]**	**trace [2]**	**trace [2]**	**allowed**	**-**
Euro 2 (1993)	-	-	-	-	-	-	-	-	-	-	-
Euro 3 (2000)	-	-	2.7	3	5	10	-	10	7	15	10
Euro 4 (2005)	-	-	2.7	3	5	10	-	10	7	15	10
US[3]	-	-	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]
US : CARB	-	-	1.8 min - 3.5 max [3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]	-[3]
Japan	-	-	1.3	0.5	3	-	-	-	-	7	-
New Zealand	-	-	1[4]	-	10	-	-	-	-	-	-
Australia	-	-	2.7[5]	-	10	-	-	-	-	-[5]	-
India (Metro)	-	-	2.7	-	5	10	-	10	7	15	8
India (Nationwide)	-	-	-	3	5	5	-	7	7	15	7
China (Beijing)	-	-	2.7	-	-	-	-	-	-	-	-
China (Nationwide)	-	-	2.7	(0.3) [6]	-	-	-	-	-	-	-
Worldwide Fuel Charter	-	-	2.7	0	10	0.1 [7]	0.1 [7]	0.1 [7]	0.1 [7]	preferred	-

[1] Most specifications place a restriction on gasoline or blending stock acidity when oxygenates, especially ethanol, are used

[2] Where alcohols are used, the alcohol must be minimum 90% ethanol, the balance iso-propanol and n-propanol and only trace quantities of other alcohols

[3] Complex rules in place including minimum oxygen limits in air quality non-attainment areas. Use of predictive model used to control overall toxic emissions. MTBE prohibited by CARB.

[4] With the exception of Ethanol and MTBE.

[5] 3.5% for fuel with ethanol. Max 1% of DIPE and 1% of MTBE.

[6] % Wt

[7] Alcohols of C>2 allowed at maximum 0.1% vol

Ethers

When added to petrol, alcohols by themselves tend to be very volatile – due to the formation of an azeotrope (when a mixture of a particular composition has a higher volatility than each of one of the components) with light hydrocarbons – and water soluble, which can lead to problems in the fuel distribution system and vehicle engine as well as in the environment. These problems of volatility and water solubility can be overcome by "stabilising" the alcohols with various petroleum-derived components through a process known as etherification. Ethers retain all the benefits of their alcohol feedstocks, without the shortcomings.

- **Fuel ethers improve air quality**

The environmental benefits of fuel ethers can be divided into two main categories. There are so-called "direct" effects, mainly resulting from more complete fuel combustion (as a result of organic oxygen presence) and "indirect" ones, coming from the dilution of other, less desirable, petrol pool components. It is important to note that their use reduces emissions from all types of petrol vehicles, regardless of the emission-control technology employed. Although it seems to be of less importance for EURO [IV] standard cars with newest catalyst techniques, fuel ethers help to improve combustion for these cars especially in the cold starting phase of the engine, when the catalytic converter is not working.

Direct effects include the reduction of both "regulated" and "unregulated" emissions. Among the specific pollutants already limited by law are carbon monoxide (CO) as well as unburned hydrocarbons (HCs). A second category includes those pollutants that have recently been the focus of attention for the EU authorities, although they are not yet the subject of legislation. Probably the most important are particulate matter (PM) and ground-level ozone.

Reducing exhaust emissions of carbon monoxide: CO poisoning occurs because haemoglobin (the protein in our blood that carries oxygen) absorbs CO 200 times faster than it can absorb oxygen. This can produce many symptoms including headaches, fatigue, nausea, dizziness, confusion and irritability. Continued exposure can lead to vomiting, brain damage, heart irregularity, breathing difficulties and muscle weakness. Absorption at concentrations as low as 800 ppm can cause unconsciousness in less than an hour and death in only 2-3 hours. CO also makes a significant contribution to ground-level ozone.

Carbon monoxide results from incomplete burning of fuel. Adding oxygen to petrol results in more efficient and complete fuel combustion, which in turn leads to significant decreases in CO emissions, in the same range as the percentage of fuel ether content in the petrol.

Unburned hydrocarbons: HCs coming out of vehicle exhaust pipes unburned (or partially burned and transformed into other chemicals) fall into the category of VOCs (Volatile Organic Compounds), which have for many years been the focus of legislative attention in Europe and worldwide. The adverse effects of HCs on human health have been widely reported.

Since most emissions of unburned HC's occur in the period before catalyst warm-up, this problem is not alleviated by improved vehicle technology. Conservatively, for each 1 or 2% of fuel ether, there is a 1% reduction in total HC emissions.

Ozone (O_3): Ozone, the main ingredient of smog, poses a serious air quality problem in many parts of Europe. Even at low levels, ozone can cause a number of adverse respiratory effects. It can irritate the respiratory system, reduce lung function, aggravate asthma, inflame and damage lung cells, aggravate chronic lung diseases and may cause permanent lung damage. O_3 also affects the natural environment: it compromises plants' growth and reproduction; it makes them more susceptible to disease and reduces agricultural yields for many economically important crops.

Fuel ethers, by reducing direct VOCs' Ozone Forming Potential (OFP), performs significantly better than other octane blending components. It generates about half of the ozone when compared to iso/alkylates (fuel components) and one-tenth that of aromatics.

Aromatics: Blending fuel ethers into petrol allows, by dilution, a consequential reduction of the level of benzene and aromatics components.

It is estimated that, for each 1% of MTBE, there is an equivalent percentage reduction in benzene emissions, both evaporative and exhaust.

- **Environmental issues**

The main route for environmental impact of MTBE is via leakage of petrol from storage tanks.

MTBE has a strong affinity for water (MTBE solubility in water is 4.3%, water solubility in MTBE 1.4%). While levels found in groundwater in the United Kingdom and United States do not appear to pose a significant health risk as such, MTBE has a distinctive taste and smell and will taint groundwater supplies, even at very low concentrations. The main benefits of MTBE are the reduction of CO emissions and its use as a source of octane, thus allowing for reduction of the level of benzene and aromatics in petrol. By comparison with alcohols, MTBE offers low water solubility, low reactivity and low volatility - characteristics that enable refiners to avoid the handling problems associated with alcohol oxygenates.

- **Consumer issues**

Like all oxygenates, the addition of MTBE can reduce the volumetric energy content of petrol, as the oxygen portion does not combust. This can have the effect of increasing fuel consumption (litres per 100 km) slightly. As noted, the effect of MTBE on volatility of petrol blends is generally not significant.

Ethanol

With the use of MTBE now being phased out in some parts of the United States and other regions of the world because of concerns over groundwater contamination, the use of ethanol as an oxygenate is expected to increase.

- **Environmental issues**

Ethanol is completely soluble in water and is not considered toxic. However, it can increase the solubility of other hydrocarbons in water and increase the mobility of hydrocarbon plumes from subsurface spills in the soil, so there are some environmental concerns.

Vehicles in the United States and Europe, where oxygenated fuels are widely used, are mandated to have advanced emissions control systems. Similar legislation has only recently been enforced in South Africa with the result that many of our vehicles on the road presently lack even basic emissions control devices. Because of these differences in vehicle technologies, it is difficult to predict with certainty the changes in tailpipe emissions that would result from using ethanol-blended petrol. There is general agreement that oxygenated fuels reduce CO emissions and this would especially occur in the non-emissions controlled vehicles. However, results of studies examining the effects of ethanol-blended petrol on exhaust emissions of hydrocarbons, volatile organic compounds, and oxides of nitrogen have been mixed.

In terms of other air emissions, combustion of ethanol produces acetaldehyde, a toxic air contaminant, and peroxyacetyl nitrate, an eye irritant and cause of plant damage. The amount of these pollutants that will be emitted from a vehicle burning ethanol-blended petrol will depend on the emissions control technologies incorporated into the vehicle.

A further area of concern in terms of air quality is evaporative emissions from the carburettor, fuel tank, or other part of the fuel system. Ethanol-blended petrol may lead to increases in evaporative emissions because rubber, plastics, and other materials in the fuel system are permeable (porous) to ethanol.

The mixing of ethanol-containing and ethanol-free petrol in vehicle fuel tanks may also increase evaporative emissions. The relationship between vapour pressure and ethanol content of a blend can be non-linear so that the mixture may have a higher vapour pressure than either product alone. Any use of ethanol should be subject to the fuel meeting all the volatility properties (distillation, RVP, FVI) for un-oxygenated fuel.

- **Consumer issues**

10% ethanol blends have been shown to perform well without any detrimental effects on vehicle performance. However it should be noted that much of the operating experience supporting this contention comes from the USA where all vehicles have been designed to run on oxygenated fuels since they were first mandated in 1990. Ethanol blends have been successfully used in South Africa for many years since the 1990's with no significant consumer issues.

In the South African market the distribution of oxygenated petrol is currently limited to that of a 2% ethanol containing blend and those containing a type of ether, although higher levels have been used and are allowed. With the drive to incorporate bio-fuels into the fuel pool the need has arisen to understand the fugibility (mixability) of the different "grades" of petrol which will be available in the market to ensure product quality in the market. Fungibility scenarios which need to be evaluated include bio-ethanol blending in the refinery and bio-ethanol blended with refomulated petrol for oxygenate blending (RBOB) at retail or depot sites.

- **Driveability**

Generally, in order to meet regulated vapour pressure limits, petrol blended with ethanol will contain less butane, which is itself volatile and has a high energy content. Like any oxygenated fuel, ethanol-blended petrol, because of its oxygen content, contains less total energy than unblended petrol. The air-fuel mixture coming from the carburettor is "leaner" with ethanol-blended petrol than with petrol alone.

Cold starting depends on vaporisation of the petrol, and more heat is required to vaporise blends containing ethanol. In addition, when ethanol-blended petrol is used, the vapour contains a greater concentration of alcohol than its concentration in the petrol. As a result of these factors, cold starting may be difficult.

The mixture of air and ethanol-blended petrol from the carburettor may be so lean that it causes "lean misfire"; that is, the mixture may be too lean to combust. Lean misfire causes one or more cylinders to pass unburned fuel into the exhaust system. Symptoms include a rough idle and hesitation or stumble on acceleration.

Mixing ethanol-blended petrol with regular petrol in a vehicle's fuel tank may also cause driveability problems. Older cars are more likely to have water in their fuel tanks, and this water may cause the alcohol in the blended fuel to separate from the fuel and mix with the water. If this happens, layering may occur in the fuel tank; the petrol-rich upper layer may no longer have a sufficiently high octane number to operate the engine properly and the alcohol rich aqueous layer may cause rough running or complete stoppage of the vehicle.

- **Effects on Fuel System Materials**

Ethanol in petrol can cause the elastomers in vehicle fuel systems to swell and lose strength, leading to failures of critical components such as fuel pumps and hoses and the risk of fire.

There may also be problems for motorists switching between ethanol-blended petrol and regular petrol, as elastomers that swell with ethanol use would subsequently shrink with petrol, potentially causing fuel system leaks. This effect could be especially pronounced in vehicles that are more than 10 years old. This was, however, not found to be the case when certain regions in South Africa contained high levels of ethanol.

There may be other proprietary components in fuel systems that are also susceptible to damage from exposure to ethanol, particularly in non-automotive engines such as lawnmowers.

- **Manufacture and Distribution of Ethanol-Blended Petrol**

Because of the effect that ethanol has on petrol properties, particularly on vapour pressure, the preparation of blends must be carefully managed. Ideally, blending would take place at a facility that is capable of performing product quality tests and correcting any deficiencies in the fuel. Blending at ports or in tankers would be difficult logistically, as it would require special petrol blendstocks that are then mixed with ethanol to produce a blend that complies with all the regulated properties. The quality of ethanol used for blending is also critical and properties such as water content and acidity need to be specified.

As ethanol can separate out on contact with water, ethanol blends must be transported through a completely water-free system.

9.12 Density [iv]

What is it?

Density is a measure of a fuel's mass per unit volume. Density is a function of fuel composition, which is constrained by volatility parameters and aromatics content. Aromatics typically have densities of 880 kg/m^3, C6+ naphthenes 780 kg/m^3 and paraffins 700 kg/m^3 or lower.

Why is it important?

The requirement to narrow the density range of petrol is driven largely by the desire of the engine manufacturers to improve fuel economy and improve combustion through improved fuel management systems.

Narrowing the limits will allow better control of fuel/air ratio in new engine designs.

Table 16: Current South African and International Density Specifications [xv]

Specification Units	Density kg/l
South Africa	**0.710 -0.785**
EN228:1993 (Euro 2)	0.725 - 0.780
EN228:1999 (Euro3)	0.720 - 0.775
EN228:2004 (Euro4)	0.720 - 0.775
US	-
US : CARB	-
Japan	0.783 max
New Zealand	-
Australia	-
India (Metro)	0.720 - 0.775
India (Nationwide)	0.710 - 0.770
China (Beijing)	0.720 - 0.775
China (Nationwide)	-
Worldwide Fuel Charter	0.715 - 0.770 [1]

[1] Category 2, 3 and 4 only, category 1 allows a maximum of 0.780 kg/l

9.13 Manganese [iv]

What is it?

The use of the organometallic compound methylcyclopentadienyl manganese tricarbonyl (MMT) as an octane booster in petrol is somewhat controversial. It has been used in Canadian and South African petrol for a number of years and is allowable in European unleaded petrol today.

MMT is also used in lead replacement petrol (LRP) to provide protection for soft exhaust valves found on older model vehicles.

Why is it important?

MMT is added in low concentrations (typically 8-18 mg Mn/litre) to boost octane. Engine manufacturers are strongly against the use of metal-based fuel additives from the perspective of potential ash formation, and there is disagreement about its environmental and health impacts. Higher concentrations (>165 mg Mn/litre) can cause problems with fuel instability, deposit build up and can adversely affect catalyst performance, particularly for hydrocarbon oxidation.

Table 17: Current South African and International MMT Specifications [xv]

Grade	Metal Free	Metal Containing
Specification	Manganese	
Units	mg/l (max)	
South Africa	**not allowed**	**36**
EN228:1993 (Euro 2)	-	-
EN228:1999 (Euro3)	-	-
EN228:2004 (Euro4)	-	-
US	-[1]	-
US : CARB	8[1]	
Japan	-	-
New Zealand	2	-
Australia	-	-
India (Metro)	-	-
India (Nationwide)	-	-
China (Beijing)	6	-
China (Nationwide)	18	-
Worldwide Fuel Charter	not allowed [2]	-

[1] No intentinal addition of heavy metals allowed

[2] Metals specified as "non-detectable" and "no intentinal addition"

Why regulate?

The use of Octane boosters such as MMT can reduce the benzene, and aromatic content of the fuel and can have a positive impact by reducing tailpipe benzene emissions. Oil companies hold different views on the results of test work completed to date on potential environmental and health impacts of MMT. Some Oil Companies that have doubts about the impacts of MMT on human health have decided not to add MMT to the petrol that they manufacture.

9.14 Phosphorus [iv]

What is it and why is it important?

Phosphorus can be used as an anti valve seat recession additive (AVSR), in Lead Replacement Petrol (LRP).

Phosphorus can degrade the performance of catalysts in catalytic converters.

Table 18: Current South African and International Phosphorous Specifications [xv]

Grade	Metal Free	Metal Containing
Specification	Phosphorus	
Units	mg/l (max)	
South Africa	**not allowed**	**14**
EN228:1993 (Euro 2)	0	-
EN228:1999 (Euro3)	0	-
EN228:2004 (Euro4)	0	-
US	13	-
US : CARB	13	
Japan	-	-
New Zealand	13	-
Australia	1.3	-
India (Metro)	-	-
India (Nationwide)	1.3	-
China (Beijing)	-	-
China (Nationwide)	1.3	-
Worldwide Fuel Charter	not allowed [1]	-

[1] Specified as "non-detectable"

Why regulate?

To ensure consumer protection as high levels can cause fit-for-purpose issues in operation.

9.15 Potassium [iv]

What is it and why is it important?

Potassium is used as a valve seat recession additive and is thus often used in Lead Replacement Petrol (LRP). While the Worldwide Fuel Charter indicates that metal based additives should not be used, for category 1 fuels the Charter indicates that "Metal-containing additives are accepted for valve seat protection in non-catalyst cars only. In this case, potassium-based additives are recommended".

Table 19: Current South African and International Potassium Specifications [xv]

Grade	Metal Free	Metal Containing
Specification	Potassium	
Units	mg/l (max)	
South Africa	**not allowed**	**10**
EN228:1993 (Euro 2)	-	-
EN228:1999 (Euro3)	-	-
EN228:2004 (Euro4)	-	-
US	not allowed	-
US : CARB	not allowed	
Japan	-	-
New Zealand	-	-
Australia	-	-
India (Metro)	-	-
India (Nationwide)	-	-
China (Beijing)	-	-
China (Nationwide)	-	-
Worldwide Fuel Charter	not allowed [1]	-

[1] Metals specified as "non-detectable" and "no intentinal addition"

Why regulate?

To ensure consumer protection as high levels can cause fit-for-purpose issues in operation.

PROPERTIES CURRENTLY NOT SPECIFIED

The following properties for petrol are not currently included in the South African specifications but have appeared in specifications elsewhere or are under discussion. Their significance is discussed here.

9.16 Olefins [iv]

What are they?

Alkenes and cycloalkenes are referred to as olefins in the oil industry. They have double bonds (i.e. are unsaturated) and are not normally present in crude oil, but are created during cracking and other refinery processing.

The olefin content of petrol will depend on source refinery configurations and feedstocks. From conventional crude based refineries, catalytically cracked petrols tend to be higher in olefins. Synthetic fuel manufactured in the Sasol process in South Africa is relatively high in olefins because of the nature of the process.

Why are they important?

Olefins are often good octane components. However they tend to be thermally unstable and this can lead to gum formation or deposits in engine intake systems. Very high levels of olefins could create problems similar to toluene. Fuel stability and engine deposits are however effectively controlled by suitable additives.

Olefins are also formed during combustion of fuel. Their evaporation into the atmosphere has been established as contributing to ozone formation and their combustion products form toxic dienes such as 1,3-butadiene. Environmental concerns are the main basis for limiting their content in petrol, although some recent studies indicated that olefins may not be the only contributor to these emissions. Furthermore, the olefin types differ depending on the manufacturing process and these have different impacts on ambient air quality.

