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A NOVEL METHOD TO DETERMINE A  
NATIONAL DIESEL EMISSIONS INVENTORY

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## DEDICATION

*This dissertation is dedicated to Captain Nicholas John Stone who doesn't like loose ends and will be glad to see the back of this one.*

*Dark was the day when Diesel  
conceived his dread engine that  
begot you, grim invention,  
more vicious, more criminal  
than the camera even,  
metallic monstrosity,  
bale and bane of our Culture,  
chief woe of our Commonweal.  
how dare the Law prohibit  
hashish and heroin yet  
license your use who inflate  
all weak inferior egos?  
Their addicts only do harm  
to their own lives, you poison  
the lungs of the innocent,  
your din dithers the peaceful,  
and on choked roads hundreds must  
daily die by chance-medley.*

*Nimble technicians, surely  
you should hang your heads in shame.  
Your wit works mighty marvels,  
has landed man on the moon,  
replaced brains by computers,  
and can smithy a "smart" bomb.  
It is a crying scandal  
that you cannot take the time  
or be bothered to build us,  
what sanity knows we need,  
an odourless and noiseless  
staid little electric brougham.*

*A CURSE by WH Auden*

## DECLARATION

I, Adrian Conrad Stone submit this dissertation in partial fulfilment of the requirements for the degree of Master of Science at the University of Cape Town.

I declare that this is my original work and that it has not previously been submitted for any degree or examination at any university.

Signed by candidate

AC Stone

## ABSTRACT

A body of data estimating the exhaust emissions from diesel commercial vehicle engines typical of the South African vehicle population was measured in an experimental programme. The core of this work was part of the recent South African Vehicle Emissions Project (VEP), a national programme commissioned by the Department of Minerals and Energy that was completed at the end of 1998. The engine sample for the tests was made up entirely of engines manufactured by Atlantis Diesel Engines (ADE) under licence from Daimler Chrysler (formerly Mercedes Benz). The ADE assembly line closed in 1999 and so this data is becoming less relevant as these engines become less prevalent. The age of the South African vehicle population (12 years average age for heavy commercial vehicles) does, however, preclude rapid change of the model composition and so analysis using the VEP data will be useful for some time to come.

This VEP data was supplemented by studies commissioned by Mossgas and BP Southern Africa and input to a so-called "emissions inventory" model. This is simply a calculation of the total emissions produced by the vehicle park over a fixed period, usually a year, and takes no account of the dispersion of the pollutants into the atmosphere. The principle of this simple approach is that if an inventory model is sensitive to technology, fuel and population drivers, policy and growth scenarios can be simulated easily and their effects on total emissions quantified with reasonable assurance of accuracy. Given that the objective of policymaking is to decide on optimal and cost-effective actions, and not to predict to an exact degree the outcome of these actions, it may be argued that such an approach is sufficient to prioritise available emissions reduction strategies. A total of 14 scenarios were modelled and compared to a baseline of emissions from South African diesel commercial vehicles. These included the increased market penetration of technologies like turbocharging and intercooling, the reduction of diesel fuel sulphur levels, the compliance of the vehicle population to various tiers of European legislation and the conversion of the vehicle population to Compressed Natural Gas (CNG)-fuelled operation.

The inventory model was based on the so-called Distance Travelled Approach (DTA). This is a relatively simple methodology whereby average fuel consumption and emission factors, are multiplied by the distance travelled by vehicles, to give estimates for total emissions and fuel consumption. These are usually expressed by mass in tons, on a per

annum basis. DTA models are typically applied to an aggregate analysis of large populations on a national basis, as was the case in this study. More sophisticated models calculate emissions on a vehicle speed dependent basis. A rigorous disaggregation of both the vehicle population and fuel use patterns was however undertaken to augment this approach and facilitate the modelling of scenarios for emissions mitigation. The model quantified the following in this regard:

- A Proportional breakdown of diesel fuel use in South Africa by feedstock, consumer and altitude was calculated.
- A proportional breakdown of the diesel commercial vehicle population into weight categories as used by the National Association of Automobile Manufacturers of South Africa (NAAMSA) was calculated. These categories were further broken down as powered by turbo-charged, turbo-intercooled or naturally aspirated engines. The naturally aspirated groups were again distinguished by technology level, called "old and "new" for which specific data was available. The average power, operating hours and mileage was determined for each population group.

A number of databases external to the experimental work of this study were sourced to enable the disaggregations described above.

A particular problem encountered was deriving a proportional representation of a model in the marketplace, given only sales data. It was proposed, that there is a relationship defined by a finite probability of a vehicle being scrapped that increases with every year that passes since the year of sale. This applies especially in the case of large vehicle samples. The scrapping factor function is certainly non-linear, as at the very least the probabilities of scrapping a vehicle compound for successive years. Accelerated deterioration of the vehicle will further compound an increased rate of scrapping with the passage of time from the year of sale. Such product lifecycle curves are typically characterised by an exponential function known as the Weibull distribution. The manipulation of two constants allows a suitable distribution to correlate with the size of the population and to some degree average age statistics. It was decided, however, to attempt a novel approach in this study using a four constant "arctan" function that offered more flexibility and the possibility of smoothing sales data to exactly match population size, average age and median age.

The Vehicle Emissions Project results indicated that emissions from naturally aspirated diesel engines deteriorate severely with increase in altitude to an elevation typical of the South African Highveld. Turbocharged engines are far less sensitive to altitude change. Significantly, particulate matter (PM) and carbon monoxide (CO) emissions were observed to increase by orders of magnitude for naturally aspirated diesel engines. These results showed good agreement with the literature.

Correlation of diesel fuel sulphur level with PM emissions suggested strongly that pre-Euro I naturally aspirated engines are far more sensitive to diesel fuel sulphur level than indicated by numerical relations derived in Europe and published in the literature.

Naturally aspirated engines will constitute a significant sector of the vehicle population for some time to come, a situation likely to be even more pronounced in developing countries with poorer or more diverse economies. This finding is therefore highly significant for those undertaking inventory modelling in the developing world, particularly for the purpose of evaluating the effects of reductions in the legislated diesel sulphur limit. Correlations in the literature showed good agreement with those shown above for turbocharged engines.

The baseline emissions for the South African diesel commercial vehicle population calculated by the inventory model were disaggregated according to altitude and vehicle class. These results indicated the following:

- Vehicles were classified as heavy, medium and light commercial according to the NAAMSA definitions. Heavy commercial vehicles accounted for between 67% and 85% of all emissions estimated ( $\text{HC}_n$ , CO,  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{CO}_2$ , PM). Medium commercials accounted for between 7% and 13% and light commercials between 8% and 25% of these emissions.
- Emissions at altitude (elevations higher than 1200 metres) accounted for between 62% and 81% of the totals of all emissions estimated ( $\text{HC}_n$ , CO,  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{CO}_2$ , PM), the balance being emitted at lower altitudes.

A rigorous disaggregation of both the vehicle population and fuel consumption patterns was undertaken which ensures that some confidence can be placed in the results of the scenario modelling even if the absolute values are in error. The scenario modelling exercise indicated the following:

- A healthy synthetic fuel industry and reduced crude-derived fuel sulphur will have a very positive effect on air quality as regards emissions of particulate matter (PM) and sulphur dioxide (SO<sub>2</sub>).
- New engine technologies like turbo-intercooling should improve air quality substantially. Naturally aspirated diesel engines are not positive from an emissions perspective, especially given the considerable economic activity at high altitude.
- Small business growth and a concomitant growth in light commercial vehicles will impact air quality negatively. Efforts to optimise the emissions of these vehicles should be undertaken.
- The inventory model indicated significant reductions in PM and SO<sub>2</sub> emissions for reductions in fuel sulphur level. PM reduction was modelled using three correlations – two from European studies and the third from the experimental phase of this study that indicated the greatest reductions. For the recently agreed new fuel sulphur limit of 0.3%, these correlations predicted a reduction in PM emissions of 7.6%, 10.2% and 12.6%. A reduction in SO<sub>2</sub> emissions of 38.1% was indicated. For a fuel sulphur limit of 0.05% typical of Europe, reductions in PM emissions of 17.2%, 22.9% and 29.0% were predicted for the three correlations. An 88.5% reduction in SO<sub>2</sub> emissions was indicated.
- A Euro II or Euro III compliant vehicle population was shown to have the greatest potential benefit for air quality. Regulatory bodies need to ensure that these engines are sold into the market operating as designed. The rate of market penetration of these vehicles will be slow if vehicle sales continue on the trend of the last 10 years.
- Market penetration of CNG-fuelled (methane) vehicles was shown to have great potential for emissions reduction, particularly PM and oxides of nitrogen (NO<sub>x</sub>). A

complete conversion of the population to CNG was predicted to reduce PM emissions by 92% and NO<sub>x</sub> emissions by 94%.

An attempt was made to predict the future technology composition of the commercial vehicle population using the inventory model's vehicle composition model. The following was proposed:

- New technology turbo-intercooled engines should power about a third of the heavy vehicle population by 2006 to 2007.
- New technology turbo-intercooled engines should power about half of the heavy vehicle population by 2012.
- By 2020 it is likely that a quarter of the heavy vehicle population will still be powered by technology that is already viewed as obsolete today, like naturally aspirated engines or turbocharged engines without intercooling.

## ACKNOWLEDGEMENTS

I would like to pay tribute to the memory of the late Dr Ryszard Karol Dutkiewicz who supervised the experimental phase of this study.

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The bulk of the experimental work has been based on the South African Vehicle Emissions Project. In this regard I would like to thank Mike de Pontes, Project Manager of the Central Energy Fund, for his support of continued work and for permission to use all data and documentation for degree purposes. I am grateful too for the support of my former colleagues at Engineering Research (Pty) Ltd, as follows:

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The relevance of this study has been greatly enhanced by work commissioned by BP Southern Africa that was supplementary to the Vehicle Emissions Project. I extend my thanks to them, particularly their Technology Support Manager John Fitton, for their patronage of emissions studies and for their permission to use data from the confidential report. This supplementary work was carried out within the Institute for Thermodynamics and Mechanics at the University of Stellenbosch whom I must also thank for their permission to access the confidential report. In addition I thank my colleagues there, Willem Botha and Hein Reyneke for their invaluable assistance in carrying out the experiments.

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## PUBLICATIONS AND REPORTS

The experimental work performed as part of the Vehicle Emissions Project has been disseminated to interested persons and organisations in the form of the following draft report:

Stone AC, "South African Vehicle Emissions Project: Phase II, Final Report: Diesel Vehicles", Department of Minerals & Energy draft report, February 2000

The supplementary data for emissions from diesel engines fuelled by coastal synthetic diesel fuel was published in the following conference paper:

Dutkiewicz RK, Jones RE, Clarke RH & Stone AC, "The Use of Heavy Alcohols as a Blend with Diesel – Environmental Effects", conference paper presented at the 12<sup>th</sup> Annual Symposium on Alcohol Fuels, 1998

The supplementary data for emissions from turbo-intercooled engines was first compiled in the following confidential technical report:

Stone AC, Botha WJC, Taylor AB, "Evaluation of Diesel Fuels in Terms of Engine Performance and Exhaust Emissions, Part II", confidential report for BP Southern Africa, Centre for Automotive Engineering, Institute for Thermodynamics and Mechanics, Department of Mechanical Engineering, University of Stellenbosch, 26<sup>th</sup> June 2000

The results of the inventory modelling study were published in the following conference paper:

Stone AC & Bennett K, "A Bulk Model of Emissions from South African Diesel Commercial Vehicles", conference paper presented at the National Association for Clean Air (NACA) Annual Conference, Port Elizabeth, November 2001

A portion of the literature review was published in the following conference paper:

Stone AC, "Reducing Particulate Emissions from Diesel Engines in South Africa: A Review of Legislation and Technology Options", conference paper presented at the National Association for Clean Air (NACA) Annual Conference, Port Elizabeth, November 2001

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## LIST OF ABBREVIATIONS

AA:	Automobile Association (of South Africa)
ADE:	Atlantis Diesel Engines. Manufactured diesel engines under licence for Daimler Chrysler until 1999. Enjoyed a monopoly of the South African market for most of the preceding 20 years.
BD100:	100% biodiesel
BD20:	20% biodiesel blended with 80% crude derived diesel
bhp:	brake horsepower. Imperial unit of power output, equals 0.745 kW
C <sub>2</sub> H <sub>4</sub> O:	Acetaldehyde
C <sub>4</sub> H <sub>6</sub> :	1,3 butadiene
C <sub>6</sub> H <sub>6</sub> :	Benzene
CH <sub>2</sub> O:	Formaldehyde
CH <sub>4</sub> :	Methane
CKD:	Complete Knock Down. A term to indicate the process of assembly of a finished product from imported components.
CNG:	Compressed Natural Gas (Methane)
CO:	Carbon Monoxide
CO <sub>2</sub> :	Carbon Dioxide
DNPH:	2,4 Dinitrophenylhydrazine. The reagent used to form hydrazone derivatives from aldehyde emission samples.
E95:	95% Ethanol (blended fuel)
ECE R49:	Economic Commission for Europe, Regulation 49 for the control of emissions from heavy-duty diesel engines, entering the market in EU member states.
EEA:	European Environment Agency
ELR:	European Load Response Cycle. Test cycle of varying load for heavy-duty diesel smoke opacity testing. Introduced in Europe in 2000.
EPA:	Environmental Protection Agency (of the United States)
ESC:	European Stationary Cycle, a steady-state engine test cycle for measuring emissions from heavy-duty engines. Introduced in Europe in 2000.
ETC:	European Transient Cycle, a transient load and speed engine test cycle for measuring emissions from heavy-duty engines. Introduced in Europe in 2000.

FID:	Flame Ionisation Detector, the detector typically used in hydrocarbon analysers.
GC:	Gas Chromatograph
GVM:	Gross Vehicle Mass
HC <sub>n</sub> :	Unburned Hydrocarbons
HCV:	Heavy Commercial Vehicle (> 3500 kg Gross Vehicle Mass)
HPLC:	High Pressure Liquid Chromatograph
LCV:	Light Commercial Vehicle (< 3500 kg Gross Vehicle Mass)
LPG:	Liquid Petroleum Gas ( $\pm$ 50/50 Butane and Propane blend)
LSD:	Low Sulphur Diesel
MCV:	Medium Commercial Vehicle (3500 kg < Gross Vehicle Mass < 7500 kg)
NAAMSA:	National Association of Automobile Manufacturers of South Africa
NATIS:	National Traffic Information System (of South Africa)
NM VOC:	Non-methane Volatile Organic Compounds
NO <sub>x</sub> :	Oxides of Nitrogen
O <sub>3</sub> :	Ozone
PAH:	Poly-aromatic hydrocarbon
PM:	Particulate Matter
PM10:	Particulate matter with mean aerodynamic diameter of less than 10 microns. The aerodynamic diameter of a particle is defined as the diameter of the standard-density sphere that behaves the same aerodynamically as the particle in question ie: they will sediment in still air at the same rate.
SABS:	South African Bureau of Standards
SO <sub>2</sub> :	Sulphur Dioxide
T95:	95% distillation temperature of a hydrocarbon fuel
ULS:	Ultra-low Sulphur (Diesel)
UV:	Ultra Violet (radiation)
VEP:	Vehicle Emissions Project. Project in 1997 / 98 to determine South African emission factors.
VOC:	Volatile Organic Compounds

## CHAPTER 1 INTRODUCTION

The 20<sup>th</sup> century was an era remarkable in human history for invention in all spheres. It may be argued perhaps that the feats of engineering from this tide of creativity have done more to alter the fundamental nature of the world than all other human endeavours, rarely without some profoundly negative side effects, particularly ecological. Amongst all these developments, the internal combustion engine stands out as revolutionary in its impact on the mobility of people and goods, driving the expansion of trade and human activity into virtually every corner of the earth's landmasses. Massive population growth and the development of enormous industrialised economies, have created such demand for these devices that the effects on the environment resulting from their operation, such as noise and the emission of harmful pollutants, have multiplied to a scale where regulation and reduction have become imperative.

The involvement of a combustion reaction in the internal combustion engine process implies that there are both reactants and products involved in an exothermic chemical reaction. The reactants are the fuel and the air, and the products are mostly carbon dioxide ( $\text{CO}_2$ ), water and unused air. Other less benign reaction products also form though, in relatively small but significant quantities as regards human health. These products are known collectively as exhaust emissions. Other than  $\text{CO}_2$ , they include a variety of gases, such as carbon monoxide ( $\text{CO}$ ), oxides of nitrogen ( $\text{NO}_x$ ), sulphur dioxide ( $\text{SO}_2$ ), unburned hydrocarbons from the fuel ( $\text{HC}_n$ ) and solid particulate matter (PM) entrained in the gases. Concentrations in the exhaust gas range from a few parts per million to a few percent. Given the prevailing vehicle population in South Africa of some five million vehicles running for many hours per day, these small amounts multiply into many thousands of tons per annum that disperse into the atmosphere with some diversion undoubtedly into the lungs of the human and animal population.

Some of these emissions are known to be poisonous when inhaled, for instance  $\text{CO}$ , which attaches itself to the haemoglobin in the blood, preventing oxygenation. Others like  $\text{NO}_x$  and  $\text{SO}_2$  are lung irritants and have been linked to problems such as atmospheric smog, acid rain and photochemical smog formation. Unburned hydrocarbons can include carcinogenic and even mutagenic compounds, specifically the polynuclear aromatic group of substances, and have also been shown to be active in photochemical smog

reactions. PM emitted from diesel engines is in the sub-10 micron size range and is thus respirable into the alveoli of the lungs. This is a particular health risk as these carbon soot particles contain roughly 15% to 30% weight unburned hydrocarbons that, as described above, may be carcinogenic. These health risks are of particular relevance to South Africa with its large underground mining industry where the use of diesel engines is widespread, often in confined environments with poor ventilation.

In most industrialised countries some form of emissions regulations attempts to curtail these pollutants. This type of legislation is most developed in the United States (US), Europe and Japan where manufacturers are compelled to conform to ever lower limits of HC<sub>n</sub>, NO<sub>x</sub>, CO and particulate emissions. This legislation effectively drives the technological initiative to reduce the pollutants emitted by combustion engines. For heavy-duty diesel engines, on which this dissertation will focus, pollutants are quantified as grams per kilowatt power output per hour (g/kW.h) instead of grams per kilometre, which is the case for passenger vehicles. This is because load carrying capacity is paramount for commercial vehicles and many heavy-duty diesels will be destined for stationary applications. Thus measurement of pollutants is power specific rather than mileage specific. This means that heavy-duty diesel engines can be tested outside of the vehicle directly coupled to a dynamometer, a device that applies resistance or load to the engine, absorbing a proportional amount of power. Various test cycles involving varying speed and load conditions that simulate real life duty have been developed so that the emissions measured approach those emitted in commercial applications.

Urban air quality has become a global concern in recent years with most modern cities experiencing some form of air pollution that is unpleasant, unsightly and potentially harmful. It has been shown that the transport sector contributes significantly to air quality problems. South African cities are no exception to this trend, with ambient pollution levels regularly exceeding international guidelines. Cape Town's local authority Scientific Services recorded nearly 60 air quality guideline exceedences in the city centre and Goodwood areas alone in 1999 <sup>(16)</sup>. This was the first year of particulate matter monitoring in Khayelitsha where over 80 exceedences of the United Kingdom (UK) / Australian guideline were recorded <sup>(16)</sup>. Cape Town's winter Brown Haze has also been the topic of intensive study, with the results implicating diesel engines as the primary contributors.

In response to this growing problem, the Department of Minerals and Energy and the Department of Environment and Tourism, in partnership with the oil and motor industries, have undertaken a comprehensive scientific study to determine the role of road transport in city air pollution. This initiative is known as the Vehicle Emissions Project (VEP) and consists of five phases as follows.

- **Phase 1:** The gathering and evaluation of ambient air quality data within South Africa. The gathering and evaluation of existing data on motor vehicle inventory in South Africa.
- **Phase 2:** The establishment of exhaust emission levels from a local in-service car fleet and the understanding of the combination of fuel, engine and altitude influences on local vehicle emissions.
- **Phase 3:** The development or adoption of an urban atmosphere air quality model. The model aims to relate motor vehicle emission to ambient concentrations of both primary and secondary pollutants. Use of the model for scenario planning.
- **Phase 4:** The formation of policy, based on the pollution levels predicted by the model.
- **Phase 5:** The development of a plan of action to ensure conformation with the new requirements.

A Cape Town based automotive research company, Engineering Research (Pty) Ltd, was commissioned to undertake Phase 2 of this project. The term "*local in-service car fleet*" referred to above in the outline of Phase 2 includes passenger cars as well as commercial vehicles powered by heavy-duty diesel engines to account for the contribution of the commercial transport industry to urban air pollution. This dissertation is concerned with the emissions of such heavy-duty diesel engines and the resulting emissions from the South African commercial vehicle fleet. The author of this dissertation was responsible for the development of the particulate sampling equipment, testing, data processing and reporting for the heavy-duty diesel phase of the VEP while in the employment of Engineering Research.

A sample of engines was tested that was considered to be broadly representative of the South African commercial vehicle population at the time. The test fuels used in the study also represented those in the market. Tests were performed at both altitude and sea level conditions. As well as giving absolute emission levels, the results highlight the typical effects on emissions performance of factors like altitude and design features like turbochargers.

Phases 1 and 2 of the VEP have been completed but Phase 3 has been delayed because of funding problems <sup>(78)</sup>. The modelling study that comprises the second phase of this dissertation, attempts in some measure to tackle the objectives of Phase 3 as regards the emissions of compression ignition (diesel) engine commercial vehicles only. The data measured from the heavy-duty diesel engine study <sup>(93)</sup> of the VEP and the limited sample of light commercial vehicle data from the passenger vehicle study <sup>(109)</sup> were augmented by two other sources and used as input to a so-called "emissions inventory" model. This is simply a calculation of the total emissions produced by the vehicle park over a fixed period, usually a year, and takes no account of the dispersion of the pollutants into the atmosphere. Cairncross <sup>(12)</sup> has identified the need for inventory model compilations in South Africa to prioritise options for emissions mitigation, including legislation.

Such models are currently used elsewhere to attain the exact objectives of Phase 3, for example the IPIECA Tcolkit <sup>(48,49)</sup>, a sophisticated inventory model that accounts for both mobile and stationary source emissions and resolves measures to reduce these into cost to the community. The principle of this simple approach is that if an inventory model is sensitive to technology, fuel and population drivers, policy and growth scenarios can easily be simulated and their effects on total emissions quantified with reasonable assurance of accuracy. Given that the objective of policymaking is to decide on optimal and cost-effective actions, and not to predict to an exact degree the outcome of these actions, such an approach, it may be argued, is sufficient to prioritise available emissions reduction strategies. Moreover, dispersion modelling is notorious for its mathematical complexity and high cost arising from the density of data required as input to achieve a reliable result. In any event, effective dispersion models require inventories as inputs and so the inventory model can be said to be a foundation of air quality improvement.

While there is a vast body of emission factors in the literature that could potentially be applied to deriving a baseline model, it was decided to apply only the results from the VEP and experimental work performed by the author of this dissertation for other studies. This maintains the integrity of the study as a start to finish exercise from experimentation to analysis but also ensures that all data is South African, using local engines and local fuel. The review of the literature for this dissertation does, however, include a discussion of the effects of vehicle technology and fuel properties on the emissions from diesel engines. This information was used to select scenarios of likely emissions reduction strategies. Data and correlations were identified where necessary so these strategies could be modelled numerically.

The rest of this chapter consists of a review of the engineering fundamentals of the diesel engine and diesel fuel pertaining to emissions. Chapter 2 outlines the aims of this study and particular exclusions. Chapter 3 presents a review of the literature dealing with the origin, nature and effects of pollutants originating from diesel engines as well as a discussion of the techniques of emissions inventory modelling. South African air quality interventions and existing legislation are also reviewed to give some context to the necessity for studies such as this. Thereafter the respective methodologies for the experimental and modelling studies are described in Chapters 4 and 5. The results of the study are presented in Chapter 6, discussed in Chapter 7 with conclusions drawn in Chapter 8.

The problem of vehicle emissions is becoming an ever increasing problem in South Africa as the country develops and its vehicle pool grows. Cities like Cape Town and industrial areas like the Vaal Triangle already experience air quality problems comparable to those in highly industrialised nations, with all the resulting threats to the health of its citizens. While legislation controlling vehicle tailpipe emissions is still in its infancy in South Africa, it is to be hoped that studies such as this will assist in providing a platform of information from which effective and practical legislation can be formulated.

## **1.1 PRINCIPLES OF DIESEL ENGINE OPERATION**

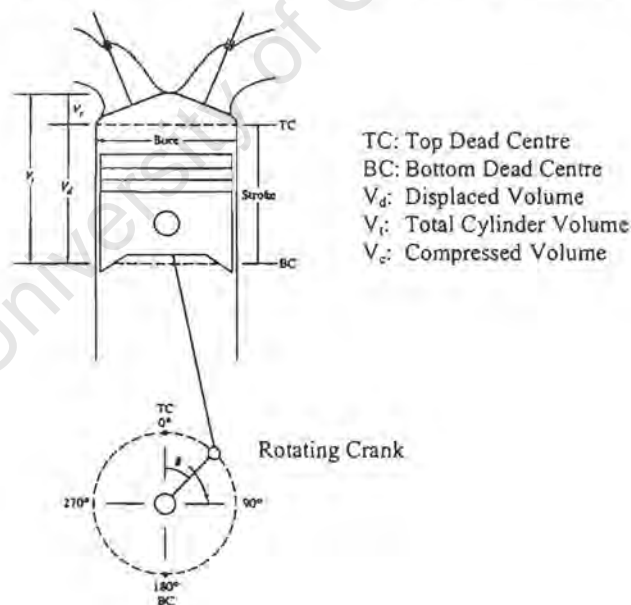
Commercial vehicles around the world are almost exclusively powered by diesel engines. Thus any study on the emissions from this transport sector essentially deals with

emissions from the diesel engine. Some discussion of the operating principles of diesel engines is therefore warranted if an understanding of the origin of commercial vehicle emissions is to be gained.

The diesel engine is more aptly also referred to as the compression ignition engine. Dr Rudolf Diesel in his original 1892 patent proposed the following:

*“An engine in which air would be compressed to such an extent that the resulting temperature would exceed by far the ignition temperature of the fuel.”*

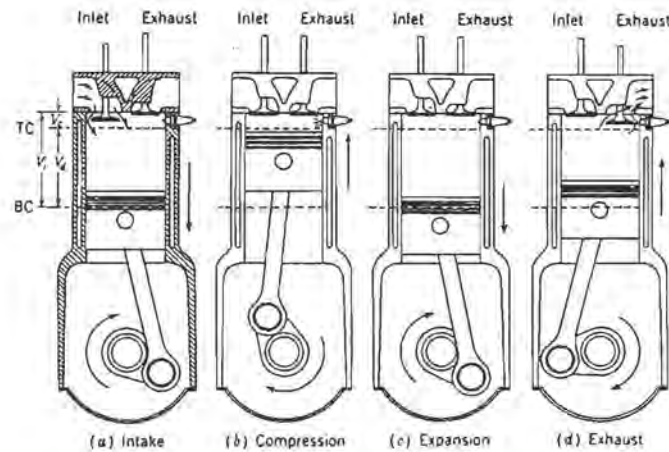
The ignition of the fuel allows for the combustion of a metered amount of fuel and the translation of the resultant heat energy into mechanical energy and useful work. As is the case with the spark ignition engines in most passenger cars, the diesel engine consists of pistons reciprocating each within a cylinder and all driving a rotating crank mechanism via hinged rods. Combustion takes place in a chamber immediately above the farthest travel of the piston. This configuration is shown graphically below in **Figure 1**.



**Figure 1:** Mechanics of the Reciprocating Combustion Engine <sup>(35)</sup>

Diesel engines operate on either a two or a four-stroke cycle involving the necessary intake of air, combustion, the transfer of energy to the crankshaft and the exhaust of the products of combustion. The four-stroke cycle is almost entirely representative of the

engines relevant to this study and so this cycle has been presented graphically below in **Figure 2**.



**Figure 2:** The four-stroke cycle of operation <sup>(35)</sup>

The air necessary for combustion is drawn in through a valve by the first stroke and then compressed by the second stroke to a pressure in excess of that required to ignite the fuel but limited by the mechanical strength of the engine components. Combustion takes place very near the beginning of the third stroke and the expanding hot gases drive the piston through the third or "power" stroke, imparting energy to the crankshaft. The fourth stroke exhausts the products of combustion through a valve.

Traditional diesel engine designs have been distinguished into two broad approaches based on the combustion chamber designs shown below in **Figure 3**. In the case of "Indirect Injection" (IDI), the first configuration shown in **Figure 3**, fuel and air are mixed to a state of high turbulence in a pre-chamber and enter the cylinder as a "torch" of burning fuel and expanding hot gases. "Direct Injection" (DI) involves the direct injection of fuel into the cylinder where it mixes to combustible limits, usually within a "bowl-in-piston" type combustion chamber as shown above in **Figure 3**.

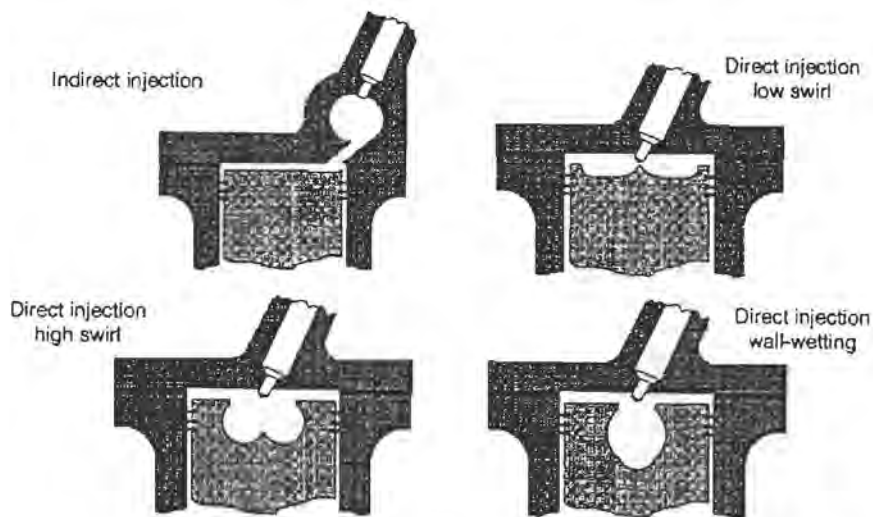


Figure 3: Types of Diesel Engine Combustion Chamber <sup>(27)</sup>

In the past, the challenges of effective fuel/air mixing in direct injection engines, especially in high-speed applications, made indirect injection designs dominant in small displacement and low-emission applications. Indirect injection engines are, however, less thermally efficient due to inherent friction that reduces volumetric efficiency and to some degree, high heat losses in the pre-chamber due to a high surface to volume ratio. The challenge facing engine designers over the last 20 years therefore, has been to achieve the emissions performance of indirect injection engines with direct injection design. Emissions legislation in Europe and the US in the early 90s in fact allowed a waiver for light-duty direct injection diesel engine technology to allow this challenge to be met <sup>(37)</sup>. This approach has by and large been successful and direct injection designs have come to dominate the market even in small displacement high-speed applications.

Fuel atomisation is another property critical to emissions performance. This is largely dependent on fuel injection pressure and injector nozzle orifice size. Typical injection pressures for diesel fuel systems are very high and range from 200 to 1,800 atmospheres depending on the type of pump. So-called rotary distributor pumps fall into the lower pressure range and have traditionally been popular due to their lower cost, especially in light-duty applications. Increasingly stringent emissions requirements have, however, necessitated very high injection pressures and the use of in-line fuel pumps, unit pumps and common rail systems where all injectors are fed from a common high-pressure rail. New generation designs are typically also electronically metered and timed relative to the crank. The engines typical of the greater part of the South African commercial vehicle

population and indeed the experimental sample of this study have mechanical in-line injection pumps.

The fuel injectors themselves are typically of the pintle type with multiple nozzle holes, the number and orientation of which conform to the shape of the combustion chamber. A typical arrangement is shown below in **Figure 4**.