Table 20: Current South African and International Olefin Specifications [xv]

Specification Units	Olefins % vol (max)
South Africa	-
EN228:1993 (Euro 2)	-
EN228:1999 (Euro3)	21 / 18 [1]
EN228:2004 (Euro4)	18
US	- [2]
US : CARB	10 [2]
Japan	-
New Zealand	18
Australia	18
India (Metro)	21 / 18 [1]
India (Nationwide)	-
China (Beijing)	25
China (Nationwide)	35
Worldwide Fuel Charter	-/18/10/10 [3]

[1] Regular / Premium

[2] Use of predictive model used to control overall toxic emissions.

[3] Category 1/2/3/4

Why regulate?

The main motivation for limiting olefin content of petrol is environmental with regard to concerns about human exposure to certain toxics such as dienes and concerns with regard to their contribution of ground level ozone.

9.17 Summary

The main specification parameters that should be considered from an emissions perspective are considered to be:

- Sulphur, as it enables advances engine and exhaust after-treatment technology to function to clean up the exhaust emissions
- Benzene from an evaporative emissions perspective

Most of the other specification parameters are considered to be fit for purpose specifications and should be considered along with the local conditions and vehicle parc.

10 Properties of diesel

This section examines the main properties that determine quality for diesel. It follows the same format as the previous section for petrol.

As is the case with petrol, there is a high degree of interdependence between certain properties and again, within a particular refinery, diesel specifications have flow-on effects for the production of other products.

Appendix B contains a description of how compression-ignition engines work and the diesel characteristics that are relevant to diesel engine performance.

PROPERTIES CURRENTLY SPECIFIED

10.1 Density [iv]

What is it?

Density is a measure of a fuel's mass per unit volume. It is temperature dependent and for diesel fuel is normally referenced to 20°C in temperate climates and 15°C in cooler climates such as in Europe. Diesel is made up of a mixture of many different hydrocarbon compounds of various densities and molecular weights, and thus the overall density is a function of the composition of the fuel and the feedstock, being crude, coal, gas or biomass. For this reason, density is strongly correlated with other fuel parameters, particularly cetane number, aromatics content, viscosity and the distillation characteristics (boiling range or volatility). Reducing the high end distillation temperatures (T90, refer Section 8.11) will reduce the maximum density by excluding the heaviest components.

Why is it important?

In diesel engines, fuel is injected directly into the combustion chamber using a volume based metering system (in most cases). The energy content of fuel is approximately proportional to the mass of fuel injected. Thus, for a constant volume injection system, variations in fuel density can result in variations in the energy content of the fuel injected. Consequently, engine power, emissions and fuel consumption may be affected. In order to optimise the engine performance and exhaust emissions, fuel density must be controlled within a fairly narrow range.

Black smoke emissions from diesel engines occur primarily at full load operation. They normally arise when the mixture is over-rich or there is incomplete mixing of fuel and air. Limits on smoke emissions therefore limit the maximum power output of engines. Although there is some relationship between visible smoke and particulates, this relationship is not well understood as the optical and size characteristics and number density of particles vary greatly.

If the fuel being used is denser than the fuel for which the engine is calibrated, this may lead to generation of smoke through over-fuelling. Conversely, lower density fuel should reduce the level of smoke, but will reduce power as well, if the fuel injection system is not set up for that lower density. For a constant maximum power output (constant mass of fuel injected) volumetric fuel consumption will increase with lowering density and decrease with increasing density.

The volumetric quantity of fuel injected can also be used as a parameter in some advanced emission control systems such as exhaust gas re-circulation (EGR) so variations in fuel density may affect their efficiency.

Currently, South African specifications only limit the minimum density and the low value reflects the local manufacture of synthetic fuel which typically results in fuel, and especially diesel, of lower density than a conventional crude refinery. As there is currently no maximum specification, over fuelling may occur as it is not possible for the automotive marketers to configure the engine operating systems.

Table 21: Current South African and International Density Specifications [xv]

Specification	Density
Units	kg/l
South Africa	**0.800 min**
EN590:1993 (Euro 2)	0.820 - 0.860 [1]
EN590:1999 (Euro 3)	0.820 - 0.845 [1]
EN590:2004 (Euro 4)	0.820 - 0.845 [1]
US	-
US: CARB	-
Japan	-
New Zealand	0.820 - 0.850
Australia	0.820 - 0.850
India (Metro)	0.820 - 0.845 [2]
India (Nationwide)	0.820 - 0.860 [2]
China (Beijing)	0.820 - 0.845 / 0.800 - 0.840 [3]
China (Nationwide)	report
Worldwide Fuel Charter - Cat 1	0.820[4] - 0.860
Worldwide Fuel Charter - Cat 2	0.820[4] - 0.850
Worldwide Fuel Charter - Cat 3	0.820[4] - 0.840
Worldwide Fuel Charter - Cat 4	0.820[4] - 0.840

[1] Temperate specifications provided, different specifications for arctic conditions
[2] Alternate specifications for diesel processed from Assam crude
[3] Grades: 5# & 0# & -10# / -20# & -35#
[4] Alternate minimum specification provided for colder climatic conditions

Why regulate?

Reductions in the upper limit have generally been made for the purposes of limiting heavier aromatic components, thereby reducing emissions, principally particulates. However, this effect is also achieved to some extent by control of the high end of the distillation curve (see Distillation, Section 11.11).

A narrower density range leads to reduced emissions by virtue of better control of air/fuel ratio and this is reflected in the trend in international specifications.

10.2 Total Contaminants, Water Content, Appearance and Colour [iv]

What are they?

Water and sediment in diesel fuel usually result from poor fuel handling and storage. The general appearance, colour and clarity are useful indicators of contamination. However, the small amount of water required to give diesel a hazy appearance is usually insufficient to affect its performance. The solids or total contamination (dirt) can cause premature fuel system failure as a result of scoring of the injector and pump elements and hence is of concern from a fit for purpose perspective.

Why are they important?

Contamination with water and sediment can result in corrosion, blocking of filters, injection system wear and deposits in engines. This is due to the ever increasing injection pressures and reducing tolerances. The total contamination specification was therefore introduced and measures the mass of particles exceeding 0.8 microns.

Current South African and International Specifications

Many specifications historically controlled colour and appearance in order to control water and contamination, however the trend has been to move to explicit measures of these parameters rather than to rely on colour and appearance alone.

Table 22: Current South African and International Water & Total Contamination Specifications [xv]

Specification	Water Content	Total Contamination	Particulate Contamination
Units	% vol (max)	mg/kg (max)	mg/kg (max)
South Africa	**0.05**	**24**	**-**
EN590:1993 (Euro 2)	0.02	24	-
EN590:1999 (Euro 3)	0.02	24	-
EN590:2004 (Euro 4)	0.02	24	-
US	(0.05) [1]	-	-
US: CARB	(0.05) [1]	-	
Japan	-	-	-
New Zealand	200 ppm [2]	24	-
Australia	(0.05) [3]	-	-
India (Metro)	(0.02) [4]	24	-
India (Nationwide)	0.05 [5]	-	-
China (Beijing)	trace [6]	-	-
China (Nationwide)	trace [6]	-	-
Worldwide Fuel Charter	500/200/200/200 [7]	-	10 [8]

[1] Water and sediment. Grades No 1-D & No 2-D

[2] Different test method prescribed

[3] Water and sediment

[4] wt %

[5] Aslo specified 0.05 wt% max sediment and 1.5 mg/100 ml max total sediments

[6] Sediment specified as "none"

[7] Units of mg/kg; Category 1/2/3/4

[8] Size distribution breakdown also given

Why regulate?

It is important to regulate this parameter from a fit for purpose perspective, especially with the newer low emissions technologies being introduced. This is to ensure that the fuel injection equipment functions within the design limits and hence remains within the emission specifications.

10.3 Cetane Number and Cetane Index [iv]

What are they?

- **Cetane Number**

  The Cetane Number (CN) of a fuel is a measure of its propensity for auto ignition. In practical terms the CN has a strong influence on the length of time from the start of fuel injection to the start of combustion in a diesel engine. The higher the CN, the shorter this ignition delay period. The CN affects the ease of starting, the combustion generated noise and the exhaust emissions of diesel engines.

  Cetane (n-hexadecane), which ignites very easily, has a CN of 100, and heptamethyl nonane has a CN of 15. The CN of a fuel is the proportion of cetane in a mix of the two that has equivalent ignition characteristics when tested in a specified test engine. The test method is standardised in ASTM D 613. The test itself has poor reliability and repeatability.

  The crude derived diesel CN is typically related to the aromatic content of the fuel and in turn to the fuel density. As the aromatic content decreases, and therefore the density, the CN will generally increase.

- **Cetane Index**

  Cetane Index (CI) is an estimation, based on crude derived data, of the Cetane Number calculated from distillation data and density. The current specification requires this to be calculated using the method outlined in ASTM D 976, as follows:

  $$CI = 454.74 - (1641.416 \times \rho) + (774.74 \times \rho^2) - 0.554 \times T50 + 97.803 \times (\log T50)^2$$

  ρ is the density in g/litre at 15°C

  T50 is the mid-boiling point temperature in °C (the temperature at which 50% of the sample (by volume) has evaporated).

The relationship between CI and CN varies depending on the refining techniques and consequent composition of the fuel. Generally, the difference between the two measures will be in the range ±2.

Cetane improving additives can be used to increase the CN by aiding the self-ignition of the fuel. They do not change the parameters on which the CI is based, which means that cetane improvers do not change the calculated CI.

Cetane index does apply to synthetic based fuels.

Table 23: Current South African and International Cetane Specifications[xv]

Specification (min)	Cetane Number	Cetane Index
South Africa	**45**	**(48)** [1]
EN590:1993 (Euro 2)	49	46
EN590:1999 (Euro 3)	51	46
EN590:2004 (Euro 4)	51	46
US	40 [2]	40
US: CARB	40 [3]	-
Japan	50/45 [4]	50/45
New Zealand	51 [5]	47 [5]
Australia	-	46
India (Metro)	51 [6]	46 [6]
India (Nationwide)	48 [6]	46 [6]
China (Beijing)	51 / 49 / 47 [7]	46
China (Nationwide)	45	-
Worldwide Fuel Charter - Cat 1	48	48(45) [8]
Worldwide Fuel Charter - Cat 2	51	51(48) [8]
Worldwide Fuel Charter - Cat 3	53	53(50) [8]
Worldwide Fuel Charter - Cat 4	55	55(52) [8]

[1] If suitable correlation is proven for the specific crude being refined, then a CI of 48 is allowed; the basic need is to ensure minimum CN of 45

[2] No 1-D and No 2 -D, both 15 and 500 ppm sulphur grades only

[3] CARB requires emissiosn certification of fuel against 48 CN reference fuel, thus most fuels will have CN close to 48.

[4] Class 1 / 2 & 3. Compliance with either CN or CI is allowed.

[5] Either 51 min cetane index or 51 min cetane number and 47 min cetane index is required.

[6] Compliance with either CN or CI is allowed. Alternative specifications provided for diesel processed from Assam crude.

[7] Grades: 5# & 0# & -10# / -20# / -35#

[8] Cetane Index is acceptable instead of Cetane Number if a standardized engine to determine the Cetane Number is unavailable and cetane improvers are not used. When cetane improvers are used, the estimated Cetane Number must be greater than or equal to the specified value and the Cetane Index must be greater than or equal to the number in parentheses.

Why are they important?

A higher CN reduces ignition delay and results in smoother combustion and lower combustion noise. It also improves the cold starting of diesel engines. An increase in CN produces a decrease in NO_x emissions as a result of lower gas temperatures and pressures in the combustion chamber. Reductions in CO and hydrocarbon emissions have also been reported. These benefits are less marked in new engine designs. However benefits are not generally achieved above a CN of about 50.

If anything, fuel consumption will tend to increase slightly with an increase in CN. Lower CN fuels will contain higher aromatics and heavier hydrocarbons and have a higher density, giving a lower volume of fuel for the same amount of energy.

Although there are uncertainties in the correlation between CN and CI, an increase in CN will cause an increase in CI.

Why regulate?

Cetane number directly reflects performance of diesel fuel in an engine and the main reason for regulation is to ensure that the consumer receives fuel of a known and consistent quality. The measurement of cetane number is a relatively complicated test procedure and the use of cetane index as a proxy has become popular as reflected by the inclusion of this measure in specifications internationally.

10.4 Cold Flow Properties [iv]

What are they?

Diesel fuel can have a high content of long chain paraffins which will start to form wax crystals as the fuel is cooled. This can lead to blockages of fuel filters and interruption to fuel supply under cold conditions. Cold flow performance is a key requirement for diesel fuels.

- **Cloud Point**

  Cloud Point is the temperature at which wax crystals start to precipitate out and the fuel becomes cloudy. If a fuel system is operated at temperatures below the cloud point the wax crystals will be removed by the filter and will ultimately cause the filter to block. Cloud point is determined according to the test method specified in ASTM D 2500.

- **Cold Filter Plugging Point**

  Cold Filter Plugging Point (CFPP) is the lowest temperature at which the fuel can pass through a standard test filter under standard conditions. CFPP is more precise and is a good indication of fuel performance in an engine. The test method is specified in IP 309.

  Cold flow properties depend on the proportion of waxy components in the diesel (controlled by the selection of crude oils and the refining and blending processes). Cold flow improving additives lower the cold filter plugging point by changing the size and shape of the wax crystals that form at cold temperatures. However, these additives generally do not change the cloud point.

- **Pour Point**

  The Pour Point is the lowest temperature at which the fuel will flow or pour and is an indication of the lowest temperature at which the fuel will remain pump-able.

Why are they important?

Inadequate cold flow performance will result in high viscosity at low temperatures, leading to difficulties with engine starting and blockage of fuel filters.

Current South African and International Specifications

As cold flow properties are related to climatic conditions, a direct comparison with specifications in other countries is not particularly useful. Most international specifications include a range of grades corresponding to different ambient temperature ranges and or geographical regions.

Table 24: Current South African and International Cold Flow Specifications [xv]

Specification	Cold Filter Plugging Point		Cloud Point		Pour Point	
Units	˚C (max)		˚C (max)		˚C (max)	
Season	Summer	Winter	Summer	Winter	Summer	Winter
South Africa	**3**	**-4**	**-**	**-**	**-**	**-**
EN590:1993 (Euro 2)	+5 / -44 [1]		-20 / -34 [2]		-	
EN590:1999 (Euro 3)	+5 / -44 [1]		-10 / -34 [2]		-	
EN590:2004 (Euro 4)	+5 / -44 [1]		-10 / -34 [2]		-	
US	-	-	-	-	-	-
US: CARB	-	-	-	-	-	-
Japan	-1/-5/-12/-19 [3]		-		5/-2.5/-7.5/-20/-30 [4]	
New Zealand	- [5]	-6 [5]	4	2	-	-
Australia	-	-	-	-	-	-
India (Metro)	18	6	-	-	15	3
India (Nationwide)	18	6	-	-	15	3
China (Beijing)	8/4/-5/-14/-29 [6]		-	-	5/0/-10/-20/-35 [6]	
China (Nationwide)	12/8/4/-5/-14/-29/-44 [7]		-	-	10/5/0/-10/-20/-35/50 [7]	
Worldwide Fuel Charter	Maximum must be equal to or lower than the lowest expected ambient temperature [8]					

[1] Depends on climatic conditions.
[2] Only applicable to countries with arctic or severe winter conditions
[3] Class 1/2/3/Special 3
[4] Class Special 1/1/2/3/Special 3
[5] Filter Blocking Tendency (different test method) is also specified at 2.5◦ C with the requirement of "Fuel must be of acceptable filterability so that it is fit for common purposes"
[6] Grades: 5# / 0# / -10# / -20# / -35#
[7] Grades:10# / 5# / 0# / -10# / -20# / -35# / -50#
[8] If compliance is demonstrated by meeting CFPP, then it must be no more than 10 ◦C less than cloud point

Why regulate?

Cold flow properties directly influence cold temperature vehicle operability and therefore these specifications provide a measure of consumer protection to ensure the fuel will provide trouble free operation in the specific climate conditions expected in the region.

10.5 Viscosity [iv]

What is it?

Viscosity is a measure of a fuel's resistance to flow. It affects the performance of diesel fuel pumps and injection systems. Viscosity is dependent on fuel composition and is reflected in the distillation parameters, density and cold flow properties.

The current test method, ASTM D 445, measures the kinematic viscosity at 40°C in centistokes (cSt – equivalent to mm^2/s).

Why is it important?

High viscosity can reduce fuel flow rates, resulting in insufficient fuel flow. A very high viscosity may cause fuel pump distortion.

Low viscosity will increase leakage from the pumping elements within the injection pumps of older technology vehicles, and this can also result in insufficient fuel delivery and hot starting difficulties. Wear may also increase with low viscosity as lubricity tends to decrease with viscosity, although fuel lubricity is controlled by a supplementary specification. As the viscosity of a fluid is temperature dependent, it is necessary to minimise the allowable range in order to optimise engine performance.

The viscosity range needs to be maintained within a reasonable band to ensure that the spray pattern generated by the fuel injectors is well controlled.

Table 25: Current South African and International Viscosity Specifications [xv]

Specification	Viscosity @ 40 ˚C
Units	mm^2/s
South Africa	**2.2 - 5.3**
EN590:1993 (Euro 2)	2.0 - 4.5 [1]
EN590:1999 (Euro 3)	2.0 - 4.5 [1]
EN590:2004 (Euro 4)	2.0 - 4.5 [1]
US	1.3 - 2.4 / 1.9 - 4.1 [2]
US: CARB	2.0 - 4.1
Japan	2.7/2.5/2/1.7 [3] (min)
New Zealand	2.0 - 4.5
Australia	2.0 - 4.5
India (Metro)	2.0 - 4.5
India (Nationwide)	2.0 - 5.0
China (Beijing)	3.0 - 8.0 / 2.5 - 8.0 / 1.8 - 7.0 [4]
China (Nationwide)	3.0 - 8.0 / 2.5 - 8.0 / 1.8 - 7.0 [5]
Worldwide Fuel Charter	2.0 - 4.0 [6]

[1] Different specifications provided for arctic conditions

[2] Grades No 1-D / No 2-D

[3] Class 1/2/3/Special 3

[4] Grades:5# & 0# / -10# & -20# / -35#

[5] Grades:10# & 5# & 0# & -10# / -20# / -35# & -50#

[6] Category 1 allows maximum of 4.5. Lower minimum values specified for lower ambient temperatures

Why regulate?

This is purely a fit for purpose specification to ensure that the fuel system operates efficiently and effectively, while main-taining the correct spray pattern in the combustion chamber. This is also dependent on the specific vehicle parc technology that is in use in the specific region.

10.6 Flash Point [iv]

What is it and why is it important?

The flash point is the lowest temperature at which the vapour above a liquid will ignite when exposed to a flame (or other ignition source with sufficient energy). It is a measure of both volatility and flammability. Flash point is important primarily from the standpoint of safe handling and storage of fuel. It is used to classify flammable liquids and therefore affects the design of equipment and the control of potential ignition sources.

Flash point is a reflection of the volatility of the diesel and is therefore set by distillation parameters. It does not affect engine performance directly.

Table 26: Current South African and International Flash Point Specifications [xv]

Specification Units	Flash Point ° C (min)
South Africa	**55**
EN590:1993 (Euro 2)	55
EN590:1999 (Euro 3)	55
EN590:2004 (Euro 4)	55
US	38 / 52 [1]
US: CARB	52
Japan	50/45 [2]
New Zealand	61
Australia	61.5
India (Metro)	35
India (Nationwide)	35
China (Beijing)	55
China (Nationwide)	55 / 45 [3]
Worldwide Fuel Charter	55

[1] Grades No 1-D / No 2-D

[2] Classes 1 & 2 / Class 3

[3] Grades:10# & 5# & 0# & -10# & -20# / -35# & -50#

Why regulate?

As flash point is such an important parameter for safe storage and handling, and given that diesel is so widely used, the requirement for diesel to meet the flash point specification should be of the 'blanket' variety, applying to all diesel fuels supplied, as is currently the situation in South Africa.

10.7 Sulphur [iv]

Sulphur occurs naturally in crude oils, coal and natural gas. The sulphur must be removed to an acceptable level during the refining process. Sulphur in diesel fuel contributes to formation of particulate matter (PM) in engine exhaust. Sulphur is directly linked to the formation of Primary Particulates (those that are formed in the combustion chamber and in the exhaust system) and contribute significantly to the formation of Secondary Particulates (those formed in the atmosphere once the exhaust has mixed with the ambient air). Sulphur also affects the performance of vehicle emissions control equipment and therefore has an indirect effect on emissions of CO, hydrocarbons and NO_X. Reductions down to 500 ppm (m/m) have a direct effect on the PM emissions; thereafter, however, the effect is smaller with further reductions typically being driven by vehicle technology.

The international norm is for diesel fuel containing 500 ppm (m/m) to be referred to as Low Sulphur Diesel (LSD) while fuel containing 50 ppm (m/m) sulphur or lower to be referred to as Ultra Low Sulphur Diesel (ULSD). "Sulphur-free" diesel generally refers to levels below 10 ppm (m/m).

Lower sulphur levels in diesel can be achieved by using a combination of lower sulphur feedstocks and sulphur removal. Hydrodesulphurisation of diesel uses hydrogen to release the sulphur from the feed and form H_2S which is removed and treated to recover the sulphur. A similar process occurs in hydrocracking.

Why is it important?

Sulphur in diesel contributes to the formation of particulate matter (PM) in engine exhaust as well as the formation of secondary particulates. The impact of sulphur on particulate emissions is complex, but generally well understood. Sulphur has no direct effect on the other regulated emission species. A small proportion of the sulphur in the fuel is oxidised to sulphates that contribute to the particulate matter emitted from diesel exhaust. The sulphates absorb water that adds to the mass of particulate matter and also increases the retention of organic compounds in the particulate matter.

As PM emissions are linked to health problems, in particular respiratory conditions, their reduction is a primary driver to reduce high (>500 ppm (m/m)) sulphur levels in diesel fuel. Studies show that reductions of sulphur content from 3000 ppm (m/m) to 500 ppm (m/m) would reduce PM emissions by 10 – 15% directly. Further reductions in sulphur would produce minimal incremental direct benefit. As PM is made up of a variety of compounds other than sulphur, reducing sulphur to zero would not reduce PM to zero.

However, sulphur also affects the performance of existing diesel engine exhaust after-treatment oxidation catalysts, and inhibits state-of-the-art diesel exhaust gas treatment technology such as NO_x adorbers and particulate filters. Oxidation catalysts used to reduce CO and hydrocarbons, and the catalyst used in particulate trap technology, are very efficient at converting SO_2 into sulphates.

Table 27: Current South African and International Sulphur Specifications [xv]

Grade	Standard	Low Sulphur
Specification	Sulphur	
Units	ppm (max)	
South Africa	**500**	**50**
EN590:1993 (Euro 2)	2000	n/a
EN590:1999 (Euro 3)	350	n/a
EN590:2004 (Euro 4)	50	10 [1]
US	15 / 500 / 5000 [2]	n/a
US: CARB	15	n/a
Japan	10	n/a
New Zealand	50	n/a
Australia	50	n/a
India (Metro)	350	n/a
India (Nationwide)	500	n/a
China (Beijing)	50	n/a
China (Nationwide)	2000	n/a
Worldwide Fuel Charter	2000/300/50/10 [3]	n/a

[1] This grade known as "Sulphur Free"; grade needs to be available on a balanced geographical basis

[2] Both No 1-D and No 2-D grades specify these different sulphur grades

[3] Category 1/2/3/4

In the US, differentiation is made between fuel used in vehicles (light duty and heavy duty) and fuel used in non-road applications including rail and marine. Sulphur was previously not regulated in non-road diesel and hence high sulphur diesel could be used, but since mid 2007 this fuel has been limited to 500 ppm (m/m) sulphur and this limit will be reduced to 15 ppm (m/m) in 2010. Light duty and heavy duty (on-road) diesel sold as Low Sulphur must comply with the 15 ppm (m/m) level while refiners may continue to manufacture up to 20% of their diesel at up to 500 ppm (m/m) sulphur until the end of 2009.

Ultra low sulphur diesel (<15 ppm (m/m)) fuel was introduced in the US as a "technology enabler" to pave the way for advanced, sulphur-intolerant exhaust emission control technologies, such as catalytic diesel particulate filters (DPF) and NO_x catalysts, which are necessary to meet the 2007 emission standards.

In the United Kingdom and some other European Commission (EC) countries, government incentives for cleaner fuels have led to ULSD becoming available well ahead of the Euro 4 timetable. 10 ppm (m/m) diesel (City Diesel) was available in Sweden many years ahead of the European specifications.

In some regions of the world, consideration has been given to the use of a combustion improver (fuel borne catalyst / additive) to provide a reduction in PM formation equivalent to that achieved through sulphur reduction. This is an alternative to direct sulphur reduction, and has been proposed as an interim measure to meet the Australian timetable for fuel quality changes. Such combustion improvers could potentially provide much of the environmental benefits associated with sulphur reduction in the existing fleet, but would not provide the enabling fuel requirements of state-of-the-art diesel vehicle technologies.

Why regulate?

- **Health and Environment**

  From a health perspective, particles smaller than 10 microns diameter (PM10) are of greatest concern as they can enter the lungs. Increased attention is also being focussed on particulates smaller than 2.5 microns (PM2.5). While diesel engine emissions are not the only source of particulates in our urban air, the Brown Haze 1 and 2 studies undertook a source apportionment of the "brown haze" which occurs regularly in the Cape Town area, and the main conclusion was that vehicle transport was the major contributor, and that particulates from diesel vehicles are a significant source.

  Regulators in Europe and other regions have specified, or are in the process of specifying, sulphur free diesel (less than 10 ppm (m/m) sulphur) as an enabling fuel to support the adoption of low emissions technology (Euro 4 and 5 levels). The approach taken has been to have two grades available, typically ULSD (less than 50 ppm (m/m)) and sulphur free (less than 10 ppm (m/m)), with requirements that the sulphur free version is widely available and thus able to serve as a technology enabling fuel. This dual grade structure significantly reduces the burden on the refining industry while supporting the environmental objectives sought.

- **Consumer protection**

  Removal of sulphur from diesel reduces its natural lubricity which can cause increased wear in fuel pumps and other engine components. This problem was first identified when ULSD was first introduced in South Africa and later in Sweden, but minimum lubricity levels can be achieved through the use of suitable additives. Lubricity tests are now commonly being included in many diesel specifications and are currently enforced in South Africa.

LSD may also have a lower electrical conductivity – insufficient conductivity can lead to a build-up of static charge during transfer (filling bulk storage tanks, road tankers and vehicle fuel tanks). This can be corrected through the use of additives and is primarily an operating requirement for industry.

Sulphur reduction may also assist in allowing an increase in engine oil change cycles by reducing the sulphuric acid and soot loading in oil. However, engine design is also a significant factor in lengthening oil change intervals by giving cleaner combustion and lower soot loading of oil.

Hydrodesulphurisation can increase paraffinic content of diesel by saturating olefinic compounds, which tends to increase the CN a little, thereby providing an additional benefit.

10.8 Copper Strip Corrosion [iv]

What is it?

As with petrol, this test is a measure of the corrosivity of the fuel to metals. Corrosion can affect metallic components in vehicle fuel systems, dispenser pumps and fuel storage systems. The same test procedure as for petrol, ASTM D 130, is used.

Current South African and International Specifications

The South African specification calls for the test to be performed for 3 hours at 100°C. A common test limit for petrol and diesel has been adopted in the European specifications using a lower temperature test (50°C) for 3 hours. The Worldwide Fuel Charter does not specify a temperature. All of the specifications call for a maximum of a "1" merit (no corrosion).

Why regulate?

As with petrol, some measure of corrosivity needs to be retained to provide protection for fuel tanks, dispenser pumps and vehicle engine components.

10.9 Ash [iv]

What is it and why is it important?

Ash refers to the small amounts of non-combustible ash-forming compounds such as suspended solids and soluble organometallic compounds which occur in crude oil and petroleum products.

Depending on size, these compounds can contribute to fuel system wear and filter and injector nozzle plugging. The metals can cause corrosion of certain high temperature alloys such as those found on diesel engine valves, and lead to increased deposit levels.

Table 28: Current South African and International Ash Specifications [xv]

Specification	Ash
Units	% wt (max)
South Africa	**0.01**
EN590:1993 (Euro 2)	0.01
EN590:1999 (Euro 3)	0.01
EN590:2004 (Euro 4)	0.01
US	0.01
US: CARB	0.01
Japan	-
New Zealand	0.01
Australia	(100) [1]
India (Metro)	0.01
India (Nationwide)	0.01
China (Beijing)	0.01
China (Nationwide)	0.01
Worldwide Fuel Charter	0.01 [2]

[1] Ash and suspended matters, ppm (max)

[2] All categories except 4 which stipulates 0.001; Category 4 limit and test method for DPF endurance under review.

Why regulate?

Some level of consumer protection needs to be retained with regard to any characteristic of fuel which may affect engine performance and condition in the long term rather than one that is immediately traceable to a fuel quality problem or particular fuel source.

10.10 Carbon Residue [iv]

What is it?

This property is a measure of the tendency of diesel to form carbonaceous deposits in engines, which can result in hot spots leading to stress, corrosion or cracking of components. The deposits which are of most concern are those which build up in the nozzles of fuel injectors. The amount of carbon in fuel can be correlated with a tendency to form deposits, hence the use of a Carbon Residue test. The test is performed on the residual volume after 90% of the fuel has been boiled off (10% residual).

Methods in common use include:

- Ramsbottom IP 14/94 (ASTM D 524-94) (currently specified in the Regulations)
- Conradson IP 13/94 (ASTM D 159-95)
- Micro method MCRT IP 389 (ASTM D 4530) – equivalent to the Conradson method.

Detergents and deposit control additives are used to prevent deposit formation in fuel system components.

Table 29: Current South African and International Carbon Residue Specifications [xv]

Specification Units	Carbon Residue % wt (max)
South Africa	**0.2** [1]
EN590:1993 (Euro 2)	0.3 [2]
EN590:1999 (Euro 3)	0.3 [2]
EN590:2004 (Euro 4)	0.3 [2]
US	0.15 / 0.35 [3]
US: CARB	-
Japan	0.1
New Zealand	0.2 [4]
Australia	0.2 [4]
India (Metro)	0.3
India (Nationwide)	0.3
China (Beijing)	0.3
China (Nationwide)	0.3
Worldwide Fuel Charter	0.3/0.3/0.2/0.2 [5]

[1] Test Method ASTM D524

[2] Test Method ASTM D4530

[3] Grades No 1-D / No 2-D

[4] Test Method EN ISO 10370:1995

[5] Category 1/2/3/4; Test Method ASTM D4530

Why regulate?

Some level of consumer protection needs to be retained with regard to properties of diesel which may detrimentally affect engine performance and condition over time rather than immediately.

If particular types of cetane improvers are used, these can give an abnormally high result. In this case the presence of a cetane improving additive needs to be confirmed as the cause, using a test such as ASTM D 4046.

10.11 Distillation [iv]

What is it?

The distillation curve (temperature vs. percentage volume recovered) characterises the volatility of the fuel. T90 is the temperature at which 90% of the fuel sample has boiled off. For diesel, the most important distillation characteristics are the temperatures at the top end of the range (T85, T90, T95 etc.) as these provide a measure of the proportion of heavier components, and correlate closely with levels of aromatics, in particular. As the density is dependent on the composition of the fuel, the distillation characteristics affect the density as well as the viscosity and Cetane Index. The distillation curve is therefore an important factor in the control of fuel quality.

This property is controlled by adjusting the cut point between diesel and heavier fuel oils. The distillation is carried out in accordance with test method ASTM D 86.

Why is it important?

The heavier components in diesel have more potential for incomplete vaporisation and combustion, resulting in increased smoke or soot. Specifying lower high end temperatures reduces the proportion of these heavy components, giving cleaner burning. It may also reduce the density and the viscosity of the fuel as these properties are closely linked. However, some studies suggest that where the effects of volatility can be decoupled from the other fuel parameters, the impact on emissions of changing the high end of the distillation curve may not be that significant.

Current South African and International Specifications

Different jurisdictions specify different distillation parameters, so direct comparisons are not always easily made, as shown below.

Table 30: Current South African and International Distillation Specifications[xv]

Specification	T50	T90	T95	FBP	E250	E350	E370
Units	°C (max)				% vol (max)	% vol (min)	% vol (min)
South Africa	-	**362**	-	-	-	-	-
EN590:1993 (Euro 2)	-	-	360	-	65	85	95
EN590:1999 (Euro 3)	-	-	360	-	65	85	-
EN590:2004 (Euro 4)	-	-	360	-	65	85	-
US	-	288 / 282 min - 338 max	-	-	-	-	-
US: CARB [1]	243 min - 293 max	282 min - 321 max	-	349	-	-	-
Japan	-	360/350/330 [2]	-	-	-	-	-
New Zealand	-	-	360	-	-	-	-
Australia	-	-	360	-	-	-	-
India (Metro)	-	-	-	-	-	-	(95)[3]
India (Nationwide)	-	-	370	-	-	85	-
China (Beijing)	300	355	365	-	-	-	-
China (Nationwide)	300	355	365	-	-	-	-
Worldwide Fuel Charter - Cat 1	-	-	370	-	-	-	-
Worldwide Fuel Charter - Cat 2	-	340[4]	355[4]	365	-	-	-
Worldwide Fuel Charter - Cat 3	-	320[4]	340[4]	350	-	-	-
Worldwide Fuel Charter - Cat 4	-	320[4]	340[4]	350	-	-	-

[1] Also specifies T10 min of 204 and max of 254

[2] Classes 1/2/3

[3] E360

[4] Compliance with either T90 or T95 is required.

Why regulate?

Reductions in high end distillation are aimed primarily at achieving environmental benefits, but this can also be dependent on the feedstock of the diesel.

As more of the heavier components are removed this reduces the yield of diesel from a given feedstock and increases the production of fuel oil. There is a cost impact associated with any change that reduces yield and creates more heavy material.

10.12 Oxidation Stability [iv]

What is it and why is it important?

As with petrol, the oxidation stability is a measure of the fuel's resistance to degradation by oxidation. Oxidation of diesel fuel can result in the formation of gums and sediments, causing plugging of filters and engine deposits. It may also lead to a darkening in colour of the fuel although this is not a problem in itself.

In the oxidation stability test, oxygen is bubbled through the fuel at an elevated temperature for a fixed time, then it is cooled and the insolubles filtered off and weighed.

For diesel fuels with low levels of natural anti-oxidants, a satisfactory level of stability can be achieved with the use of anti-oxidant additives.

Table 31: Current South African and International Oxidation Stability Specifications [xv]

Specification Units	Oxidation Stability mg/100ml (max)
South Africa	**2.0**
EN590:1993 (Euro 2)	2.5
EN590:1999 (Euro 3)	2.5
EN590:2004 (Euro 4)	2.5
US	-
US: CARB	-
Japan	-
New Zealand	2.5
Australia	2.5
India (Metro)	2.5
India (Nationwide)	-
China (Beijing)	2.5
China (Nationwide)	2.5
Worldwide Fuel Charter	2.5 [1]

[1] Supplimentary induction period test method also under consideration

Why regulate?

Severe hydrotreating of crudes to produce low sulphur diesels can remove some of the natural anti-oxidants in diesel which create the potential for instability problems when such fuel is stored for long periods. Therefore with the wider introduction of lower sulphur diesels in the future, oxidation stability should continue to be regulated for consumer protection.

10.13 Lubricity [iv]

What is it and why is it important?

As noted in Section 10.7, removal of sulphur from diesel can reduce its natural lubricity, causing increased wear in fuel pumps and other engine components. This problem was first identified when ULSD was first introduced in Sweden, but adequate lubricity levels can be achieved through the use of suitable additives. Lubricity tests are therefore commonly included in diesel specifications.

Lubricity is not easily measured in a laboratory. The High Frequency Reciprocating Rig (HFRR) test uses a laboratory rig to measure the effective wear that can be expected on fuel pump parts. This is measured as a wear scar diameter in microns (mm). The specification is a maximum wear scar diameter of 460 μm (microns) at 60°C, measured in accordance with test procedure IP450. This test method has been correlated with field data over a number of years and with differing fuel system technologies.

Table 32: Current South African and International Lubricity Specifications [xv]

Specification Units	HFRR wear scar diameter μm (max)
South Africa	**460**
EN590:1993 (Euro 2)	-
EN590:1999 (Euro 3)	460
EN590:2004 (Euro 4)	460
US	520
US: CARB	520
Japan	-
New Zealand	460
Australia	460
India (Metro)	460
India (Nationwide)	460
China (Beijing)	460
China (Nationwide)	-
Worldwide Fuel Charter	400

Why regulate?

Severe hydrotreating of crudes to produce low sulphur diesels can remove some of the natural lubricity of diesel which creates potential for wear problems in vehicle fuel injection systems. Therefore, with the wider introduction of lower sulphur diesels in the future, lubricity should continue to be regulated for consumer protection.