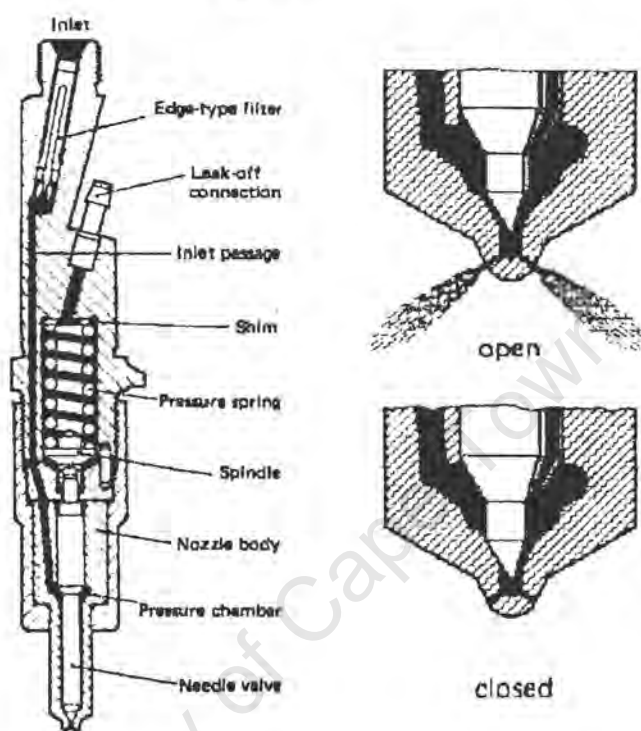
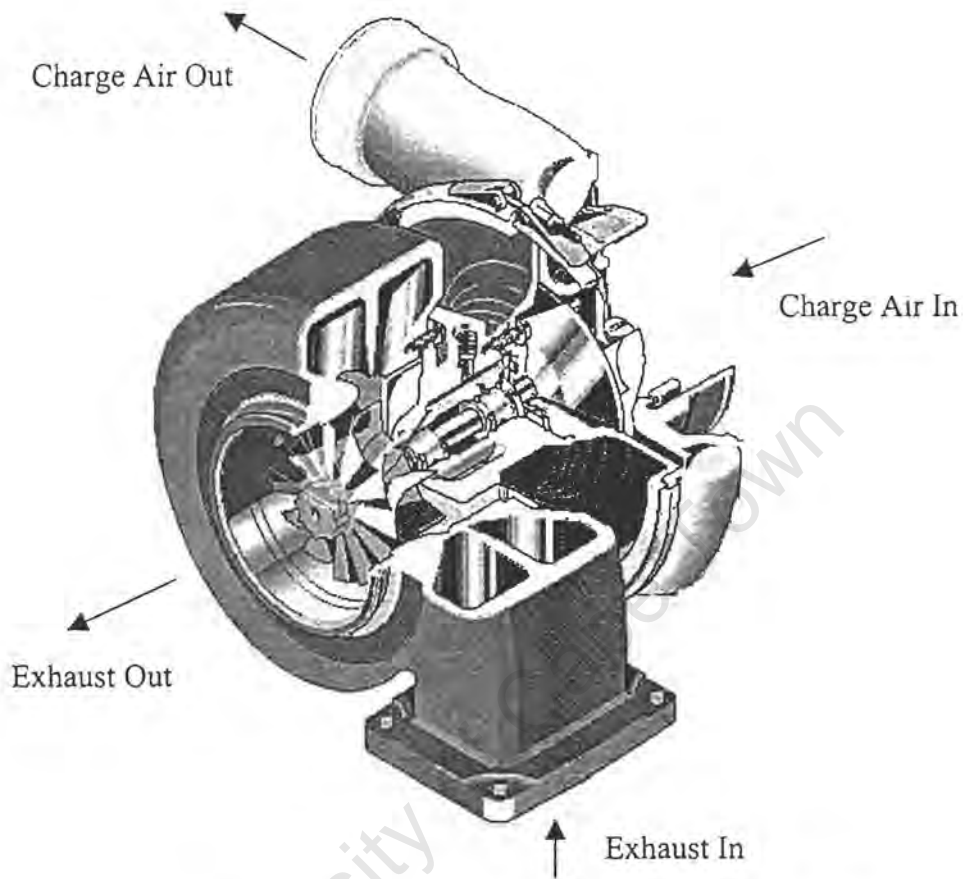


Figure 4: Typical Diesel Injector Design <sup>(81)</sup>

Air density is also critical to the effective mixing of fuel and air in the diesel engine. Increasing the mass of air in the charge by pressurising the intake air with a supercharger or turbocharger promotes effective mixing, increases volumetric efficiency and potentially increases peak cylinder pressure. A supercharger is a blower driven mechanically by the engine crankshaft and is therefore a parasitic load, but offers the advantage of delivery right across the speed and load range of the engine.

A turbocharger drives a compressor, usually radial, by means of a turbine mounted in the exhaust of the engine. This allows for the recovery of waste energy from the exhaust and therefore offers an efficiency advantage over supercharging, although pressure ratios are relatively low at part load and speed when exhaust flows are low. This effect can be compensated for by "wastegating", where the turbine and compressor are slightly under-designed for the peak exhaust flow of the engine. At high loads the excess exhaust gas is

vented by a valve usually actuated by a differential pressure membrane device triggered by the boost pressure of the charge air. The result is that the boost of the turbine picks up at a lower speed and efficiency gains are achieved over a wider speed and load range. A typical heavy-duty automotive turbocharger is shown below in **Figure 5**.



**Figure 5:** Cutaway View of Automotive Turbocharger <sup>(36)</sup>

Cooling the charge air after it leaves the compressor can further augment the gains in air density achieved by turbocharging. This is known as "intercooling" or "aftercooling" and is achieved by the application of a heat exchanger, usually of the air-to-air cross-flow finned tube type. In modern commercial vehicles, this heat exchanger is commonly mounted in "piggy-back" fashion on the existing cooling water radiator of the engine installation and both are cooled by one fan.

## 1.2 THE FORMULATION OF DIESEL FUEL

Diesel engines can run on a variety of liquid fuels from different sources, including plant oils like rapeseed oil and sunflower oil, heavy fuel oils and diesel fuel refined from crude oil. Although the ignition quality of straight cold-pressed plant oils is satisfactory for diesel engines, plant oil needs to be esterified to reduce fluid viscosity, otherwise serious fuel injector plugging occurs within a few hundred hours of operation. Gaseous fuels like natural gas can be used in a compression ignition cycle with a so-called dual-fuel system where liquid fuel is injected with the gas to ignite the charge. The prevailing source of fuel for diesel engines, certainly for those powering road vehicles, is liquid hydrocarbon fuel refined from crude oil (fossil fuel) or synthesised from hydrocarbon gas. This refined product has become highly specialised to meet the needs of advancing engine technology. Refiners have to design processes so that diesel fuel meets a number of strictly specified chemical and physical properties.

Globally, diesel fuel is refined from a great variety of hydrocarbon basestocks, including crude oils from many locations, natural gas and even gasified coal, but is refined to conform to the properties required by diesel engines. The resulting fluid consists of a great many distinct organic compounds but falls within a fairly narrow range of hydrogen to carbon ratio of 1.7 to 1.8 and specific gravity of 0.8 to 0.9 <sup>(1,35,88)</sup>. The essential diesel properties that South African refiners have to deliver to the market are presented below in **Table 1**, the South African Bureau of Standards (SABS) automotive diesel specification <sup>(90)</sup>.

Table 1: SABS Automotive Diesel Specification <sup>(90)</sup>

Property	Requirement	Test method	
		ASTM	IP or ISO
Distillation temperature for 90 % (by volume) recovery, °C, max.	362	D 86	IP 123
Flash point, °C, min.	55	D 93	IP 34
Sulfur content, % (by mass), max.	0,55	D 2622/D 5453	IP 336
Cetane Number <sup>1)</sup> , min.	45	D 613	IP 41
Copper strip corrosion (3 h at 100 °C), classification, max.	1	D 130	IP 154
Cold filter plugging point (CFPP) <sup>2)</sup> , °C, max.	-4 or 3	-	IP 309
Carbon residue on 10 % (by volume) distillation residue, % (by mass), max.	0,2	D 524	IP 14
Ash content, % (by mass), max.	0,01	D 482	IP 4
Water content, % (by volume), max.	0,05	D 95 or D 1744	IP 74
Sediment content, % (by mass), max.	0,01	D 473	IP 53
Viscosity at 40 °C, mm <sup>2</sup> /s	2,2 to 5,3	D 445	IP 71
Density <sup>3)</sup> at 20 °C, kg/ℓ, min.	0.8000	D 4052	IP 365 or ISO 3675
Oxidation stability, mg/100 ml, max.	2,0	D 2274	IP 388

NOTES

1 Provided a proven correlation between Cetane Number and Cetane Index (ASTM D 976/ASTM D 4737) has been established (for the crude being refined), the Cetane Number specification may be replaced by a Cetane Index specification with a minimum value of 48. The basic need is that the product shall have a minimum Cetane Number of 45. The reference method is ASTM D 613/IP41.

2 Unless otherwise acceptable, a product with a maximum CFPP of

- 4 °C and supplied between 1 April and 30 September (inclusive) (WINTER), and
- 3 °C and supplied between 1 October and 31 March (inclusive) (SUMMER), may be considered to be acceptable.

3 Test method ASTM D 1298/IP 160 may be used to determine density at 15 °C and the result converted to values at 20 °C (using standard calibrations) with the proviso that this is NOT a reference method.

The above specification was tabled in 1969. Certain of these fuel properties have been shown to affect the quantity of emissions from diesel engines. Since then the increasing demand for lower emissions from diesel engines has narrowed the prescribed limits on such properties and expanded the scope of diesel specifications in the developed world. These effects and comparative specifications are discussed below in **Section 3.6**.

## CHAPTER 2 OBJECTIVES OF THE STUDY

The study described in this dissertation was carried out in two phases. The first phase consisted of experimental work whereby exhaust emissions were measured from a sample of engines and fuels. This provided input for the second phase of modelling the total emissions from the South African diesel commercial vehicle fleet. This baseline of total emissions was then compared to modelling runs that included the effects of selected emissions reduction strategies. The particular objectives of these two phases are discussed separately below.

### 2.1 OBJECTIVES OF THE EXPERIMENTAL PHASE

As stated in **Chapter 1**, the experimental work that forms the foundation of this study was part of Phase 2 of the South African National Vehicle Emissions Project (VEP). Therefore the primary objective of the experimental phase was that of VEP Phase 2, namely:

*"The establishment of exhaust emission levels from a local in-service car fleet and the understanding of the combination of the fuel, engine and altitude influences on local vehicle emissions."*

The achievement of the above goal rested as much on the study design as on the quality of the experimental work. It must be stressed that the author of this dissertation played no role in the design of the VEP heavy-duty emissions study. This task was undertaken by the Steering Committee for the project. As far as the activities of the author are concerned, these being relevant to this dissertation, the objectives of the experimental work were far more concrete and explicit as follows:

- Measure the exhaust emissions of six locally manufactured Atlantis Diesel Engines (ADE) diesel engines with capacities ranging from 3.8 litres to 12 litres in both coastal and Highveld conditions with the fuels marketed in those areas and an international reference fuel. The coastal tests were to be performed in Cape Town and the Highveld tests in Sasolburg at an altitude of 1,488 metres above sea level.
- Measurement procedure was to be to the European standard current at the start of the heavy-duty project in 1997. This was the procedure devised by the European

Community which is described in EEC Directive 70/220/EEC and the United Nations' Economic Commission for Europe Regulation No. 49 (ECE R49). The procedure entails running the engine through a 13-mode steady state dynamometer cycle to test the emissions performance of medium and heavy-duty diesel engines.

- The pollutant species to be measured included the regulated emissions carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), unburned hydrocarbons (HC<sub>n</sub>) and particulate matter (PM), and the unregulated emissions carbon dioxide (CO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>), formaldehyde (CH<sub>2</sub>O), acetaldehyde (C<sub>2</sub>H<sub>4</sub>O), methane (CH<sub>4</sub>), 1,3 butadiene (C<sub>4</sub>H<sub>6</sub>) and benzene (C<sub>6</sub>H<sub>6</sub>).

## 2.2 OBJECTIVES OF THE MODELLING PHASE

Objectives for the modelling phase of the study were defined as follows:

- Create a simple robust emissions inventory model that will yield total annual emissions and emission factors for the South African diesel commercial vehicle population.
- The model should reflect the variability of the VEP data and supplementary data, that is, account for the following characteristics of the vehicle population:
  - ❖ Fuel use: synthetic or crude
  - ❖ Altitude or sea-level operation
  - ❖ Aspiration: natural, turbocharged or turbo-intercooled
  - ❖ Engine displacement
  - ❖ Technology level of naturally aspirated engines
- The model should be disaggregated as much as possible by the above criteria to facilitate accuracy and to provide a sensitive baseline so that changes to the model inputs can be evaluated.

- The model should facilitate scenario modelling of emissions, given changes to fuel or the vehicle population, for instance, changes in the regulated diesel sulphur limit.
- The model should be compiled on a Microsoft™ Excel® spreadsheet to facilitate easy dissemination and modification.

It is important to stress the exclusions from the modelling exercise. Some supplementary data was added to the VEP data set as input to the model. This was, however, measured by the author using the identical experimental apparatus and procedure, for sponsors other than the VEP, and is thus part of an extended data set unique to this study. While data from the literature was applied in the scenario modelling there was no supplementary data from the literature applied to the baseline calculation. Thus features found on some inventory models not supported by the data set were excluded. Some examples are as follows:

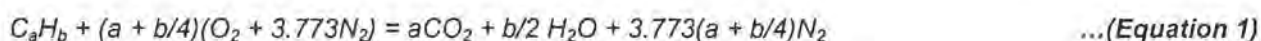
- Exclusion 1. The vehicle population was not disaggregated on the basis of average speed or variations in speed or load relating to the type of road or urban environment. The data set did not include vehicle speed-related emission factors.
- Exclusion 2. The model did not take into account the deterioration of emissions with vehicle age or accumulation of mileage. Investigation of these effects was not part of the experimental objectives.
- Exclusion 3. The objectives did not include the modelling of costs either to industry or the community as is done by more rigorous models like the IPIECA Toolkit (48,49).
- Exclusion 4. The model calculated emissions for the entire South African diesel commercial population. Other than the breakdown on the basis of altitude versus sea level there was no breakdown of emissions by region or urban centre. While this could be accomplished with the existing data set using regional fuel consumption figures, the focus of this phase was on the modelling of scenarios. These were not sensitive to regional breakdown given the aggregate modelling of vehicle usage patterns referred to in Exclusion 1.

## CHAPTER 3 THE NATURE, ORIGIN, EFFECTS, MEASUREMENT AND CONTROL OF POLLUTANTS FROM DIESEL ENGINES

This chapter presents a review of the literature dealing with the origin, nature and effects of pollutants originating from diesel engines, as well as a discussion of the techniques of emissions inventory modelling. South African air quality interventions and existing legislation are also reviewed to give some context to the origins of the particular study on which this dissertation is based. The discussion of the effects of vehicle technology and fuel properties on the emissions from diesel engines in particular, is fundamental to the development of the modelling phase of this study. This information was used to select scenarios of likely emissions reduction strategies. Data and correlations were identified where necessary so these strategies could be modelled numerically.

### 3.1 NATURE AND DEFINITION OF POLLUTANTS FROM DIESEL ENGINES

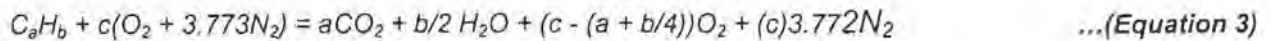
The diesel engine is fundamentally an energy converter. The chemical energy in a hydrocarbon fuel is converted to useful pressure energy and waste heat energy by a combustion reaction. The useful pressure energy does work on a reciprocating piston assembly that transmits the energy to the wheels of a vehicle or some such secondary device. The involvement of a combustion reaction in the process therefore implies that there are both reactants and products involved in an exothermic chemical reaction. The basic reaction having proceeded to completion can be expressed as follows for a general hydrocarbon fuel with average molecular composition  $C_aH_b$  <sup>(35)</sup>:



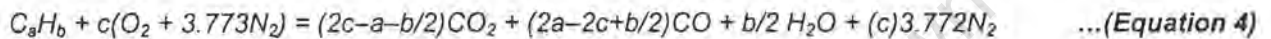
From this we can determine the *stoichiometric* or theoretically correct proportions of fuel and air for complete combustion. Applying the molecular weights for oxygen, nitrogen, carbon and hydrogen gives the following relationship for stoichiometric air/fuel ratio by mass <sup>(35)</sup>:

$$(\text{Air/FuelRatio})_s = \frac{34.56 \left( 4 + \frac{b}{a} \right)}{12.011 + 1.008 \left( \frac{b}{a} \right)} \quad \dots(\text{Equation 2})$$

If the air/fuel ratio deviates from stoichiometric proportions, **Equation 2** above will include different products. In the case of an excess of air to that required, or what is known as lean combustion, some of the oxygen will not participate in the reaction and will appear on the right hand side of the equation, as follows:



In the case of insufficient air for complete combustion, or what is known as rich combustion, there is insufficient oxygen to burn all the carbon in the fuel to  $CO_2$  and therefore some oxidises to CO, as follows:



**Equations 3** and **4** thus clearly indicate that the amount of  $CO_2$  produced by an engine is purely dependent on fuel consumption, while the amount of CO produced will be dependent on the air/fuel ratio, tending to be negligible at lean air/fuel ratios given adequate mixing of fuel and air. The overall air/fuel ratio for one combustion cycle in diesel engines is always significantly lean, although there are areas of very rich air/fuel mixture during the actual process. As a result diesel engines produce far less CO than spark ignition engines where the overall air/fuel ratio is around stoichiometric and often rich. In fact, in a real diesel engine **Equations 1, 3** and **4** will occur simultaneously in different areas of the combustion chamber. **Figure 6** below indicates the relationship between CO emissions and air/fuel ratio.

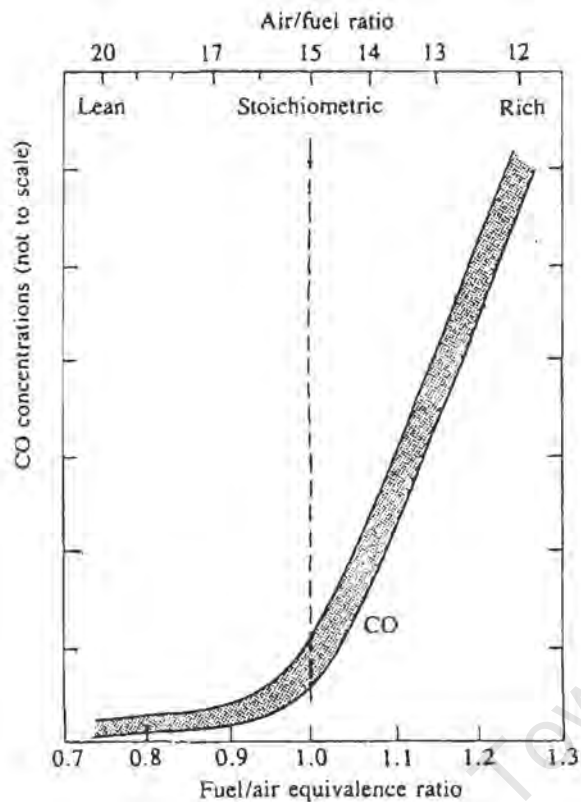
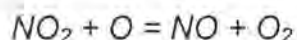


Figure 6: CO emissions vs. Air/Fuel Ratio for typical combustion engine (adapted Reference 35)

The reaction chemistry in practical combustion is more complicated than indicated by the basic derivations above. Significantly, from a pollution point of view the high temperatures generated by combustion cause the oxidation of atmospheric nitrogen. The products of these reactions are nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) although NO is the predominant oxide produced, usually constituting between 70% and 100% of the total NO<sub>x</sub> produced in diesel engines <sup>(35)</sup>. The governing reactions have been proposed as follows <sup>(35)</sup>:



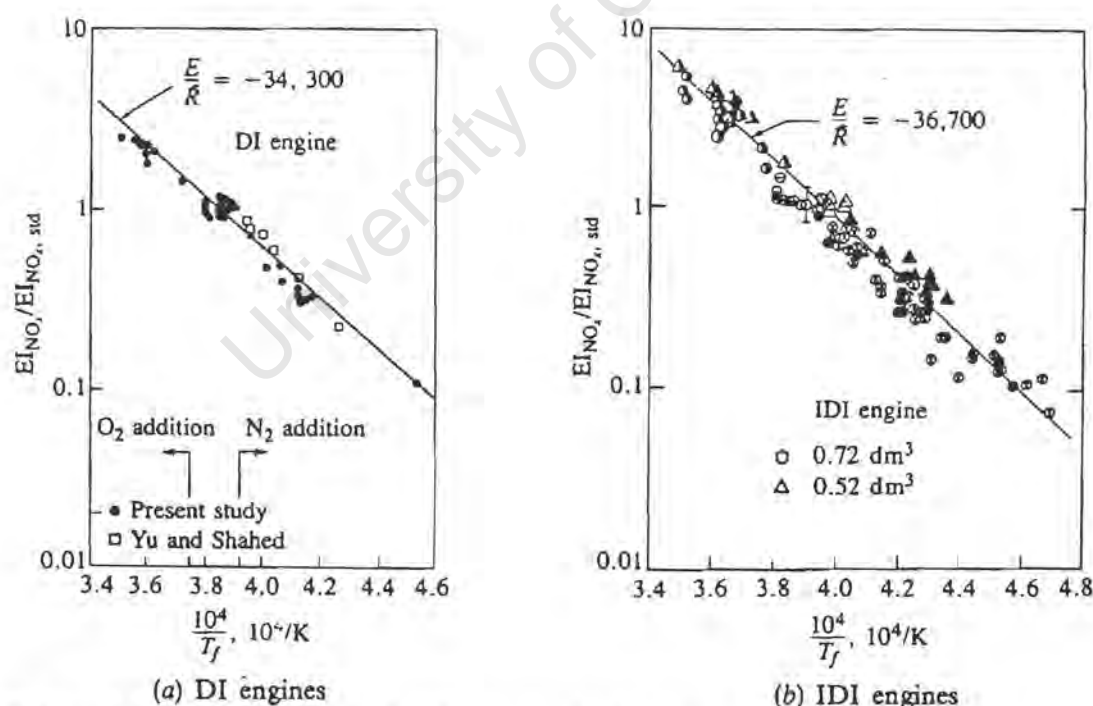


...(Equation 9)

It has been proposed <sup>(35)</sup> that  $NO_2$  forms primarily in the actual flame zone during combustion by **Equation 8** but that, subsequently, conversion back to  $NO$  occurs by **Equation 9** in the cooling reaction products, unless they are suddenly quenched by mixing with much colder gases. This may account for the predominance of  $NO$  in the  $NO_x$  produced by combustion engines. These reactions are highly temperature dependent, as illustrated by **Figure 7** below that presents a correlation of  $NO_x$  Emissions Index (EI) with the inverse of flame temperature. EI is defined below by **Equation 10**.

- If:
- $EI_{NO_x}$  = Emissions Index (EI) for  $NO_x$
  - $m'_f$  = Engine Fuel Flow Rate (kg/s)
  - $m'_{NO_x}$  = Rate of  $NO_x$  Emission from Engine (g/s)

$$EI_{NO_x} = \frac{m'_{NO_x}}{m'_f} \quad \dots(\text{Equation 10})$$



Values of  $EI_{NO_x}$  normalized with value at standard conditions.

Figure 7: Relation of  $NO_x$  formation and flame temperature for DI and IDI engines <sup>(35)</sup>

As a result,  $NO_x$  emissions in diesel engines tend to be highly load (torque output in N.m) dependent, as higher loads on the engine necessitate higher pressures and thus also

temperatures in the combustion chamber. This gives rise to significant  $\text{NO}_x$  emissions from operating diesel engines in the field, given that they are generally used in high load applications.

Another significant product of combustion not evident in **Equations 2, 4 and 5** are fuel hydrocarbons that do not combust and are emitted as part of the exhaust from the engine. These tend to be the higher molecular weight hydrocarbons in the fuel that are less easily evaporated and mixed with air but can include light ends like methane as well. In general these unburned hydrocarbons originate ( $\text{HC}_n$ ) when the combustion flame quenches on the cylinder wall or in regions of diffuse combustion that are too lean to allow complete combustion. Excess fuel dribbling or evaporating from the injector late in the cycle also contributes to the emission of unburned hydrocarbons.

Another organic species that originates in similar fashion are aldehydes, which are oxygenated hydrocarbons and have the group  $-\text{CHO}$  at one end of the hydrocarbon chain. They can be obtained from alcohols from the removal of hydrogen and thus tend to be more severe when alcohol containing fuels are combusted. It makes sense in the study of pollutant effects to consider hydrocarbons, their oxygenated products and otherwise reacted species as a group. Thus it is common to refer to Volatile Organic Compounds or VOCs in any discussion of the emission of uncombusted or partially combusted fuel from internal combustion engines.

**Table 2** below lists the toxic VOCs identified in a 1997 inventory of mobile source emissions in the state of Michigan in the US, including the estimated total emissions per pollutant <sup>(11)</sup>. These data are for the entire Michigan vehicle population and include both diesel and spark-ignition engines in light and heavy-duty applications, but can serve as a broad indication of the types and approximate relative quantities of toxic VOCs emitted from diesel engines.

**Table 2:** Emissions Inventory of Toxic VOCs Emitted from Mobile Sources for the State of Michigan, US (1997)<sup>(11)</sup>

Pollutant Name	Chemical Formula	Total Annual Emissions (lb/year)
Acetaldehyde	C <sub>2</sub> H <sub>4</sub> O	1 883 479.58
Acrolein	C <sub>3</sub> H <sub>4</sub> O	275 083.41
Benzene	C <sub>6</sub> H <sub>6</sub>	12 681 043.35
1,3 Butadiene	C <sub>4</sub> H <sub>6</sub>	1 639 157.93
Ethylbenzene	C <sub>8</sub> H <sub>10</sub>	5 388 275.29
Formaldehyde	CH <sub>2</sub> O	4 877 195.28
Naphthalene	C <sub>10</sub> H <sub>8</sub>	804 617.64
Styrene	C <sub>8</sub> H <sub>8</sub>	2 972 171.21
Toluene	C <sub>7</sub> H <sub>8</sub>	37 019 594.57
m-Xylene	C <sub>8</sub> H <sub>10</sub>	10 609 339.06
o-Xylene	C <sub>8</sub> H <sub>10</sub>	5 748 407.29
Xylenes Isomers	C <sub>8</sub> H <sub>10</sub>	20 917 805.74

The majority of measurements made in the experimental phase of this study were, however, for total hydrocarbons using a flame ionisation type analyser. Some speciation was attempted with limited success and therefore little subsequent analysis of speciated hydrocarbons was pursued.

The very variable air/fuel ratio that characterises combustion in compression ignition engines results in certain areas of very rich air/fuel mixture in the combustion chamber. These fuel-rich zones give rise to the formation of solid mostly carbonaceous particulates or soot that are emitted from diesel vehicles as a visible smoke, generally black in colour. Known collectively as particulate matter, these particles tend to adsorb some of the unburned hydrocarbons discussed above and also typically include solid sulphates that form from sulphur in the fuel. Both a soluble fraction and a dry soot have been identified in particulate matter. Typically around 15% to 30% mass is extractable using solvents, although this can range from 10% to 90%<sup>(35)</sup>. Trace amounts of sulphur, zinc, phosphorous, calcium, iron, silicon and chromium have been found in particulate matter originating from both the lubricant and the fuel. **Figure 8** below presents a graphical model for a diesel particulate<sup>(6)</sup>.

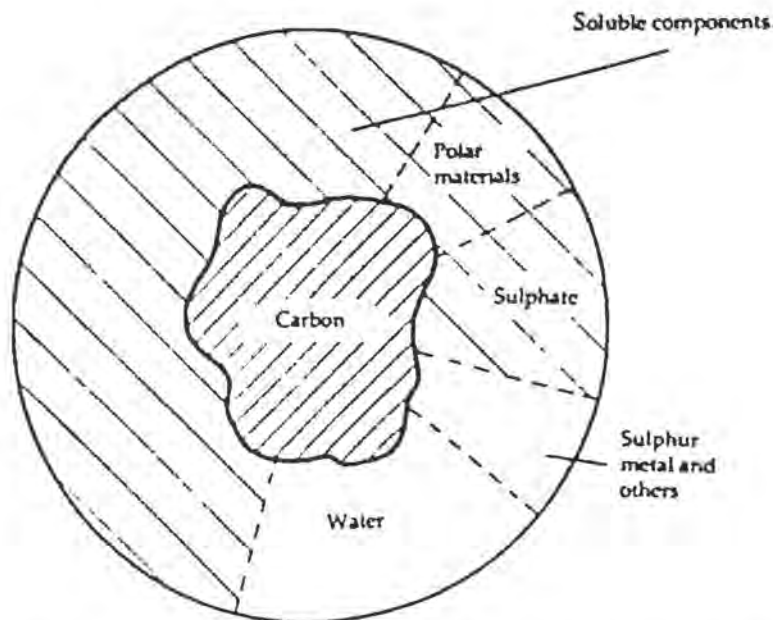


Figure 8: Makeup of PM Emitted by Diesel Engines (AVL GmBh) <sup>(6)</sup>

To summarise formation process of PM, fuel molecules containing between 12 and 22 carbon atoms with an H/C ratio (hydrogen/carbon atom ratio) of around 2 pyrolyse into soot particles with equivalent diameter of a few 100nm. These in turn consist of clusters or chains of spherules around 20nm to 30nm in diameter, each containing of the order of  $10^5$  carbon atoms with an H/C ratio of around 0.1. Pyrolysis is distinct from combustion and can be defined as:

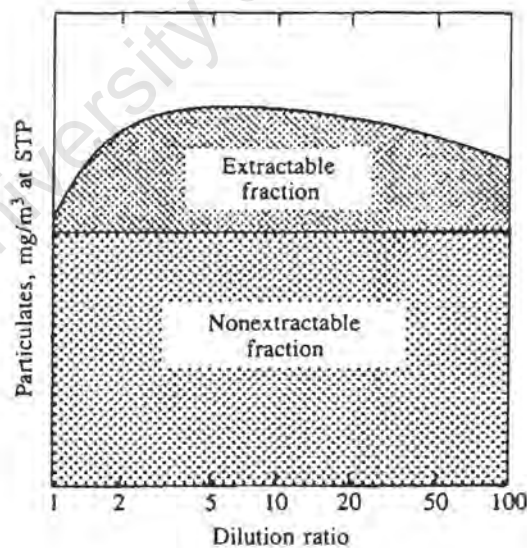
*"The extensive decomposition and atomic rearrangement of the fuel molecules in a highly fuel rich environment that precludes actual combustion."* <sup>(35)</sup>

The particulate formation process itself is not well understood and it is likely that a number of processes occur in parallel, given the physical and chemical variability inherent in diesel combustion. It is, however, more or less agreed that very small nuclei (< 2nm diameter) form from the condensed phase of fuel oxidation and/or pyrolysis products. From this point particles grow through surface growth, coagulation and aggregation. A number of reaction paths are thought to drive this process <sup>(35)</sup>:

- ◆ *Thermal cracking:* Fragmentation of fuel molecules into smaller molecules that condense into nuclei.

- ◆ *Condensation and polymerisation reactions:* Larger fuel molecules polymerise and condense into nuclei.
- ◆ *Dehydrogenation:* Hydrogen is removed, lowering the H/C ratio of hydrocarbons eventually resulting in condensed soot.

During the combustion cycle in an engine, particulate concentrations rise rapidly after top dead centre (TDC) and then after peaking at about  $20^\circ$  after TDC are reduced substantially by oxidation in the diffusion flame to about a third of the peak. Most of the unburned hydrocarbon *adsorption* occurs thereafter as the particulates are exhausted and the reaction products cool upon dilution with ambient air. *Adsorption* as distinct from *absorption* is the adherence of the unburned hydrocarbons to the surfaces of the soot particles by chemical or physical (Van der Waals) forces. The process is driven by the partial pressure of gaseous hydrocarbons in proximity to particulates. In the case of high emissions of unburned hydrocarbons, *condensed* hydrocarbons can also add significantly to particulate emissions. The degree of dilution with ambient air has a strong effect on these processes, as indicated by **Figure 9** below, which shows the variation in solvent extractable mass from particulates with dilution ratio <sup>(35)</sup>.



**Figure 9:** Dilution ratio vs. extractable particulate mass <sup>(35)</sup>

The reduced extractable fraction at high dilution ratios is caused by reduced hydrocarbon concentration and thus lower vapour pressure, which in turn inhibits adsorption. Most regulatory methods used to measure particulate matter will therefore dilute the exhaust sample appropriately before measurement so as to simulate this real life process. Such a

technique was applied in the experimental phase of this study. Typically again the adsorbed hydrocarbons tend to be of high molecular weight and include polycyclic aromatic hydrocarbon (PAH), compounds that are known toxins and carcinogens. Kado et al <sup>(52)</sup> extracted PAH compounds from particulate matter sampled from a Cummins 5.9 litre capacity diesel engine operated on the US Environmental Protection Agency (EPA) Heavy Duty Vehicle Cycle in a study at the University of California. **Table 3** below presents specific emissions for the compounds they identified using combined gas chromatography and mass spectrometer techniques.