10.14 Biodiesel / FAME

What is it and why is it important?

The use of renewable energy is becoming increasingly topical by virtue of concerns around global warming and climate change, with the main objective of reducing well-to-wheels CO_2 emissions. Various forms of bio-derived transport fuels are being considered and being used in various parts of the world. Bio-diesel in the form of Fatty Acid Methyl Ester (FAME) is one of the most common of these, together with bio-ethanol (used mostly as a petrol component or extender). FAME is made through the transesterification of vegetable oils or animal fats (although the latter is less common). FAME can be used as a neat fuel in modified engines or blended with petroleum diesel in unmodified diesel engines. There are also reports that the use of FAME leads to reduced particulate matter emissions. FAME also improves the lubricity of diesel fuel, when blended at low levels.

There are some concerns around food security and the actual carbon (CO_2) benefit of some bio-derived fuel pathways. These concerns aside, one of the most significant concerns for the widespread adoption of bio-derived fuels, and FAME in particular, has to do with product quality assurance. The preferred model for the production of sufficient volumes of these fuels is one that incorporates de-centralised, small scale production facilities, which naturally leads to the manufacture of many small batches of product. This makes quality assurance difficult or impossible. The oil is transesterified, in the presence of a catalyst, with an alcohol (methanol in the case of FAME, ethanol can also be used to make Fatty Acid Ethyl Ester or FAEE). The final product needs to be thoroughly filtered to remove catalyst material and other solids and carefully separated to remove residual alcohol, free fatty acids, water and glycerin which is a by-product of the reaction. Product tests to certify that this has been sufficiently achieved are not easily performed on a distributed basis.

Some other concerns around biodiesel include:

- Cold flow properties
- Oxidation stability
- Hygroscopic nature, leading to water contamination
- Engine deposit formation

Table 33: Current South African and International FAME Specifications [xv]

Specification	FAME
Units	% vol (max)
South Africa	**5**
EN590:1993 (Euro 2)	-
EN590:1999 (Euro 3)	-
EN590:2004 (Euro 4)	5
US	-
US: CARB	-
Japan	-
New Zealand	5
Australia	-
India (Metro)	5
India (Nationwide)	5
China (Beijing)	-
China (Nationwide)	-
Worldwide Fuel Charter	5 / 5 / 5 / not detectable [1]

[1] Category 1/2/3/4

PROPERTIES CURRENTLY NOT SPECIFIED

The following properties for diesel are not currently included in the South African specifications but have appeared elsewhere in specifications or their inclusion is under discussion. For this reason their significance is discussed here.

10.15 Polycyclic Aromatic Hydrocarbons (PAH) [iv]

What are they?

Aromatics containing multiple benzene rings are known as polycyclic aromatic hydrocarbons (PAHs or PCAs). Whereas aromatics containing a single benzene ring are an issue with petrol, it is primarily PAHs which are of concern with diesel. Current evidence suggests that only the PAHs contribute to particulate emissions, so it is only these and not total aromatics in diesel which need be considered for regulation. Some PAHs such as benzo(a)pyrene are known to be carcinogenic.

PAHs are predominantly present in the heavier ends in diesel so their content is controlled through the distillation parameters such as T85 and T95.

Why are they important?

Data on the impact of PAHs on regulated emissions is fairly sparse. However, it appears that there are consistent trends with decreased PAH resulting in decreased hydrocarbon and NO_x emissions but having no impact on CO. Reduced PAH has a significant benefit on PM for older engines which produce higher levels of particulates. For modern lower emission engines, the impact is little to none. These effects are attributed to the higher flame temperature and higher C:H ratio of aromatics. For this reason, there is a trend in international fuel specifications towards placing limits on aromatics and PAHs in particular.

Table 34: Current South African and International PAH Specifications [xv]

Specification Units	PAH[1] % wt (max)
South Africa	-
EN590:1993 (Euro 2)	11
EN590:1999 (Euro 3)	11
EN590:2004 (Euro 4)	11
EN590:2009 (Euro 5)	8
US	-
US: CARB	1.4
Japan	-
New Zealand	11
Australia	11
India (Metro)	11
India (Nationwide)	-
China (Beijing)	11
China (Nationwide)	-
Worldwide Fuel Charter	-/ 5.0 / 3.0 / 2.0[2]

[1] Polyaromatic Hydrocarbons

[2] Category 1/2/3/4; Total aromatics also specified.

Why regulate?

Available information indicates positive benefits in emissions reduction from reducing PAHs in diesel and this has been the basis for the introduction of limits in European and other specifications.

Reducing PM emissions through control of PAHs will have environmental benefits. However, the reduction in PM emissions achieved through changes to bring T95 and sulphur levels in line with Euro specifications are likely to outweigh any immediate changes to PAH levels. This is dependent on the fuel type as synthetic diesel has been found to react differently.

As PAHs are higher density components of diesel, reduction of T90/95 limits and maximum density will effectively reduce the PAH content. As already noted, this reduces the overall yield of diesel and these components then have to be used elsewhere, either in heavier products or upgraded to lighter components through further processing, with the result that there are cost implications in imposing any reduction in PAHs in diesel over present levels.

10.16 Conductivity

Diesel that is low in sulphur may also have a lower electrical conductivity. Insufficient conductivity is a safety issue because it can lead to a build-up of static charge during transfer (such as when filling bulk storage tanks or road tankers). Conductivity is generally not an issue for vehicle fuel tanks because of the low velocity of fuel through pump nozzles. This is primarily an operating consideration for the oil industry and it can be corrected with conductivity improving additives. As this is an industry safety concern this is addressed at the point of manufacture and there is no need for regulation at this stage.

10.17 Summary

The main specification parameters that should be considered from an emissions perspective are considered to be:

- Sulphur, which has an impact on the exhaust after-treatment that is required to meet the stringent emission targets.
- Poly Aromatic hydrocarbons and T 95 point, which can have an impact on the particulate emissions.

Most of the other specification parameters are considered to be fit for purpose specifications.

11 Properties of Biofuels

The 1998 South African Energy White Paper set the pace for the introduction and promotion of renewable energy sources in South Africa. Globally, the interest in renewable energy sources has been driven mainly by high and escalating oil prices, environmental concerns and also as part of a broader energy diversification strategy. It is widely accepted that biofuels make a meaningful contribution to renewable energy and are recognised as a potential contributor to the supply of renewable liquid transport fuels. In South Africa, transport fuels make up about 30% of energy consumption (by energy content) and 70% (by value). Renewable Energy supply could include a contribution from biofuels.

Against this background, DME published the "Proposed Biofuels Industrial Strategy of the Republic of South Africa" in December 2007 which outlined government's approach to policy, regulations and incentives relating to the introduction of biofuels in the South African fuels market.

The integrated Renewable Energy Strategy outlines the benefits in terms of Greenhouse Gas emission reductions, job creation and reduction in dependence on imported fuel feedstocks. Economic realities need to be taken into account. The fuel quality (fit for purpose), the objectives of the (still to be finalized) Vehicle Emissions Strategy and the Energy Efficiency Strategy should not be compromised by the introduction of biofuels. It is essential that the Strategy ensures that the introduction of biofuels in South Africa is conducted in a sustainable manner with regard to environmental, economic and social perspectives.

11.1 Fuel specifications

The implications of taking up biofuels into the petrol and diesel streams on the fuel specifications currently adopted need to be addressed. Particular attention needs to be paid to petrol, with regards to volatility, Motor Octane Number (MON) rating and fugibility (wet/dry). The behaviour of biodiesel (FAME) even though it meets the specification tests may make resulting diesel blends unfit for purpose (through oxidization, cold filter plugging, and functions of Diesel Particulate Filters (DPFs)).

11.2 Financial implications for RSA

Depending on the decisions still to be taken on the final fuel specifications, the cost to the Oil Industry of taking up ethanol can be expected to be considerable. These relate, *inter alia*, to the need to maintain the volatility of the petrol at the existing level with the associated costs of refinery process changes, the additional storage and distribution facilities for the various blendstocks, the need (under some scenarios) to maintain a completely dry storage and distribution system, etc.

The uptake of biofuels should take place in a cost neutral environment i.e. their use should not result in an increase in the overall production or distribution costs of the fuels to be carried by the oil industry. In this regard, it needs to be determined whether there is opportunity to be gained by concentrating the provision of biofuels into a smaller geographical area rather than distributing it widely i.e. nationally, or into a niche market segment (dedicated vehicle fleets using high-ethanol fuels).

11.3 Security of petrol supply

Should a decision be taken to directly blend ethanol into petrol, it is essential that supplies of ethanol are guaranteed in order to ensure the maintenance of the required level of fuel specifications. A special "blendstock for oxygenate blending" needs to be produced at refinery level to facilitate the addition of ethanol at the depot level, without increasing the volatility of the final petrol blend beyond the required standard. Should ethanol not be available when required for blending, the original petrol blendstock cannot be marketed as it will not meet the required specifications without the addition of ethanol. Under certain specification regimes, these security of supply issues can be avoided.

11.4 Quality control and product liability

It is imperative that the biofuel blendstock that is to be taken up in the petrol or diesel is of a certified quality to ensure that the relevant fuel specifications are adhered to and that the fuel remains "fit for purpose". As it is envisaged that some of the biofuels may be produced on a small scale, it is important that the practicalities of implementing this are adequately addressed.

11.5 Blending of biofuels

Consideration needs to be given to the location and manner in which the biofuels are to be blended into the petrol and diesel streams. It is suggested that a flexible approach be adopted owing to the different circumstances pertaining to the different refineries and the varying availability of biofuel. These solutions however must allow for optimum use of constrained national infrastructure.

11.6 Technical aspects that need to be considered for biofuels implementation

11.7 Biodiesel

Biodiesel (fatty acid methyl esters or fatty acid ethyl ester) as a blend component is rapidly gaining international acceptance at a blend level of up to 5% for on-road use. Extensive documented experience is however limited to the introduction of mostly canola methyl ester (CME) in Germany and France. The maximum level allowed in any specific market is determined pre-dominantly by the level of vehicle technology, ambient conditions and emission standards. In some markets consideration is being given to the blending of higher proportions of esters, particularly for off-road and closely controlled specialised on-road use. In certain quarters, there is a growing resistance to the use of biodiesel because it tends to have blending and performance characteristics that are not consistent, especially with new ultra high pressure common rail injection systems and associated emission control devices.

Quality control – Care needs to be taken to ensure acceptable quality of the manufactured biodiesel (SANS 1935), so that when blended with conventional diesel at up to 5% by volume, the resultant product complies with the national automotive diesel specification (SANS 342) and is therefore fit for use as an on-road transport fuel.

Every batch of biodiesel, whether additised or unadditised, needs to be certified to the relevant SANS specification at the point of manufacture and blending.

The cost of biodiesel analysis is very high and technically complex. Analytical facilities in South Africa are limited. It is not feasible for small-scale producers to carry out the analysis due to the high costs involved and a means of overcoming this needs to be addressed.

The storage stability of biodiesel blends is relatively poor and hence requires oxidation stability additives. B5 (5% biodiesel) blends therefore need to be carefully distributed and best practice storage and handling procedures need to be followed.

The cold flow properties of certain biodiesel may not meet on-road diesel standards and therefore may need to be additised or blended specifically.

11.7.1 Ethanol

Ethanol is a high octane, high vapour pressure blend component with more complex issues associated with its blending into petrol than is the case with biodiesel into diesel. The level of blending is dependent upon the vehicle technology, petrol specification and ambient conditions. Europe currently has a limit of 5.0% vol and the US, Australia and China 10% vol.

With necessary infrastructural changes, ethanol (as per SANS 465) could be accommodated in South Africa as per the current SANS 1598 specifications which allow for a maximum of 7.5% ethanol at the coast and 9.5% inland in the absence of any other oxygenates. Mixtures of oxygenates will be controlled by the maximum oxygen content as per the SANS specifications for both inland and at the coast.

Octane – The Motor Octane Number (MON) of ethanol is much lower than its Research Octane Number (RON). This means that MON is likely to be the controlling octane specification in ethanol blends, and reduces the value of ethanol as an octane enhancer.

The SANS 1598 specifications for petrol-alcohol blends above 2% furthermore stipulate a two MON higher number than conventional petrol. This reduces the value of the ethanol as a petrol component. There needs to be full justification for the retention of this in South Africa, which is the only country in the world with such a requirement.

Volatility – The addition of moderate levels of ethanol results in a sharp increase in the volatility, expressed as Reid Vapour Pressure (RVP), of the base petrol to which it is added. It can also result in a distortion of the distillation curve. Thus the volatility and distillation of petrol/ethanol blends must be properly controlled to prevent potential engine running problems, e.g. difficult starting after hot shutdown, rough idle, surge and vapour lock. RVP is also indicative of evaporative emissions during supply and distribution, during refuelling operations and from the vehicle. In order for the blend to meet the volatility specifications, it is necessary to blend the ethanol with specially-tailored base petrol blendstock with lower volatility than that of the resulting blended petrol. The provision of base petrol blendstock has significant implications for the refinery, in that it requires light components to be backed out of the blend, which will result in challenges regarding the alternate disposition of these components. The addition of this new blendstock for alcohol blending into the supply chain also presents a challenging logistical constraint on both transportation and storage, especially since the base petrol blendstocks may not be fungible (between batches and/or refineries and/or imports).

In addition, ethanol and petrol mixtures exhibit behaviour, such that a mixture of petrol and petrol containing ethanol (E10) - that both meet the RVP requirements, can be off-specification when blended together. To ensure petrol is always on specification in the retail stations there either needs to be significant RVP give away, or the assurance that clear petrol and ethanol containing petrol are not co-mingled in the supply chain. Even with these actions in place, the fuel in a customer's tank may exceed the RVP specification, with consequent increased evaporative volatile organic compound emissions from the vehicle and possible vehicle operability issues in hot weather.

Such problems do not arise if the ethanol is first converted into ethyl ethers and added to petrol as part of the normal blending process. The quantity of petrol available from the refining process actually increases if this approach is adopted. However, it is unlikely that the typical RSA refinery can uplift a volume of ethanol equivalent to that needed for E10 (10% ethanol) and convert all of this to ether.

Fire danger – Conventional hydrocarbon fire fighting techniques cannot be applied to ethanol. Ethanol flames have limited visibility, leading to a riskier environment for fire fighters. Thus special fire-fighting procedures are required for ethanol and ethanol/petrol mixtures as a result of ethanol's particular properties. For example, a different type of foam compound (polar) and different foam application methods are necessary. This will have cost implications at depot level and for local authorities.

Ethanol solubility in water – Ethanol is infinitely soluble in water. If there is any water present in storage or a vehicle's petrol tank, the ethanol will be extracted into the water phase. If sufficient water is present, complete phase separation can occur. This can lead to the following:

- Lower concentration of ethanol in the petrol lowers the octane and disturbs the vapour pressure and distillation properties
- Any waste water/ethanol, water/ether or water/ethanol/ether mixes will require appropriate wastewater management procedures.

- Bioethanol can be consumed by the public. The alcohol can easily be separated from the fuel by mixing in water or a soft drink. A suitable denaturant thus needs to be added to the ethanol to make it taste bitter or too unpleasant for human consumption.

Storage tanks have to be kept free of water at all times, requiring careful operating procedures and appropriate tank design. For example, floating roof tanks are unsuitable and will need to be replaced with fixed roof tanks.

The above issues ideally require that ethanol addition to petrol occurs as far down the supply chain as possible, that is at the depots. This will require investment in ethanol storage facilities and injection equipment at these depots. This is the approach currently being used in Brazil, the USA and Australia.

To the extent that ethers can be made, this problem is avoided by converting the ethanol into ethyl ethers.

The optimum blend value of ethanol can only be extracted by sophisticated blending at a refinery.

Another option is to follow the unique approach adopted by Sasol with the earlier alcohol blends by blending at the refinery and transporting the blend from there by pipeline. This solution is only possible in absolutely dry pipeline systems and appears incompatible with the quality of normal petrol, diesel and Jet (which are "wet" products) carried in the same pipeline.

Additives – Additives are required to ensure that the ethanol does not result in metal corrosion. The corrosion mechanism differs from that normally experienced with petroleum fuels and requires careful analysis and sophisticated solutions. Additives cannot prevent the ethanol from having adverse effects on rubber and certain plastic components.

Market complaints – Certain vehicles and their components are not compatible with ethanol and it is anticipated that problems will be experienced with certain cars. The extent of these potential problems will affect the maximum allowed ethanol content. The determination and apportionment of liability for vehicle damage needs to be addressed. The vulnerability of some vehicles to ethanol petrol blends is increased if the user switches intermittently between ethanol blends and non ethanol blends.

Logistics – The accommodation of ethanol blends in the storage and distribution system has a number of logistical and cost implications:

- additional tankage and additive dosing facilities are required at depots

- absolutely dry storage and transport systems are required
- floating roof tanks need to be replaced with fixed-roof tanks
- accurate blending equipment is required at depot level
- ethanol petrol will need to be treated as an additional grade at depot level, unless blending takes place directly into delivery vehicles
- additional analytical facilities will be required at depot level
- inability to transfer ethanol blends in pipelines used to convey jet fuels will lead to complications in the distribution system.

Quality assurance – Ethanol blending may occur at the depot. Full certification of the hydrocarbon base fuel and ethanol will be required as well as calibration certification of the injection system at the depot level. Calculations showing that the expected finished fuel properties meet the specifications will be required and this will only be possible if the blend components are fungible by type. It is not practical to test every batch/tanker that leaves the depot.

Emissions – Petrol/alcohol mixtures have positive and negative impacts on emissions and air quality. The balance of positive and negative impacts is very different for catalyst and non-catalyst equipped vehicles. A reduction in certain exhaust emissions, such as unburned hydrocarbons, can result from the use of an ethanol-containing petrol. Other emissions, such as aldehydes and formaldehydes, might, on the other hand, increase. These environmental considerations need to be taken into account, paying particular attention to the proportion of vehicles in the South African fleet operating with fully-functional catalytic converters.

In all vehicles, the use of ethanol/petrol blends increases the evaporative and permeation losses, even at constant vapour pressure.

11.8 Summary

It is clear that there are many complexities associated with the uptake of biofuels from an Oil Industry perspective which have not been adequately addressed in the proposed Biofuels Strategy. It is essential that these complexities be properly addressed to ensure that the introduction of biofuels does not have any unforeseen significant negative impacts on the country as a whole.

12 The requirement for regulation

Following on from the individual specifications for petrol and diesel, this section examines the continuing requirement for fuel regulations in general terms, with reference to international data.