**Table 3:** Specific PAH Emissions Extracted from Diesel PM <sup>(52)</sup>

PAH EMISSIONS ( $\mu\text{g}/\text{mile}$ )	
COMPOUND	
Naphthalene	2.30
Acenaphthylene	<3.18
Acenaphthene	<.214
Fluorene	<.305
Phenanthrene	27.54
Anthracene	<.620
Fluoranthene	28.98
Pyrene	16.94
Benz[a]anthracene	2.31
Chrysene/Triphenylene	2.57
Benzo[b]fluoranthene	2.73
Benzo[k]fluoranthene	2.09
Benzo[e]pyrene	1.39
Benzo[a]pyrene	1.38
Perylene	0.70
Indeno[1,2,3-dc]pyrene	1.61
Dibenz[ah]anthracene	<.201
Benzo[ghi]perylene	2.85

$\mu\text{g}/\text{mile}$  = micrograms of PAH per mile

< = less than the method detection level

Another reaction product commonly referred to in relation to diesel engines is *smoke*, a generalised term for the visible component of the exhaust from a combustion engine powered vehicle. It consists primarily of the particulate matter described above, but while the engine is below operating temperature or in a poor state of service the visible smoke can also include a liquid aerosol or a gas/liquid mixture of unburned fuel (white in colour) or lubricating oil (bluish in colour). Severe misfire resulting in a large part of the fuel not burning would, for instance, result in a white smoke of diesel fuel aerosol being exhausted.

Crude-derived hydrocarbon fuels can contain fairly high concentrations of sulphur that originate from the plant matter from which the crude oil formed. Refining methods and the base stock of crude cause the amount of sulphur in diesel to vary considerably but at the time of writing the regulated limit on sulphur in South African diesel was 0.55% weight, as indicated in **Table 1**. This limit is soon to be reduced to 0.3% weight.

During combustion some of the fuel sulphur products will add to the PM emissions through the formation of sulphates, as outlined above. Most of the sulphur will, however, oxidise to form  $\text{SO}_2$ , a serious pollutant. The concentration of  $\text{SO}_2$  in diesel exhaust is thus highly dependent on fuel sulphur concentration. This can be greatly reduced if diesel is refined using techniques like hydrotreating or if the base stock is synthetic sulphur free.

The reaction products of diesel combustion are summarised below in **Table 4**. The human health and environmental effects of these substances and measures to reduce and quantify them are discussed in the remainder of this chapter.

**Table 4:** Typical Profile of Diesel Engine Emissions

Reaction Product	Symbol	Phase	Approx. Concentration
Carbon Dioxide	$\text{CO}_2$	Gaseous	1-15%
Carbon Monoxide	$\text{CO}$	Gaseous	0.05 – 0.2%
Nitrogen Dioxide	$\text{NO}_2$	Gaseous	100 – 1000 ppm
Nitrogen Oxide	$\text{NO}$	Gaseous	200 – 2000 ppm
Particulate Matter	PM	Solid	30 – 300 mg/kg
Unburned Hydrocarbons	$\text{HC}_n$	Gaseous	100 – 500 ppm
Sulphur Dioxide	$\text{SO}_2$	Gaseous	0 – 500 ppm
Sulphur Trioxide	$\text{SO}_3$	Gaseous	< 100 ppm
Aldehydes	$\text{HC}_n(\text{CHO})_m$	Gaseous	10 – 50 ppm <sup>(Hey)</sup>
Water	$\text{H}_2\text{O}$	Gaseous	± 5 %
Nitrogen	$\text{N}_2$	Gaseous	± 70 %
Oxygen	$\text{O}_2$	Gaseous	± 20 %

### 3.2 SECONDARY POLLUTANTS FROM DIESEL ENGINE EMISSIONS

Secondary pollutants are substances that form as a result of the reaction, in the atmosphere, of pollutants from primary sources like diesel engines. There are two distinct manifestations: photochemical smog and the formation of acidic aerosols and particulates. Both these forms of secondary pollution occur in the troposphere (lower portion of the atmosphere 9km to 13 km high) surrounding urban areas and have been implicated as a threat to human health and the environment <sup>(22,25,30,111)</sup>. They share some of the same precursors and will occur together to a degree, dependent on prevailing atmospheric conditions. While primarily a concern of the urban environment, these pollutants can be transported over vast distances to areas remote from the source of primary precursors by prevailing airflow. Thus eco-systems and health in a given location can be affected by pollution from a distant settlement, or even another country <sup>(22)</sup>.

The chemistry of both photochemical smog and secondary particulates is largely driven by photolysis and the presence of water in the atmosphere. Donahue <sup>(22)</sup> defines photolysis as follows:

*"Photolysis occurs when a molecule absorbs a photon and breaks into two or more fragments."* <sup>(22)</sup>

Photochemical smog and acidic particle formation are discussed briefly below.

#### 3.2.1 PHOTOCHEMICAL SMOG FORMATION

Photochemical smog consists of a number of substances formed by numerous reactions between several pollutants. The two most critical products of photolytically driven reactions between primary pollutants are, however, ozone ( $O_3$ ) and peroxyacetyl nitrate or PAN, both strong oxidants.  $NO_x$  and VOCs have been identified as the most important precursors <sup>(22,25,30,111)</sup>. Indeed, while the photolysis of diatomic oxygen ( $O_2$ ) in the stratosphere is the ultimate source of the upper atmosphere ozone that shields us from ultra-violet radiation, the photolysis of  $NO_2$  is the primary source of polluting tropospheric ozone, as indicated by the following two reactions <sup>(22,111)</sup>:



The symbol  $h\nu$  represents a photon, the product of Planck's constant and the frequency of light. Ozone is in turn the main source of the free radical hydroxyl (OH), also by a process of photolysis whereby some ozone forms electronically excited oxygen ( $\text{O}^*$ ) that reacts with water in the atmosphere as follows <sup>(22,111)</sup>:



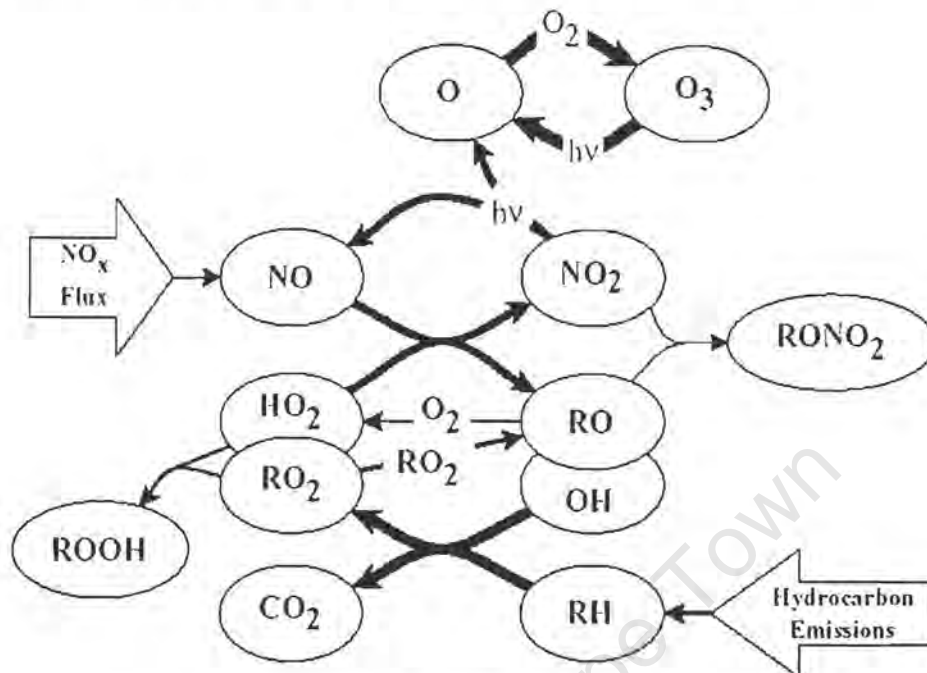
Hydroxyl is the predominant atmospheric oxidant and also forms readily from the photolysis of oxygenated hydrocarbons like aldehydes, common primary pollutants. The VOCs are, however, generally oxidised by the hydroxyl radical to form a peroxy radical,  $\text{CO}_2$  and water that will in turn cycle more hydroxyl radical. Therefore, given an organic radical R, forming the structural basis of a VOC, and a product radical R', the following generalised reaction paths can occur <sup>(22,111)</sup>:



**Equation 15** assumes 3 hydrogen atoms are freed from the radical as a result of the oxidation of 1 carbon atom. The  $\text{NO}_2$  formed in **Equation 17** in turn forms ozone by **Equation 11** and **12**. Donahue has summed the above processes up as follows:

*"...NO and  $\text{NO}_2$  serve as catalysts for the oxidation of hydrocarbons to  $\text{CO}_2$ , producing ozone as a by-product." <sup>(22)</sup>*

If this is a somewhat simplified account of photochemical smog formation, the interdependence of the reaction pathways is rather more complicated. **Figure 10** presents a graphical explanation as proposed by Donahue <sup>(22)</sup>.



Organic fragments are indicated by the symbol R (the parent hydrocarbon is RH, the peroxy radicals are RO<sub>2</sub>).

**Figure 10:** Photochemical Smog Reaction Pathways <sup>(22)</sup>

A result of the interdependencies shown above is that ozone production is dependent on the relative quantities of NO<sub>x</sub> and VOCs. If NO<sub>x</sub> is abundant, NO<sub>2</sub> reacts directly with the hydroxyl radicals to produce nitric acid (HONO<sub>2</sub>) and so depletes the system of hydroxyl radicals. This is known as the *hydrocarbon limited* condition. In the case of abundant VOCs, the peroxy radicals tend to react with one another rather than with NO, which then precludes the production of ozone. This is known as the *NO<sub>x</sub> limited* condition <sup>(22)</sup>. The chemistry of this process is now well understood and ozone levels can be related to the ratio of VOCs and NO<sub>x</sub> in the atmosphere. This is shown in **Figure 11** below, which presents an ozone isopleth plot versus VOC and NO<sub>x</sub> levels as output from the US EPA's EKMA model <sup>(102)</sup>.

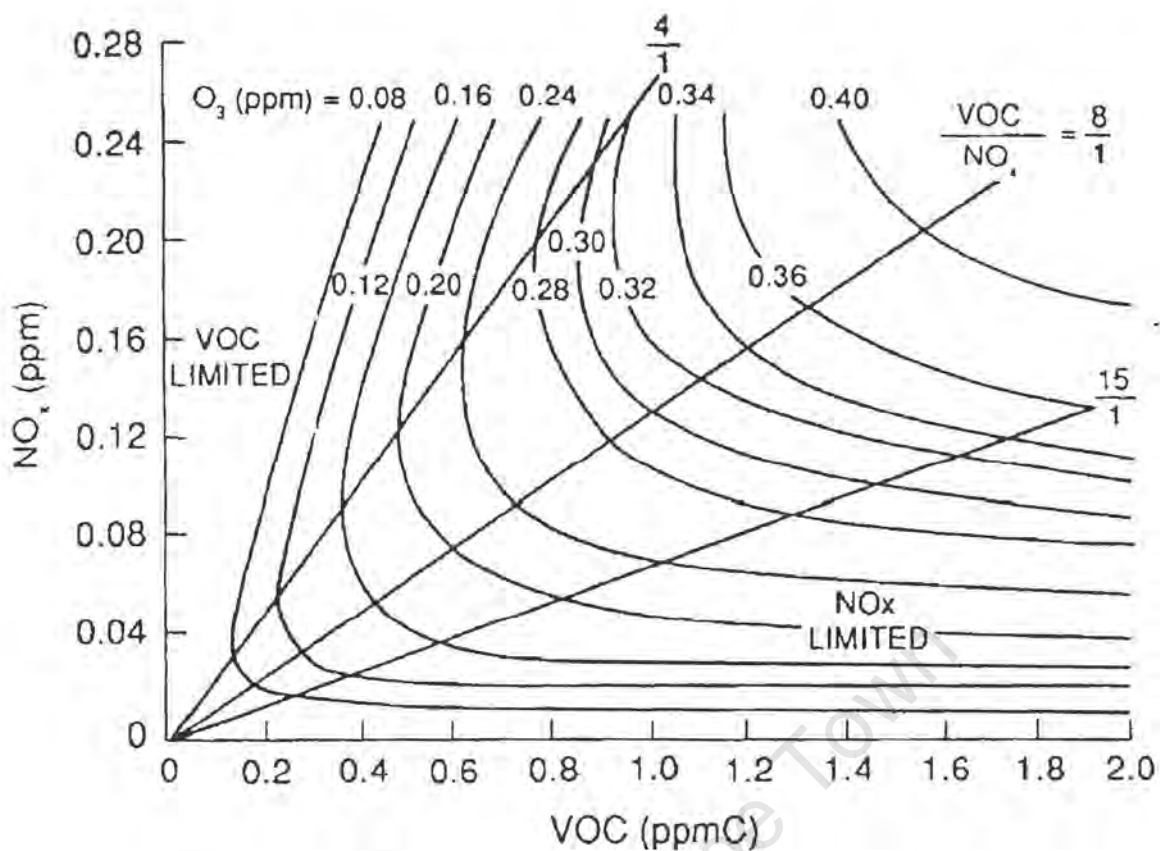


Figure 11: Ozone Isopleths Showing Effect of VOC/NO<sub>x</sub> Ratio<sup>(102)</sup>

As is evident from **Figure 11**, maximum ozone production occurs at a VOC/NO<sub>x</sub> ratio of about 8:1. The exact value depends on the atmospheric composition<sup>(22,102,111)</sup>. The fundamental implication is, however, that reducing only one pollutant may actually aggravate smog conditions, especially if the atmosphere surrounding an urban area tends to be one of the limited zones. Effective ozone reduction depends on identifying the priority precursor pollutant or reducing both together by a sufficient amount.

### 3.2.2 SECONDARY AIRBORNE PARTICLES AND AEROSOLS

We have seen above how NO<sub>x</sub> can be oxidised to nitric acid in a hydrocarbon-limited atmosphere. Similar processes can occur with the oxides of sulphur and VOCs, typically the large hydrocarbons. These pollutants may also be oxidised directly to acids by strong oxidants like ozone<sup>(22)</sup>. SO<sub>2</sub> is furthermore highly soluble and will readily form weak acids through contact with water vapour or liquid<sup>(25,30,34)</sup>. These reactions may occur in fogs, clouds and rain droplets to form secondary aerosol pollutants such as sulphuric acid (H<sub>2</sub>SO<sub>4</sub>)<sup>(25,34)</sup> aerosol and ammonium sulphate [(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] particulate<sup>(107)</sup>.

Hext et al report that in the UK, sulphates are the most abundant fraction of fine particulates (< 2.5µm diameter) after carbonaceous primary combustion products. Nitrates, ammonium and chlorides represent smaller portions <sup>(34)</sup>. There are two important features of secondary particulates and aerosols:

- Chemically derived aerosols tend to be much smaller than primary particulates <sup>(22,34)</sup>.
- Secondary particulates and aerosols are generally acidic <sup>(22,25,30,107)</sup>.

The health and environmental implications of this are discussed below.

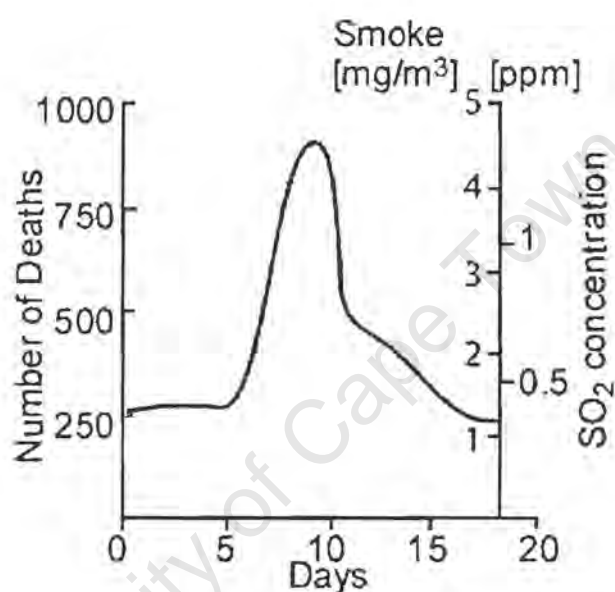
### 3.3 EFFECTS OF POLLUTANTS ORIGINATING FROM DIESEL ENGINES ON HUMAN HEALTH

The regulation of pollutants emitted from combustion engines stems from increasing concern for the potential effects on human health. Various studies have linked air pollution, including that originating from diesel engines, with both morbidity and indeed mortality. Morbidity may either be:

- *Acute*: disease of sudden onset and lasting a short time.
- *Chronic*: disease marked by long duration and frequent occurrence.

Acute symptoms caused by high concentrations of most toxic pollutants are well documented but whether chronic morbidity and mortality can be attributed to the low concentrations typical of ambient air, even in large metropolises, is a subject for debate. Certainly, epidemiological studies investigating a variety of ambient pollutants have generally reported only slightly increased relative risks, usually less than 1.5. This means a risk of morbidity or mortality, when exposed, which is 1.5 times that of an unexposed control group <sup>(34,65,82)</sup>. Hext, Rogers and Paddle <sup>(34)</sup> assert that these risks would not generally be statistically significant in occupational health investigations but that their importance is considerable, given that they apply to very large population groups. They propose furthermore that some perspective can be gained on the issue by examining three relevant questions as follows:

**Has air pollution caused ill health?** This is beyond dispute. The 20<sup>th</sup> century has seen a number of serious episodes, the first of which claimed the lives of 63 people dwelling in the Meuse Valley in Belgium in 1930 after a strong inversion trapped pollutants for five days<sup>(25)</sup>. The most serious to date was probably the London smog of 1952 which also lasted for several days but claimed an estimated 4,000 lives<sup>(25,34,68,111)</sup>. Yip and Madl report a relationship with these deaths and estimated ambient SO<sub>2</sub> and smoke as shown below in **Figure 12**.



**Figure 12:** Mortality attributed to London Smog of 1952 versus ambient SO<sub>2</sub> and Smoke<sup>(111)</sup>

**Is ambient air pollution associated with ill health?** Again, the answer is yes. A body of evidence indicates a statistical association between health problems and air pollution. This includes both chronic and acute morbidity and mortality. A variety of epidemiological study designs and populations have shown similar findings<sup>(25,34, 65, 82,111)</sup>.

**Does ambient air pollution cause ill health?** In examining this question two groups of reviewers, Morgan et al<sup>(65)</sup> and Hext et al<sup>(34)</sup>, have referred to Bradford Hill's criteria for establishing a cause and effect association by means of epidemiological study as follows:

**Strength of association:** The relative risk values discussed above can be used to represent strength of association. Morgan et al<sup>(65)</sup> assert that an association greater than 3 is likely to be causal but that risk between 1.5 and 3 is merely

suggestive and that associations less than 1.5 are usually explicable by bias and confounding factors such as smoking. Indeed, these authors deplore the insufficient efforts of researchers to accumulate comprehensive smoking histories for study subjects so that this confounding factor can be conclusively accounted for. Hext et al <sup>(34)</sup> concur with the role of bias and confounding factors but propose that current relative risk findings are of grave concern because they apply to very large populations and in the words of the authors, "*could hardly be much larger without causing a major breakdown in public health standards*".

**Consistency:** This is indicated by repeated observations of an association under different conditions of study. Hext et al argue that a causal relationship between ill health and air pollution is strongly supported by this criterion as several groups of researchers in as many countries, using at least three study designs, have arrived at positive conclusions. They caution though that mortality from all causes has frequently been associated with industrialisation and related social and economic phenomena. As air pollution relates in turn to these, consistency may stem from a complex synergy of causative factors. In contrast, Morgan et al concluded that there was little to no consistency in the studies they reviewed, particularly in the case of the carcinogenic effects of diesel exhaust.

**Temporality:** This criterion requires that the cause precede the effect, which is the case in the air pollution/health association situation.

**Biological Gradient:** This asserts that an exposure response curve or trend correlating with exposure will add credibility to causative association. Few epidemiological studies are able to obtain the data necessary for this exercise. Again confounding factors like smoking behaviour make conclusions difficult. Bioassays are more suited to this approach. These are active exposure studies on animal subjects and bacterial colonies. Certainly these have indicated biological gradient, particularly in evaluations of carcinogenicity (the tendency to cause cancer) <sup>(34,52,65)</sup>. Pollutant concentrations are, however, typically high and extrapolation to human beings has to be interpreted with caution.

**Plausibility and Coherence:** This criterion requires that a finding does not seriously conflict with the body of knowledge relating to a disease. Generally this is

met by the air pollution health association but in the case of carcinogenicity as measured by bioassay described above, is open to debate.

**Experimental Evidence:** This criterion is satisfied when removal from exposure or reduction of exposure reduces the incidence of the effect. Sufficiently detailed exposure data does not generally exist for epidemiological air pollution studies to evaluate this criterion.

A generalised review of the effects of air pollution on health therefore indicates that there is limited risk to healthy individuals, but that a measurable risk exists for those with existing respiratory disease. The issue of carcinogenicity leading to incidences of mortality after a long lead-time is far from resolved. Indeed, epidemiological studies have served more to emphasise the indisputable risks of smoking in this regard <sup>(65)</sup>. It is, however, essential to review what is known about the specific health effects of individual pollutants, particularly if air quality control measures need to be prioritised. Individual pollutants and species of pollutants are discussed below.

### 3.3.1 HEALTH EFFECTS OF EXPOSURE TO CARBON MONOXIDE (CO)

The toxicity of CO is probably the best documented and understood of all combustion pollutants, due in part to the enduring popularity of vehicle exhaust inhalation as a means of committing suicide. In the case of the conventional spark ignition engine passenger car, CO poisoning will invariably be the primary cause of death <sup>(89)</sup>. As we shall see later though, those entertaining such notions using a diesel-powered vehicle are inviting an even more gruesome end by particulate matter-induced asphyxiation <sup>(89)</sup>. The toxic properties of CO arise from its affinity for the haemoglobin in the blood in preference to oxygen. It reacts readily to form carboxy-haemoglobin on the oxygen binding sites of the haemoglobin, preventing oxygen uptake from the lungs and thereby causing effective oxygen starvation <sup>(25,111)</sup>. Ambient CO levels are not generally hazardous in this way, but build-up in enclosed spaces like mining environments, presents an occupational hazard.

### 3.3.2 HEALTH EFFECTS OF EXPOSURE TO VOLATILE ORGANIC COMPOUNDS

The toxic effects of VOCs (which include  $HC_n$  and oxidised  $HC_n$ ) are highly dependent on the species. Methane, for instance, occurs naturally and is fairly benign, especially at ambient concentrations. Benzene on the other hand, shown by **Table 2** above to be highly prevalent in VOC emissions from mobile sources, is a known toxin and carcinogen <sup>(12)</sup>. Formaldehyde, widely used as a preservative for biological material, is also highly toxic in sufficient concentration. Anyone familiar, at least anecdotally, with the effects of ethyl alcohol poisoning will have a broad idea of the general symptoms of VOC poisoning. Light-headedness, disorientation, nausea and headaches are acute symptoms of short-term exposure at high concentrations while irreversible liver damage and impairment of the mental faculties can occur from prolonged exposure at high but sub-lethal levels.

Ambient concentrations are well below these levels. Therefore much of the issue around public health revolves around the role of VOCs in ozone production and the potentially carcinogenic effects of particularly PAHs. The effects of ozone are discussed below, while those of PAHs pertain also to those adsorbed onto particulate matter and are discussed below as integral to the health effects of diesel particulate matter.

### 3.3.3 HEALTH EFFECTS OF EXPOSURE TO OXIDES OF NITROGEN

$NO_x$  are also highly active precursors of atmospheric ozone in addition to being toxins.  $NO_2$  is more toxic than  $NO$  that predominates in vehicle exhaust.  $NO$  is, however, readily oxidised to  $NO_2$  which therefore accounts for around two thirds of ambient  $NO_x$  pollution <sup>(25)</sup>.  $NO_2$  has been linked to increased susceptibility to respiratory infection and complications associated with asthma <sup>(25,111)</sup>. **Figure 13** below summarises the known potential health effects of exposure to  $NO_x$ .

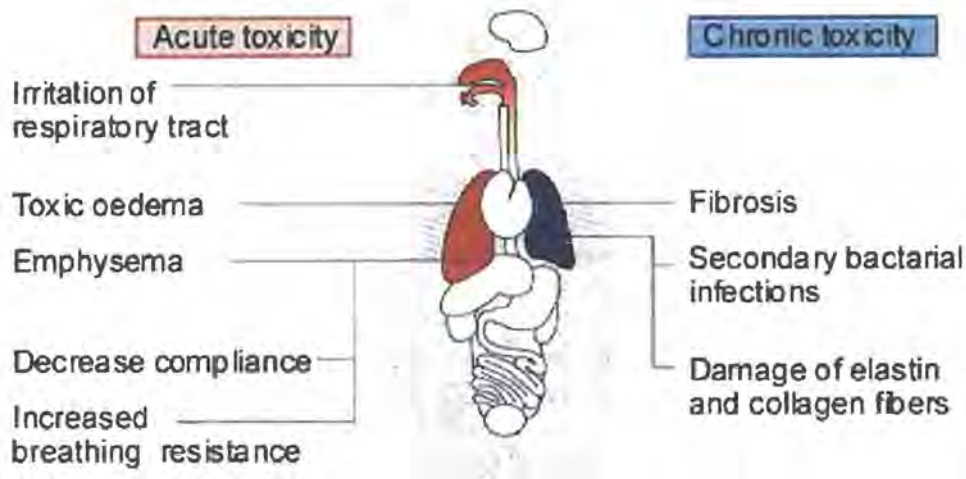


Figure 13: Health Effects of Exposure to NO<sub>x</sub> <sup>(111)</sup>

The European APHEA Project studied the short-term health effects of individual pollutants in 16 cities in 11 countries. Epidemiological data was correlated by multiple regression with ambient concentrations to calculate relative risks of exposure. Small but consistently elevated risks of mortality (1.0075 – 1.034) were associated with NO<sub>2</sub> exposure. Slightly higher relative risks were observed (0.89 – 1.342, average 1.065) for admissions to hospital with respiratory disease, but these and risks for other morbidities like asthma and airways obstruction were observed to be inconsistent <sup>(82)</sup>. It has not yet been conclusively demonstrated that any of the effects shown in **Figure 13** above can be caused by typical ambient levels of NO<sub>x</sub>.

### 3.3.4 HEALTH EFFECTS OF EXPOSURE TO OZONE

O<sub>3</sub> is a highly reactive oxidising agent. It has been shown that adverse health effects can occur even at relatively low concentrations <sup>(22,26)</sup>. The World Health Organisation (WHO) has recommended a 1 hour maximum ambient concentration of 0.076ppm to 0.100ppm and an 8 hour maximum of 0.05ppm to 0.06ppm <sup>(26)</sup>. These limits are regularly exceeded in cities around the world, including in South Africa. The adverse effects arising from such exceedences include eye irritation, coughs, chest discomfort, headaches and an increase in the incidence of asthma. Acute and chronic health effects of O<sub>3</sub>, according to Yip and Madl, <sup>(111)</sup> are summarised diagrammatically below in **Figure 14**.

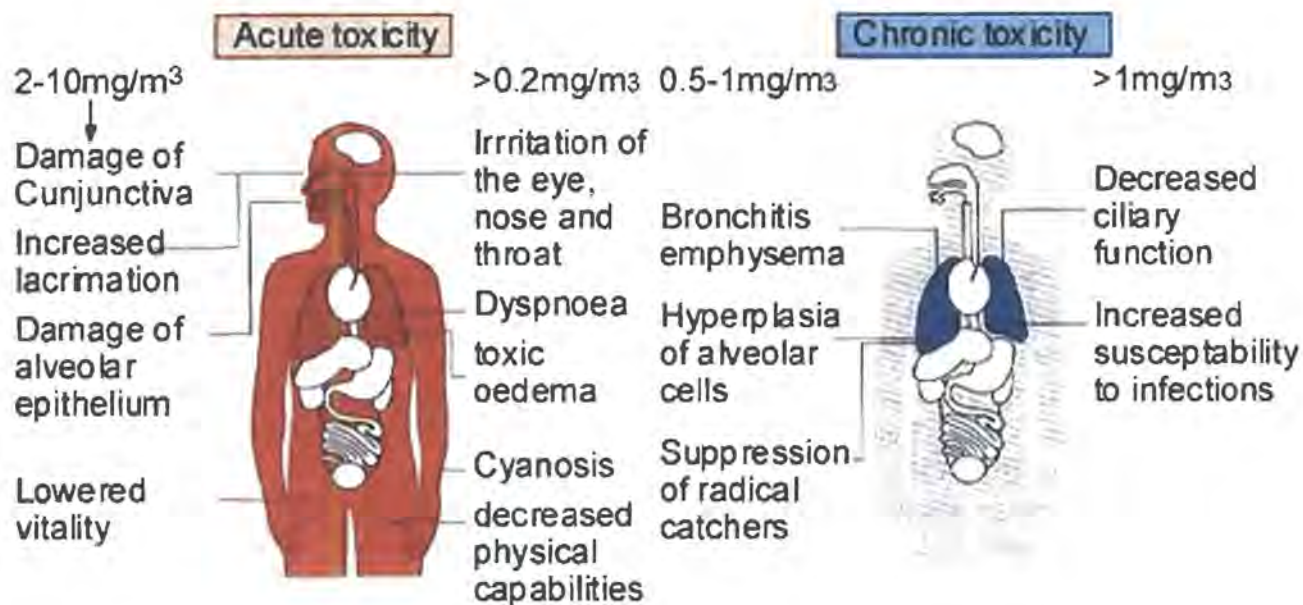


Figure 14: Health Effects of Ozone Exposure according to Yip and Madl<sup>(111)</sup>

These authors also report on a study where mice were exposed to high concentrations of O<sub>3</sub>, around a factor of 10 higher than the WHO recommended limits. Carcinogenic properties were indicated by occurrences of lung cancer. There is no evidence, however, of carcinogenic effects at ambient concentrations with rodents, let alone human subjects, and thus carcinogenicity cannot conclusively be determined as a health effect of ambient O<sub>3</sub>.

### 3.3.5 HEALTH EFFECTS OF EXPOSURE TO SULPHUR DIOXIDE

SO<sub>2</sub> emissions from transport sources are generally a very small fraction of total emissions relative to, say, the power generation industry. In the UK, SO<sub>2</sub> emissions from transport sources account for just 1% of total national SO<sub>2</sub> emissions<sup>(68)</sup>. A discussion of the health effects of SO<sub>2</sub> exposure is, however, warranted as localised exposures due to road transport may be high. In humid conditions, SO<sub>2</sub> reacts readily with water to form a sulphuric acid aerosol (H<sub>2</sub>SO<sub>4</sub>) that can be inhaled as such or adsorbed onto particulate matter. The corrosive properties of such acidic particles can result in irritation and even morbidity of the nasal tissue, trachea and alveolar in the base of the lungs<sup>(111)</sup>. Hext et al<sup>(34)</sup> have identified ambient acidic particles as probably the greatest risk to health of all airborne pollutants. Dutkiewicz<sup>(25)</sup>, in a review of health effects, reports that SO<sub>2</sub>

concentrations as low as 0.23ppm, combined with smoke at 750 micrograms per cubic metre cause a detectable rise in mortality.

SO<sub>2</sub> itself can cause respiratory problems, especially in children and the elderly, which include bronchitis, asthma, irritation of the trachea and airways resistance. SO<sub>2</sub> at ambient concentrations in isolation is not considered harmful unless in synergy with dust or high humidity <sup>(25,30,111)</sup>.

### 3.3.6 HEALTH EFFECTS OF EXPOSURE TO PARTICULATE MATTER

Investigations into the health effects of diesel PM have included laboratory testing and both short- and long-term epidemiological studies. Laboratory studies have generally focussed on carcinogenicity, either through the use of bacterial assays such as the Ames test or dose threshold testing on rats. These methodologies have in turn focussed on the hydrocarbons adsorbed onto PM, particularly PAH compounds such as those presented in **Table 3** above, as being the likely precursors for mutagenesis (gene mutation) leading to cancer.

In 1997, scientists at Kyoto University isolated a substance from diesel engine particulate matter, 3-nitrobenzanthrone that gave the highest ever carcinogenicity rating on the Ames test at that time <sup>(77)</sup>. Exposure of rats to high doses of PM has also indicated an increased risk of lung cancer. Indeed, it was on the basis of such results that the International Agency for Research on cancer (IARC) classified diesel exhaust as a Group 2A carcinogen in 1989 <sup>(65)</sup>. This classification is based on sufficient evidence of carcinogenicity in experimental animals but limited evidence in humans thus clearly identifying diesel exhaust as at least a potential human carcinogen. These results have been interpreted with caution, as the validity of extrapolating the findings of animal bioassays to the physiology of human beings is often tenuous.

Morgan et al <sup>(65)</sup> report on a study where rats were exposed to both diesel exhaust and carbon black which was mutagen-poor, that is, would not have indicated carcinogenicity in the Ames test by causing Salmonella bacteria to mutate. The incidence of tumours between both groups of rats was roughly equal, with carbon black slightly more

carcinogenic. Mutagenicity is thus not always an indication of carcinogenicity. To quote Morgan et al:

*"Ames himself has deplored many of the tendentious associations and frightening pronouncements that have been made as a result of a positive Ames assay."* <sup>(65)</sup>

Furthermore, Hext et al assert that there is evidence that the rat lung may over-respond to the presence of particles in the lung, especially at high doses, making extrapolation of the results of rodent studies to humans somewhat tenuous <sup>(65)</sup>.

Nonetheless, laboratory studies provide an opportunity to study the *biological gradient* of PM exposure, one of the key criteria for establishing a cause/effect association as discussed above. This is of particular interest when comparing the relative toxicity of different fuels, for instance conventional fossil fuel, refined diesel and esterified plant oils (better known in industry parlance as *biodiesel*). As is discussed below in **Section 3.6**, biodiesel offers the advantage of reduced greenhouse gas emissions, but the gross output of toxic emissions with biodiesel as a fuel is only moderately reduced, mostly due to the high oxygenate content, while fuel cost is significantly higher than fossil fuel diesel <sup>(6)</sup>. There is compelling evidence though, that the mutagenic potential of PM emitted using rapeseed esters is substantially lower than that of PM from diesel <sup>(52,55)</sup>.

Koo-Oshima, Hahn and Van Gerpen <sup>(55)</sup> reviewed 10 studies, all of which indicated substantially reduced mutagenicity for biodiesel compared to fossil fuel diesel. Biological gradient was indicated by all studies, with diesel/biodiesel blends being less mutagenic than straight diesel but more mutagenic than 100% biodiesel. Kado, Okamoto and Kuzmicky <sup>(52)</sup> used a modified Ames assay with particulate samples in a microsuspension to compare the mutagenicity of diesel, biodiesel and blends of the two. PM samples were filtered according to the US Federal Test Procedure from the diluted emissions of a Cummins 5.9 litre turbocharged diesel engine. Mutagenic potential was calculated as a specific unit by deriving the number of revertant *Salmonella* bacteria colonies per mile. **Figure 15** below presents the results of these tests without any catalytic after-treatment of the exhaust.

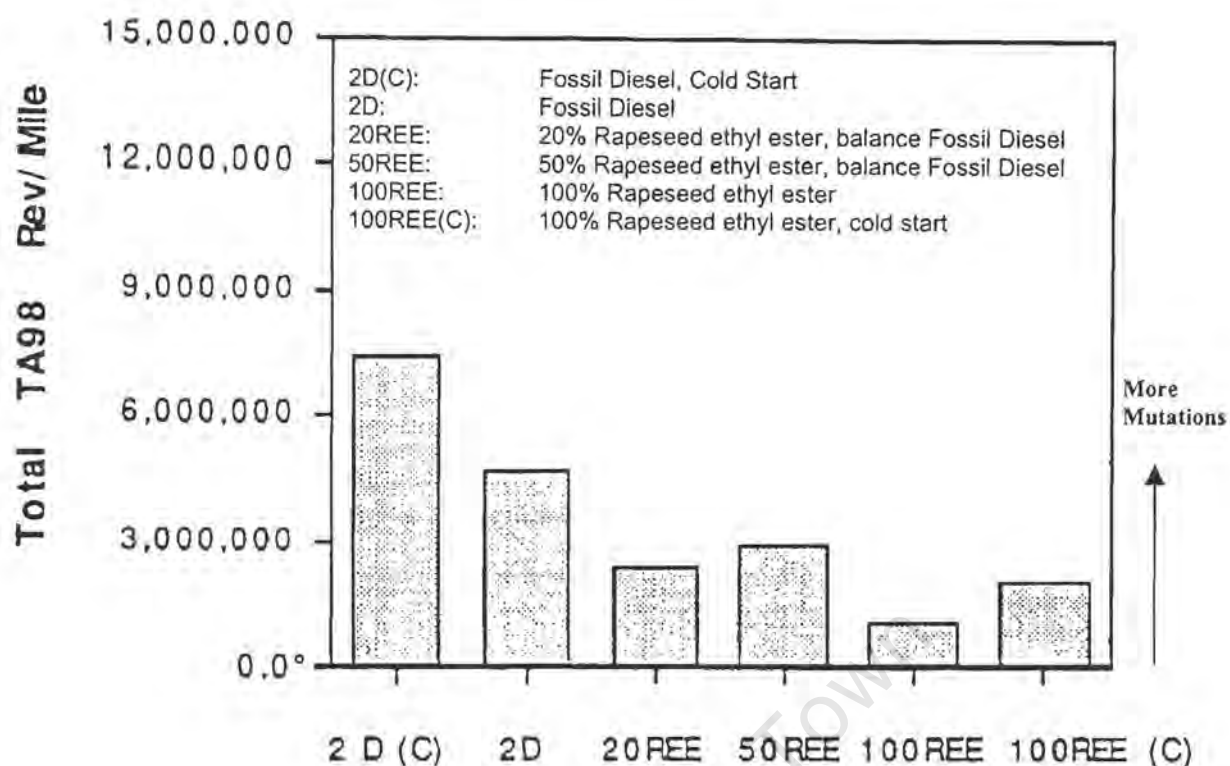
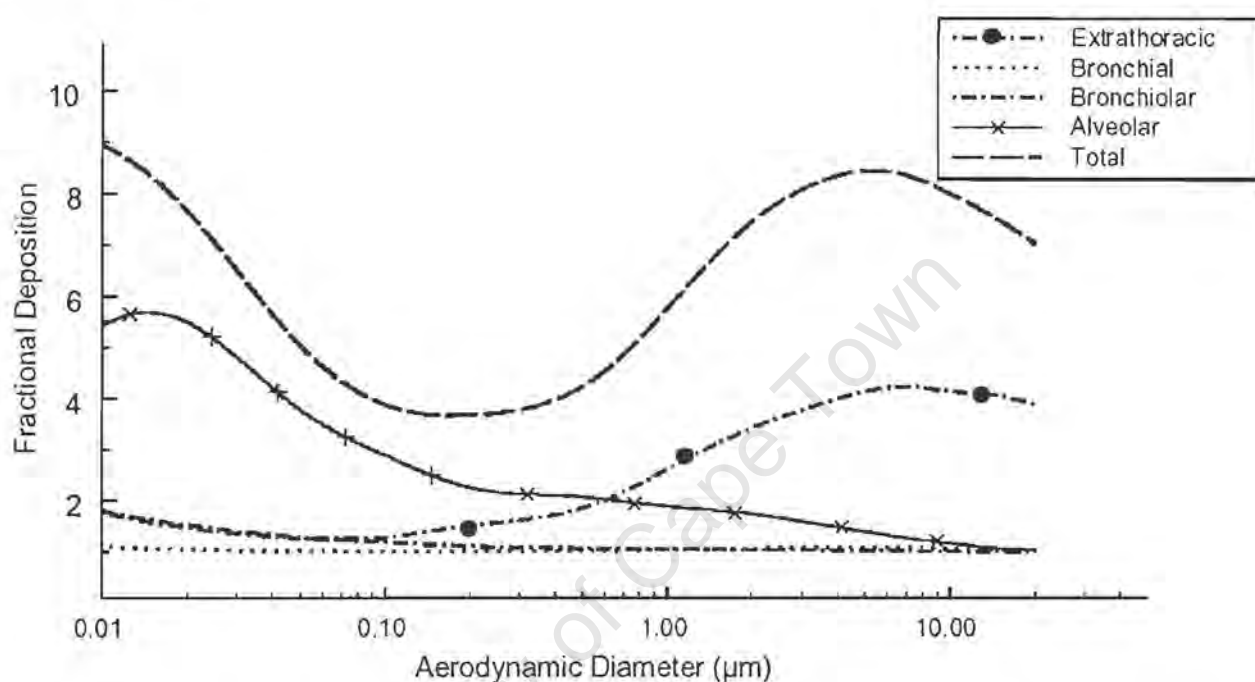


Figure 15: Comparison of Mutagenic Properties of Biodiesel and Fossil Fuel Diesel <sup>(52)</sup>

Needless to say epidemiological studies have been less conclusive. Long-term studies have usually been confounded by tobacco smoking behaviour, which has a very strong and well-documented link with lung cancer risk <sup>(65)</sup>. Short-term risk studies linking diesel PM to chronic respiratory disease and episodes of affliction like asthma, requiring hospitalisation, have indicated that in general there is limited risk to healthy individuals. Individuals with respiratory disease may, however, be at risk of developing adverse responses due to exposure to PM <sup>(34,82)</sup>.

Various studies have indicated an association between respiratory disease and the inhalation of particles with a mean aerodynamic diameter of less than 10 microns, abbreviated as PM10 <sup>(25,34,65,68,107)</sup>. The aerodynamic diameter of a particle is defined as the diameter of the standard-density sphere that behaves the same aerodynamically as the particle in question ie: they will sediment in still air at the same rate. This size limit is the International Standards Organisation's convention for particles likely to be inhaled into the thoracic region of the human respiratory system <sup>(68)</sup>. Of particular concern are so-called ultrafine particles having a mean aerodynamic diameter of less than 0.1 microns, according to Hext et al <sup>(34)</sup> and 0.05 microns, according to Morgan et al <sup>(65)</sup>. The threshold aside, particles an order of magnitude smaller than PM10 have greater deposition

efficiencies in the lung and a greater surface area to volume ratio <sup>(25,34,65)</sup>. Diesel PM is close to this size range <sup>(35)</sup>. The filter media used for the experimental phase of this study were purpose-designed for diesel exhaust sampling and are manufactured to trap particles with an average diameter of 0.3 to 0.5 microns <sup>(1)</sup>. **Figure 16** below shows the deposition efficiencies in different regions of the lung versus aerodynamic diameter, as reviewed by Hext et al <sup>(34)</sup>.



**Figure 16:** Particulate Deposition Efficiencies in the Human Lung as a Function of Aerodynamic Diameter <sup>(34)</sup>

The alveolar are in the base of the lung. It is evident from **Figure 16** that deposition efficiency increases dramatically in this region for ultra-fine particulates while there is a concomitant reduction for the extrathoracic region of the mouth, nose and throat.

The APHEA study of 16 European cities, discussed above in relation to the health effects of NO<sub>x</sub>, showed that short-term increases in the risk of mortality or hospitalisation linked to the presence of a range of air pollutants were generally small. Such effects as were found were, however, most strongly linked to SO<sub>2</sub> and PM <sup>(82)</sup>. Indeed, a synergy between these pollutants in the form of secondary acidic particulates of sulphuric acid aerosol (H<sub>2</sub>SO<sub>4</sub>) or primary particulates that have adsorbed acidic material have been implicated as the greatest risk to health by Hext et al in their review of the health effects of fine and ultrafine particles <sup>(34)</sup>. As discussed above in **Section 3.2.2**, secondary particulates are

generally smaller in diameter as well as being acidic. In contrast to the above findings, the National Environment Protection Council of Australia has estimated that particulate matter causes up to 2,400 deaths per year in Australia with associated health costs of A\$17.2-billion<sup>(8)</sup>.

At the other extreme of exposure from the ambient, a 1998 British post mortem of a man who committed suicide by inhaling diesel exhaust indicated that the cause of death was not CO poisoning, as is usual in such cases involving petrol vehicles, but was rather a result of soot from the diesel exhaust clogging the bronchi and alveoli of the lungs<sup>(89)</sup>. The issue of mortality from diesel PM, like that of the toxic gaseous pollutants, is thus, it seems, a question of dose and exposure.

### **3.4 ENVIRONMENTAL EFFECTS OF POLLUTANTS ORIGINATING FROM DIESEL ENGINES**

Other than the effect on human health, air pollution from the products of combustion can have deleterious effects on the environment at large, the well-being of other species, materials, structures and visibility. The phenomena most critical to these effects have been identified as follows:

- The phenomenon of global warming
- Acidic deposition
- Toxic effects on plants and animals
- Visibility degradation

These are briefly discussed below:

#### **3.4.1 GLOBAL WARMING**

Calculation of the average global temperature, taking into account the surface temperature of the sun, the approximate emissivity of the earth and the distance between them, yields a somewhat chilly approximation of around 253K or -20°C. The insulating effect of the earth's atmosphere accounts for a much more habitable average global

temperature at the surface of 15°C. A shield of trace gases in the troposphere is responsible for this so-called "Greenhouse Effect" <sup>(1,30,32)</sup>.

The earth absorbs most of the solar radiation incident upon its surface. The rest is reflected back into space. The warmed surface of the earth in turn emits infra-red radiation and it is a portion of this that is reflected back to the surface and within the atmosphere, warming it, by the trace gases in the troposphere <sup>(1,30,32)</sup>. A number of gases, including natural water vapour, contribute to the Greenhouse Effect, each to a different degree. The measure of this contribution is known as Global Warming Potential and is measured on an arbitrary scale relative to CO<sub>2</sub>, with CO<sub>2</sub> itself allocated a value of unity. **Table 5** below indicates the most important anthropogenic greenhouse gases and their relevant properties according to the Swiss Agency for the Environment, Forests and Landscape <sup>(32)</sup>.

**Table 5:** Greenhouse Gases and Relevant Properties <sup>(32)</sup>

	Carbon Dioxide (CO <sub>2</sub> )	Methane (CH <sub>4</sub> )	Nitrous Oxide (N <sub>2</sub> O)	Chlorofluoro- carbons (CFCs)
Natural Atmospheric Concentration (ppm)	280	0.7	0.275	0
Increase since Industrialisation (%)	30	145	15	banned
Atmospheric Lifetime (years)	50 - 200	12	120	10 - 500
Global Warming Potential	1	21	310	≈ 3000

About 40% of methane is believed to be from natural sources <sup>(1)</sup>. The remainder of anthropogenic methane is derived from mining fossil fuel deposits, crop cultivation (especially rice) and stock farming. Nitrous oxide (N<sub>2</sub>O) is largely soil-derived, particularly from soils treated with fertilisers with high nitrogen content. Chlorofluorocarbons (CFCs) were popular as refrigerants and propellants until they were banned in most industrialised countries in 1996 due to their role in the depletion of stratospheric ozone. Their role in global warming is therefore only residual. Despite CO<sub>2</sub>'s low global warming potential it accounts for around half the global warming effect due to the quantity in the atmosphere. **Figure 17** below shows the relationship between atmospheric CO<sub>2</sub> and global average temperature over the last 160,000 years. Certainly in terms of extremes, global temperature change seems to be strongly associated with CO<sub>2</sub>.

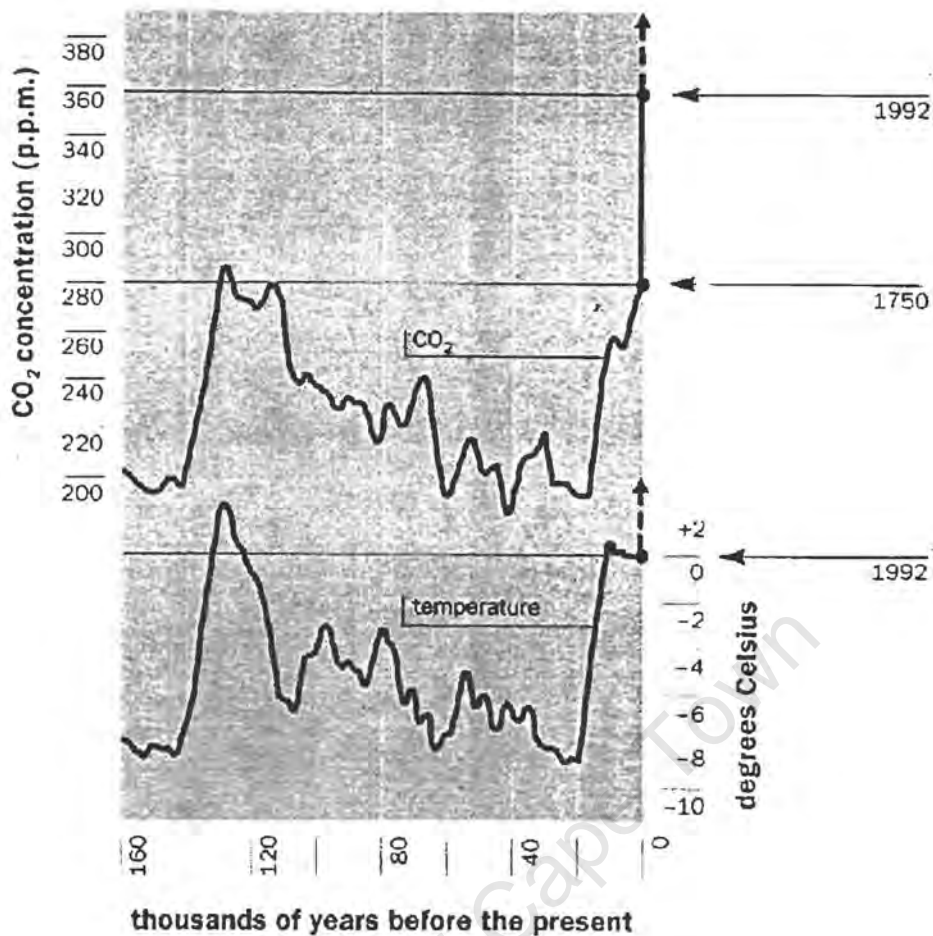


Figure 17: Correlation of Atmospheric CO<sub>2</sub> and Global Temperature <sup>(32)</sup>

Anthropogenic CO<sub>2</sub> is almost entirely produced by the burning of fossil fuels, but the effects on global warming of deforestation in reducing the mitigation effect of vegetation is of the same order. Combustion engines, including diesel engines, are still a significant individual contributor to global warming. **Table 6** below indicates the approximate contribution of anthropogenic sources of CO<sub>2</sub> compared to the other greenhouse gases, as reported by Dutkiewicz <sup>(25)</sup>.

Table 6: Contribution of Anthropogenic CO<sub>2</sub> to Global Warming <sup>(25)</sup>

Source	Contribution (%)
CO <sub>2</sub> deforestation	34
CO <sub>2</sub> oil & gas	25*
CO <sub>2</sub> coal power	16*
CFCs, methane, ozone, N <sub>2</sub> O	50**

\*Gerson (30): Energy use contribution 45 - 60%

\*\*Gerson (30): 45%

The stabilising influence of greenhouse gases notwithstanding, the earth's climate has been very variable. Many traces of this remain, including the scarring of the landscape by glaciers; lime deposits on the sea bottom, indicating precipitation; and gas pockets trapped in polar ice, recording historical atmospheric chemistry. A number of phenomena may give rise to climate change, for example variations in ocean currents and small changes to the planetary orbit and inclination relative to the sun. It is not certain whether CO<sub>2</sub> levels may play such a role but it is evident from historical temperature data that we are nearing the apex of a 10,000 year upswing in temperature from the last ice age with a high rate of temperature increase that seems to relate to CO<sub>2</sub> production. **Figure 18** below shows global average temperature changes over three telescoped epochs.

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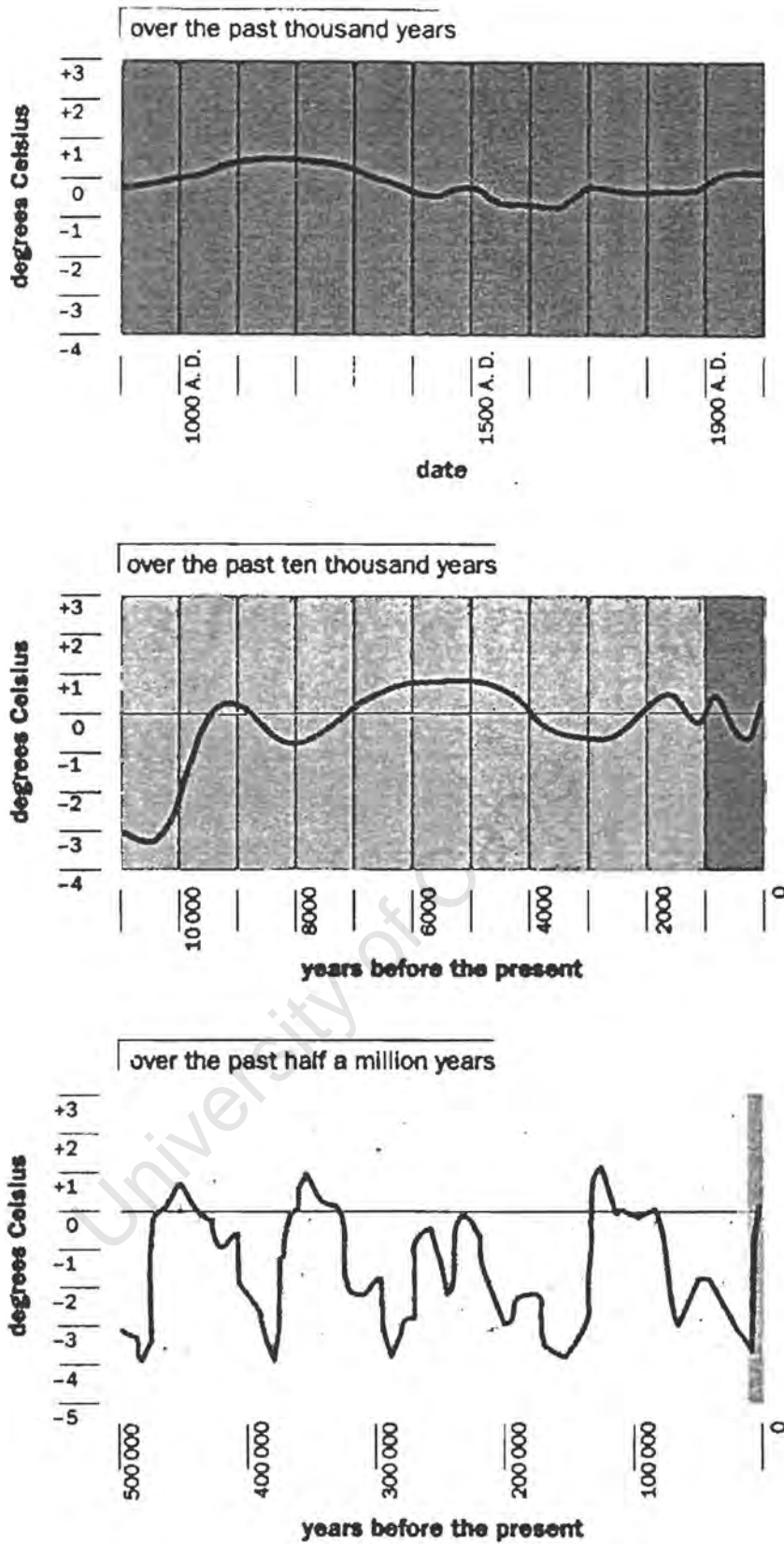


Figure 18: Global Temperature Fluctuation <sup>(32)</sup>

Climatic models indicate that a doubling of atmospheric CO<sub>2</sub> could lead to an increase in average global temperature at the surface of 1.5°C to 4.5°C. This is expected to occur

near the middle of this century. The impacts on the environment predicted from this are dire, for example the following:

- Stratospheric cooling
- Increased global precipitation and changes in precipitation patterns
- Decreased sea ice
- Decreased snow cover
- Melting of polar ice sheets
- Thermal expansion of the ocean combining with the above to inundate coastal cities
- Agricultural dislocations due to climatic changes

Conner<sup>(19)</sup> reports that damage to coral reefs are already being observed due to a rise in the ocean temperature. The microscopic plants on which the coral organisms feed can die if the water is too warm, causing coral reefs to “bleach” and die. Such damage is irreversible and can potentially destroy entire marine ecosystems. The projected extent and repercussions of global warming are still a matter of conjecture, but it will be very difficult to reverse the process once the damage is done.

### 3.4.2 DIRECT EFFECTS OF POLLUTANTS ON THE NATURAL ENVIRONMENT

The constituents of smog have been discussed above. Several of these, NO<sub>x</sub>, SO<sub>x</sub>, PAN and O<sub>3</sub> are *phytotoxic* (toxic to plants)<sup>(25,30)</sup>. These effects usually manifest in necrosis of leaf tissue and loss of chlorophyll<sup>(30)</sup> but in the long term can impair growth and reduce carbohydrate level as well<sup>(25)</sup>. The effects of acidic secondary pollutants, as described in **Section 3.2.2**, are, however, generally greater. Smog components can be transported far from the primary pollution source and react to form secondary aerosols and particulates depositing out as acidic particles on plants, soils and into water sources, or directly as acid rain. Deposition in catchment areas in the dry season can lead to acid formation later when rain falls. The capacity of water to absorb this acidic material without a change in pH is known as buffering and depends largely on the concentration of calcium and magnesium carbonates<sup>(30)</sup>.

Acidic depositions have been linked to the death of fish and trees in Europe <sup>(25,30)</sup>. Aquatic plants and animals especially have a limited range of tolerance for pH. Bottom dwelling or *benthic* species are the most severely affected <sup>(30)</sup>. In South Africa, damage to benthic species in streams on the Drakensberg escarpment has been observed and linked to acidic depositions originating from air pollution <sup>(30)</sup>.

The toxicity of pollutants as regards human beings was discussed above in **Section 3.3**. It may be assumed that much of this can be applied to animals as well, especially mammals. Hext et al <sup>(34)</sup> have reported that the rat lung may *over-respond* to particulate matter. Seen from the perspective of the rat, for the purpose of analogy, this not an *over-response* but an increased sensitivity. Given the limitations of pollutant epidemiology on human beings, however, it is not any more certain whether any animals are especially threatened by air pollution except those that have the misfortune of being vivisected in bioassays.

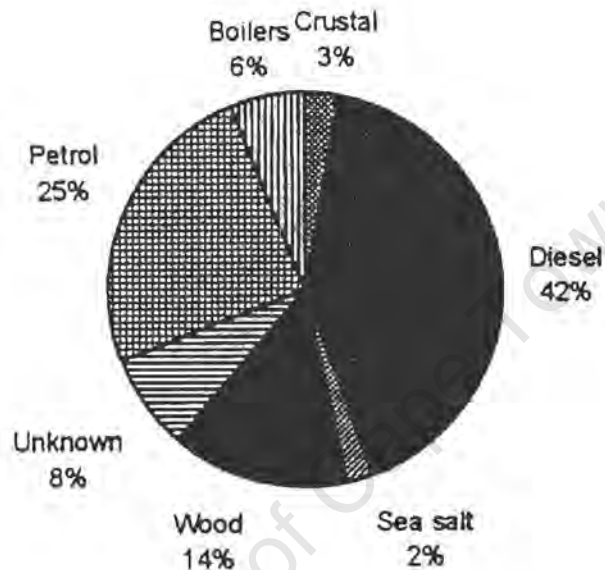
### 3.4.3 EFFECTS OF AIR POLLUTANTS ON MATERIALS, STRUCTURES AND AESTHETICS

Acidic deposition and acid rain can damage the stonework of buildings, particularly limestone, marble, slate and mortar. Metallic structures are similarly threatened <sup>(25,30)</sup>. Particulate deposition on high-voltage transmission equipment can form a conductive layer, shorting out insulators and leading to faults and damage to equipment <sup>(30)</sup>. Atmospheric acids can degrade fabrics, particularly nylon <sup>(25,30)</sup>.

Visibility impairment is a problem in many cities of which Cape Town itself is one <sup>(25,107)</sup>. Internationally, sulphate, nitrate and organic particulates have been identified as contributing the most <sup>(30,107)</sup> to reduced visibility. Four main mechanisms have been proposed <sup>(107)</sup>:

- Absorption of photons by gases to drive photochemical reactions.
- Light scattering by gases (Rayleigh scattering).
- Light scattering by particles, in particular those around 0.5µm in diameter.
- Absorption of light by black and hued particles. These are usually carbonaceous or organic particulates.

The phenomenon of episodic photochemical smog in Cape Town, giving rise to an unsightly haze of smog, motivated an intensive investigation known as the Brown Haze Study, carried out from 1995 to 1997. The study focussed mainly on the visibility ramifications of the Brown Haze, but an apportionment of PM less than  $2.5\mu\text{m}$  in diameter (PM<sub>2.5</sub>) was carried out, which implicated diesel vehicles as the main contributors in Cape Town<sup>(107)</sup>. The results of this apportionment are shown graphically below in **Figure 19**.



**Figure 19:** Apportionment of sub  $2.5\mu\text{m}$  particulate matter in Cape Town urban atmosphere<sup>(107)</sup>

A visibility apportionment was also performed which agreed very closely with the above, diesel contributing to 48% of the visibility degradation effect of the Cape Town Brown Haze<sup>(107)</sup>.

### 3.5 ENGINE TECHNOLOGY AND EXHAUST AFTER-TREATMENT TO REDUCE POLLUTANTS FROM DIESEL ENGINES

The introduction of regulations to limit emissions from combustion engines has placed a great deal of pressure on manufacturers to expend effort on developing new technologies. The resulting efforts have been largely successful, with engine manufacturers achieving substantial reductions of the regulated pollutants over the last 20 years. In the case of diesel engines these developments have focussed on the engine itself rather than on after-treatment of the exhaust gas, as was the case with spark

ignition powered passenger vehicles. The control of two pollutants, PM and  $\text{NO}_x$ , have been the primary goals, as emissions of CO and  $\text{HC}_n$  are an order of magnitude lower than from spark ignition engines and have thus only recently presented a regulatory challenge.

These twin goals present the engine designer with a direct trade-off as a result of the formation processes of  $\text{NO}_x$  and PM discussed above in **Section 3.1** <sup>(24,27,47,73)</sup>. In the case of fuel-derived pollutants like PM, any measure that improves fuel conversion (thermal) efficiency will almost certainly lead to a reduction of specific emissions. Whether through reducing losses or by improved control of combustion, this necessitates increased peak cylinder pressures and thus also increased temperatures, increasing fuel conversion efficiency. The trade-off is increased  $\text{NO}_x$  emissions, as these are directly dependent on flame temperature as indicated by **Figure 7** above and are not fuel-derived. In the converse situation whereby  $\text{NO}_x$  may be reduced by a measure like retarding the injection timing, PM will increase due to the drop in fuel conversion efficiency and also the shortened ignition delay, which results in less pre-mixed combustion which itself emits less PM <sup>(24,27,86)</sup>. There are few technologies available to the designer not inhibited by this trade-off. Some effective measures are presented graphically below in **Figure 20**. The trade-off relative to US regulations is shown.

Note: Current engines improve significantly on these trends meeting U.S. 1998 standards without a trap.