12.1 Why do we need Regulations? [iv]

This guide has drawn attention to the fact that Regulations are still necessary from a consumer, health and safety and environmental perspective. They provide:

- Consistency in terms of product;
- Guidelines for suppliers and manufacturers in respect of what is acceptable;
- A signal for future developments and therefore potential expenditure; and
- Protection in terms of health, safety and the environment.

Consumers are not in a position to determine the quality of fuel at the point of purchase but good quality fuel is essential to the proper running and long life of engines. Often, problems with fuel quality may not be experienced immediately. Hence fit-for-purpose specifications and regulations are required to ensure trouble free motoring. Regulations provide a minimum standard for fuel, and therefore certainty as to what is acceptable. In this respect, they provide buyers of petrol and diesel with an additional layer of protection, to assure them that fuel bought is fit for purpose while also addressing health, safety, and environmental concerns.

12.2 Fit for Purpose [iv]

Fuel processing technology and additives used in petrol and diesel to control fuel quality change with time. This is critical in terms of future changes and the relatively old vehicle parc in South Africa.

12.3 Test Methods [iv]

South Africa has agreed to certain changes to some of the test methods to bring them into line with current international practice (European - ISO) and technological developments. These changes will impact the certifying laboratory not only in terms of equipment, but also training and quality related systems – as a consequence lead times are required for certain changes to be implemented.

12.4 Ensuring Fuel Consistency [iv]

It is important that the variability of our fuel is kept within acceptable bounds to enable us to rely on consistent performance from a particular grade of fuel. It is also expected that fuel properties with public health and environmental impacts will be controlled within acceptable bounds. Consistency is achieved by setting minimum or maximum limits on key properties. In some cases where the range is critical, such as with the density and viscosity of diesel, both limits are specified.

12.5 Pool Averaging [iv]

An alternative approach to fixed limits is the use of "pool averages". Pool averages allow variability across the national or regional fuel supply, provided that an average value or specification is met over a specified period. A cap or maximum limit is also specified, but usually at a higher value than the equivalent single flat limit.

This approach has been adopted in some other countries, primarily for those parameters, such as benzene and aromatics levels in petrol, that are controlled in order to minimise environmental impact.

12.6 Mandated Geographical Differences

Mandated geographical differences in fuel quality were considered in the New Zealand Review in response to the geographical nature of some air pollution issues. This type of approach is being used elsewhere to deal with specific urban air quality problems. Such an approach would be in line with the underlying principle that fuel quality standards reflect the level of risk to health and the environment, which in the case of air pollution is essentially a local problem.

The most obvious split would be fuel specifications specific to the coastal and inland regions, owing to the altitude differences. The concept of "city fuels" could also be investigated, but this needs to be considered with respect to logistical implications as well.

12.7 Additives [iv]

A wide range of additives is used in petrol and diesel to improve certain properties or characteristics of the fuel. For petrol, these include dyes, detergents, stabilisers, combustion improvers and octane enhancers in petrol. Similar sorts of products are used in diesel along with cetane number, lubricity and cold flow improvers. Some are added at the refinery during blending and others, such as those used for branding or product differentiation may be added during distribution.

It is essential that the additives used are proven to be fit-for-purpose in the specific fuels, but also throughout the logistic system, especially multi product pipelines.

For the most part, the use of additives is neither required nor prohibited by the Regulations. However, there are exceptions to this rule for cases where a specific additive or component of an additive is harmful to vehicle systems or to human health and the environment. Lead, for example, was banned because of health concerns, and the impact that it has on exhaust catalysts.

13 Key issues

The Petroleum Products Amendments Act that regulates the fuel specifications in South Africa has been in place since June 2006. Sections 3, 4 and 5 of this Reference Guide have described the technological and legislative context, and the commercial and political climate in which petrol and diesel are supplied and used both internationally and in South Africa. This information provides the basis for assessing the specifications and regulations in detail and for making any recommendations for changes.

It is apparent that there are competing tensions in some of the underlying arguments, and that trade-offs may have to be made in some cases. These need to be taken into account when a strategy is determined for South Africa.

13.1 Key Issues for the Fuel Supply Market

Changes in the South African fuel specifications are inevitable, as a result of local and international environmental pressures. Changes in automotive engine technology to meet the environmental emission limits are also forcing changes in these fuels specifications.

Any changes to the specifications and/or regulations should promote competition in the fuel supply market, while taking the strategic value and impact on balance of payments into account for the country as a whole. Significant changes in the refineries can have an impact on product supply, both during the change over period (shutdowns) and by changing the product mix and volume manufactured.

A hybrid fuel specification should be avoided that is difficult or expensive to produce, given South Africa's market size, vehicle parc, geography (altitude), and fuel distribution infrastructure.

Taking these issues into account, there should be movement towards international harmonisation in enabling fuel specifications as far as possible, to enable imports and exports of fuel and vehicle technology. However this should be done using a pragmatic approach as has been followed in other parts of the world, including New Zealand, Australia and Asia.

13.2 Key Issues for Fuel Use

Vehicle fleet

South Africa's vehicle parc is unique, and our fuel needs to match both current and future needs, bearing in mind that more than half the vehicle parc operates at higher than 1 200 meters above sea level. The introduction of new cleaner/ more efficient vehicle technology should be encouraged together with the availability of the enabling fuels such technology requires. The timing of the recommended changes must therefore reflect expected development and uptake times for the relevant technologies.

The vehicle parc in South Africa is considered to be old and most of the vehicle emissions are being emitted from older technology vehicles. This is illustrated in Figure 18 which has been extrapolated from data on vehicles sold, average kilometres travelled and available emissions data, with the result that absolute accuracy cannot be guaranteed. This indicates that approximately 80% of the emissions comes from the older vehicle technologies.

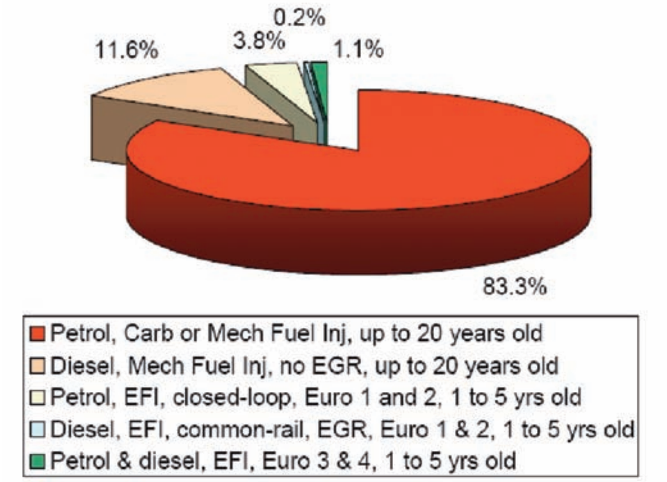

Figure 18: Contribution of different vehicle technologies to vehicle parc emissions

Consumer protection

Fuels must provide reliable, fit-for-purpose and consistent performance. This can be achieved by controlling variability, but control must be balanced against over-regulation, which creates an unnecessary compliance burden on suppliers and can have a possibly negative effect on South Africa's economy.

The specifications must ensure that South Africa does not become a dumping ground for poor quality fuel and vehicles.

13.3 Key Issues for Environment and Health [iv]

While the effects of fuel quality changes alone on emissions from vehicles are relatively small, real benefits accrue when the fuel enables new technologies to be introduced. This is intrinsically linked with timing considerations in aligning the required fuel quality with the vehicle fleet.

South Africa's air monitoring data confirms that reductions of some priority pollutants are needed now in order to protect public health in some areas of the country, primarily industrial corridors. Some changes in fuel quality will provide direct public health benefits. (eg. the reduction of sulphur in diesel to minimise secondary pollutant levels and the reduction of benzene levels in petrol).

Cleaner fuels will not necessarily make a dirty vehicle clean and hence inspection and maintance is considered to be critical elements in ensuring that the quality of the urban air is improved. Other aspects such as traffic management and vehicle parc renewal should also be considered in the approach.

The potential for regional specifications to address local air quality problems must be recognised although, as noted earlier, this may be limited by the distribution infrastructure.

13.4 Timing

The timing of any proposed changes need to be taken into consideration with regard to the level of engineering changes required, the logistics infrastructure, the current vehicle parc and the cost to the country. Hence it is very difficult to make any decisions upfront, without a detailed understanding of the requirements for the country as a whole.

14 Appendices

Appendix A: South African Specifications

A.1 Unleaded Petrol

Property	Units	Limit	SANS 1598 - 2006
Appearance			Clear and free from visible water, sediment and suspended matter
Colour			
Density @ 20°C	kg/l	min	0,710
		max	0,785
Octane Number, Research		min	95; 93; 91
Octane Number, Motor		min	85; 83; 81
Motor octane number (MON) for blends that contain more than 2% (by volume)		min	87; 85; 83
Alcohol			
Lead Content	g Pb/l	max	0,013
Gum, Existent	mg/100ml	max	4
Gum, Potential	mg/100ml	max	4
Induction Period	mins	min	360
Distillation			
IBP	Deg C		
10% vol	Deg C	max	65
50% vol	Deg C	min	77
50% vol	Deg C	max	115
90% vol	Deg C	max	185
FBP	Deg C	max	215
Residue	% v/v	max	2,0
Reid vapour pressure	kPa	min	45
		max	75
Coast FVI,			
Summer		max	95
Winter			100
Inland FVI,			
Summer		max	89
Winter			94
Copper Corrosion		max	1
Sulphur Content	mg/kg	max	500
Aromatic content	% v/v		50
Benzene content	% v/v	max	5
Oxygen content	% m/m	max	Coast 2,8
			Inland 3,7
Ethers	% v/v		Allowed

A.2 Automotive Diesel Fuel

Property	Units	Limit	SANS 342 - 2006
Appearance		max	
Colour	max		
Density @ 20°C	kg/l	min	0,8000
Ash Content	% m/m	max	0,01
Cetane Number		min	45
Carbon Residue, Ramsbottom	% m/m	max	0,2
(on 10% residue)			
CFPP – Winter			-4
– Summer			3
Corrosion, Copper Strip, 3 hrs @ 100°C		max	1
Distillation			
90% vol. Recovery	Deg C	max	362
Sulphur Content	mg/kg	max	500
Flash point, PMCC	Deg C	min	55
Kinematic Viscosity @ 40 Deg C	cSt	min	2,2
		max	5,3
Water Content, Karl Fischer	ppm (v/v)	max	500
Total Contamination	mg/kg	max	24
Lubricity Wear scar diameter	um	max	460
Oxidation Stability	mg/100ml	max	2,0
Fatty Acid Methyl Ester (FAME) content	vol %	max	5

Appendix B: Internal Combustion Engine Basic Operating Principles and Technology Trends[iv]

This Appendix outlines the basic operation of petrol and diesel engines, and how this relates to basic fuel characteristics. The impact of engine design factors and condition on fuel consumption and emissions is presented. The trends and technologies employed to minimise fuel consumption and emissions, and the impacts on fuel quality requirements of these technologies are reviewed.

B.1 Basic Operating Principles

Internal combustion engines convert chemical energy contained in fuel into mechanical power. The combustion process is, however, quite different between a petrol engine and diesel engine, and this impacts on the required properties of the fuel for each type of engine. Although it is common to refer to engines as either petrol or diesel, the more correct distinction is between the nature of the ignition and combustion. The relative quantities of the various exhaust emission materials that are formed vary as a result of the difference in the combustion process.

In petrol engines the air and fuel are usually premixed before initiation of combustion, and the mixture then burns progressively as a flame front moves across the combustion chamber. In diesel engines the fuel burns primarily as a diffusion flame as the injected fuel mixes with air to produce a combustible mixture. The respective fuels have developed to suit the requirements of each type of combustion process, rather than by their nature defining the combustion process.

In addition to classification by fuel/combustion type, engines may further be described by the number of piston strokes to complete a full cycle. Thus a **four cycle**, or **four stroke** engine, performs the four basic phases of a cycle, induction, compression, combustion and expansion, and exhaust in four piston strokes. A **two stroke** engine performs the four basic phases of operation condensed into two piston strokes. Two stroke spark ignition engines have historically exhibited significantly higher fuel consumption and exhaust emissions, but enjoy a higher power to weight ratio, and are therefore primarily used in small mobile equipment and motor cycles.

B.1.1 Diesel Engines (Compression Ignition)

Light-duty (LD) diesel engines are generally defined as engines of displacement less than 4.0 litres and power output of typically up to 150 kW, and are characterised by relatively high engine speeds of up to 5000 rpm. LD engines would normally be found in passenger vehicle and light commercial vehicle applications.

Heavy duty (HD) diesel engines may be generally defined as engines of displacement greater than 8 litres and power outputs of greater than 150 kW with maximum engine speeds of less than 3000 rpm. HD engines are found in heavy road transport, industrial and marine applications. Medium duty engines fill the gap in the middle and are found in medium size trucks, buses and light industrial equipment.

A **diesel** engine is referred to as a **compression ignition engine**. Air alone is drawn into the cylinder on the downward induction stroke of the piston. No throttling of the intake is used; therefore, for a non-turbocharged engine, the amount of air drawn into the cylinder at a certain engine speed is relatively independent of the engine output, or load. The air is compressed and therefore heated in the combustion chamber before injection of the fuel which, as a result of the temperature and pressure within the combustion chamber, spontaneously ignites shortly after it is injected. The amount of fuel injected is varied to change the output power of the engine.

Fuel may be injected either directly into the main combustion chamber formed between the piston and the cylinder head, termed **direct injection (DI)**, or into a smaller separate pre-chamber located in the cylinder head, and connected to the main combustion chamber by a small passage. This second configuration is termed **indirect injection (IDI)**. The IDI system achieves high mixing rates as the fuel injected into the pre-chamber ignites and the expanding gases pass through the orifice in a high-speed jet. This allows higher engine speeds to be utilised and therefore IDI was traditionally used extensively for small light-duty engines, while DI is used almost exclusively in larger heavy-duty engines that operate at lower engine speeds. Challenges with emissions and advances in DI injection technology has resulted in the predominance of DI engines in all modern vehicles.

The fuel is injected under high pressure (of order 30-100 MPa) through fine holes to form a spray of fuel droplets that are typically of the order of 10-50μm in diameter. This must mix with the air in the combustion chamber until the local air-fuel ratio is within flammability limits before combustion can occur. The time taken from the start of injection to the start of combustion is termed the ignition delay.

Once ignition occurs the portion of the fuel injected that has mixed to a flammable air-fuel ratio burns rapidly in **premixed** combustion. This rapid combustion of the initial portion of the charge causes a rapid pressure rise and causes the characteristic "diesel knock". It is desirable to minimise the ignition delay and resulting proportion of premixed combustion in order to reduce the intensity of diesel knock. The auto ignition characteristic of the diesel fuel, specified by the cetane number, is an important parameter contributing to the time taken to initiate combustion after fuel injection. A higher cetane number reduces the ignition delay and the premixed combustion.

The rate of subsequent diffusion combustion is primarily controlled by the rate of injection of fuel and the rate of mixing of the fuel in the air. The rate of mixing is in turn dependent on the motion of the air in the combustion chamber and fuel injection parameters such as injection pressure and number and size of injector holes. These are therefore important design parameters in order to maximise the efficiency of diesel engine combustion and reduce emissions.

B.1.2 Petrol Engines (Spark Ignition)

By contrast, a petrol engine is defined as a **spark ignition engine**. Air and fuel are normally mixed together in the intake, and compressed in the combustion chamber, although recent technology advances have resulted in the move to Direct Injection petrol engines in which the fuel is injected directly into the combustion chamber. As the air-fuel ratio needs to be kept within certain flammability limits, the intake of the mixture is throttled to change the engine output, while the air-fuel ratio is kept relatively constant. The correct amount of fuel is metered into the incoming air stream by either a carburettor or by fuel injection. A timed spark ignites the air-fuel mixture which then burns progressively but rapidly across the combustion chamber. The timing of the spark is adjusted over the range of operating conditions, and the optimum timing is dependent on factors such as the combustion chamber geometry, compression ratio and fuel octane rating. Spark timing and the air-fuel ratio have strong effects on the efficiency and emissions produced by spark ignition engines.

The fuel is required to evaporate in order to be mixed thoroughly with the air prior to combustion, and needs to resist auto ignition (or "knock") as the mixture is compressed. Therefore essential characteristics of the fuel include appropriate volatility and resistance to premature ignition (measured by the octane rating). A higher octane fuel is more resistant to knock. In terms of engine performance, carburettor equipped engines are generally more sensitive to fuel volatility.

Two stroke engines may have lower octane requirements than four stroke, but are also more prone to spark plug fouling and combustion chamber deposit formation. Petrol specification impacts on this problem, and any changes (improvements) in petrol specifications are more likely to provide benefit in this area rather than cause additional problems.

B.2 Relative Efficiency of Diesel and Petrol Engines

The overall efficiency of internal combustion engines may be defined as the ratio of useful work output to the amount of fuel energy consumed.

As the diesel engine operates on the self-ignition principle (achieved by the high pressure and temperature in the chamber) the compression ratio is much higher than in the case of a petrol engine. The requirement to prevent uncontrolled combustion (commonly experienced as "knock") in a petrol engine limits the compression ratio. The compression ratio for a diesel engine is normally around 15-20 whereas for a petrol engine it is in most cases between 8 and 11. The high compression ratio of the diesel engine is one reason for its higher efficiency. The octane rating of the petrol has a direct influence on the maximum compression ratio that can be used in petrol engines.

The unthrottled intake of the diesel engine also contributes to an efficiency advantage over the spark ignition engine, by decreasing the work required to "pump" the charge in and out of the engine. Heat losses from diesel engines are less at part loads also, as the overall gas temperature in the combustion chamber is lower, and this also contributes to the efficiency advantage over petrol engines.

These factors combine to give diesel engines approximately a 15 to 25% increase in efficiency over spark ignition engines, and about the same percentage improvement in fuel economy over comparable sized vehicles powered by petrol engines whilst sacrificing some acceleration and maximum speed performance. Some of this benefit in volumetric fuel consumption enjoyed by diesel engines is a result of diesel's higher density and thus higher volumetric energy content. Diesel is typically 10% more dense than petrol. The higher density also implies that per litre burned, diesel produces approximately 10% more CO_2 emissions.

B.3 Engine Design

Over the history of the internal combustion engine, the design of both petrol and diesel engines has evolved, initially to meet demands for increased performance, fuel consumption and driveability, but in the past few decades primarily driven by legislated requirements to reduce emissions. Current and future European and United States legalisation requires large reductions in emissions, while increasing concerns of global warming continue to drive the need for improved fuel efficiency and hence reduced CO_2 emissions.

The regulated emissions species of internal combustion engines are carbon monoxide (CO), unburnt hydrocarbons (HC), oxides of nitrogen (NO_x), and for diesel engines particulate matter (PM). In the ideal situation, all of the carbon in the fuel would be oxidised to CO_2, while all the hydrogen would be oxidised to H_2O. CO, HC and PM are products of incomplete combustion which may occur due to a rich mixture and/or inefficient combustion. NO_x is formed in the high temperature burnt gases in the combustion chamber by reactions between oxygen and atmospheric nitrogen. NO_x formation is highly sensitive to temperature, time and oxygen concentration.

For diesel engines the current and future challenge is to significantly reduce emissions of PM and NO_x, while for petrol engines significant reductions of all regulated emissions are required.

B.4 Diesel Engine Technology

Engine design technologies which impact on the fuel efficiency and emissions of diesel engines are summarised below [iv].

Mechanical Design Features / Technology	Fuel Sensivity		
		Light Duty	Heavy Duty
Multi-valve heads	None	Production	Production
Variable valve timing	None	Emerging	N/A
Turbocharging and after/intercooling	Low	Production	Production
Combustion chamber/charge air motion optimisation	Low	Production	Production
Engine Control Technology			
Electronic engine management	Low	Production	Production
Common rail injection	Low	Production	Production
Exhaust gas recirculation	Low	Production	Production
Exhaust Aftertreatment			
Oxidation catalysts High	High (S<500 ppm)	Production	Production
Particulate filters/traps	High (S<~50 ppm)	Production	Production
NOx reduction technology High	High (S<~50 ppm)	Production	Production

B.4.1 Mechanical Design

In general, all the mechanical design developments discussed here do not have significant impacts on fuel specification requirements.

Friction

Continuing small incremental improvements are being made to reduce the energy losses to friction within engines. Modern designs are highly evolved in this area, and hence future gains are likely to be limited to the order of a few percent. Future developments for diesel engines are likely to include the increased use of roller cam followers and overhead camshafts, and low friction bearing and piston design.

Volumetric Efficiency

Volumetric efficiency is the measure of how completely an engine cylinder is filled with air or air-fuel mixture in each operating cycle. A volumetric efficiency of 100% means that in each operating cycle the engine cylinders are completely filled with mixture at atmospheric pressure. Improved volumetric efficiency and air availability improve the performance of diesel engines in several ways.

Pumping losses are typically reduced with features that improve volumetric efficiency, resulting in small improvements in overall engine efficiency. The increased air availability means that more fuel may be burnt, thus increasing power density. Hence engine size for a specific application may be reduced, which typically will result in higher overall efficiency when operating at the same loads. The greater air availability may also be used to increase excess air to ensure complete combustion and lower combustion chamber temperatures, leading to reduced emissions of all regulated species. The term excess air refers to air availability in the cylinder in excess of that theoretically required to burn all HC to CO_2 and H_2O.

Where the generalisation "reduced emissions" is used in this discussion, there is some beneficial impact on all species, but the magnitude may vary between species.

Several technologies have developed to increase volumetric efficiency:

Multi-valve cylinder heads are now common on both heavy-duty and light duty diesel engines.

Variable valve timing offers increased volumetric efficiency and torque increases across the entire speed range. Control of residual burnt gas remaining in the cylinder from the previous cycle is possible by control of valve overlap, and this can reduce NO_x emissions in the same manner as exhaust gas recirculation (EGR). This technology offers greater potential to light-duty engines, where the higher speed range over which they operate results in a greater compromise when fixed valve timing is used, than to heavy-duty engines. Whilst not currently widely employed in diesel engines, this technology may in future become common.

Turbocharging is now common with both heavy-duty and light-duty engines. This provides significantly increased air for combustion resulting in higher power outputs, and can contribute to reduced emissions and specific fuel consumption through increasing excess air. Significant advances have been made in turbocharging technology resulting in higher boost pressures, greater efficiency and improved engine response and hence driveability. Current and future development concerns variable geometry turbochargers and electronic boost control. Dual turbocharging has become common in high performance diesel engines and boost pressures continue to increase.

Associated with turbocharging, **after cooling** and **air to air intercooling** of the boosted intake air has become almost universal in modern engines. This increases air availability for combustion by increasing the density of the intake air. This also results in higher power density and improved efficiency. NO_x emissions are decreased by the reduction in combustion temperatures.

B.4.2 In-Cylinder Air Motion and Combustion Chamber Design

The design of the inlet tract and combustion chamber has a major influence on the performance and, particularly, emissions of diesel engines. A high level of air motion and turbulence is required within the combustion chamber in order to promote rapid and complete mixing of the injected fuel with air to combustible proportions. The objective is to optimise the in-cylinder air motion to provide smooth, complete combustion within the time available, and to minimise resulting emissions. However there are often volumetric efficiency tradeoffs in some design approaches to generating the desired air motion.

The combustion chamber contributes to the air motion achieved, and is also required to be as compact as possible with minimal crevices and quench areas where fuel may escape complete combustion. There are many ways of achieving this and many types of air motion including swirl, tumble, reverse tumble, and swish, and combinations of these. Advances in high pressure injection technology now mean that the primary source of in-cylinder turbulence for fuel-air mixing is now derived from the fuel spray. This allows a reduction in the requirement for bulk air motion due to swirl, etc., thereby reducing volumetric efficiency and heat transfer losses.

Continual developments in design techniques have contributed significantly to reduced fuel consumption. Emissions have decreased by an order of magnitude over the last 20 years as a result of improved air motion and chamber design, in conjunction with improved fuel injection. Extensive research efforts continue and increasingly sophisticated modelling techniques are developing in this area. Small fuel consumption benefits will continue to be gained along with larger emission reductions.

Recent significant developments in the area of combustion chamber design include the application of direct injection (DI) designs to light-duty engines. Historically high (engine) speed light-duty engines have been required to be of indirect injection (IDI) design in order to provide high enough levels of charge air motion to mix and combust the fuel in the short time available. DI engines offer reductions of 10-20% in fuel consumption and improved emission control over IDI engines. Heavy-duty engines are almost exclusively of DI design and most modern light duty engines are now DI also.

B.4.3 Engine Control Technology

Fuel Injection Systems

The design of the fuel injection system is an area where significant improvements have been made in the last 10-15 years. Diesel injection pressures have increased to the order of 150-200 MPa using electronically controlled unit injectors and high pressure common rail injection systems and injectors have tended towards multiple smaller orifices. This results in improved fuel atomisation and mixing with the compressed air within the cylinder, and the ability to vary injection timing to a greater degree than mechanically controlled systems. This has resulted in significant reductions in PM mass emissions of up to 60%, and smaller reductions in HC and NO_x. However the size of particles generated has decreased and there is growing concern that the number of ultra fine particles may be more important than particle total mass in determining health impacts. The requirement for very late post-injection to facilitate the regeneration of certain types of exhaust gas after-treatment has resulted in common rail being the technology of choice for future passenger car engines.

Electronic Injection Controls and Common Rail Injection Systems

Greater control over injection timing through electronic control has become common in modern diesel engines. Much research is being conducted in systems to provide injection rate shaping and multiple injections to further control the combustion process. Very high speed actuation allows for precise timing of the injection and for techniques such as pilot injection and multiple injections.

The decoupling of the generation of the injection pressure from engine speed allows high pressures to be consistently available even at low engine speeds. This technology provides significant decrease in combustion noise, NO_x and PM emissions, and allows for "post" injection late in the combustion process to enable the use of emission after-treatment technologies such as passively regenerating PM traps and NO_x adsorbers. These systems are now entering the market in LD vehicles but are also applicable to HD vehicles.

Closed-loop control of injection timing, based on either a cylinder pressure signal, or a vibration signal (similar to knock sensors used on Spark Ignition (SI) engines), will be implemented in engines which need to meet the strictest emission limits (for example US Tier 2). This requires robust sensing technology, and glow plugs incorporating cylinder pressure sensors are now available for passenger car diesel engines.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) has been used for many years in both petrol and diesel LD engines to reduce NO_x emissions by diluting the charge air/fuel mixture and thereby reducing peak gas temperatures and decreasing oxygen concentrations. A portion of the exhaust gas is recirculated to the combustion chamber through a control valve and mixed with the incoming air in the inlet system. The application of EGR is being continuously refined with more sophisticated electronic systems to give greater control over EGR ratios, and thereby further reduce NOx. In order to meet future emission regulation levels this technology has been extended to HD applications, in particular using cooled EGR systems. As well as NO_x reductions of up to 50%, fuel consumption reductions of 2% have also been achieved, although soot emissions are generally increased. The requirement for cooling high levels of recirculated exhaust gas places a significant additional burden on engine cooling systems, particularly in the case of HD engines. EGR cooler fouling and the formation of corrosive condensates is a problem with high levels of cooled EGR, resulting in a preference for ULSD. Low pressure EGR loops, with EGR extracted from the exhaust downstream of a particulate filter is likely to be implemented by some manufacturers. Currently EGR is an alternative to NO_x after-treatment for meeting emission limits, but in future both measures will be required.

B.4.4 Exhaust After-treatment

Although advances in mechanical design, advanced fuel injection systems and electronic controls have achieved large reductions in emissions, and small incremental gains in fuel consumption, after-treatment devices are considered indispensable in order to meet stringent emission regulations. In general, all of these devices are very sensitive to fuel specification, in particular requiring a very low sulphur content.

Oxidation Catalysts

Oxidation catalysts have been fitted to European LD diesel vehicles for many years to reduce emissions of HC, the SOF content of PM (soluble organic fraction; the HC adsorbed onto the surface of particles), and CO. Oxidation catalysts promote the oxidation of HC and CO with oxygen in the exhaust to form CO_2 and H_2O. Fuel sulphur levels of maximum 500 ppm (m/m) are required to avoid excessive production of sulphate based PM and to minimise catalyst deactivation by sulphur poisoning. Lower levels of sulphur (50 ppm (m/m)) can increase the effectiveness of oxidation catalysts by up to 50% and contribute to greater durability. Oxidation catalysts have not generally been used in HD vehicles with the exception of urban buses, and are not considered necessary to meet HC and CO requirements of future HD emission regulations.

Particulate Traps

Much development has been directed towards filtration systems for trapping diesel PM. Most systems developed use filters based on ceramic monoliths, but the key to achieving commercial practicality is the development of regeneration methods to either periodically or continuously "burn" off the PM trapped to avoid build up of excessive exhaust back pressure. Very high PM reduction efficiencies of >90% are possible. This technology is considered essential for attaining future PM emissions standards. Typically though, there is a fuel consumption penalty with the application of these traps as the regeneration techniques rely on fuel energy to burn the PM off the catalyst, and sometimes requires periodic operation of the engine in an inefficient manner during the regeneration cycle.

Sulphur levels of less than 50 ppm (m/m) are typically required for these technologies.

NO_x Reduction Catalysts

As is the case with PM traps, NO_x catalyst or adsorbers are considered necessary to attain large reductions of NO_x in future regulations. As diesel engines run on excess air, the highly efficient three way catalysts used on petrol engines are not effective to reduce NO_x. Much work is being undertaken to develop lean NO_x catalysts using a variety of catalytic technologies.

Selective Catalytic Reduction

This uses reducing agents such as urea or ammonia to catalytically reduce NO_x to N_2. This highly effective technology has been used for many years in industrial processes and stationary engines, but has been limited in application to vehicles by virtue of the large size and complexity of the technology. There are also safety concerns with the use of ammonia. However, these systems have been used in a small number of light duty vehicle models as well as in some heavy duty applications. It is likely that this technology will see wide-spread use in heavy duty applications and larger passenger cars in future, particularly as the distribution infrastructure for aqueous urea (Adblue) has largely been established in Europe.

NO_x Adsorbers

Unlike catalysts, which continuously convert NO_x to N_2, NO_x adsorbers are materials which store NO_x under lean conditions and release and catalytically reduce the stored NO_x under rich conditions. NO and NO_2 (together referred to as NO_x) are acidic oxides and can be trapped on basic oxides. Periodic rich operation of the engine is used to generate the necessary conditions to convert the stored NO_x at programmed intervals. Common rail fuel systems offer the potential of "post" (combustion) injection to produce the required reductants for adsorber regeneration. As with particulate traps, this regeneration comes with a fuel consumption penalty.

NO_x adsorders appear to be the technology of choice for small to medium sized passenger cars (up to 1500 kg), with Selective Catalytic Reduction (SCR) being the more cost-effective option for heavier vehicles. ULSD is required, as the adsorbant used in the catalyst preferentially traps SO_2, which then reduces the NO_x conversion efficiency. Even with fuel sulphur levels of 10-15ppm (m/m) periodic desulphation of the catalyst is required, which results in an additional fuel consumption penalty.

Lean NO_x Catalysts

These use catalyst formations to reduce NO_x with HC. Owing to the low levels of HC available in diesel exhaust, passive systems are limited in their reduction capability, and active systems using periodic rich running or post injection using common rail injection technology have the greatest potential, although NO_x reduction is still limited to around 35-50%. This strategy also carries a small fuel consumption penalty. Low sulphur fuel (<30 ppm (m/m)) is required to limit sulphate generation and catalyst poisoning.

Catalyst Regeneration

For after-treatment systems which require regeneration (particulate traps and NO_x adsorbers), an alternative to late post-injection for introducing reductants into the exhaust and increasing temperatures, is to introduce fuel directly into the exhaust. This can be done either by direct injection of raw fuel, or by pre-combusting the fuel to form synthesis gas ($CO + H_2$), which is particularly effective as a reductant. Injection of fuel directly into the exhaust pipe avoids the problem of oil dilution which is associated with late post-injection.

B.5 Petrol Engine Technology

Engine design technologies which impact on the fuel efficiency and emissions of petrol engines are summarised below [iv].

Mechanical Design Features / Technology	Fuel Sensivity	Status
Multi-valve heads	None	Production
Variable valve timing	None	Production
Turbocharging and after/intercooling	Low	Production
Combustion chamber/charge air motion optimisation	Low	Production
Engine Control Technology		
Electronic engine management	Low	Production
Exhaust gas recirculation	Low	Production
Direct Fuel Injection	High (S<~50 ppm)	Production
Lean burn	High (S<~50 ppm)	Production
Exhaust Aftertreatment		
Advanced catalysts	High (S<~50 ppm)	Production

B.5.1 Mechanical Design

In general, all the mechanical design developments discussed here do not have significant impacts on fuel specification requirements.

Friction

The same general comments as for diesel engines apply, see Section B.4.1.

Volumetric Efficiency

Similar comments to those for diesel engines in Section B.4.1 apply, with the exception that excess air is not used in homogeneous charge spark ignition applications.

Several technologies have developed to increase volumetric efficiency:

- **Multi-valve cylinder heads** are now almost standard in automotive applications.
- **Variable valve timing** offers increased volumetric efficiency and torque increases across the entire speed range. Control of residual burnt gas remaining in the cylinder from the previous cycle is possible by control of valve overlap, and this can reduce NO_x emissions in the same manner as exhaust gas recirculation (EGR).

Variable Intake Geometry

By using variable length inlet tracts, the air flow can be improved across the engine speed range. This results in a flatter torque curve and higher power output. Thus smaller displacement engines may be possible.

Turbocharging, while common in performance based petrol vehicles, is not generally utilised for any fuel efficiency or emissions benefit. However, by increasing the specific power output, smaller engines can be used which may give some vehicle mass benefit and associated fuel savings. This is commonly referred to as "downsizing" and this has become more and more popular recently as the pressure to reduce fuel consumption and CO_2 emissions increases.

B.5.2 Combustion Chamber Design

While the main focus and the biggest reductions in emissions for spark ignition engines has come from catalyst technology, development of combustion chamber geometry has contributed much to improved engine out emissions and fuel consumption. Minimising crevice volumes where fuel can escape primary combustion, and achieving stable robust combustion with low variability are the main objectives. More robust combustion allows higher levels of EGR to be used to reduce NO_x emissions and also provides some small fuel consumption benefits. Future impacts of further refinement in conventional spark ignition engines are limited.

B.5.3 Engine Control Technology

Carburettor Fuel Systems

A large proportion of the South African vehicle fleet use carburettors for fuel metering. Due to the generally poorer fuel atomisation of carburettors relative to fuel injectors, carburettor engines may be more sensitive to fuel parameters such as high-end volatility and heavy aromatics content. Although carburettors were developed intensely through the late 70's and 80's, they are unable to provide the close air-fuel ratio control required to effectively reduce CO, HC and NO_x using three way catalyst technology. They were thus phased out rapidly overseas as this technology became prominent. Carburetted vehicles were manufactured in significant volumes in South Africa up until the application of emissions legislation in January 2008.

Fuel Injection Systems

The control of air-fuel ratio and spark timing is critical to minimising both fuel consumption and emissions production in spark ignition engines. Multi-point fuel injection (MPFI) systems with sequential fuel injection (SFI) are now dominant. SFI allows individual optimising for each combustion event and more precise control of fuelling, particularly during transient events.

Gasoline Direct Injection (GDi)

Direct fuel injection in spark ignition engines allows fuel injection directly into the cylinder (rather than into the manifold as with conventional fuel injection systems) during the compression stroke. GDi engines can be configured to create a stratified, or non-homogeneous, charge or to create a fully homogenous charge similar to fuel injected engines. Stratified charge operation allows ultra lean burn conditions under part load conditions (AF ratio ~50 compared to stoichiometric AF ~14.5) which give large fuel consumption and emissions benefits. Pumping losses are greatly decreased by reducing the degree of throttling required at part loads. At high loads the GDi engine can operate in a homogeneous mode in the same manner as a conventional engine. Although engine out NO_x is reduced compared to a conventional homogeneous charge engine, the lean operation renders conventional 3-way catalysts ineffective, and NO_x adsorber type catalysts with periodic stoichiometric operation regeneration may be required to meet Euro ^{IV} limits. This requires a very low sulphur fuel (<30 - 50 ppm (m/m)) to enable this technology to meet this NO_x level.