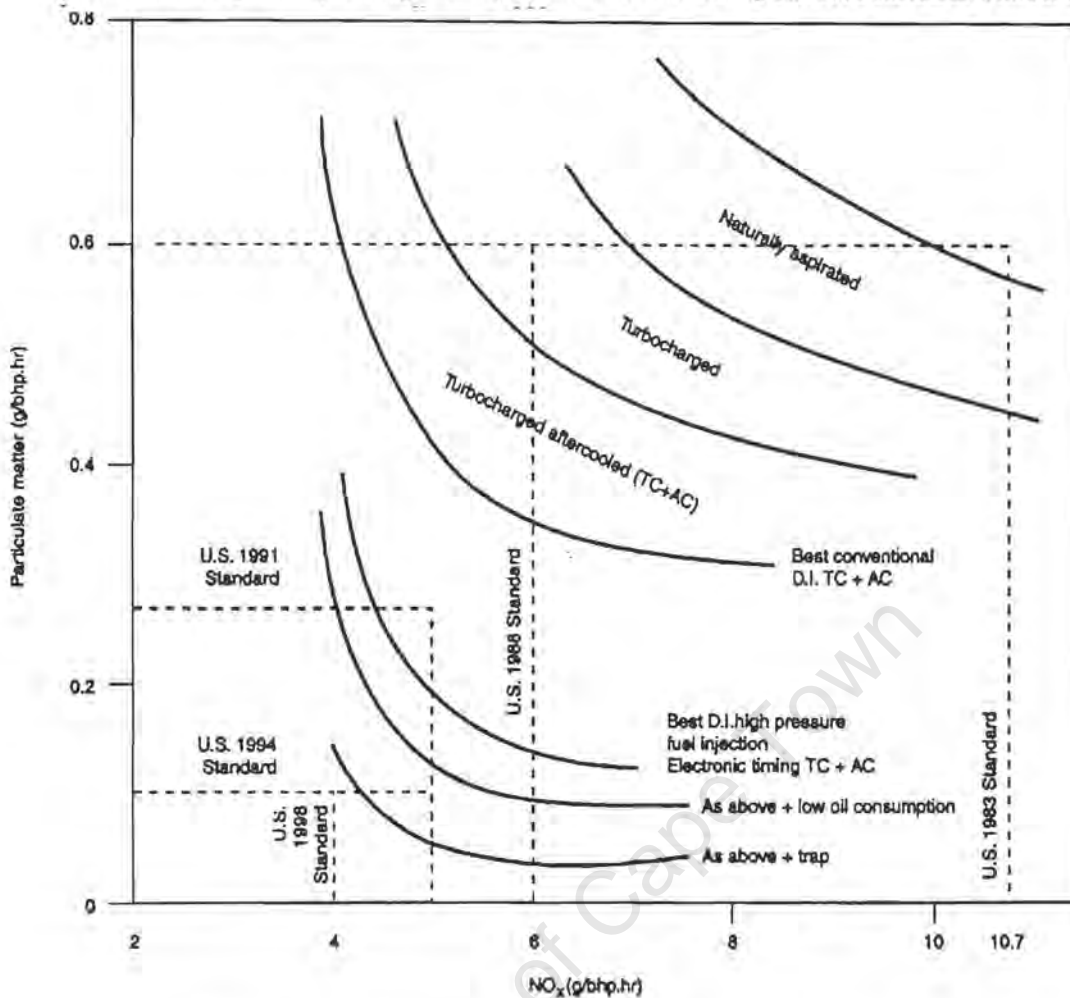


Figure 20: Emissions Reduction Measures showing PM/NO<sub>x</sub> Trade-off<sup>(27)</sup>

The principle of turbocharging is described above in **Section 1.1**. The increased air density promotes fuel air mixing and the recovery of exhaust energy increases fuel conversion efficiency, resulting in substantially lower PM emissions<sup>(27,47,73)</sup>. The boosting of intake air increases peak cylinder temperatures however, which will tend to increase NO<sub>x</sub>, although this is not completely clear from **Figure 20**. Cooling the compressed charge using a heat exchanger, known as intercooling or aftercooling, is a highly effective solution to reduce NO<sub>x</sub> while further increasing charge air density and reducing PM<sup>(27,47,73)</sup>, as indicated by **Figure 20**. Variable Geometry Turbocharging (VGT) allows the turbine nozzle guide vane angle to be optimised throughout the engines speed range, allowing higher boost pressures at low speeds without overboosting at high speeds. This is especially effective in reducing fuel consumption PM and NO<sub>x</sub> at transient conditions<sup>(27,73)</sup>.

A particular advantage of turbocharging in the South African situation is the mitigating effect on change in altitude. One of the findings of this study was that two thirds of national diesel consumption takes place well above sea-level. Reduced intake air density as a result of high altitude has been shown to have a highly deleterious effect on the HC<sub>n</sub>, CO and PM emissions of naturally aspirated diesel engines. Human et al <sup>(46)</sup> at the Southwest Research Institute simulated the effect of increasing altitude to 1,800 metres above sea level on the emissions from heavy-duty diesel engines in a specially fitted laboratory. They compared the relative deterioration of emissions, as measured by the US Heavy Duty Federal Test Procedure, of a 10.4 litre 160kW naturally aspirated engine with that of a 14.0 litre 260kW turbocharged engine. The results of this comparison are presented below in **Table 7**.

**Table 7:** Altitude Effect on Emissions; Comparison between a Naturally Aspirated and Turbocharged Heavy-Duty Diesel Engine <sup>(46)</sup>

Emission	CAT 3208 (Naturally Aspirated)			Cummins NTCC-350 (Turbo)		
	Sea-Level	1800 m	Difference	Sea-Level	1800 m	Difference
	(g/kW.h)	(g/kW.h)	(%)	(g/kW.h)	(g/kW.h)	(%)
HC <sub>n</sub>	1.13	4.90	334%	1.28	1.53	20%
CO	7.02	28.30	303%	3.18	6.00	89%
NO <sub>x</sub>	12.90	11.60	-10%	6.99	6.48	-7%
PM	0.80	1.80	125%	0.63	0.92	46%
Aldehydes	0.31	0.66	113%	0.16	0.26	63%

The above data indicates the profound effect of altitude on the emissions of naturally aspirated engines relative to turbocharged engines. The latest multiple stage turbocharged and intercooled heavy-duty diesel engine designs, like the Cummins QSK78, which has 12 individual turbochargers in two intercooled stages, are claimed to be impervious to the effects of altitude within the range of human activity <sup>(20)</sup>. This engine meets the US 1998 emissions regulations as indicated in **Figure 20** above without resort to exhaust after-treatment like a particulate trap. Other than the innovative turbocharging system it has very high injection pressures of up to 2,000bar. The effect of increasing injection pressure on the NO<sub>x</sub>/PM trade-off is shown below in **Figure 21**.

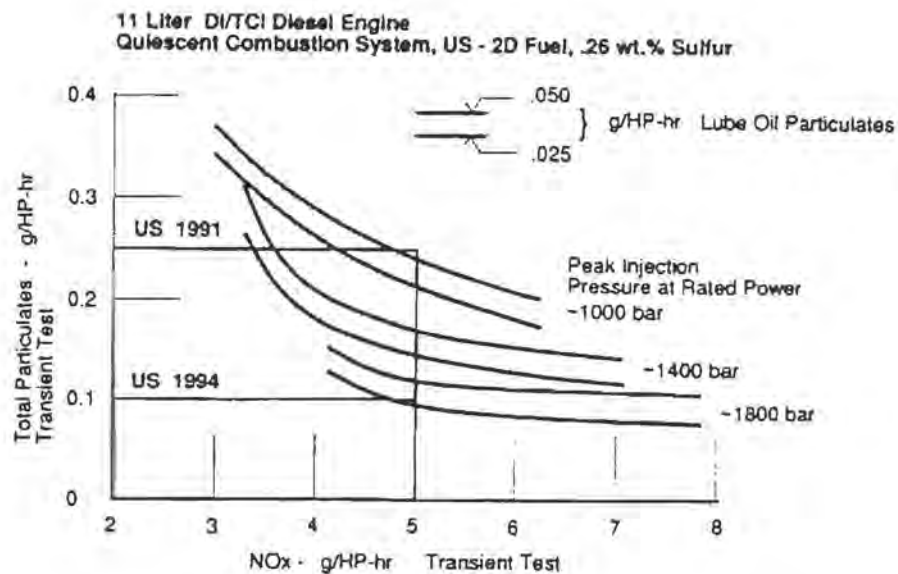


Figure 21: Effect of High Injection Pressures on Diesel Engine Emissions <sup>(112)</sup>

High injection pressures increase fuel air mixing and improve fuel atomisation but also allow injection timing to be retarded without PM penalties due to the higher rate of fuel injection <sup>(27,54, 73,86,112)</sup>. Typically, these very high pressures are applied in low swirl direct injection engines where the fuel spray accomplishes most of the charge mixing, thus reducing the amount of initial mixing and in turn pre-mixed combustion and NO<sub>x</sub> emissions <sup>(73)</sup>. Such fuel injection systems generally require either unit injectors or common rail fuel injection systems. The engines tested in the experimental phase of this study and representative of the market at the time were fitted with so-called pump-line nozzle injection systems. This includes pumping elements for each cylinder driven by the engine crankshaft via cams and built into one unit that supplies the injector nozzles in the top of each cylinder by means of fluid lines. Pressure wave effects and mechanical strength limitations limit the injection pressures from these systems to about 800bar <sup>(27)</sup>.

The rate at which fuel is injected also presents considerable scope for optimisation. In particular the injection of a small quantity of fuel, called pre-injection, before the injection of the bulk of the fuel reduces the ignition delay and therefore the amount of pre-mixed combustion, in turn reducing NO<sub>x</sub> emissions <sup>(24,27,50,86,97,112)</sup>. PM penalties are avoided by increased rate of primary injection to reduce the late burning phase. **Figure 22** below shows the effect of varying the amount of fuel injected during the ignition delay period on NO<sub>x</sub> emissions, as reported by Zelenka et al <sup>(112)</sup>.

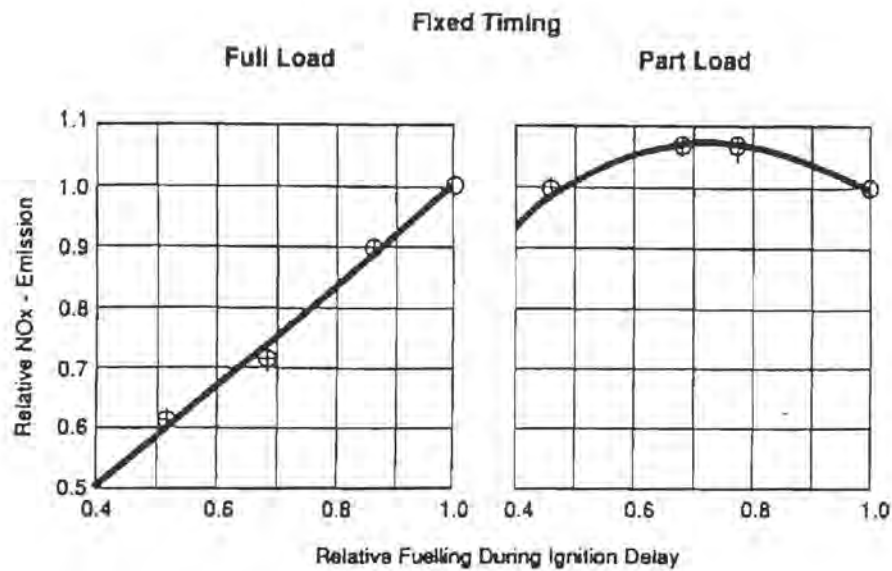


Figure 22: Effect of Fuelling Quantity during Ignition Delay on NO<sub>x</sub> Emissions <sup>(112)</sup>

Work by AVL and elsewhere in the late 1980s also indicated that the charge mixture could be optimised for the NO<sub>x</sub>/PM trade-off by varying the injection profile throughout combustion <sup>(27,112)</sup>. **Figure 23** below presents a graphical example for an engine that mixes charge by using swirl. These developments led directly to the requirement for electronically controlled fuel injection that characterises all modern diesel engines. The timely application of new generation fast-acting solenoids, common rail injection systems and suitably adapted electronic control units (ECUs) already common in passenger cars has allowed the engine designer almost complete flexibility in controlling the rate of fuel injection <sup>(27,56)</sup>. The engines tested in the experimental phase of this study did not represent these technologies.

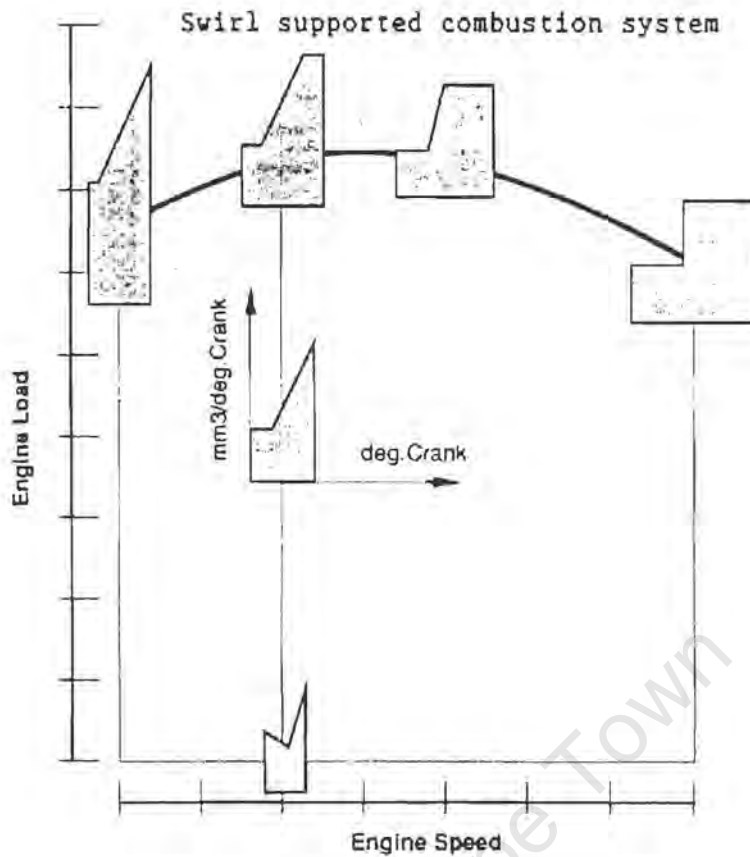
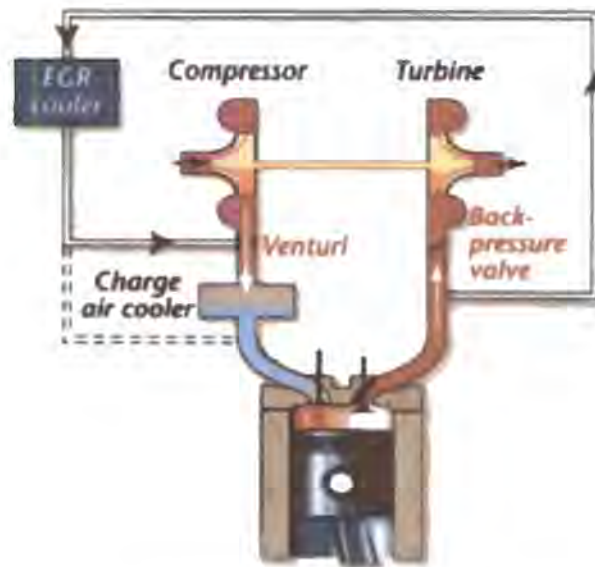


Figure 23: Example of Optimised Fuel Injection Rate Profile for Emissions Reduction (AVL) <sup>(112)</sup>

Considerable reductions in PM emissions can be achieved by reducing the contribution of the lubricant <sup>(27,73,112)</sup>. Lubricant-derived hydrocarbons account for about 25% of PM emission mass with a range of about 15% to 40% <sup>(73)</sup> (Faiz <sup>(27)</sup>: 10% to 50%). As PM emissions have been reduced by the various means described above this fraction has become increasingly critical. Reductions can be achieved by improvements to seals but the fundamental contribution is from the cylinder wall losses <sup>(112)</sup>. Mechanical design improvements to reduce bore distortion and the development of special lubricants have allowed total PM emissions reductions of 10% to 20% <sup>(27,112)</sup>.

Another promising technique borrowed from spark ignition engines for emissions reduction, especially that of NO<sub>x</sub>, is that of Exhaust Gas Recirculation (EGR) <sup>(10,33,47,54,56)</sup>. This entails diverting a portion of the exhaust gas, up to a maximum of about 40%, into the air intake <sup>(33,56)</sup>. The high specific heat capacities of the CO<sub>2</sub> and water in the exhaust reduce the peak combustion temperature and thus NO<sub>x</sub> emissions. A schematic of the system is presented below in **Figure 24**.



**Figure 24:** Schematic of Exhaust Gas Recirculation System <sup>(10)</sup>

It should be noted that the exhaust gas is bled in after the compressor instead of before, thus requiring the exhaust back pressure to be high enough to force positive flow. The acidic effects of the exhaust preclude contact with the aluminium components of the compressor and so prevent EGR on the low-pressure side of the turbocharger <sup>(10,47,56)</sup>. This can result in fuel economy penalties but with careful optimisation these are small and PM emissions can be kept constant. The problem of acidity that extends to the lubricant as well as mechanical components has discouraged all the European truck manufacturers except MAN from applying this technology. The current US emissions regulations, on the other hand, are currently more stringent and EGR is in common use by US manufacturers <sup>(10)</sup>.

Compressed Natural Gas (CNG) has become the fuel of choice for alternative heavy-duty applications globally. Heavy-duty gas engines are manufactured from diesel engine parts off the assembly line for reasons of economy. The octane rating of CNG ( $\pm 120$ ) therefore requires less reduction of the original engine compression ratio than Liquid Petroleum Gas (LPG) (octane rating 90 – 100) as well as allowing for higher thermal efficiency <sup>(67)</sup>. CNG is normally applied to captive fleets (fleets that travel a consistent route in urban areas) because the fuelling and supply infrastructure worldwide is still in its infant stage. A barrier to this development is that CNG, being a gas, is difficult to store and transport. Natural Gas is expensive to liquefy due to its low density and is thus usually handled in its compressed gaseous form. It must be stressed that the CNG engine is not a diesel engine but rather a spark ignition engine (Otto cycle not Diesel Cycle). Therefore,

essentially in terms of a strategy for reducing emissions from diesel engines, CNG conversion entails replacing diesel engines with another type of engine and not only using a different fuel. **Table 8** below compares the emissions for MAN's 11.97 litre heavy-duty CNG engine with the Euro 2 and Euro 3 emissions limits (see **APPENDIX D**). It should be noted that not only are PM emissions greatly reduced compared to diesel engines but HC<sub>n</sub>, CO and particularly NO<sub>x</sub> emissions are also profoundly lower.

**Table 8:** Emissions Data for Heavy-Duty MAN E 2866 CNG Engine Compared to Euro Limits for Diesel <sup>(57)</sup>

	HC <sub>n</sub>	CO	NO <sub>x</sub>	PM	TEST
	(g/kW.h)	(g/kW.h)	(g/kW.h)	(g/kW.h)	CYCLE
<b>MAN E 2866 CNG</b>	0.5	1.0	1.0	0.02	13 mode R49
<b>EURO 2</b>	1.1	4.0	7.0	0.15	13 mode R49
<b>EURO 3</b>	0.66	2.1	5.0	0.10	13 mode ESC

There are various options for the after-treatment of exhaust gas from diesel engines. Some of these are as follows:

- **Oxidation catalyst:** This is the same technology used traditionally in passenger cars to oxidise CO and HC<sub>n</sub> to CO<sub>2</sub> and H<sub>2</sub>O. PM from diesels is also decreased. Low sulphur fuel of at most 0.05% is required <sup>(8,56)</sup>.
- **Selective catalytic reduction (SCR):** This involves the injection of urea, which selectively reduces NO<sub>x</sub> to N<sub>2</sub>. This allows the engine to be optimised for low particulate emissions without NO<sub>x</sub> penalties and thus indirectly decreases particulate emissions. Ultra-low sulphur fuel (0.005%) is required <sup>(56)</sup>.
- **Particulate Trap:** The PM is trapped in a monolith. Some trap regeneration occurs naturally from the oxygen-rich exhaust of the diesel engine but ultimately the filter element must be replaced routinely to prevent blockage. Various filter media have been used in working models, including ceramic monoliths, sintered metal, wound fibre, knitted fibre, fibre weaves and even paper filters tolerant of temperatures up to 300°C These designs are fuel sulphur tolerant <sup>(56,63)</sup>.
- **Continuously regenerating trap (CRT):** The particulate matter is also trapped in a monolith. The trap is regenerated by using the oxygen-rich exhaust of the diesel

engine to oxidise the PM by a process of combustion, enhanced usually by oxidation with NO<sub>2</sub> rather than oxygen. The NO<sub>2</sub> is produced by an upstream oxidation catalyst. Thus this trap can operate for an extended period without any maintenance being required to prevent blockage. This technology requires diesel sulphur of 0.005% (8,56,63)

**Table 9** below shows the profound reductions in PM emissions resulting from particulate trap technology <sup>(8)</sup>:

**Table 9:** PM Emissions with various Exhaust After-treatment Devices (Schmidt & Pütz in Ref. 8)

Fuel	PM (g/kW.h)
LSD	0.121
LSD + Oxidation catalyst	0.11
ULSD + CRT	0.01
ULSD + SCRT	0.01

LSD: Low Sulphur Diesel

ULSD: Ultra-Low Sulphur Diesel

CRT: Continuously Regenerating Trap SCRT: Selective Catalytic Reduction with Particulate Trap

Thus the application of exhaust after-treatment devices can virtually eliminate PM emissions from diesel engines and thus also reduce the lifecycle emissions for low sulphur diesel fuels, as is discussed below in **Section 3.6**, such that very low sulphur levels are beneficial from an emissions perspective <sup>(8)</sup>. It is unlikely that after-treatment of the exhaust will be a common feature in Europe until the Euro 4 emissions limits are enforced <sup>(47,56)</sup> in 2005, at which time engines emitting almost particulate-free exhaust can be expected on the market. Particulate traps that filter out PM in the exhaust are already at an advanced stage of development. At this stage it seems most manufacturers will rely on these devices to meet future emissions regulations.

### 3.6 FUEL REFORMULATION MEASURES TO REDUCE POLLUTANTS FROM DIESEL ENGINE OPERATION

The specifications which diesel fuel must meet have been discussed above in **Section 1.2**. Modern specifications in the developed world have become somewhat more stringent, mostly due to the demands of exhaust emission control. The engine

manufacturers themselves are now making demands for higher fuel specifications to reduce emissions and enable emissions technology like continuously regenerating particulate traps. Four industry organisations, the Alliance of Automobile Manufacturers, European Automobile Manufacturers Association (ACEA), Engine Manufacturers Association (EMA) and Japan Automobile Manufacturers Association (JAMA), have compiled a charter called the World-Wide Fuel Charter, outlining their expectations for reformulated fuel specifications. The proposed specifications are divided into categories based on the emissions requirements of the market. The SABS specification presented in **Table 1** would be Category 1 for "Markets with no or minimal requirements for emissions controls: based primarily on fundamental vehicle/engine performance concerns". Category 2 and Category 4 specifications are presented in **Table A - 1** and **Table A - 2** respectively in **APPENDIX A**. Two things are evident. First, the list of specifications has lengthened and secondly, properties like sulphur content have dropped from the South African level of 0.55% to 0.03% for Category 2 and sulphur free for Category 4. This section will briefly explain the rationale behind these proposals by examining some fundamental effects of fuel formulation on diesel engine emissions.

### **3.6.1 EFFECT OF DIESEL PROPERTIES ON EMISSIONS FROM THE EXHAUST**

A number of fuel properties affect the regulated emissions to a greater or lesser extent. In general the magnitude of the effect achieved by fuel reformulation is smaller than that achieved by vehicle technology improvements, but is nonetheless significant. Furthermore, fuel reformulation can reduce emissions in the entire vehicle park while new vehicles take a long time to penetrate the market. **Table 10** below shows the general effect of fuel properties on emissions as reported by Owen and Coley<sup>(75)</sup>.

Table 10: Effect of Diesel Fuel Properties on Emissions according to Owen and Coley <sup>(75)</sup>

PROPERTY	Change	Effect: I = Improvement					
		SFC	Smoke	NO <sub>x</sub>	HC	CO	PM
SULPHUR	lower		I				I
VISCOSITY	lower	I	I		I	I	I
FBP*	lower		I	I	I		I
DENSITY	lower	I	I		I		I
AROMATICS	lower						
POLY-AROMATICS	lower		I				I
CETANE	higher	I	I	I	I	I	I

\*FBP: Final Boiling Point

The above effects have been quantified in more detail by the European Programme on Emissions, Fuels and Engine Technologies (EPEFE) <sup>(27,88)</sup>. An intensive testing programme was undertaken in co-operation with the European oil and motor industries to generate scientifically sound data on, amongst other objectives, the effect of fuel properties on emissions. Table 11 below summarises the results for heavy-duty diesel engines. The fuel matrix consisted of 11 fuels with properties varying in the range shown, tested on five 1996 heavy-duty diesel engines <sup>(88)</sup>.

Table 11: Quantified Effect of Diesel Fuel Properties on Heavy-Duty Emissions (EPEFE) <sup>(27)</sup>

(percent)

Diesel fuel property <sup>a</sup>	CO	HC	NO <sub>x</sub>	PM	CO <sub>2</sub>
Density 855 to 828 g/l	+5.0 <sup>b</sup>	+14.25 <sup>c</sup>	-3.57	-1.59	+0.07
Polyaromatics 8 to 1 percent	0.08 (NS)	-4.02	-1.66	-3.58	-0.60
Cetane 50 to 58	-10.26	-6.25	-0.57	0 (NS)	-0.41
T95 370 to 325°C	+6.54	+13.22	-1.75	0 (NS)	+0.42
Sulfur 2000 to 500 ppm	—	—	—	-13.0	—

— Not applicable

NS = Non-significant.

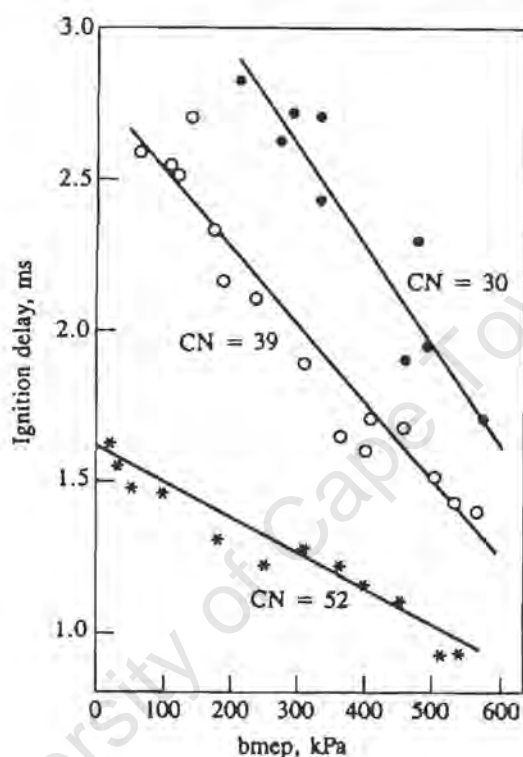
a. Baseline properties: density 855 g/l; polyaromatic content 8 percent cetane number 50; T95 370°C; sulfur 2000 ppm.

b. Negative values indicate a decrease in emissions.

c. Positive values indicate an increase in emissions.

It should be stressed that the effect of density is to effectively derate the engine by injecting a lower mass of fuel per fuel pump stroke. There is no effect on the combustion

process itself. Reducing the polyaromatics content of diesel reduces the quantity of high molecular weight hydrocarbons that may not combust or combust partially and are then emitted as gaseous  $HC_n$  or as  $HC_n$  adsorbed onto PM. Increasing cetane number (CN) reduces ignition delay and thus reduces pre-mixed combustion and in turn CO and  $HC_n$  emissions.  $NO_x$  emissions are not reduced significantly, although if injection timing is retarded to take advantage of the shorter ignition delay, reduction should be greater. **Figure 25** below shows the effect of cetane number on ignition delay.



**Figure 25:** Effect of Cetane Number on Ignition delay<sup>(35)</sup>

T95 is the 95% distillation temperature of the fuel or the temperature at which 95% of the fuel can be boiled off a distillation column. In other words, this is a measure of the heavy end volatility similar to Final Boiling Point (FBP). The findings for T95 are therefore in direct contrast to those of Owen and Coley<sup>(75)</sup> shown in **Table 10**.

Broadly similar results to those presented in **Table 11** have been reported by Martin et al<sup>(62)</sup> in a study of 12 fuels with greater variation in fuel properties than above. Sulphur, however, was not correlated with emissions effects and T95 showed no significant increase in  $CO_2$  and had only a small effect on  $HC_n$ . Sienicki et al<sup>(87)</sup> found that reducing 90% distillation temperature (T90) by 40°F reduced PM by about 20%. This is supported by Tsurutani et al<sup>(96)</sup>, who found that PM was reduced very profoundly by two thirds at part load with a 90% distillation temperature reduction of 80°C. Neither of these groups of

researchers, however, took into account the proportional reduction in density, evident in their test fuel specifications, with reduced upper distillation temperature. The EPEFE fuel matrix, on the other hand, was designed to allow pairwise comparisons with fuels varying only in one individual property to decouple related fuel parameters. This may also account for the discrepancy between Owen and Coley's <sup>(75)</sup> assessment of distillation temperature effects and the findings of EPEFE <sup>(88)</sup>.

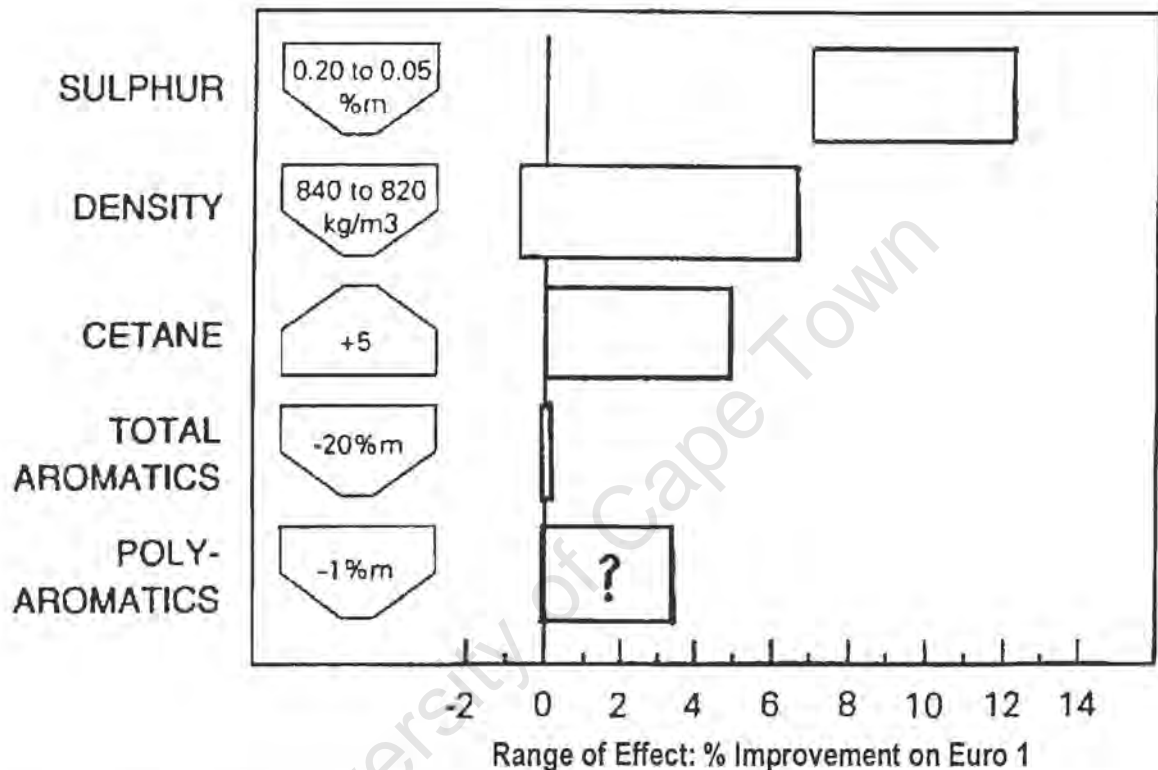
Sasol Oil has demonstrated simultaneous significant emissions reductions of all the regulated emissions with more extreme property variation than tested by EPEFE <sup>(84)</sup>. Their product, called Slurry Phase Distillate (SPD), is an ultra-high cetane, low density, low aromatic, ultra-low sulphur diesel fuel derived from synthetic feedstock. A seven-fuel matrix was tested on a six-cylinder, 12.7 litre, turbo-intercooled, direct injection, electronically controlled engine using the US FTP transient hot start cycle. Some degree of pairwise comparison was made to decouple fuel properties. These indicated that CO, HC<sub>n</sub> and NO<sub>x</sub> emissions reductions were related to high cetane number rather than aromatic content but that reductions in PM emissions were unlikely to relate to cetane number. In one comparison of two fuels with matched densities, a lower sulphur fuel (0.018% wt) with high aromatics (27.05% wt) did not give lower PM emissions than a higher sulphur fuel (0.028% wt) with low aromatic content (9.91% vol.). Polyaromatics were not measured for the high aromatic fuel though. The other fuel properties were not decoupled. **Table 12** below compares the properties and emissions of the Slurry Phase Distillate and a standard California (CARB) low sulphur diesel.