Homogeneous Charge Lean Burn Engines

Lean burn engines offer high fuel efficiency and low engine out HC and CO emissions. However, engine out NO_x emissions are higher than allowable. Difficulty in effective after-treatment to reduce NO_x in lean burn engines has limited their development in favour of stoichiometric 3-way catalyst technology. Development of this technology has continued, however, and improved high swirl combustion chamber design leading to better combustion stability has extended the lean limit to air–fuel ratios of approximately 25:1. Further developments in NO_x adsorber and lean NO_x reduction technologies (see diesel engine section) may see this technology enter the market. As for diesel engines, a low sulphur fuel is required to enable the NO_x after-treatment technologies. Toyota produced a lean burn vehicle in 1994 which was claimed to reduce fuel consumption by as much as 20% over certification test cycles. Subaru and Hyundai have also produced lean burn engines in production vehicles.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) has been used for many years in petrol automotive engines to reduce NO_x emissions by diluting the charge air/fuel mixture and thereby reducing peak gas temperatures. Pumping losses are decreased through the use of EGR in spark ignition engines, as wider throttle openings are required to obtain the desired power. The application of EGR is being continuously refined with more sophisticated electronic systems to give greater control over EGR ratios, and thereby lower NO_x formation. Improved combustion chamber designs allow higher EGR ratios without causing combustion instability. Future developments will also extend EGR to higher engine operating loads. As well as large NO_x reductions, fuel consumption benefits also results from EGR.

B.5.4 Exhaust After-treatment

Although advances in mechanical design, fuel injection systems and electronic controls have achieved large reductions in emissions, and small incremental gains in fuel consumption, after-treatment devices are considered indispensable in order to meet future emission regulations. In general, all of these devices are sensitive to fuel specification, in particular requiring a low sulphur content.

Oxidation Catalysts

Oxidation catalysts were the first application of catalyst exhaust after-treatment in automobiles. These catalysts promote oxidation of CO and HC in the exhaust to CO_2 and H_2O. As oxygen is required for this process, a stoichiometric or leaner mixture is required. Initial engines fitted with oxidation catalysts had carburettor fuel systems which provide adequate air-fuel ratio control for this technology. This technology is largely outdated now in application to petrol engines and no modern vehicles are made with this technology.

Three Way Catalysts

Three Way Catalysts (TWC) are by far the most important technology in countering gaseous emissions from petrol vehicles. The TWC essentially uses a catalyst to complete the combustion reaction as much as possible: it attempts to use all the oxygen in the exhaust (oxygen that escaped combustion and the oxygen in the NO_x emissions) to oxidise the CO to CO_2 and the unburned hydrocarbons to H_2O and CO_2. It derives its name because it effectively combats all three regulated emissions. However in order for the chemistry to work, the amount of oxygen available has to exactly match the CO and HC that needs to be reacted. This implies that the air to fuel ratio has to be exactly correct for complete combustion (having only CO_2 and H_2O as products). This air to fuel ratio is known as the stoichiometric air to fuel ratio for that specific fuel.

This requirement for stoichiometric air to fuel ratios means that TWC's can not be applied to diesel engines or to lean or stratified charge (such as GDi engines) as these engines do not operate near to the stoichiometric air to fuel ratio. This requirement also led to the requirement for advanced electronic fuel injection systems with exhaust oxygen sensing feedback to precisely maintain the correct air/fuel mixture.

Under steady state operation, TWC's are extremely efficient with conversion efficiencies above 98%. In real world driving conditions, as a result of transient effects, this efficiency may drop to of the order of 90%, although state-of-the-art advanced engine control systems do not lose as much efficiency because of transient effects. By far the most significant issue with vehicles fitted with TWC's is the so called cold start emissions. The TWC is only effective once its operating temperature is above a critical threshold, said to have reached "light-off", (typically 250 - 350°C) and is therefore unable to react any engine out emissions for some time after a cold start, until the catalyst has reached this critical temperature. Advanced TWC's, discussed below, are applied in an attempt to reduce this effect.

Advanced Three Way Catalysts

As emission limits have reduced, the proportion of emission produced in the cold operation phase before the catalyst reaches "light-off" has become increasingly significant. Catalysts having faster warm-up and lower light-off temperatures are necessary. Close coupling of catalysts to the exhaust manifold decreases warm up time, but increases thermal stress on the catalyst under high load conditions, which may result in accelerated catalyst ageing and failure. Other approaches, such as electrically heated catalysts and adsorbers, have proved feasible to reduce cold start emissions, but are not yet an element of production technology, partly because of the cost implications.

Increased tolerance to fuel sulphur has also been a significant focus of development of advanced catalysts to provide high conversion efficiencies over an extended life, to meet durability regulations. Reduction of sulphur levels in petrol will aid this development. European work has shown that reductions in sulphur from 380 ppm (m/m) to 18 ppm (m/m) decreased CO, HC and NO_x emissions by 10%. Similar work in the United States showed reduction of between 10-20% in the various species using 1983-89 technology vehicles with sulphur reductions from 450 to 50 ppm (m/m).

Much of the development work of existing catalyst technology is focussing on improved formulations including optimum washcoats and the type and concentrations of the precious metals used, in order to provide improved performance in the areas discussed above.

NO_x Reduction Catalysts

These have been discussed in the diesel section and also in the lean burn and GDi petrol engine sections. Again, low levels of sulphur are required to enable this technology, which for petrol engines is in turn a technology enabler for lean burn and GDi, with their associated fuel efficiency benefits.

Appendix C: New Zealand's Vehicle Emissions Control Strategy[iv]

C.1 Background
C.2 Vehicle Fleet Emissions Model
C.3 Environmental Capacity Analysis
C.4 VFECS Policy Outcomes

C.1 Background

The impact of vehicle traffic on local air quality in New Zealand has come under much attention in the last five years. To a large extent, the general perceptions of the public at large on how vehicle emissions affect the environment, and what should be done about the problem, are drawn from what is seen to be happening overseas. Internationally, efforts to regulate vehicle emissions commenced over 30 years ago, but urban air quality is still a problem in many countries.

In 1996 the Ministry of Transport (MOT) embarked upon the Vehicle Fleet Emissions Control Strategy (VFECS), a programme of work to define how road transport affects local air quality, thereby giving direction to the appropriate means for its control. The relevance of this to the fuel quality debate is that the work has indicated that fuel quality, engine and emissions control technology are only some of the factors contributing to the vehicle-related air quality problem. Vehicle numbers, traffic density and driving conditions are all significant factors, and increasing congestion may even outweigh the benefits of improvements in vehicle and fuel technology.

This work involved the development of two main outputs:

- The Vehicle Fleet Emissions Model (VFEM)
- Environmental Capacity Analysis (ECA)

C.2 Vehicle Fleet Emissions Model

The Vehicle Fleet Emissions Model (VFEM) was developed to predict the average fleet performance, or "fleet weighted average emissions rate" of the key exhaust contaminants (CO, NO_x and PM) and their projection over time in response to fleet turnover.

The fleet weighted "average" vehicle, at a particular date, reflects the full range of vehicle types, fuels, age and engine/emissions control technology in the vehicle fleet at that time. For example the model predicts that in 1999 for instance, the "average" vehicle under freely flowing central urban driving conditions emitted 11 g/km of CO. For 2005, say, the corresponding emissions rate for the average vehicle under the same driving conditions will be lower (around 8 g/km) because of the introduction of cleaner vehicles resulting from fleet turnover.

The primary structure of the VFEM is not the age or source of the vehicle, or other such factors conventionally used to characterise emissions performance, but the interaction of the engine technology with road design and traffic driving conditions. The characterisation process for emissions measures relates directly to road types and driving conditions. This is combined with fleet profiles which consider vehicle type, age and emissions control technology (both what is installed on any particular vehicle and how effectively it actually functions), fuel type and fuel economy.

The projections from this model indicate that the emission rate of a particular pollutant per kilometre increases significantly and exponentially with the degree of traffic congestion. For the above example of central urban driving conditions, the emission rate of CO per kilometre from the "average" vehicle in 1999 under free-flow conditions increases by a factor of three in congested flows, when the traffic volume approaches the capacity of the roadway. This is illustrated in Figure below [iv]. There is a significant increment again for the running period immediately after a cold start, which can represent a significant proportion of a typical local urban trip.

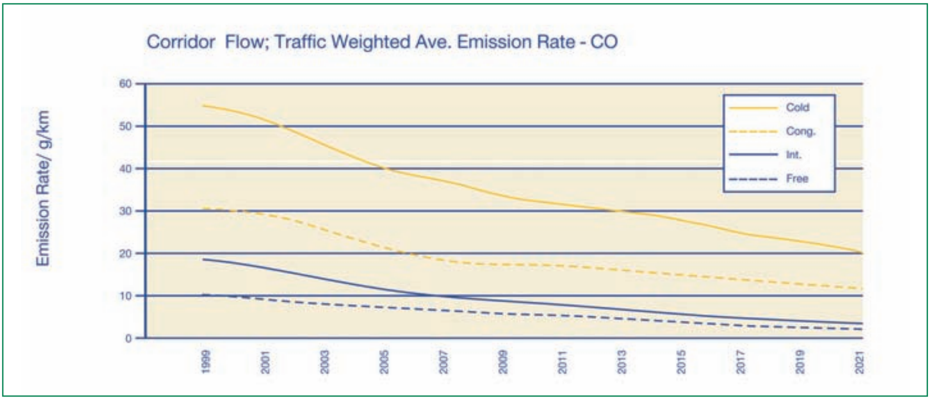

Figure 19: Predicted CO Emission Rates in New Zealand [iv]

The projections are based upon the New Zealand fleet evolving generally as per international practice in emissions standards through the future, for new entrants to the fleet. The effect of improving vehicle technology on overall emissions rates is governed by the rate of turnover of the fleet, with the result that it takes time for the net effect to make a contribution to what is essentially a local area air quality problem. The direct benefits of the new, cleaner vehicles are not captive to the area of need.

The conclusion drawn might be that, in contrast to improvements in vehicle technology, improvements in fuel quality would be immediate and be effective nationwide but as discussed elsewhere, the direct impacts of fuel quality on emissions are fairly limited. The more important effect is that they "enable" new emissions control technology. However, the fleet turnover is influenced by a number of factors, which have often have much more to do with affordability and availability of vehicles (economic and trading considerations) than transport policy or fuel quality.

In summary, what the VFEM points to is that the emissions output of vehicle traffic as a collective source in the local airshed (local area) is dependent on more than tailpipe performance indicators. It is the product of three factors:

- **Vehicle technology**: the average "Fleet Performance".
- **Road network density**: the amount of potential traffic activity within a given area air-shed.
- **Traffic density**: on each road corridor in the network, the congestion influence on actual per kilometre vehicle emission rates.

It can be seen from Figure 19, for the CO example, that the benefits of fleet improvement over 10-15 years can be countered by the local increase in traffic volumes, moving the corridor flow from the interrupted to the congested condition, and this is a contemporary trend with the increasing demand for travel in New Zealand.

C.3 Environmental Capacity Analysis

The main outcome of the VFECS programme has been the concept of "Environmental Capacity Analysis" (ECA). Traffic engineers refer to the "capacity" of the road network, that is, the fact that it can carry a finite volume of traffic before reaching the congested state. By analogy, reference may also be made to the capacity of the urban air-shed, which can absorb only so much vehicle emissions loading before concentrations reach pollution levels of concern. This capacity is at its lowest under calm, or stable air conditions.

This concept of capacity can be used to represent a limiting benchmark for managing the emissions activity in a given urban airshed, in a manner that recognises the different circumstances of different localities, both currently and as they change through the future.

The ECA framework is built around the city traffic network modelling process, a facility routinely maintained by every urban management authority. The emissions factors produced by the VFEM are designed to be integrated with any traffic model, in a way that it is possible to calculate the vehicle emissions loading for each link in the network, for the current and future projected traffic flows. The road network provides the skeletal structure in this inventory process, allowing direct comparison of the local emissions outputs from the various sources in the vicinity, for each pollutant.

C.4 VFECS Policy Outcomes

The primary objective of VFECS was to ensure that the right solutions are employed, to suit the nature of the air quality problems attributed to vehicles. The greater part of New Zealand does not experience air quality problems, so the policy recommendations were designed to target the improvement where it was needed. A number of measures were advocated at the national level, aimed at ensuring that fleet-wide performance improved over time in line with global auto technology developments. These mainly concerned the formalisation of new vehicle emissions standards, and review of fuel specifications to ensure they would be compatible with current and prospective engine technologies.

Appendix D: Air Contaminants[iv]

D.1 Carbon Monoxide
D.2 Nitrogen Dioxide
D.3 Sulphur Dioxide
D.4 Particulates
D.5 Ozone
D.6 Benzene
D.7 Toluene and Xylene
D.8 1,3-Butadiene
D.9 Formaldehyde and Acetaldehyde
D.10 Benzo(a)pyrene

This Appendix provides an overview of the key air contaminants arising from use of petrol and diesel. Where appropriate, relevant information specifically from New Zealand is included. The air contaminants included are the five key contaminants (CO, NO_2, SO_2, particulates and O_3), plus a number of hazardous air pollutants (benzene, toluene, xylene, 1,3-butadiene, formaldehyde, acetaldehyde and benzo(a)pyrene). For each contaminant a discussion of its sources, health effects and emission control strategies is presented.

As stated elsewhere in this report, it is well recognised that the primary concern in South Africa from an air quality perspective is indoor air quality in less affluent areas which rely on solid fuel fires for cooking and space heating. The discussion in this appendix is concerned only with outdoor urban air contaminants with a specific view on those related to the consumption of petrol and diesel in transport.

D.1 Carbon Monoxide

Carbon monoxide (CO) is a colourless, odourless and tasteless gas that is poisonous to humans in high concentrations. CO is a trace constituent in the atmosphere, produced by both natural processes (eg. volcanoes) and human activities, (eg. the incomplete combustion of carbon-containing fuels).

Petrol-fuelled motor transport is the major source of CO in urban airsheds. CO emitted from vehicles is solely the result of a lack of available oxygen within the combustion zone, caused by an over rich mixture or poor fuel volatilisation/

mixing with air. Studies in New Zealand have indicated that mobile sources make up approximately 90% of CO emissions in the Auckland region. Domestic fires also contribute a significant proportion of CO emissions in winter, possibly up to 50% in Christchurch.

Adverse Effects

CO affects human health by reducing the amount of oxygen that can be carried in the blood to the body tissues. When inhaled, CO combines with haemoglobin (Hb), the blood's oxygen-carrying protein molecule, to form carboxyhaemoglobin (COHb). In this state the Hb is unable to carry oxygen.

CO levels are of concern from a human health perspective if they exceed recommended air quality guidelines, which are generally based on a No Observed Adverse Effect Level (NOAEL) of 2.5% carboxyhaemoglobin in blood.

Emission Control Strategies

In essence, to minimise CO emissions, vehicles must run at their optimal efficiency, and create CO_2 instead of CO. Fuel oxygenate content has a direct impact on CO emissions. Adding oxygenates induces a lean shift (i.e. introduces oxygen) which reduces CO emissions. Reducing the aromatic content of petrol could also reduce CO emissions, but tends to increase NO_x emissions by a similar rate.

The New Zealand VFECS reached the following conclusions (MOT, 1997):

- Of the technical control measures assessed, only two provide the necessary reductions in CO emissions, and over an extended timeframe:
- Introducing a system of emissions standards for new vehicles.
- Adopting a wholesale change to diesel fuelled light vehicles (diesel engines operate under excess air at all conditions) would have an impact on particulate levels.
- Non-technical measures applied to traffic corridor management appear to provide the best means of preventing local air quality CO exceedances in the near term.

D.2 Nitrogen Dioxide

In the high temperature zones of combustion processes, nitrogen in air and in the fuel reacts with oxygen in air to form nitrogen oxides: nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). These are collectively referred to as NO_x. For most combustion processes nitrogen oxides are emitted primarily in the form of NO, which slowly oxidises to NO_2 in the atmosphere. Nitrogen dioxide is a pungent, acidic, reddish-brown gas, that is corrosive and strongly oxidising.

According to a New Zealand report [iv], sources of nitrogen oxides include "all types of road vehicles … domestic burning of wood, coal, natural gas and LPG and certain industrial processes. Depending on the presence of other local sources such as thermal power stations and industry using significant combustion processes, motor vehicles are estimated to contribute up to 80 to 95% of total emissions" of nitrogen oxides. NO_x emissions are a consequence of the thermodynamics of the combustion cycle, rather than fuel chemistry. The extent of NO_x formation is determined by residence time at high temperatures in the presence of excess oxygen.

Adverse Effects

NO_2 in the human respiratory system causes increases in both the susceptibility to and the severity of infections and asthma. Recent epidemiological studies have shown an association between ambient NO_2 exposure and increases in daily mortality and hospital admissions for respiratory disease.

NO_2 is a significant pollutant not only because of the health effects it directly causes, but also as a result of the role it can play in the generation of photochemical smog events and the production of secondary particles that cause visibility degradation. NO_2 does have some synergistic effects, but the mechanisms are poorly understood.

Oxides of Nitrogen coming from transport has been specifically linked to the Brown Haze events in Cape Town.

Emission Control Strategies

Petrol

For petrol engines, tailpipe NO_x emissions are predominantly controlled with the use of three-way catalysts, although exhaust gas recirculation (EGR) will also provide some benefit. Changes in fuel quality can influence the NO_x emissions performance, but generally the magnitude is small. The main fuel parameters which can influence NO_x emissions from petrol cars are sulphur and aromatics, and to a lesser extent, olefins.

Reducing sulphur levels in petrol (to 100 ppm (m/m) or less) increases catalyst efficiency and may reduce NO_x emissions by up to 10%.

Reducing the aromatic content of fuels also increases NO_x emissions, as catalysts are thought to work more efficiently with relatively high aromatic fuels.

Diesel

For diesel engines, a number of fuel quality parameters have competing effects on NO_x emissions. Changes in diesel engine technology which can reduce NO_x emissions will generally increase particulate emissions and fuel consumption. However, increasing cetane number has been found to reduce NO_x emissions. The cetane number can be related to the aromatic content of the fuel; as the aromatic content decreases the cetane number increases. Therefore, decreasing the aromatic content of diesel may reduce NO_x emissions.

Advanced after-treatment systems require low sulphur content diesel, 50 ppm (m/m) or lower.

D.3 Sulphur Dioxide

Sulphur dioxide (SO_2) is a colourless, soluble gas with a characteristic pungent smell. It reacts with water in air to form sulphuric acid aerosol (H_2SO_4).

SO_2 is primarily produced through the combustion of fuels that contain sulphur, but can also be emitted from a number of specific industrial operations, such as sulphuric acid manufacturing, the roasting or smelting of mineral ores containing sulphur, and oil refining.