**Table 12:** Reduction of Emissions with Sasol SPD versus CARB Diesel <sup>(84)</sup>

	Density	FBP	Cetane	Sulphur	Aromatics	HC <sub>n</sub>	CO	NO <sub>x</sub>	PM
	(kg/l)	(°C)	Number	(% wt)	(% wt)	(% reduction vs. CARB)			
<b>Sasol SPD</b>	0.7769	356	>73.7	0.001	2.68	49%	33%	27%	21%
<b>CARB</b>	0.8308	351	49.4	0.028	9.91	-	-	-	-

The European Environment Agency's COPERT III emissions factor model applies equations derived from regressions applied to the results of the EPEFE programme, discussed above, to account for the effect of fuel properties on emissions. COPERT III is discussed in detail in **APPENDIX F**. The equations accounting for the effect of fuel properties are presented in **Figure F - 2** for heavy-duty diesel engines and in **Figure F - 3** for light-duty diesel engines.

In terms of the trade-off between  $\text{NO}_x$  and PM, fuel reformulation seems to present an opportunity to reduce PM appreciably without  $\text{NO}_x$  penalties. Studies that have focussed on PM reduction with fuel reformulation are also in broad agreement with EPEFE. The results of a Shell Oil study that also blended test fuels with only one variable property are presented below in **Figure 26**.



**Figure 26:** Effect of Fuel Properties on PM Emissions (Shell Research Laboratories) <sup>(76)</sup>

The effect of fuel sulphur on PM emissions seems to be the most profound and reproducible of the fuel property effects, given an initial high level, as is the case with crude-derived diesels in South Africa. The issue of fuel sulphur was of particular interest to this study as it is a topical local industry issue. It was therefore decided to model the effect of fuel sulphur reduction as a scenario in the modelling phase of this study. The relationship between fuel sulphur level and PM emissions is well researched and some studies have generated linear single variable correlations that can be applied to a numerical model. Good agreement was found between three different sources <sup>(110,75,112)</sup>. These are presented below in **Equations 19 - 22**:

- If:  $\Delta PM$  = The change in PM emissions (g/kW.h)  
 $\Delta S$  = The change in fuel sulphur content (0.1 % weight)

ACEA proposes in the World Wide Fuel Charter <sup>(110)</sup>:

$$\Delta PM = 2.553 \times 10^{-2} \Delta S \quad \text{for bsfc} = 200 \text{ g/kW.h} \quad \dots(\text{Equation 19})$$

$$\Delta PM = 1.809 \times 10^{-2} \Delta S \quad \text{for bsfc} = 270 \text{ g/kW.h} \quad \dots(\text{Equation 20})$$

Barry et al propose in Owen & Coley <sup>(75)</sup>:

$$\Delta PM = 2.282 \times 10^{-2} \Delta S \quad \dots(\text{Equation 21})$$

AVL GmbH in Zelenka et al <sup>(112)</sup> propose:

$$\Delta PM = (2.685 \times 10^{-2} \pm 0.537 \times 10^{-2}) \Delta S \quad \dots(\text{Equation 22})$$

It was decided to apply **Equation 22** only to the model as **Equations 19** and **20** were derived for a maximum fuel sulphur level of only 0.05% while the model covers a range an order of magnitude greater. **Equation 22** is more recent research than **Equation 21** and is derived from a larger data set.

Manipulation of the EPEFE PM fuel property correction equation <sup>(74)</sup> presented in **Figure F - 2** in **APPENDIX F** yields a slightly more complicated expression dependent both on the reduction of fuel sulphur and the initial baseline fuel sulphur content. Inserting the equation from **Figure F - 2** into **Equation 38** in **APPENDIX F**, keeping all fuel properties except sulphur constant, yields the following relation:

- If:  $\Delta PM_{HDD}$  = Change in heavy-duty diesel PM emissions (%)  
 $\Delta PM_{LDD}$  = Change in light-duty diesel PM emissions (%)  
 $\Delta S$  = Change in fuel sulphur content (ppm)  
 $S_B$  = Baseline fuel sulphur content (ppm)

$$\Delta PM_{HDD} = \left( \frac{8.6}{961.3 + 0.086 \cdot S_B} \right) \times \Delta S \quad \dots(\text{Equation 23})$$

$$\Delta PM_{LDD} = \left( \frac{1.5}{93.25 + 0.015 \cdot S_B} \right) \times \Delta S \quad \dots(\text{Equation 24})$$

The baseline inventory model compiled for the modelling phase of this study was solved using **Equation 23** and **Equation 24**. The model was also solved using **Equation 22** to determine a comparative prediction of the effect of fuel sulphur reduction on heavy-duty emissions. The results are reported in **CHAPTER 6**.

The significant effect on particulate emissions of fuel sulphur reduction has led to fuel sulphur levels being reduced in many countries. South Africa currently has a relatively high fuel sulphur limit of 0.55%, although over a third of actual production is synthetic diesel that is effectively zero sulphur. This limit is going to be reduced to 0.3% in January 2003, with further reductions possible <sup>(78)</sup>. In contrast, most European countries regulate diesel sulphur to 0.05%, with many Nordic countries regulating to 0.005% <sup>(27)</sup>. The primary barrier is the high cost of sulphur reduction. Molden <sup>(64)</sup> has estimated the cost of reducing diesel sulphur from the new limit of 0.3% to an even lower 0.05% at R3-billion. Sulphur reduction, while reducing the particulate emissions from the vehicle, sometimes causes increases in particulate and other emissions in the production process <sup>(8)</sup>. This is discussed below.

### 3.6.2 LIFECYCLE EMISSIONS OF DIESEL AND ALTERNATIVE FUELS

It is important when analysing the emission effects of fuels to apply the so-called "wells to wheels" approach; in other words, assess the emissions from the total lifecycle of the fuel from extraction through production to consumption. **Table B - 1** in **APPENDIX B** presents total lifecycle emissions for various fuels, including low sulphur diesels and alternative fuels, for heavy-duty bus operation as estimated by the CSIRO in Australia <sup>(8)</sup>. These estimates indicate that a point is reached where diesel sulphur reduction actually increases total particulate emissions. South Africa has large urban-area-located refinery capacity around which highly vocal ratepayers and activist groups have formed. These

lifecycle effects are therefore of serious public consequence. Sulphur reductions to the levels shown in **Table B - 1** may have the greatest benefit through enabling technology like particulate traps, considering the high cost.

Also shown in **Table B - 1** are promising alternative heavy-duty fuels CNG, LPG, Ethanol and Biodiesel. The first three offer profound reductions in PM emissions as they are used in Otto cycle engines. Biodiesel is combusted in a standard diesel engine. Biodiesel has been defined by Koo-Oshima as:

*"The mono alkyl esters of long chain fatty acids derived from lipid feedstock ie: animal fats or oilseed crops like rapeseed."* <sup>(55)</sup>

A more accessible explanation is perhaps that biodiesel is oil, pressed from natural renewable sources and esterified by refining so as to reduce the viscosity to prevent clogging of the fuel system and coking of the fuel injectors. Biodiesel is indicated by **Table B - 1** as having higher PM emissions than diesel, which is in contrast to the findings of the International Energy Agency (IEA). **Table 13** below presents their emissions factors for alternative fuels.

**Table 13:** Normalised Comparison of IEA Emissions factors for Heavy Duty use of Alternative Fuels (diesel emissions factors normalised to 100) <sup>(8)</sup>

European tailpipe emissions for heavy-duty vehicles as a percentage of diesel emissions

Fuel	NO <sub>x</sub>	CO	HC	PM	CO <sub>2</sub>
Diesel	100	100	100	100	100
LPG	20-25	200-500	200-209	24	98-100
NG	15-34	100-620	150-646	15	87-103
Ethanol	81-90	107-400	140-145	19	83-100
Biodiesel	106-115	67-100	80-96	67	102-106
Diesel (g/km)	14.1-16.0	0.5-4.3	0.4-0.5	1.1	885-1195

Source: IEA/AFIS (1999)

European well-to-wheel lifecycle emissions for heavy-duty vehicles as a percentage of diesel emissions

Fuel	NO <sub>x</sub>	CO	HC	PM	CO <sub>2</sub>
Diesel	100	100	100	100	100
LPG	22-32	199-445	69-177	24	94
NG	16-35	99-530	255-588	15	87
Ethanol (cellulose)	94-103	577-1075	160-256	N/D	16-26
Ethanol (sugar)	103-104	119-891	114-235	55	34-67
Biodiesel	118-127	81-212	68-120	90-98	28-44
Diesel (g/km)	14.-16.7	0.6-4.3	1.1-1.8	1.1	977-1363

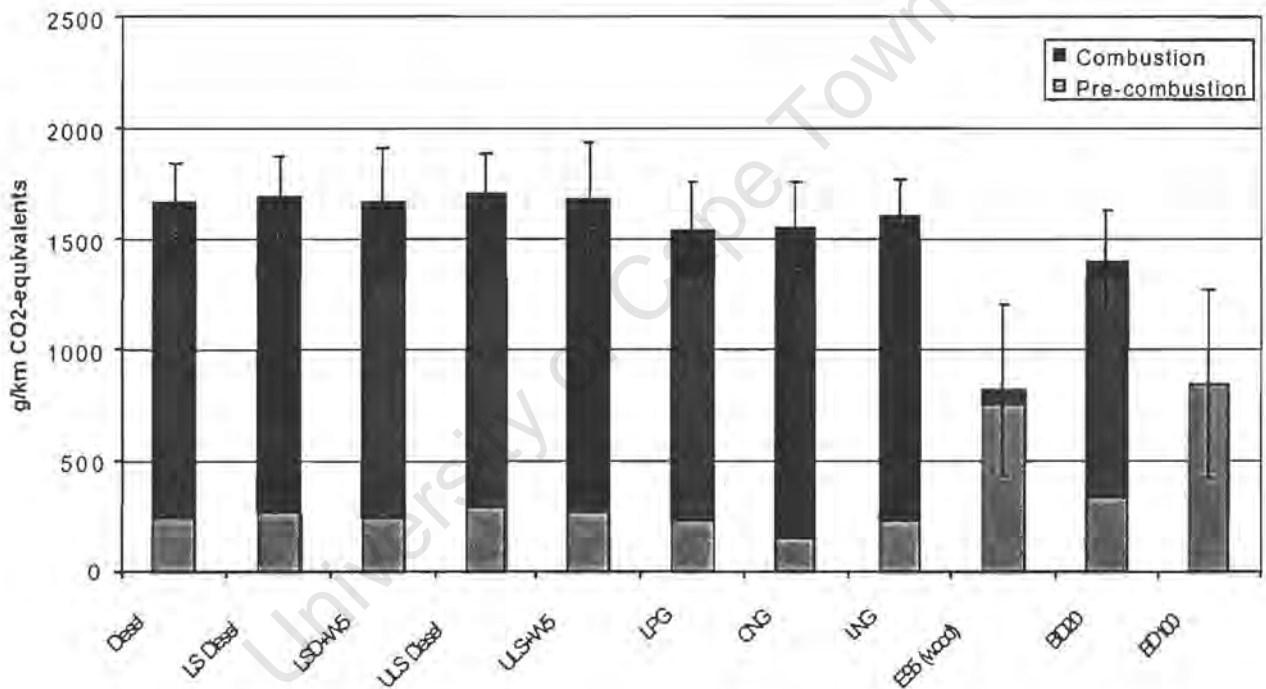
N/D = No Data

Source: IEA/AFIS (1999)

A review paper by Koo-Oshima et al reports on a study that found 100% biodiesel reduced PM emissions by 30% and CO emissions by 50%, while NO<sub>x</sub> increased by 13%. The same review reports on a study that compared the emissions of a 20% blend of biodiesel with diesel against straight diesel. Results indicated a 16% to 33% reduction in PM emissions, a 17% to 25% reduction in CO and a 19% to 32% reduction in HC<sub>n</sub> emissions<sup>(55)</sup>. These effects are attributed to the oxygenate content of biodiesel.

The fundamental benefit of biodiesel and other renewables like ethanol is, however, proposed to be the reduction in greenhouse gases for the entire lifecycle of the fuel<sup>(8,101)</sup>.

**Figure 27** below shows the relative greenhouse gas lifecycle emissions estimated by Beer et al<sup>(8)</sup> of the CSIRO for the fuels in **Table B - 1** in CO<sub>2</sub> equivalent units.



**Figure 27:** Lifecycle Greenhouse Gas Emissions for Buses operated on Various Fuels as estimated by Beer et al<sup>(8)</sup> (see **APPENDIX B** for key to abbreviations and data)

The emissions listed as renewable combustion in **APPENDIX B** for ethanol and biodiesel are not included in the above calculation. The combustion of recently photosynthesised carbon is not accounted for as a source of greenhouse pollutant CO<sub>2</sub> by international agreement<sup>(68)</sup>. This is because this carbon is from a renewable resource, that is, the crops cultivated for fuel production are themselves a CO<sub>2</sub> sink. This is the theory of the so-called CO<sub>2</sub> cycle presented graphically below in **Figure 28**.

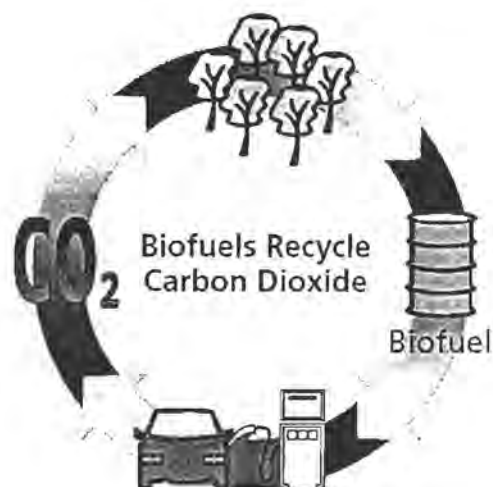


Figure 28: CO<sub>2</sub> cycle for Renewable Fuels <sup>(101)</sup>

This concept is somewhat contentious as its applicability is dependent on a number of factors. Clearly, if an area of land is deforested to make way for oilseed crops, the net result is a possibly less efficient CO<sub>2</sub> sink and about the same combustion emissions, while pre-combustion emissions, if according to **Table B - 1**, are even higher than for fossil fuel diesel. Any greenhouse mitigation by biofuels must surely depend on whether any previous mitigations are affected by initiating the process. In any event, biodiesel or even ethanol are unlikely to become large scale heavy-duty fuels in South Africa due to the land intensive production, lack of current infrastructure and high cost at 5 to 6 times that of fossil fuel diesel <sup>(8,27)</sup>.

As seen from **Table B - 1**, LPG is a very attractive short-term emissions reduction measure, especially as regards PM, as there is a current surplus in production from South African refineries and a storage and transport infrastructure is already in existence <sup>(95)</sup>. Like CNG as discussed above, LPG would fuel an Otto cycle (spark ignition) engine and not a diesel engine for vehicle application. CNG is more attractive from the technical point of view of the engine itself and is proposed by this study as the best medium-term method of profound PM emissions reduction. The supply of CNG to Sasolburg and the mooted pipeline from the Kudu Gas fields to Cape Town could drive a rapid development of a vehicle gas industry. Given the capacity of the commercial vehicle population estimated by this dissertation at some 55GW or the equivalent of 14 large Highveld coal-fired power stations, potential gains for fuel suppliers are great even given a duty cycle of only 30% and limited market penetration. Fuelling a large percentage of new vehicles on CNG will slow up the demand for increased refinery capacity for diesel while allowing oil

companies to diversify into a new energy source market. The State has openly declared its interest in offering incentives and it is to be hoped that this farsighted approach is matched by industry <sup>(39)</sup>.

### **3.7 EMISSIONS REDUCTION SCHEMES AND PUBLIC TRANSPORT**

Bell <sup>(9)</sup> has reviewed various emissions reduction schemes that might be applied in South Africa as part of emissions legislation, particularly local authority legislation. These usually focus on reducing the number of vehicle kilometres driven within areas with bad air quality or increasing vehicle average speed. Some examples are as follows:

#### **3.7.1 RESTRICTED DRIVING SCHEMES**

This type of scheme excludes certain types of vehicles from restricted zones either completely or on certain days of the week. Vehicle registration may be used to enforce limited access of specific vehicles. Other than the problems of enforcing compliance the following may occur <sup>(9)</sup>:

- Emissions are displaced elsewhere or shifted to other vehicles like mopeds or taxis.
- A second vehicle is often purchased and often two old and poorly maintained vehicles replace one vehicle in good condition.

#### **3.7.2 PEDESTRIANISATION OF ROADS**

While arguably of social benefit, pedestrianisation has been shown to have dubious benefits for urban emissions, as often congestion and overall travel times increase in an area immediately adjacent. <sup>(9)</sup>

### 3.7.3 REDUCTION OF CONGESTION

The reduction of congestion, for instance by road enlargement, has been shown to reduce emissions. In the long term, however, congestion is usually observed to increase again to the limit of public tolerance <sup>(9)</sup>. Emissions, however, have been shown to be strongly dependent on vehicle speed as shown by **Figure C - 1** in **APPENDIX C**. For this example the optimum trade-off between fuel economy (low CO<sub>2</sub>) and emissions is around 60km/h. In general, therefore, measures to facilitate traffic flow like robot synchronisation will reduce emissions.

### 3.7.4 REDUCTION IN VEHICLE MILES TRAVELLED (VMT)

The two primary methods for reduced vehicle miles travelled (VMT) are first encouragement of ridesharing schemes, for instance by reserving freeway lanes for cars with passengers, and secondly the overall improvement of public transport. Schemes requiring public compliance like ridesharing generally have mixed results. In South Africa where there is a poor history of public discipline, enforcement is the key to success and this is likely to be very resource-intensive.

Improved public transport, particularly the electric train network, has great potential for urban emission reduction. Unless commuter buses are alternative fuelled or equipped with the latest technology, improvement to the bus infrastructure will probably increase particulate emissions although all other emissions may be reduced. Gas buses running either on LPG or CNG are common in Europe and are negligible emitters of PM, making them highly suitable for low particulate public transport <sup>(57)</sup>. Fuelling infrastructure will, however, require considerable investment while in contrast, the rail network is already largely developed.

Given the presence of a nuclear power station in Cape Town with all its attendant negative public image, it seems logical to at least exploit the undeniable advantage of nuclear power – particulate-free kW. Electric train traction from coal power stations of course merely diverts emissions to the power station, although urban air quality may benefit. Currently the major barrier to developing electric train public transport is undeniably the threat to the personal safety of passengers both from accidents and

crime. Violent crime perpetrated on rail commuters has remained epidemic at the time of writing. In the words of one commuter interviewed by a local newspaper recently: "We can't take it any more".<sup>(108)</sup> The incident happened the day after the 200-strong Police Rail Commuter Unit for the Cape Metropolitan area was cut back to 30 members. Historical figures as tabled in Parliament for suburban trains in South Africa, presented below in **Table 14**, give some indication of the scale of the problem<sup>(44)</sup>:

**Table 14:** Historical Data for Criminal Assaults on Suburban Trains in South Africa<sup>(44)</sup>

	1993/94 April – March	1994/95 April – March	1995/96 April – March
<b>Fatalities</b>	60	24	28
<b>Injured</b>	491	306	724
<b>Assaulted</b>	-	-	138

Certainly these figures pale into insignificance compared to the  $\pm 10,000$  fatalities annually on South African roads<sup>(5)</sup>, but there will always be a psychological chasm in the mind of the commuter between accident and assault. It seems, perhaps not surprisingly, that like most of South Africa's woes, air pollution and public transport inefficiencies too have strong social drivers that sometimes eclipse technological concerns. These have, however, been clearly recognised by the State and it is fair to concede that rail commuter safety initiatives have not been lacking<sup>(42)</sup>. Transport Minister Dullah Omar has perhaps best summed up the imperatives as follows<sup>(60)</sup>:

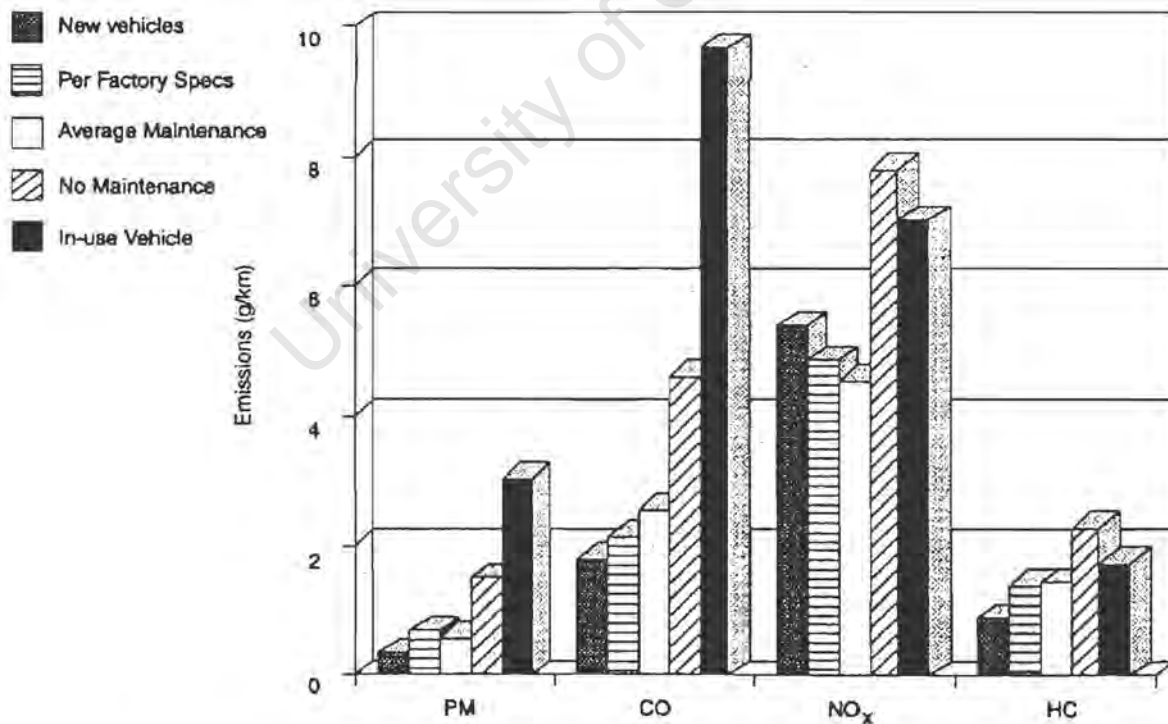
*"It remains our responsibility to guarantee safety in all our trains. We would like to move both people and goods from our roads to rail. This can only be achieved if we build confidence in the system for people to use."*

It is perhaps a fair proposal, therefore, that the promotion of public transport, primarily at first through improved safety systems, becomes part of the actual air pollution reduction strategy of local authorities with whatever support can be offered by central government.

### 3.7.5 INSPECTION AND MAINTENANCE (I&M) SCHEMES

The quality of in-service vehicle maintenance has been shown to have a profound effect on the emissions of heavy-duty diesel engines <sup>(27,74)</sup>. **Figure 29** below presents the results of a study on the effects of maintenance on emissions of diesel buses in Santiago, Chile. The four textured bars represent four buses that had their engines completely rebuilt. The first was tested in that condition and the remaining three were tested in service after operation under different maintenance regimens, factory-specified maintenance, average maintenance and no maintenance whatsoever. These were then compared to the emissions of a poorly maintained bus that had not had the engine rebuilt, represented by the black bar.

While the sample for this study is small, three principles are clearly highlighted. First, emissions can increase manyfold if maintenance is poor. Secondly, the emissions of new vehicles can deteriorate rapidly if maintenance is poor. Thirdly, all the regulated emissions tend to deteriorate together, although there is some secondary effect evident of the PM/NO<sub>x</sub> trade-off.



**Figure 29:** Maintenance Effects on the Emissions from in-service Diesel Buses <sup>(27)</sup>

### 3.8 METHODS FOR MEASUREMENT OF DIESEL EMISSIONS

The requirement of regulating emissions from diesel engines has done as much to advance techniques of emissions measurement as it has to advance engine and fuel technology. The design and operation of such equipment are now the ambit of prospering multinationals like AVL and Horiba. It is beyond the scope of this study to describe the myriad of measurement and analytical techniques that have been developed over the last 30 years. A brief outline of the basic techniques and devices is given below.

In diesel emission testing, for the purpose of regulating new model engines, the systems can first be split into two distinct pollutant types. These are systems for gaseous emission measurement and systems for solid PM measurement. The measurement techniques are somewhat different for these two types of pollutant.

#### 3.8.1 MEASUREMENT OF GASEOUS POLLUTANTS

The measurement of gaseous pollutants from heavy-duty diesel vehicles is fundamentally the same in terms of the measurement devices for passenger cars. Diesel exhaust is very dilute, so gaseous diesel pollutants are generally sampled undiluted unless the test cycle is transient. In the case of transient testing a diluted sample is drawn from a Constant Volume Sampling (CVS) dilution tunnel into a teflon sampling bag during the test and a conglomerate sample is analysed afterwards <sup>(27)</sup>. Sometimes due to low concentrations, gaseous emissions are measured continuously during transient testing and the logged concentration results integrated on the logging timebase to calculate the mass emitted over the cycle. Such a case is illustrated in **Figure D - 6**.

The on-line gas analyser has become the mainstay of gaseous emissions measurement. This is a device that draws a constant flow of sample gas into its analytical cell where a variety of techniques is used to derive a response to concentration. Traditionally indication was by needle gauge on the instrument face but modern systems have very compact card type analysers that distribute the data directly to a personal computer for display and recording. There are a number of analytical approaches but the current industry standard techniques can be summed up as follows per pollutant:

- **HC<sub>n</sub>: The Flame Ionisation Detector (FID)** is the typical analytical device. The luminosity of a hydrogen flame will change in proportion to the number of carbon atoms ionised by the flame. This is therefore essentially a carbon atom counter for hydrocarbons. The output is proportional to the number of carbon atoms per molecule of calibration gas. This is typically propane with 3 carbon atoms so concentrations read from the instrument need to be multiplied by 3 to calculate the industry standard of a mass proportional concentration equivalent to a single carbon atom hydrocarbon, or "ppm C", as it is termed <sup>(25)</sup>.
- **CO / CO<sub>2</sub>: A Non-Dispersive Infrared (NDIR) detector** is the typical analytical device used for both these measurements. Both gases will absorb distinct frequencies in the infrared spectrum that causes them to heat up. The instrument uses the resulting thermal distortion relative to a reference cell to actuate a capacitive transducer. Heating occurs according to the Beer Lambert law which is exponential, so electronic linearisation is usually required <sup>(25)</sup>.
- **NO<sub>x</sub>: A Chemiluminescent Detector** is the typical analytical device used. The reaction between NO and O<sub>3</sub> to form NO<sub>2</sub> emits light in proportion to the mass of the reactants. This has to be amplified by a photomultiplier to enable detection. To measure NO<sub>x</sub>, the NO<sub>2</sub> in the sample has to be reduced to NO by heating before being passed through the reaction cell <sup>(25)</sup>.

### 3.8.2 MEASUREMENT OF PARTICULATE MATTER

For the purposes of legislative testing to evaluate diesel engines entering the market, PM is generally filtered out from a diluted exhaust stream while the engine is run on some service life representative cycle of loads and speeds. This can be transient in nature or a series of steady state points. The quantity of filtrate is determined gravimetrically and related to the power output of the engine so that an energy-output-specific result is obtained, usually in units of grams PM emitted per kW.h of operation. The exhaust gas of the engine is diluted by entrainment with air in a dilution tunnel, where adequate mixing is promoted to ensure a homogeneous sample. These procedures are laborious and expensive, requiring sophisticated infrastructure. Such is the concern globally about air

pollution though that such test procedures have become an extension of the manufacturing process <sup>(25,80)</sup>.

The importance of sample dilution has been discussed in **Section 3.1**. Initial designs of equipment to achieve this entailed the dilution of the entire exhaust of the engine. The exhaust gas flow of a large diesel engine can exceed  $2\text{m}^3/\text{s}$ . Diluting this flow by a typical factor of 10 immediately implies considerable hardware in terms of piping and fans. This type of testing was therefore denied to all but large laboratories for reasons of economy until the Technical University of Berlin adapted the design of O'Neal and Storment of the South West Research Institute to develop the so-called "*mini-tunnel*" for regulatory testing <sup>(25,31)</sup>. This allows for an accurately determined fraction of the exhaust to be diverted to a much smaller dilution tunnel, reducing the size and cost of all hardware and associated equipment. This methodology was applied in the experimental phase of this project and is described in detail in **CHAPTER 4**.

Although the sampling equipment for this study was manufactured in-house to European regulatory specifications, commercial mini-tunnels are available and have reached a high level of sophistication <sup>(6)</sup>. Despite this, mini-tunnel testing has not been approved for regulatory purposes in the US, where testing of diesel engines has been transient in nature since 1985 <sup>(27)</sup>. Transient testing is in general more severe in evaluating PM and  $\text{HC}_n$  emissions than steady-state testing. It is more difficult to determine the fraction of exhaust diluted and control the dilution ratio within acceptable limits with a partial dilution approach under transient conditions than under steady-state conditions. Mini-tunnels have, however, been shown to correlate well with full-flow tunnels for the ECE R-49 test procedure adopted for the experimental work of this study <sup>(31)</sup>.

### **3.8.3 IN-SERVICE SMOKE MEASUREMENT**

Other more compact and cost-effective methods exist that are suitable for in-service testing of diesel vehicles to provide an indication if the engine is being maintained so that smoke pollution is minimised. These generally fall under the category of opacity meters like the Hartridge meter or photometric filtration methods like the Bosch meter. Opacity meters operate by measuring the degree of obscuration caused by an exhaust sample in a chamber across which a light is being shone onto a photocell <sup>(25,59)</sup>. The Bosch meter

draws a fixed volume of exhaust through a paper filter. The resulting discolouration is then evaluated by a calibrated photocell. Both the above devices operate on an arbitrary scale that has a degree of correlation, although the Bosch meter tends not to detect hydrocarbon aerosols, as these do not discolour the filter to any degree <sup>(25)</sup>.

### **3.9 THE REGULATION OF HEAVY-DUTY DIESEL EMISSIONS**

Almost all countries with levels of significant industrialisation have formulated legislation regulating the emissions from new and in-service vehicles. The former serves to reduce emissions from new vehicles while the latter serves to enforce maintenance of vehicles so that initial emissions outputs are at least maintained. Innovation of such regulatory frameworks, including the scientific and engineering methodologies, has primarily been undertaken in Europe, the US and Japan. Most other countries have applied legislation from these three entities selectively as needed. Even developing countries like India, China and Mexico have adopted regulatory practices of relative complexity adjusted appropriately to their situation. South Africa, with its heavy industry and transport-intensive economy, is notable by its absence from these ranks, although at the time of writing the first regulatory initiatives are bearing fruit. This study was itself commissioned to provide an informed basis for emissions regulation in South Africa. Regulatory practices in Europe and the US are discussed below, followed by a discussion of legislative initiatives and air quality interventions in South Africa.

#### **3.9.1 HEAVY-DUTY DIESEL EXHAUST EMISSION REGULATION IN EUROPE AND THE US**

Promulgation of emissions legislation began in the early 1970s in both Europe and the US. Regulations in Europe have historically been formulated by the United Nations Economic Commission for Europe (UN-ECE). However, this body does not have the power to enforce them and it fell to the European Economic Community (EEC) to adopt them as Directives, such that they had the force of law in the EEC member states under the provisions of the Treaty of Rome <sup>(83)</sup>. Therefore, by way of example, the 1972 standard test method and limits for black smoke from heavy-duty vehicles was adopted as standard ECE R24.03 by the UN-ECE and immediately thereafter adopted as Directive 72/306/EEC by the EEC. These roles have since become reversed. The EEC, now the

European Union (EU), has assumed the leading role in the formulation of emissions legislation and the ECE is unlikely to adopt any standard that has not been vetted by the EU.

The US Federal Government originally legislated emissions limits for cars and heavy vehicles in 1970. Fierce lobbying and political wrangling instigated by the three large automotive corporates GM, Ford and Chrysler delayed functional legislation until the Clean Air Act of 1977 that proposed limits for 1981<sup>(23)</sup>. Even then there was delay for many vehicle classes like heavy-duty gasoline until 1987. Between 1990 and 1995 there were, however, strong regulatory measures to decrease NO<sub>x</sub> and PM emissions from heavy-duty diesel engines<sup>(83)</sup>.

The more recent emissions standards, limits and details of test methods for both Europe and the US are presented in **APPENDIX D**.

### **3.9.2 VEHICLE EMISSIONS LEGISLATION AND INTERVENTIONS IN SOUTH AFRICA**

In general South Africa can be regarded as being at fairly high risk from air pollution problems due to the predominance of heavy industry, the reliance on coal-fired power plant and the increasing substitution of goods rail transport with road transport, mostly diesel engine driven<sup>(95)</sup>. Road transport in South Africa itself exerts unique environmental pressures due to the large number of older, poorly maintained vehicles on the road and the prevalence of very heavy axle loads and high road speeds, resulting in high fuel consumption.

Actions by regulatory authorities and government in South Africa with regard to vehicle emissions, including those from heavy-duty diesel engines, have taken place on three levels. These can be classed as interventions, application of current legislation and initiatives for future legislation, which are discussed below.

### 3.9.2.1 VEHICLE EMISSIONS INTERVENTIONS IN SOUTH AFRICA

Concerns over air pollution issues have increased in South Africa over recent years in line with global trends. The phenomenon of episodic photochemical smog in Cape Town giving rise to an unsightly haze of smog prompted an intensive investigation known as the Brown Haze Study, carried out from 1995 to 1997. This has been discussed in **Section 3.4.3** above. More recently, environmental activist groups like *Earthlife Africa* and the *Environment Society of South Africa* have put pressure on the State to prioritise emissions in the tender process for the Taxi Recapitalisation Plan <sup>(106)</sup>. These groups have even threatened the State with legal action should their concerns not be addressed. However, the State has some significant history of intervention in the problem of vehicle emissions. A study of emissions from South African vehicles and fuels called the Vehicle Emission Project was commissioned in 1995 <sup>(93,109)</sup>. The testing phase of this project was completed in 1998 and included the tests on a sample of local heavy-duty diesel engines run on a variety of local fuels that forms the basis of the experimental phase of this dissertation. This data is intended as input to a modelling exercise for the purpose of policymaking. The modelling phase of this dissertation attempts to make a contribution to the achievement of this goal too.

### 3.9.2.2 HISTORICAL LEGISLATION IN SOUTH AFRICA

Vehicle legislation in South Africa has a more than 35-year history, stemming from the promulgation of the Atmospheric Pollution Prevention Act of 1965. In addition, national legislation for the evaluation of vehicle roadworthiness is listed in the National Road Traffic Act of 1996 (Act No. 93 of 1996), within which Volume I – 2 – 155, Regulation 140 states:

*(1) An appropriately graded inspector of vehicles ...must examine and test the vehicle as stipulated by the Code of Practice SABS 047, "The Testing of Motor Vehicles for Roadworthiness".<sup>(71)</sup>*

In the case of heavy vehicles (over 3,500kg Gross Vehicle Mass), this refers specifically to SABS Code of Practice 047-3:1992, "The Testing of Motor Vehicles for Roadworthiness, Part 3 Heavy Vehicles" <sup>(91)</sup>. This certification is required annually and

the certificate must be displayed with the vehicle licence. Vehicles of this class are almost without exception diesel-powered and therefore the 1992 Code of Practice stipulates in Section 5.2 that a vehicle applying for roadworthiness certification should be rejected if:

- a) *in the case of a non-turbocharged diesel engine, the exhaust smoke emission (measured using an acceptable smoke meter) exceeds the limits prescribed by the Atmospheric Pollution Prevention Act, 1965 (Act 45 of 1965); or*
- b) *in the case of any type of engine, the exhaust smoke emission is so dense during a road test that it would, in the opinion of the examiner, hinder other users.*

The Atmospheric Pollution Prevention Act, 1965 (Act 45 of 1965), Regulation No. R 1651<sup>(4)</sup> in turn stipulates that smoke should be measured during free acceleration to governed speed using a Hartridge-B.P. smoke meter (opacity meter, see **Section 3.8.3**). The average of three peak readings within five Hartridge units of each other may not exceed a limit of between 60 and 70, depending on the location of the local authority where the test is being performed. It is prohibited that this test be applied to turbocharged vehicles<sup>(4)</sup>.

### **3.9.2.3 EMERGING NEW INITIATIVES IN SOUTH AFRICAN VEHICLE EMISSIONS LEGISLATION**

Local authorities like the Cape Metropolitan Council, now part of the Cape Town Unicity, still apply Regulation R. 1651 on a routine roadside testing basis<sup>(66)</sup>. However, this practice is not wide spread nationally. It is noteworthy that to date compliance to the smoke emissions section of the roadworthy test has been essentially nil due to the allowance of a waiver if the testing installation is not equipped for smoke tests. Considering though, the focus on diesel emissions in South Africa over recent years through studies like the Brown Haze Study<sup>(107)</sup> and lobbying from pressure groups like *Environment Africa*<sup>(106)</sup> in the media and through legal action, it might be considered inadvisable to remove the platform of existing legislation. Indeed, modification of the legislation and enforced compliance would seem more appropriate.

In-service maintenance has been shown to have a profound effect on the emissions of heavy-duty diesel engines as discussed above in **Section 3.7.5**. **Figure 29** indicates how emissions of all the pollutants tend to deteriorate simultaneously. Smoke measurement by Hartridge meter, which evaluates PM emissions and to some degree hydrocarbon emissions could therefore be an effective tool for indirectly controlling all emissions in the in-service situation, with the added advantage of simplicity and low cost.

However, is roadworthy testing using an opacity method as formerly specified by SABS Standard 047 <sup>(91)</sup> an appropriate method of controlling emissions? Various contrary arguments have been made as follows:

- All diesel engines are now imported and thus conform to First World emissions legislation. Therefore diesel emissions testing in South Africa is futile.
- Free acceleration opacity meter testing has not been applied to turbo-charged vehicles under the 1965 legislation. The majority of vehicles sold into the market currently are turbocharged and therefore this method is inapplicable.
- Gravimetric methods of testing smoke (see **Section 3.8.2** and **APPENDIX D**) are more accurate and opacity meter testing is obsolete.

The first of the above points would have considerable merit if our vehicle fleet was being replaced at a rate comparable to European countries. This is not the case. The average age of our commercial vehicle fleet is around the 12-year mark <sup>(61)</sup>. This high average age figure is not the result of a few very old trucks increasing the national average. Extrapolation of the last Central Statistical Services (CSS) measurements of commercial vehicle median age, as shown below in **Figure 30**, indicates a probable median age of over 10 years <sup>(17)</sup>. That is to say half the entire commercial vehicle fleet is older than 10 years.

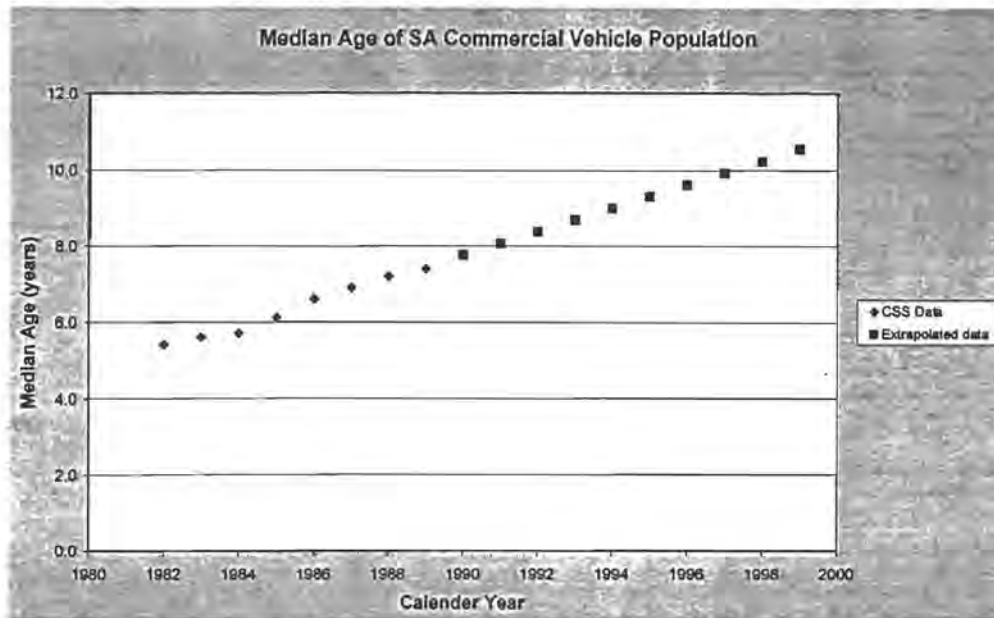


Figure 30: Estimated Median Age of South African Commercial Vehicles <sup>(17)</sup>

The argument might also be made that most of the mileage is being driven by newer vehicles so their effect on total population emissions dominates. It can be countered though, that most of these new vehicles are running inter-city long-haul routes while the older, potentially non-compliant vehicles are active in delivery and industrial roles in the urban environments where air pollution is a concern. In addition, it is true that newer vehicles may total an annual mileage of as much as 100,000km <sup>(79)</sup> but this only creates a situation where a vehicle can deteriorate into a poor state of service within as little as a year with a resulting increase in emissions. Practical control of diesel emissions in South Africa can be assisted greatly by in-service testing, preferably during the roadworthy evaluation.

As regards the evaluation of turbocharged vehicles by the methods of the current legislation, the grounds for exemption of this technology have long since ceased to be relevant. The inlet air of turbocharged diesel engines is compressed by energy recovered from the exhaust by a turbine. This results in air being drawn into the cylinder at higher pressure, resulting in higher efficiency. Initially, the fuel pumps of these engines were set to provide the correct fuel delivery for maximum boost when the rack of the pump was opened fully. In practice though, if the rack is suddenly opened, the exhaust turbine takes some time to speed up, a phenomenon known as turbo-lag. Thus boost pressure would remain low but maximum fuelling would occur, resulting in excessive smoking until boost pressure was achieved. Thus free acceleration testing was deemed to be

unrepresentative for turbocharged vehicles. Current turbocharged diesel engines employ a device known as an LDA or Manifold-pressure compensator which adjusts fuelling relative to inlet air boost pressure, thus compensating for the over-fuelling effect of turbo-lag and reducing smoke <sup>(80)</sup>.

These grounds aside, sudden acceleration from idle is a critical concern for emissions in urban areas and there is no reason why any technology should be exempt from a method like a free acceleration test. Indeed, the manual for the Hartridge type meter, the Lucas Smokemeter 4, currently used by the Cape Metropolitan Council, clearly states that it is suitable for free acceleration testing of both naturally aspirated **and** turbocharged vehicles <sup>(59)</sup>. Free acceleration testing of both turbocharged and naturally aspirated vehicles is also an integral part of British Legislation for Local Authority Emissions Checking <sup>(85)</sup>. Guidance regulations issued under Section 88 of the Environment Act of the UK of 1995 state:

*“At the end of the fourth acceleration if the opacity level is  $2.5m^{-1}$  or less for non-turbocharged engines,  $3.0m^{-1}$  or less for turbocharged engines, the vehicle has passed the test.”*

The question remains whether the opacity meter is an appropriate tool for future emissions measurement. It is true that gravimetric methods are more precise and repeatable but even with these methods, controversy persists regarding their relevance to limiting the impact on human health. Opacity meters, while not perhaps suitable for evaluating new products for the market, provide a quick, cheap and highly mobile evaluation of vehicle smoke. Broadly speaking, poor maintenance that is causing unnecessary smoke emissions can be curtailed. In addition a vehicle that has high smoke emissions as a result of poor maintenance is probably emitting high levels of gaseous emissions too, so this sort of testing has knock-on air quality benefits. The Cape Metropolitan Council's current programme of testing has shown a 22% failure rate of vehicles tested <sup>(66)</sup>. If this is indicative of a national situation, there is considerable scope for the reduction of smoke emissions by the reintroduction of a modified, actively enforced version of the roadworthy smoke evaluation as previously laid out in SABS 047.

The existing capacity and legislation for opacity meter testing are thus still suited to an in-service regulation programme that would involve routine roadside testing and compliance

to an annual roadworthy test. How then is such a programme to be applied? Linde <sup>(58)</sup> has proposed the drafting of bylaws that would enable local authorities to enforce such measures. This is provided for by the terms of the Constitution <sup>(58)</sup>. Certainly the former Cape Metropolitan Council is in an ideal position to lead the way for the country, having modern equipment, trained staff and a currently functioning programme run under the old legislation. Such an approach has been applied with success in the American state of California where locally applied legislation has led the rest of the country for some 30 years.

Since the closure of the ADE engine plant, manufacture of diesel engines in South Africa has ceased. Therefore any national legislation as regards heavy-duty diesel engines would effectively imply selective importing on the part of local Original Equipment Manufacturers (OEMs) rather than having any impact on production. While the National Association of Motor Assemblers of South Africa (Naamsa) has taken the initiative in driving national legislation by requesting the SABS to implement a technical regulation requiring vehicles homologated after January 2003 to meet Euro 1 emissions, this has not been extended to heavy-duty diesel engines <sup>(78)</sup>. Homologation is the process by which a new model vehicle is approved for sale. In practice such legislation would be merely for the purposes of initiating a process as even the 1998 VEP figures showed that most ADE engines were close to Euro 1 compliant <sup>(93)</sup>. Certainly now in the case of electronic turbo-intercooled engines being imported, new diesel engines conform to standards significantly more stringent. Can South Africa then afford to neglect heavy-duty diesel legislation for engines entering the marketplace? This may present the risk of South Africa becoming a dumping ground for retrograde technology. It is the aim of this dissertation to provide data, through modelling emissions reduction scenarios, to assist in the process of designing appropriate emissions legislation for diesel commercial vehicles.

### **3.10 POLLUTANT INVENTORIES AND EMISSION FACTORS**

The aim of the modelling phase of this study was to perform a national level emission inventory for South African diesel commercial vehicles. Dr Linda Murchison, chief of the California Air Resources Board's Emission Inventory Branch, has defined emission inventories as follows <sup>(67)</sup>:

*“An emission inventory is a comprehensive listing of the sources of air pollution and an estimate of their emissions. This information is usually developed for specific geographic areas and for given time intervals. Inventories along with air quality monitoring are the scientific foundation upon which air quality plans are built.”*

The overall aim therefore, as alluded to by the quotation above, is the improvement of what has become known as “Air Quality”. This is the quality of ambient air relative to quantitative standards determined such that the impact on human health and the environment in general is minimised. A detailed discussion on the setting of such standards is beyond the scope of this study but certainly the type of epidemiological and toxicological studies discussed in **Section 3.3** are some of the tools applied. That there is a temporal and in some way quantifiable link between the mass of exhaust emissions from combustion engines and the concentrations of ambient pollutants defining air quality cannot, however, be disputed. The degree to which mobile sources in general or heavy vehicles may contribute to air quality is a task for exercises in modelling the dispersion and dilution of pollutants from the source. An emissions inventory model such as was performed for this study may certainly add to our understanding of such questions and is an essential input for a dispersion model.

The International Petroleum Industry Environmental Conservation Association (IPIECA) has identified three types of mathematical model essential to a complete air quality modelling methodology <sup>(48)</sup>:

- Inventory models with forecasting or scenario development capabilities to model the effect of emission reduction strategies on total emissions from given sources.
- Meteorological transport models to forecast wind and weather phenomena like inversions.
- Dispersion models to determine the contribution of the total emissions calculated by the inventory on actual concentrations near the ground.

The link between these models is shown diagrammatically below:

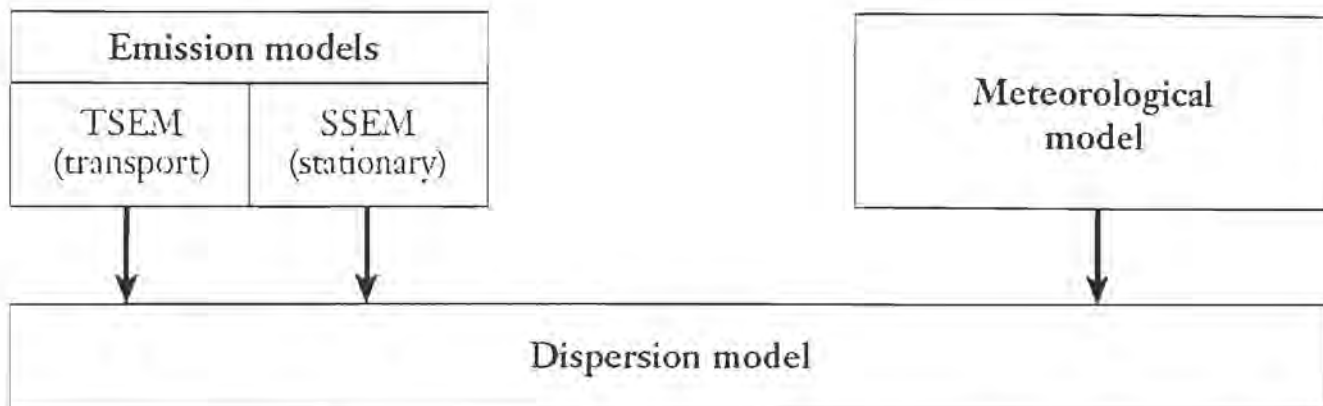


Figure 31: Links between Air Quality Mathematical Models <sup>(48)</sup>

As indicated above, if an inventory is to have any value in an air quality evaluation, it must include both mobile and stationary sources so that their relative contribution is clearly understood and priorities can be identified. **Figure 32** below shows the relationship between human activities, the resulting anthropogenic emissions, interventions like modelling and reduction strategies and the impacts on health and the environment. Known as the DPSIR diagram, this forms the basis of the emissions inventory strategy of the National Environmental Technology Centre, which compiles the official atmospheric emissions inventory of the UK <sup>(68,69)</sup>.

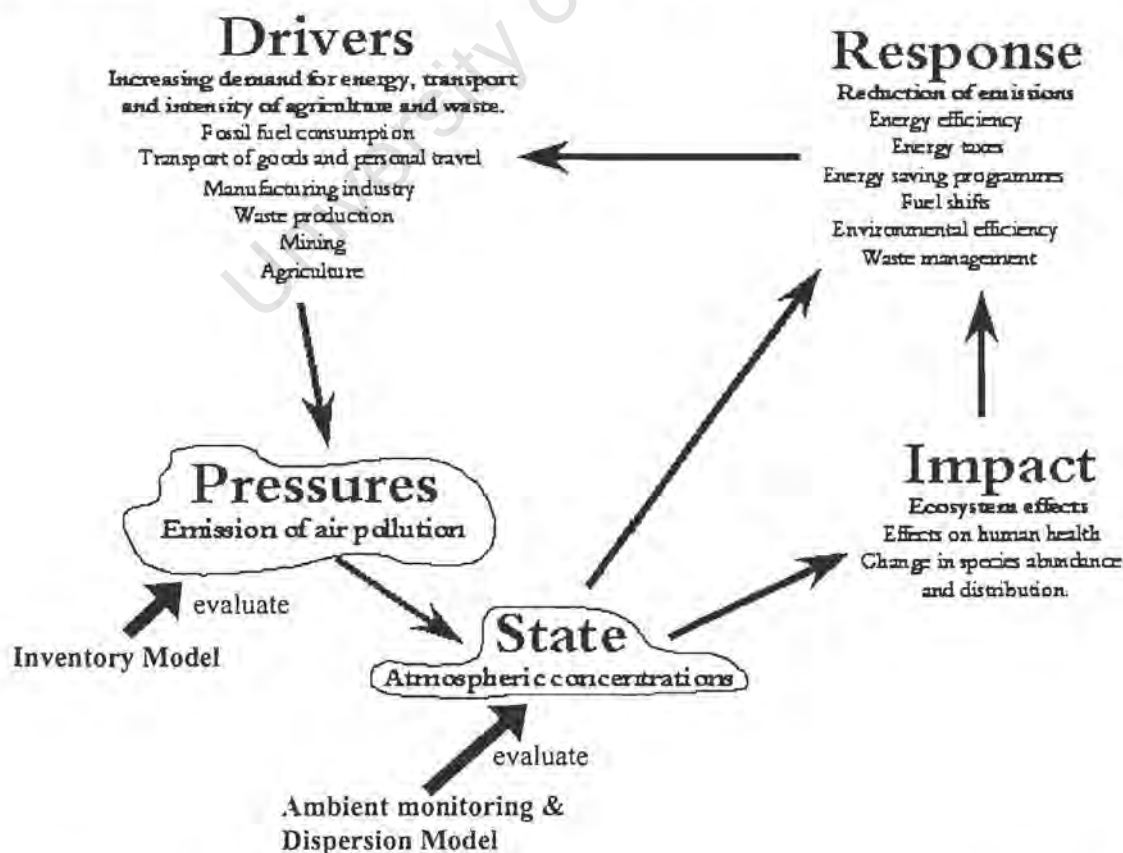
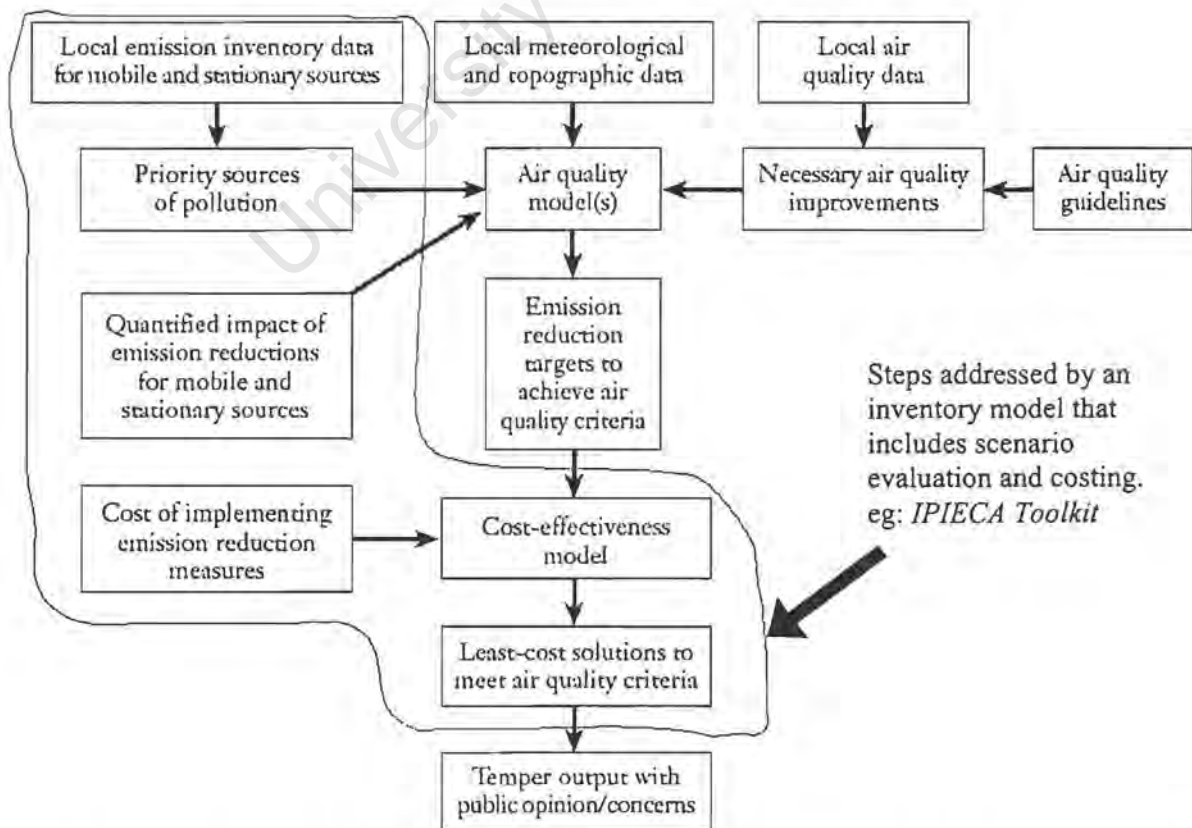


Figure 32: DPSIR Diagram: Factors inherent to an Air Quality Improvement Programme <sup>(68,69)</sup>

Does this then imply that nothing can be done about air quality until a vast array of time-consuming, complicated and expensive modelling techniques are applied to the problem? Certainly vast quantities of money can be wasted if spent on emissions reduction strategies that have little return. IPIECA have however proposed that where cost and time are an issue, simple approaches have great value <sup>(48,49)</sup>. It proposes that a detailed and rigorous inventory capable of modelling the cost of emissions reduction strategies and the effects on total emissions can be used to initiate effective policy. This relies, however, on the following assumptions which IPIECA has proposed as reasonable <sup>(48)</sup>:

- That the relationship between the mass of emissions calculated and air quality is linear. O<sub>3</sub> must be excluded from this.
- No significant chemical transformation of the pollutants takes place in terms of total mass. O<sub>3</sub> must also be excluded from this.

IPIECA has developed such an inventory model called the “*IPIECA Toolkit*”. The potential role of this model in the management of air quality is indicated diagrammatically below in **Figure 33**, a layout of the IPIECA Urban Air Quality Framework.



**Figure 33:** IPIECA Urban Air Quality Framework showing contribution on Inventory Model <sup>(49)</sup>

An inventory model capable of evaluating scenarios can be used effectively even when the air quality situation is poorly understood and air quality criteria are tenuous. The exercise of developing an inventory and putting costs to mitigation will add invaluable perspective to the problem. In this way air quality policy actions can be expedited even if resources are limited.

Emissions inventories have been defined and their application in the management of air quality has been outlined. The technical basis of emission inventories, the different approaches and some data generated by and for inventories internationally are discussed below.

### 3.10.1 THE DESIGN OF EMISSIONS INVENTORIES

Emissions inventories have been defined above as, "a comprehensive listing of the sources of air pollution" <sup>(67)</sup>. It is essentially therefore a bookkeeping exercise of which the governing equations are relatively simple. These have been expressed by the National Environmental Technology Centre of the UK <sup>(68)</sup> as follows:

- If:
- $E_i$  = The emission of a pollutant from a single source "i", say a vehicle
  - $E_{sector}$  = The cumulative emission of a pollutant from a sector, say "n" trucks
  - $F$  = Emission factor usually experimentally determined
  - $S$  = Scalar quantity defining the operation of the source, say distance travelled
  - $M_{fuel}$  = The mass of an element, say carbon, in the fuel consumed by the source
  - $M_{em}$  = The total mass of the same element in the emissions from the source

$$E_i = F \times S \quad \dots(\text{Equation 25})$$

$$E_{sector} = \sum_i^{1...n} E_i \quad \dots(\text{Equation 26})$$

$$M_{fuel} = M_{em} \quad \dots(\text{Equation 27})$$

It is clear from the above that the quality of the emission factors and the principle of conservation of mass are fundamental to the accuracy of an emissions inventory. In practice, the accuracy of a mobile source inventory, will also be enhanced by the following <sup>(48,49,68,69)</sup>.

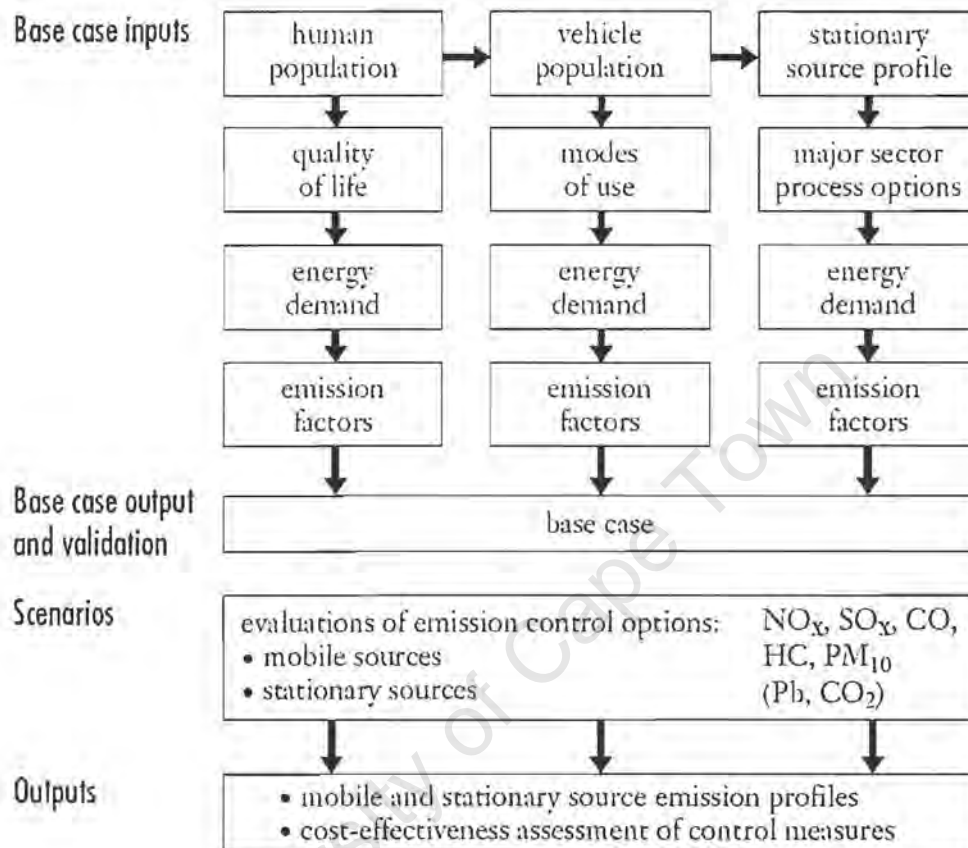
- A high degree of disaggregation. This requires that the vehicle population is analysed in detail so that it can be split into groups according to vehicle type, operational characteristics and any specific fuel properties like low sulphur diesel. Obviously emission factors are required for each group.
- Emission factors should be based as much as possible on experiment rather than assumption.

- Large populations and long time periods facilitate greater accuracy. Localised inventories require greater disaggregation to compensate for sample size.
- Bearing the above in mind, geographically bound inventories are advisable. While a particular source may only contribute to 20% of total emissions on a national level it may contribute to 80% of total urban emissions.
- A facility for modelling the effects of emission reduction strategies and projecting levels of emissions into the future makes an inventory a powerful tool.

While all emission inventories will be based on **Equation 25 to 27**, different approaches to inventory modelling and their sophistication can be determined by the degree to which the above principles are applied. IPIECA has identified three general approaches to emission inventories.

- Distance Travelled Approach (DTA):** This is the simplest approach whereby average fuel consumption and emission factors are multiplied by the distance travelled by vehicles to give estimates for total emissions and fuel consumption. This is best applied to a so-called aggregate analysis where an entire country or region is being analysed. Urban transport measures are not easy to assess because traffic conditions and the effect of speed changes are not taken into account.
- Average Speed Approach (ASA):** This approach takes account of the effect of speed variation on emissions by matching emissions factors and fuel consumption with predicted average speed. While speed versus emissions and fuel consumption curves are available for most vehicles, improvement on the DTA approach depends on the degree to which vehicle journeys can be disaggregated into different average speeds through the road network. A common technique is to categorise roads as urban, rural, motorway and sub-groups of the three. This is applied by the National Environmental Technology Centre of the UK <sup>(68)</sup>, as shown by its catalogue of emission factors presented in **Table G - 1 to Table G - 4** in **APPENDIX G1**. Average speeds have to be determined for these categories by surveys that relate speed to traffic flow. The IPIECA Toolkit <sup>(48,49)</sup> referred to above is also an ASA-type model with added features that include economic and

population growth models and detailed fuel property and vehicle technology effect models. This enables the evaluation of a wide range of emission control scenarios. The processes applied in this evaluation are shown diagrammatically below in **Figure 34**.



**Figure 34:** IPIECA Toolkit Inventory and Scenario Evaluation Process <sup>(49)</sup>

Current emissions are determined as a base case to which scenarios are compared. The outputs of the model entail an annualised profile of the scenario emissions compared to the base case projected into the future for a predetermined term. The same exercise is performed for the costs of the scenario. The costing model estimates the economic costs to the community. Two other noteworthy ASA type models are the US EPA's *Mobile6* model <sup>(7,103,104)</sup> discussed in **APPENDIX E** and the European Environment Agency's *COPERT III* model discussed in **APPENDIX F** <sup>(2,74)</sup>.

- iii. **Vehicle Kinematics Approach (VKA):** This is the most detailed approach to inventory modelling of mobile sources. Disaggregation of the vehicle population and its operation is applied according to selected kinematic characteristics relating

to traffic flows. Examples are changes in average speeds, speed and acceleration profiles, road gradients, number of cold starts, altitude and varying vehicle load. Such data is rarely available for studies at the macro level and therefore such models are usually applied to evaluate the effect of emissions reduction measures in a highly localised application for which the sophisticated type of data required is available. Some macro ASA models have VKA characteristics though. The United Kingdom's NAEI model <sup>(68)</sup> estimates the fraction of total kilometres driven with a cold engine based on an empirical relationship with ambient temperature and then applies a separate set of cold start emission factors. This analysis is not however applied to heavy vehicles. The COPERT III emission factor model (**APPENDIX F**) augments an ASA approach with correction for cold starts, road gradient, load variation and fuel property effects <sup>(74)</sup>.