Adverse Effects

The health effects of SO_2 have been recognised for many years. SO_2 is a potent respiratory irritant when inhaled and ambient levels of SO_2 have been associated with increases in daily mortality, hospital admissions for respiratory and cardiovascular disease, increases in respiratory symptoms, and decreases in lung function. Due to the high correlation between ambient SO_2 levels and other pollutants, especially particles, it is difficult to attribute the observed effects to SO_2 alone.

Emission Control Strategies

While SO_2 from vehicles may not be considered to be of significant concern,

SO_2 is a significant pollutant because of the role it can play in the production of secondary particles. As such, any assessment of the benefits of reduction measures must also take into account the benefits that may be derived as a result of reduced levels of particles.

Ensuring that fuel is compatible with the emissions control and fuel-efficient technologies (particularly catalytic converters) is a key issue. Sulphur reduces the efficiency of the catalysts used to remove a number of the other key air contaminants, namely NO_x and hydrocarbons (i.e. sulphur "poisons" the catalyst). This is particularly relevant for diesel after-treatment technologies, and will become increasingly important in the future for petrol engines.

In essence, to reduce sulphur emissions and to enable technologies to work optimally, sulphur levels in fuel must be controlled.

D.4 Particulates

Particles are emitted from motor vehicles (particularly diesel vehicles), domestic fuel burning, fossil fuel-based electricity generation, some industrial processes, and industrial and domestic incinerators. Secondary production of particles can be significant, with the most important being:

- Sulphates, which derive primarily from SO_2 emissions.
- Nitrates, which derive primarily from NO emissions.
- Organic aerosols, which derive primarily from volatile organic compound emissions.

Natural sources of particles include dust (which can be exacerbated greatly by human activities such as transport), pollens and sea spray.

Airborne particles can occur in a range of different sizes. From a health perspective, particles smaller than 10 microns in diameter are of greatest concern as they are able to enter the lungs. Most air-quality monitoring is for particles less than 10 microns in diameter (PM_{10}), although increasingly attention is turning to particles less than 2.5 microns in diameter ($PM_{2.5}$).

From New Zealand, the Auckland emissions inventory showed that, on a "typical winter day", domestic sources contribute approximately 48% of the annual total emissions, commercial sources contribute approximately 5%, major industry contributes 32% and mobile sources contribute the remaining 15%.

In Christchurch, where the extent of domestic fuel burning in winter is more significant than in Auckland, home heating contributes approximately 82% of the PM_{10} on a typical winter day, with motor vehicles contributing 10% and industry 8%. The "winter smoke" phenomenon is also experienced in some other South Island urban areas.

Adverse Effects

The major effects of concern with regard to airborne particles are increased mortality, aggravation of existing respiratory and cardiovascular disease, hospital admissions and lost work days.

Studies into the health effects of air pollution in Christchurch in New Zealand have focussed on particles (as PM_{10}), NO_2 and CO. A study into the effects of air pollution and weather on daily mortality showed that PM_{10} levels in Christchurch are associated with increases in daily mortality. The results of this study are consistent with international studies.

Particulates mostly from diesel vehicles has been specifically linked to the Brown Haze events in Cape Town.

Emission Control Strategies

Emissions of particulate matter are generally associated with diesel vehicles.

In New Zealand, the VFECS contains specific initiatives aimed at reducing the direct emission of particles from motor vehicles, which constitutes one of the most visible air pollution issues in New Zealand. These include emission standards for new diesel vehicles, and an education programme to improve tuning and maintenance of diesel fuel vehicles. South Africa has legislation which controls the smoke (and thus particulate) emissions from diesel vehicles. Roadside testing can be performed and non-compliant vehicles are issued with a repair notice and are subject to fines if the vehicle is not submitted for re-testing and shown to be compliant.

Changes in particulate pollution levels depend both on changes in emission of primary particulate and gaseous pollutants (NO_x, SO_2 and hydrocarbons), given the as yet unquantifiable contribution of other vehicle emission species to secondary particle formation. Specific (diesel) fuel parameters which affect PM emissions are density (reduced density will reduce PM emissions, but at the expense of fuel consumption) and sulphur (directly via SO_2 emissions, and indirectly via the performance of after-treatment catalysts).

Visible Smoke

Distinction must be made between particulates and visible smoke: particulate matter is defined as anything that is collectable on a filter (particulates may be present in exhaust even though no visible smoke is apparent); the defining character of exhaust smoke is that it is comprised of solid or liquid aerosol particles that absorb or deflect light.

D.5 Ozone

Ozone (O_3) is a secondary air pollutant formed by reactions of primary pollutants (nitrogen oxides and photochemically reactive organic compounds) in the presence of sunlight. O_3 is the principal component of photochemical smog.

The primary pollutants that can lead to the generation of O_3 arise from a range of sources. Nitrogen oxides come from motor vehicles, and commercial, industrial and domestic combustion activities. Sources of reactive organic compounds include industrial and domestic uses of solvents and coatings (for example, paints), and other combustion activities. Biogenic emissions or reactive organic compounds from vegetation can also be important.

Adverse Effects

Epidemiological evidence indicates that a wide variety of health outcomes are possible from exposure to O_3: short-term effects on mortality, hospital admissions, respiratory symptoms and lung function. At an experimental level, evidence suggests that short-term effects present a greater risk than long-term effects.

Emission Control Strategies

The control of O_3 requires management strategies that target reductions in nitrogen oxides and/or reactive organic compounds.

One component (either nitrogen oxides or reactive organic compounds) is likely to be the 'limiting' pollutant, and it may be that targeting these emissions will provide the most effective mechanism to reduce O_3 levels. In the absence of an understanding of which pollutant is 'limiting', it may be appropriate to take a precautionary approach and instigate measures to reduce the range of precursor pollutants. This is likely to be achieved as a result of any programmes adopted to reduce emissions of the other key air pollutants.

D.6 Benzene

Motor vehicle related emissions of benzene derive partly from evaporative emissions or unburnt benzene in the fuel (primarily from petrol engines), and partly from the dealkylation of other aromatic hydrocarbons in the petrol during combustion. Benzene can also be formed in the combustion process from non-aromatic sources, although this may be less significant.

Adverse Effects

Adverse health effects arising from exposure to benzene are well documented. The most significant effects are haemotoxicity, genotoxicity and carcinogenicity. Benzene has been classified as a Group 1 (known human) carcinogen by the International Agency for Research and Cancer (IARC) and is assessed as a carcinogen by the World Health Organisation (WHO), which recommends that jurisdictions establish their own guideline values by considering the unit risk factors and the level of risk deemed acceptable.

Acute exposures to very high levels of benzene can affect the nervous system, producing a range of symptoms such as headaches, dizziness, nausea, lack of co-ordination, and unconsciousness.

Population Exposure to Benzene: a New Zealand Study

A study undertaken in New Zealand over the period 1996-1999 was designed to establish current exposure levels to benzene and other toxic organic compounds in air for typical New Zealand populations. The study involved monitoring of benzene and other aromatic compounds at 26 sites, covering both indoor and outdoor environments in a range of urban and suburban zones. It focused on typical situations in which most people are likely to be exposed, rather than specific (such as occupational) or unusual exposures.

The results indicated that:

- Cigarettes are, by far, the largest source of benzene exposure for people smoking or non-smokers living in homes with smokers.
- Benzene concentrations in indoor air in non-smoking homes are essentially the same as outdoor air at the same location, except where the house has an in-built garage.
- The highest concentrations for any site (about 20 times typical ambient air levels) were from a home with an internal double garage, and almost certainly resulted from evaporative emissions from two petrol-fuelled

carburetted cars, regularly used and parked in the garage.

- Benzene concentrations in vehicles while being driven are typically 10-50 times higher than ambient air (and sourced primarily from the traffic corridor rather than from the vehicle in question). For most non-smokers, vehicle travel for 2.5-10 hours per week contributes up to half of their overall benzene exposure.

The study indicated that, because benzene exposures in motor vehicles, where vehicle emissions are essentially the only benzene source, are a major exposure for most people, vehicle emissions make an even larger contribution to overall personal exposures than indicated by their estimated contributions to ambient air.

Emission Control Strategies

Both the benzene and the total aromatics content of petrol are important when addressing possible control measures. Reductions in benzene and total aromatic levels in petrol will have a direct effect on benzene emissions from motor vehicles. However, aromatics are an important source of octane number and must be replaced with either olefins or branched chain alkane content. Aromatics are also known to improve catalyst efficiencies.

Fitting catalysts to cars is the most effective tail-pipe treatment to reduce benzene emissions. Maintaining low levels and/or reducing the sulphur content in petrol will also, indirectly, assist in minimising benzene emissions by ensuring that catalysts can work efficiently.

D.7 Toluene and Xylene

Toluene (methyl benzene) and xylene (dimethyl benzene) are benzene based molecules that contain methyl groups attached, one group in the case of toluene and 2 groups for xylene.

Adverse Effects

A range of health effects have been associated with chronic and acute exposure to toluene, the most significant being those on the central nervous system. The range of health effects associated with chronic and acute exposure to xylene includes breathing difficulties, nose and throat irritation, and neurological effects (such as headaches, dizziness and fatigue).

Ambient air quality guidelines have been derived from the WHO Lowest

Observable Adverse Effect Level (LOAEL). Neither toluene nor xylene are considered carcinogenic.

Emission Control Strategies

For petrol handling and combustion, the aromatics content is the relevant fuel-quality parameter in managing emissions of toluene and xylene. Reductions in total aromatic levels in petrol will have a direct effect on toluene and xylene emissions from motor vehicles. However, as discussed in Section 9, aromatics are an important source of octane number and must be replaced with either olefins or branched chain alkane content. Aromatics are known to improve catalyst efficiency.

D.8 1,3-Butadiene

1,3-Butadiene is a Volatile Organic Compound (VOC), like benzene, toluene and xylene. The atmospheric half-life of 1,3-butadiene is quite short (several hours), compared with benzene (several days). There is little or no pre-formed 1,3-butadiene in petrol, its major source is combustion of petrol.

Emissions of 1,3-butadiene are believed to vary with the level of olefins in petrol, although one study has concluded that over 90% of 1,3-butadiene emissions originate from the common alkane and aromatic fractions of petrol.

Adverse Effects

Adverse health effects arising from exposure to 1,3-butadiene are well documented. Chronic non-cancer effects include cardiovascular and blood diseases, and neurological effects (blurred vision, headaches). 1,3-Butadiene has been classified as a Group 2A carcinogen by IARC (probably carcinogenic to humans). New Zealand has therefore adopted a precautionary approach to setting ambient criteria.

Emission Control Strategies

Olefins, along with aromatic compounds, are an important source of octane number. Lowering olefin content while maintaining octane levels requires an increase in either the aromatic content or the branched chain alkane content of petrol. However, based on the findings of a recent New Zealand study, lowering olefin content may not reduce 1,3-butadiene emissions.

Catalytic converters are efficient at reducing 1,3-butadiene emissions.

D.9 Formaldehyde and Acetaldehyde

Formaldehyde and acetaldehyde are carbonyls. They are both emitted as primary air pollutants, formed during the combustion of petrol and diesel, and are also formed by secondary photochemical reactions in the atmosphere.

Sources include motor vehicles, domestic solid-fuel combustion, and various types of industry, such as the manufacture of particle board, which would be a significant source at a local level.

Adverse Effects

Chronic non-cancer effects arising from exposure to formaldehyde include respiratory symptoms, eye, nose and throat irritation. Formaldehyde has been classified as a Group 2A carcinogen by IARC (probably carcinogenic to humans). WHO does not assess formaldehyde as a carcinogen, recommending a guideline value based on the NOAEL (No Observed Adverse Effect Level).

Chronic non-cancer effects arising from exposure to acetaldehyde are similar to those for formaldehyde. Acetaldehyde has been classified as a Group 2B carcinogen by IARC (possibly carcinogenic to humans). WHO has assessed acetaldehyde as a carcinogen, recommending a guideline value based on the unit risk factor.

Emission Control Strategies

There are no specific control strategies for formaldehyde and acetaldehyde. Controlling VOC emissions should ensure ambient air levels remain below the recommended criteria, and this will be ascertained by further monitoring.

D.10 Benzo(a)pyrene

Benzo(a)pyrene is one of over 40 polyaromatic hydrocarbons (PAHs), but is considered the most hazardous and is commonly used as an indicator species for the group. PAHs arise from the incomplete combustion of solid and liquid fuels. They are semi-volatile compounds, and occur both in the gas phase or attached to fine particles.

A New Zealand study found that the primary sources of PAHs in the urban environment are domestic solid-fuel consumption and motor vehicles (primarily diesel), with industrial sources providing potentially significant local sources.

Adverse Effects

Chronic non-cancer effects arising from exposure to benzo(a)pyrene include dermatitis and eye irritation. Epidemiological studies have reported increases in lung cancer in humans exposed to coke oven and roof tar emissions, and cigarette smoke, all of which contain PAH mixtures. Benzo(a)pyrene has been classified as a Group 2A carcinogen by IARC (probably carcinogenic to humans). WHO has assessed benzo(a)pyrene as a carcinogen, recommending a guideline value based on the unit risk factor.

Emission Control Strategies

A New Zealand study concluded that domestic solid-fuel consumption is the primary target for reducing (wider) benzo(a)pyrene emissions.

Fuel PAH levels affect PM and PAH emissions, therefore reducing total PAH content and, to a lesser extent, aromatics, will reduce PAH emissions. Published data also indicates that exhaust treatment systems are highly effective at reducing PAH emissions.

15 Index

—1—

1,3-Butadiene, 181, 190

—A—

Acetaldehyde, 181, 190, 191

Additives, 148

Air Emissions, 44, 45

air pollutants, 181, 187, 191

Air Quality, 12, 42, 47

Aromatics, 57, 72, 90, 104, 135, 189, 190

Ash, 127, 157

—B—

Benzene, 90, 93, 94, 95, 156, 181, 187, 188, 189

Benzo(a)pyrene, 181, 191, 192

Biodiesel, 133

BP, 23, 29

brown haze, 42, 43, 125

—C—

Carbon Monoxide, 181

Carbon Residue, 128, 129, 157

CEF, 12

Cetane Index, 12, 114, 115, 130

Cetane Number, 12, 70, 114, 115, 157

Chevref, 23

Chevron, 23, 29

Cold Flow, 117, 119

Colour, 77, 78, 113, 155, 157

combustion, 45, 164, 171

Conductivity, 137

consumer protection, 40, 41, 106, 107, 119, 127, 129, 132, 133

Copper Strip Corrosion, 84, 126

Crude, 23, 25

—D—

Density, 104, 110, 112, 155, 157

Distillation, 78, 79, 80, 112, 129, 130, 155, 157

Distribution, 26, 46, 49, 103

DPF, 138

—E—

Emission Control Strategies, 182, 183, 184, 186, 187, 189, 190, 191, 192

Emission Control Technology, 35

Emission Standards, 34, 53

emissions, 1, 2, 16, 17, 30, 34, 35, 36, 37, 43, 44, 45, 46, 47, 48, 49, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 66, 67, 68, 69, 70, 71, 74, 78, 80, 82, 83, 85, 87, 90, 91, 92, 93, 94, 95, 96, 97, 100, 101, 108, 110, 111, 112, 114, 115, 117, 123, 125, 130, 134, 135, 136, 152, 158, 159, 160, 161, 162, 164, 166, 167, 168, 169, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192

Emissions, 2, 12, 13, 30, 31, 34, 44, 47, 48, 55, 59, 83, 165, 176, 186, 190

Engen, 23, 29

Enref, 23

Environment, 42, 47, 125, 152

Environmental Protection Agency, 12, 53, 58, 69, 70, 76, 91

European vehicle emission standards, 30, 34, 43, 54, 57, 60, 61, 62, 64, 66, 67, 70, 82, 85, 87, 125, 137, 172

Evaporative Losses, 46

—F—

FAME, 133, 134, 135, 157

Fit for Purpose, 41, 146

Fit-for-Purpose, 55

Flash Point, 121, 122

Formaldehyde, 181, 190, 191

Fuel Market, 22
Fuel Quality, 41, 42, 52, 55, 59, 62, 196
—G—
Gum, 83, 84, 155
—H—
Health Effects, 49
—I—
Induction Period, 88, 155
Inspection & Maintenance, 12, 44
—L—
Lead, 12, 86, 89, 90, 106, 107, 148, 155
Lubricity, 126, 132, 133, 157
—M—
Manganese, 105
MMT, 12, 75, 76, 105
Monitoring, 41, 42
MTBE, 12, 49, 69, 95, 96, 97, 100, 101
—N—
Natref, 23
Niche products, 41
Nitrogen Dioxide, 181, 182
—O—
Octane Number, 12, 13, 73, 74, 155
Olefins, 108, 190
Oxidation Stability, 88, 131, 132, 157
Oxygenates, 57, 76, 95, 96, 97
Ozone, 13, 181, 187
—P—
PAH, 13, 135, 136, 137, 192
Particulates, 48, 123, 181, 185, 186
petrol composition, 57, 83
PetroSA, 23, 29
Phosphorus, 106
polyaromatic hydrocarbons, 13, 48, 90, 91, 135, 136, 137, 191, 192
Pool Averaging, 147
Potassium, 13, 107
properties of diesel, 110, 129
Properties of petrol, 72
—R—
Rail, 24
Refining, Production and Supply, 23, 26, 27, 54, 76, 150
reformulated gasoline, 13, 58, 69, 97
Reformulated Gasoline, 13, 58, 69, 97
Regulation, 29
Residue, 83, 84, 128, 155, 157
Road, 18, 24, 178
—S—
Sapref, 23
Sasol, 23, 29, 86, 108
Sasol Secunda, 23
secondary photochemical, 191
Smoke, 187
Specifications, 13, 16, 20, 29, 52, 55, 62, 66, 76, 77, 78, 81, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 97, 98, 104, 105, 106, 107, 109, 112, 113, 114, 116, 118, 119, 121, 122, 124, 126, 127, 129, 130, 132, 133, 135, 136, 155
Sulphur, 1, 12, 57, 59, 85, 87, 122, 123, 124, 126, 156, 157, 168, 181, 184, 185
Sulphur dioxide, 184
—T—
Test Methods, 147
Toluene, 181, 189
Total, 23, 29, 90, 91, 113, 157
Total SA, 23, 29
Transnet Pipelines, 24
—V—
Vehicle Fleet, 13, 29, 30, 176
Vehicle Technology, 59
Viscosity, 119, 121, 157
Volatile Organic Compound, 2, 13, 57, 190, 191
Volatility, 57, 78, 80, 82, 83, 96
—W—
Water Quality, 47
—X—
Xylene, 181, 189

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