In all the above approaches, the distance travelled is usually adjusted until the carbon in the fuel and the emissions balance to satisfy **Equation 27**. In this way gross errors can be avoided, provided emissions factors are reasonably correct relative to each other. This type of carbon balance validation was applied to the modelling phase of this study.

### **3.10.2 TECHNIQUES IN POPULATION DISAGGREGATION BY VEHICLE AGE**

While the governing equations of inventory models are relatively trivial, the numerical techniques relating to disaggregation of the vehicle population can pose more of a challenge. The approach of disaggregation by vehicle speeds has been discussed above with reference to ASA type models. Vehicle age also affects emissions, both through the advance of technology with each successive tier of emissions legislation, such that older vehicles are designed to meet historical limits, and through the deterioration of emissions with age. The rate at which vehicles are scrapped combined with fluctuating sales affects the distribution of vehicle types and technologies in the population.

There are various approaches to defining an age profile of the vehicle population. An extensive survey can generate a complete curve of numbers of vehicles versus age. In general, though, limited surveys and departmental registration data will yield such estimates as the average age and total population size. A vehicle age profile can be estimated from this by generating a scrapping curve using an exponential distribution

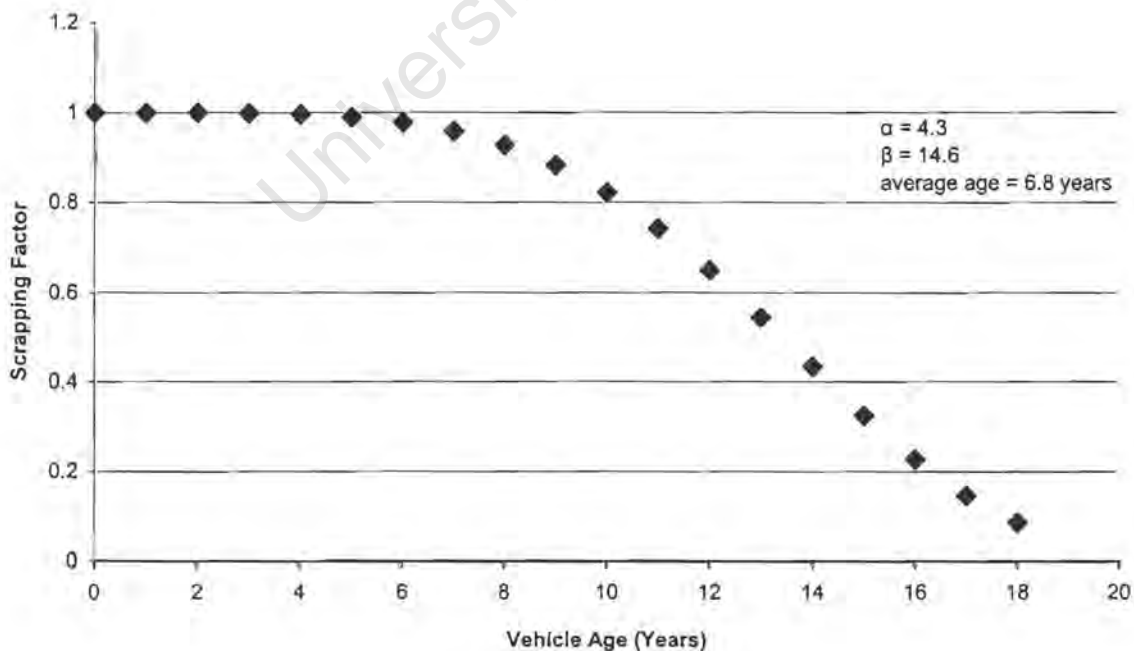
such as the Weibull distribution. This technique is applied to the life analysis of a variety of industrial components and is also applied in the IPIECA toolkit <sup>(49)</sup>. The scrapping curve indicates the rate of scrapping by plotting the probability of a vehicle remaining in operation against age. In the case of vehicles this curve is highly dependent on economic factors. In developing countries like South Africa where average vehicle age is high it will be less attenuated than in European countries. The Weibull cumulative distribution function adapted to the generation of a scrapping curve can be expressed as follows:

- If:
- $x$  = age of the vehicle
  - $f(x)$  = the probability of the vehicle remaining operational
  - $\alpha$  = a constant
  - $\beta$  = a constant

$$f(x) = e^{-\left(\frac{x}{\beta}\right)^\alpha}$$

...(Equation 28)

A typical scrapping factor plot generated using **Equation 28** is presented below:



**Figure 35:** Typical Weibull Distribution type Vehicle Scrapping Factor Curve

Given a constant number of vehicles sold per year, the curve of the total number of vehicles in the population versus their age would have exactly the same shape as the above. A similar technique was applied to the modelling phase of this study using a different function to generate the scrapping factor curves.

The US EPA's Mobile 6 emission factor model exploits the availability of detailed registration data in the US. Curves are fitted to registration data to predict past, present and future distributions of different vehicle types into age categories. **Table E - 2** in **APPENDIX E** presents curves applied to various vehicle categories in Mobile 6. The dependent variable "y" yields the number of vehicles in the population of a certain "age", the independent variable.

It was found that Weibull distributions converged on the axis too quickly and underestimated the older segment of the population in some cases <sup>(104)</sup>. These were modelled either by combinations of Weibull and exponential curves or exponential curves alone. This problem is inherent in modelling the South African vehicle population with its erratic sales history and high average vehicle age. A novel solution was applied in the modelling phase of this study through the application of a function in arctan as described in **Section 5.3** of **CHAPTER 3**.

There are various options for adjusting for age in the calculation of emissions, taking deterioration into account. In some cases emissions factors are available for a representative average age, or age-specific emissions factors may allow disaggregation into age groups. In the case of the UK's NAEI inventory <sup>(68,69)</sup> it was assumed that emissions of CO and NO<sub>x</sub> from catalyst equipped cars increase by 60% over 80,000km, while emissions of non-methane VOCs (NMVOCs) increase by 30% over the same mileage. Based on the average annual mileage of cars in the UK, 80,000km corresponds to a time period of 6.15 years. In the case of diesel cars and light goods vehicles it was assumed that PM<sub>10</sub> emissions increase by 100% over 80,000km. Age-related adjustments to the emissions from heavy vehicles were not reported on.

### 3.10.3 EXAMPLES OF EMISSION FACTORS AND INVENTORY RESULTS

Some examples of emissions factors and the results of the NAEI inventory of the UK's atmospheric emissions <sup>(68,69)</sup> are presented in **APPENDIX E**. The emissions factors for diesel goods vehicles applied in the NAEI inventory and the calculated road transport emissions, including some data of the diesel vehicle contribution, are presented in **APPENDIX G1**. Emissions factors and estimated transport sector emissions for South Africa as determined by Gerson <sup>(30)</sup> for 1989 are presented in **APPENDIX G2**. Various emission factors determined for commercial vehicles in Europe and the US are presented in **APPENDIX G4**. These figures allow for some comparison with the emissions and emission factors calculated for the modelling phase of this study.

University of Cape Town

## CHAPTER 4 METHODOLOGY OF THE EXPERIMENTAL PHASE

The design of the test programme, test equipment and test procedures are described separately below in **Section 4.1**, **Section 4.2** and **Section 4.3** respectively.

### 4.1 DESIGN OF THE TEST PROGRAMME

The emissions from any vehicle powered by a combustion engine are going to be highly dependent on the driving patterns that predominate. Therefore, because urban air pollution is the priority, the test method that is used should evaluate the vehicle or engine under conditions that are representative of the local urban environment. Thus authorities in Europe, the US and Japan have devised different cycles of varying engine-operating points for testing purposes.

It was decided by the VEP Steering Committee that to devise a similar South African cycle was unwarranted, considering the effort and cost involved and that the traffic situation in Europe approximates our own closer than that in the US. Therefore the tests performed for this project applied the procedure devised by the EC (now the EU), which is described in EEC Directive 70/220/EEC and the United Nations' Economic Commission for Europe Regulation No. 49 (ECE R49). This procedure entails running the engine through a 13-mode dynamometer cycle to test the emissions performance of medium- and heavy-duty diesel engines.

The exhaust emissions of six locally manufactured engines with capacities ranging from 3.8 to 12 litres were measured in both coastal and highveld conditions. The coastal tests were performed in Cape Town and the highveld tests in Sasolburg at an altitude of 1,488 metres above sea level, which is similar to Johannesburg's altitude. All the engines were supplied by ADE, a local manufacturer based in Cape Town that produced engines under licence from Mercedes Benz. ADE ceased trading and stopped production of fully assembled engines at the end of 1999. Since then the remaining infrastructure has made only castings and forgings for DaimlerChrysler. Traditionally, ADE has been the largest supplier in the South African market, accounting for some 69% market share in the range of engine capacities selected for testing (see **APPENDIX M**) in 1998.

#### 4.1.1 TEST ENGINES

**Table 15** lists the test engines used in the programme and their ratings. More complete specifications are presented in **APPENDIX H**. These engines represent a variety of applications in both the mining and transportation industries.

The first 3 engines (A-C) listed in **Table 15**, the so-called 3-series engines, represent the 1 litre per cylinder range produced by ADE while engines D-F, the so-called 4 series engines, represent the 2 litre per cylinder range. There are 2 litre per cylinder engines with larger total capacities in the V-engine configuration that are not represented because the dynamometer facilities available were unsuitable for engines of this size.

Turbocharged engines are represented in both the 3 and 4-series types by the 364T and the 447T. Information from the manufacturer indicates that there are two levels of technology in the market place, the old technology, which has been discontinued, and the latest technology. The long life of diesel engines will ensure that a large number of the old technology engines will remain in use for some time to come. The old technology is represented by the 314N and the 407N, the other test engines being the more recent technology since 1987. Production of the 314N was started in 1981 and was discontinued in 1991. Production of its more recent technology equivalent, the 364N, started in 1987.

All the engines tested had an in-line cylinder configuration and were of the direct injection type. Fuel pump delivery and timing were factory set for sea level conditions.

**Table 15:** Test Engine Specifications

No.	Engine Type	Aspiration	Capacity	Rated Power	Max. Torque
A	ADE 314N	natural	3.780 litres	58kW	220 Nm
B	ADE 364N	natural	3.972 litres	66 kW	269 Nm
C	ADE 364T	turbocharged	3.972 litres	85 kW	387 Nm
D	ADE 407N	natural	11.412 litres	149 kW	709 Nm
E	ADE 447N	natural	11.967 litres	177 kW	833 Nm
F	ADE 447T	turbocharged	11.967 litres	213 kW	1292 Nm
G	ADE 447TI	Turbo-intercooled	11.967 litres	294 kW	1700 Nm

### 4.1.2 TEST FUELS

Different test fuels were used in the coastal and highveld programmes and represent the fuels supplied at the pump in those areas. The Reference Diesel was used in both programmes for purposes of comparison. **Table 16** lists the test fuels and some specifications. More complete specifications are presented in **APPENDIX I**.

**Table 16:** Test Fuel Specifications

<b>COASTAL PROGRAMME</b>				
<b>Code</b>	<b>Type</b>	<b>Feedstock</b>	<b>Density</b>	<b>Cetane No.</b>
A	Pump Fuel	Crude	0.8576	51
-	BP Reference Diesel RF-03-A-84	Crude	0.8366	52

<b>HIGHVELD PROGRAMME</b>				
<b>Code</b>	<b>Type</b>	<b>Feedstock</b>	<b>Density</b>	<b>Cetane No.</b>
-	BP Reference Diesel RF-03-A-84	Crude	0.8366	52
B	Pump Fuel	Synthetic	0.8322	53
C	Pump Fuel	Crude	0.8517	52

### 4.1.3 TEST MATRIX

The test matrix of the VEP entailed one test per engine per fuel for each programme. Thus a total of 12 tests were performed for the coastal programme and 18 tests for the highveld programme. One repeat test per engine was performed to establish the test repeatability for each programme.

### 4.1.4 EXHAUST EMISSIONS MEASUREMENT

The products of combustion or exhaust emissions from diesel engines consist of air not used in combustion, water, CO<sub>2</sub>, CO, NO<sub>x</sub>, SO<sub>2</sub>, HC<sub>n</sub> from the fuel and solid PM entrained in the gases. Of these CO, NO<sub>x</sub>, HC<sub>n</sub> and PM are regulated by the EU and are dealt with in EEC Directive 70/220/EEC and the United Nations' Regulation No. 49. HC<sub>n</sub> refers to

the total hydrocarbons in the exhaust, including methane. The regulated emissions CO, NO<sub>x</sub>, HC<sub>n</sub> and particulates were strictly measured as stipulated in ECE R49. The R49 procedure was also adapted to measure the following unregulated emissions:

- Carbon Dioxide (CO<sub>2</sub>)
- Sulphur Dioxide (SO<sub>2</sub>)
- Formaldehyde (CH<sub>2</sub>O)
- Acetaldehyde (C<sub>2</sub>H<sub>4</sub>O)
- Methane (CH<sub>4</sub>)
- 1,3 butadiene (C<sub>4</sub>H<sub>6</sub>)
- Benzene (C<sub>6</sub>H<sub>6</sub>)

The last 5 substances are photochemically active and thus potential precursors to smog formation. **Table 17** lists each emission measured and relevant information concerning the method of measurement.

**Table 17:** Test Methods used for Measuring Exhaust Emissions

Emission	Symbol	Sample State	Measurement Method
<b>Carbon Monoxide</b>	CO	Raw Exhaust	Non-Dispersive Infra-Red Analyser
<b>Unburned Hydrocarbons</b>	HC <sub>n</sub>	Raw Exhaust	FID Analyser
<b>Oxides of Nitrogen</b>	NO <sub>x</sub>	Raw Exhaust	Chemiluminescent Analyser
<b>Particulate Matter</b>	Parts	Dilute Exhaust	Dilution Tunnel / Mass on Filters
<b>Carbon Dioxide</b>	CO <sub>2</sub>	Raw Exhaust	Non-Dispersive Infra-Red Analyser
<b>Sulphur Dioxide</b>	SO <sub>2</sub>	Raw Exhaust	Non-Dispersive Ultra-Violet Analyser
<b>Formaldehyde</b>	CH <sub>2</sub> O	Raw Exhaust	DNPH solution / HPLC with UV detector
<b>Acetaldehyde</b>	C <sub>2</sub> H <sub>4</sub> O	Raw Exhaust	DNPH solution / HPLC* with UV detector
<b>Methane</b>	CH <sub>4</sub>	Dilute Exhaust	Sample Bag / GC* with FID detector
<b>1,3 Butadiene</b>	C <sub>4</sub> H <sub>6</sub>	Dilute Exhaust	Sample Bag / GC with FID detector
<b>Benzene</b>	C <sub>6</sub> H <sub>6</sub>	Dilute Exhaust	Sample Bag / GC with FID detector

\*GC: Gas Chromatograph

\*HPLC: High Pressure Liquid Chromatograph

## 4.2 TEST APPARATUS

Specialised apparatus included the test cell that enabled the engine to be mounted and operated under a controlled load as well as apparatus for the sampling and measurement of the exhaust emissions. These are described below in **Section 4.2.1** to **Section 4.2.5**.

### 4.2.1 TEST CELL APPARATUS

**Table 18** below lists the test cell apparatus used for the coastal and altitude programmes:

**Table 18:** Test Cell Equipment

Equipment	PROGRAMME	
	Coastal	Highveld
Dynamometer Model	Froude G4	Schenck Type W400
Dynamometer Type	Water Brake	Water Brake
Fuel Flow Measurement	In-house design	AVL 733 Dynamic Fuel Meter
Air Flow Measurement	Cussons Laminar Flowmeter	Cussons Laminar Flowmeter

### 4.2.2 ON-LINE GAS ANALYSERS

On-line gas analysers were used to measure CO, HC<sub>n</sub>, NO<sub>x</sub>, CO<sub>2</sub> and SO<sub>2</sub> emissions. The models used for this purpose in the coastal and highveld programmes are presented below in **Table 19**:

**Table 19:** On-Line Gas Analysers used for Testing

Emission	Coastal Programme Instrument	Highveld Programme Instrument
CO	Signal Series 2000 IRGA	ADC 1381 Double-Beam Luft Type
HC <sub>n</sub>	Signal Model 3000HM	Signal Model 3000
NO <sub>x</sub>	Signal Model 4000VM	Signal Model 4000
CO <sub>2</sub>	Signal Series 2000 IRGA	Signal Series 2000 IRGA
SO <sub>2</sub>	Hartmann & Braun Uras 3 G	Hartmann & Braun Uras 3 G

The exhaust gas sample was conveyed to the analysers via heated lines controlled to 190°C to prevent condensation of the hydrocarbon and water vapour emissions. A three-way valve at the point of sampling was used to switch between background and raw exhaust measurements. A Signal chiller condensed moisture out of the sample before distribution to the CO, CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> analysers. This basic arrangement was identical for both coastal and highveld programmes.

#### 4.2.3 PARTIAL FLOW DILUTION TUNNEL

Regulation 49 allows for the use of a partial flow dilution tunnel for the measurement of particulates. This system entails the dilution of part of the engine's exhaust with ambient air in a dilution tunnel. A fraction of this diluted mixture is sampled through a pair of filters that collect the PM. The filters used were 47mm teflon, Fiberfilm T60A20 filters manufactured by Pallflex. The amount of PM was determined by weighing the filters using a Mettler semi-microbalance (to the nearest 0.01mg).

A gasmeter was used to determine the amount of gas sampled so the weighted average concentration of PM in the diluted sample can be determined. The dilution ratio was determined by measuring the relative CO<sub>2</sub> levels in the raw exhaust, dilute mixture and ambient air. Once the dilute concentration of PM and the dilution ratio are known the concentration of particulates in the raw exhaust can be calculated. Dilution ratio can be varied by changing the speed of a fan at the outlet of the dilution tunnel, called the suction blower. **Figure 36** below shows a schematic of this system.

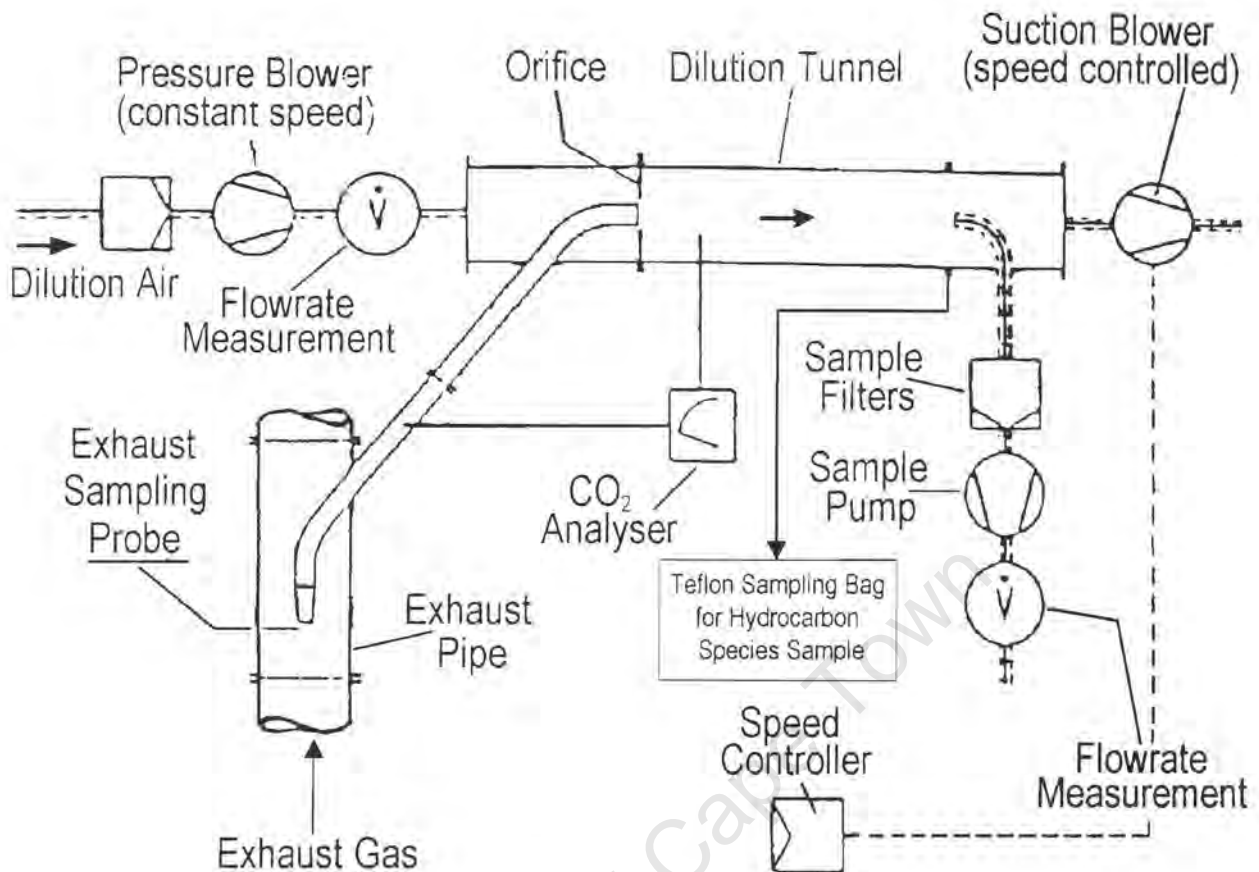


Figure 36: Schematic of Partial Flow Dilution Tunnel (Adapted from Reference 98)

#### 4.2.4 EQUIPMENT FOR ALDEHYDE DETERMINATION

The aldehydes (formaldehyde and acetaldehyde) were determined by bubbling the raw exhaust sample through a solution of 2,4 dinitrophenylhydrazine (DNPH) reagent which reacts with the aldehydes to form stable derivatives (hydrazones). The quantity of derivative was determined by liquid chromatography from which the quantity of aldehyde was determined proportionally. This procedure is described more completely in **Section 4.3.5**. The following equipment was used for the aldehyde measurements:

- Trace heated stainless steel sampling line for raw exhaust gas sample.
- One heated filter to remove particulates.
- One solenoid valve to allow intermittent sampling for the 13 modes of the test.
- Two washbottles containing 200ml of DNPH reagent diluted 1:1 with distilled water, through which the raw exhaust sample was bubbled.

- One washbottle containing silica gel to scrub the sample before the pump.
- One empty volumetric flask to damp flow oscillations
- One gasmeter to measure the sample volume.
- One vacuum pump fitted with a critical flow venturi to keep the sample flowrate at 3.5l/min.
- The aldehyde derivatives from the test sample were determined using a Hewlett Packard HP1090 Liquid Chromatograph with a Pinnacle ODS 3 $\mu$ m column and an UV type detector ( $\lambda = 370$  nm).

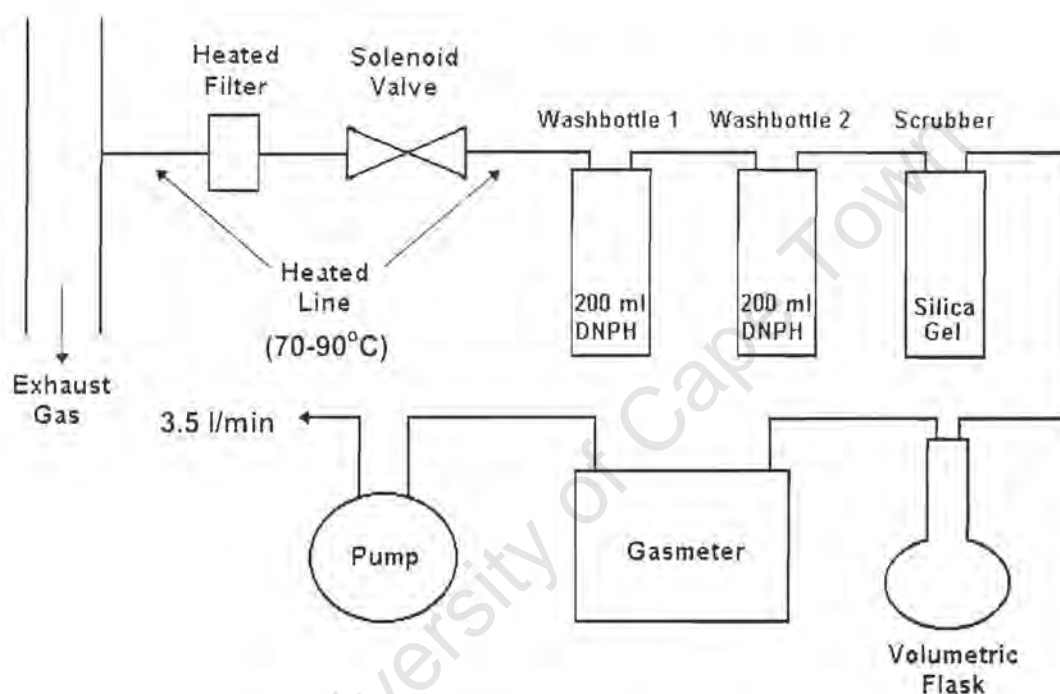


Figure 37: Schematic of Aldehyde Sampling System

#### 4.2.5 EQUIPMENT FOR UNREGULATED VOLATILE ORGANIC COMPOUNDS (VOC)

The sample used to determine the unregulated hydrocarbons, methane, 1,3 butadiene and benzene, was drawn directly from the dilution tunnel (also used for particulate sampling) into a teflon sample bag. This is illustrated in **Figure 36** above. The concentration of pollutants in the bag was determined by gas chromatography. The procedure is described in more detail in **Section 4.3.6**. The following is a summary of the equipment used to determine these emissions:

- Dilution Tunnel (**Figure 36**) to dilute the exhaust gas before sampling.
- One in-line filter to remove particulates.
- One Solenoid valve to facilitate intermittent sampling for the 13 modes of the test.
- One vacuum pump fitted with a critical flow venturi to keep the sample flowrate at 4.74 l/min.
- Teflon sampling bag to collect the gas sampled in the 13 modes.
- Rotameter to control the purging of the sampling bag.
- Sampling syringe with 1ml capacity to take sample from bag.
- The hydrocarbon species concentrations were determined for the coastal programme by a GOW MAC Microprocessor Controlled Gas Chromatograph and for the highveld programme by a SRI 8610B Gas Chromatograph. Both instruments were fitted with a Restek Rt-Alumina Column.

## 4.3 TEST PROCEDURE

### 4.3.1 MODAL SAMPLING AND WEIGHTING IN REGULATION 49

All the emissions measurements performed for this project conforms to the guidelines laid out in the European Community Directive 70/220/EEC and the United Nations' Regulation 49. In the case of the regulated emissions these guidelines were followed as directed in the published procedure <sup>(98)</sup>. In the case of the unregulated emissions the guidelines had to be adapted so that all measurements were comparable.

The Regulation 49 procedure derives a cumulative result from steady state operation at 13 operating points at a range of speeds and percentages of full load. The quantity of emissions measured at each operating point or mode is given a weighting factor and the summation of all the weighted measurements represents the emission figure. Details of the speeds, loads and weighting factors for the test procedure are presented below in **Table 20**:

Table 20: Operating Points and Weighting Factors for the ECE R49 13-Mode Test <sup>(98)</sup>

Mode No.	Engine Speed	% Load	Weighting Factor
1	Idle	-	0.0833
2	Intermediate	10	0.08
3	Intermediate	25	0.08
4	Intermediate	50	0.08
5	Intermediate	75	0.08
6	Intermediate	100	0.25
7	Idle	-	0.0833
8	Rated	100	0.10
9	Rated	75	0.02
10	Rated	50	0.02
11	Rated	25	0.02
12	Rated	10	0.02
13	Idle	-	0.0833

The following definitions apply to **Table 20** above:

**Rated speed:** The speed at which the engine achieves maximum power with full rack setting on the fuel pump.

**Intermediate speed:** The speed corresponding to the maximum torque value if such a speed is within the range of 60 to 75% of rated speed. In other cases it means a speed equal to 60% of rated speed.

**% Load:** The fraction of the maximum available torque at a given engine speed.

#### 4.3.2 ENGINE RUNNING PROCEDURE

The engine was run according to the following procedure:

- The engine was warmed up for 20 minutes. Water and oil temperatures reached the manufacturers specifications in the first 10 minutes.
- During the second 10 minutes of the warm-up the 100% torques at the test speeds were determined for the test fuel and the operating points for the other modes calculated.

- After the warm-up the background emissions were measured for a few minutes before commencing the test. For the highveld programme, sample lines were much shorter and the resulting short analyser response times made it possible to measure background emissions during the first few minutes of every mode.
- The engine was run for 8 minutes at every mode, reaching torque and speed set points in the first 2 minutes. R49 stipulates 6-minute modes but the long sample lines at the coastal facility necessitated longer modes to allow the analyser readings to stabilise.
- Sampling was performed as late as possible in each mode.

#### 4.3.3 PROCEDURE FOR MEASURING CO, HC<sub>N</sub>, NO<sub>x</sub>, CO<sub>2</sub> AND SO<sub>2</sub>

These emissions were all measured by on-line gas analysers (listed in **Section 4.2.2**) from a raw sample and thus an identical procedure was applied.

- The analysers were calibrated immediately before every test. The calibration details are presented in **APPENDIX L**.
- Background pollutants were sampled at the beginning and end of every test for the coastal programme.
- Background pollutant levels were determined in the first 4 minutes of every mode for the highveld programme.
- The measured values of the analysers were logged once every second on a personal computer.
- Analyser calibration was spot-checked after the test.
- After the data was retrieved, the last 60 seconds of every mode was averaged and corrected for background levels.
- The 13 resulting figures were weighted and summed, then converted to the specific units to give the final result.

#### 4.3.4 TEST PROCEDURE FOR PARTICULATE MATTER EMISSIONS

Unlike the gaseous emissions where 13 individual values are weighted to give the final result, there is only one quantity obtained for particulate measurement at the end of the

test. This is the mass of particulates trapped by the pair of teflon filters in the sampling line. These are marked *Sample Filters* in **Figure 36**, presented in **Section 4.2.3**.

The 13 modes are, however, still weighted as indicated in **Table 20** above by sampling a mass of exhaust gas proportional to the required weighting factor at each mode. Thus the final result will effectively be weighted in the same way as the gaseous emissions. Briefly the procedure is as follows:

- Two clean teflon filters are weighed and stored in a controlled environment.
- The dilution tunnel is calibrated to determine a set of suitable dilution ratios with corresponding dilution tunnel pressure and fan settings.
- Assuming a constant sampling flowrate, sampling times are calculated based on the calibration data to comply with the weighting factors.
- During the test the tunnel is reset to the calibration conditions for each mode so that the dilution ratio is known and sampling is performed at constant flowrate through the filters for the calculated time.
- After the test the filters are removed and conditioned in a controlled environment before weighing.
- The mass of particulate on the filters can then be converted to the specific units to give a final result as described in **APPENDIX J2**.

#### 4.3.5 TEST PROCEDURE FOR ALDEHYDES

Aldehydes were determined by a wet chemistry method based on that used for the gasoline vehicle tests of the VEP <sup>(109)</sup>. As with the particulates, one quantity, the mass of aldehyde, is obtained at the end of the test. Similarly the result is weighted by sampling a mass of gas proportional to the relevant weighting factor at each mode. The sampling procedure can be summarised by the following steps:

- The exhaust gas is bubbled through a solution of DNPH reagent for a sampling time proportional to the modal weighting factor.
- The carbonyls in the exhaust, including formaldehyde and acetaldehyde, react with the DNPH reagent to form hydrazone derivatives.

- After the test dichloromethane extracts, the aqueous layer of the solution, and the organic layer evaporated to leave the derivatives in a dry residue.
- The dry derivatives are then dissolved in methanol, separated and quantified by high-pressure liquid chromatography (HPLC).

The method used for the diesel engines differed in the following major respects from that used for the gasoline vehicle tests of the VEP:

- Raw exhaust was sampled directly from the exhaust pipe and directed to the washbottles containing the DNPH solution via heated stainless steel lines at 60 °C to 80 °C.
- The use of raw exhaust necessitated a far more concentrated DNPH solution of 1:1 with distilled water instead of 1:20 because other exhaust components like NO<sub>x</sub> can react preferentially with the DNPH and can deplete the reagent.
- The sample was taken in 13 discrete steps weighted by the factors presented in **Table 20** above.

#### 4.3.6 PROCEDURE FOR UNREGULATED VOLATILE ORGANIC COMPOUNDS

The VOCs methane, benzene and 1,3 butadiene were also determined from a cumulative sample of exhaust gas. The method to determine these emissions was again similar to that of the gasoline passenger vehicle tests in the VEP. <sup>(109)</sup> Dilute exhaust gas was sampled into a teflon bag from which a sample was taken for concentration analysis. The sample had to be dilute to prevent condensation of the hydrocarbons. The basic procedure was as follows:

- During the test a dilute sample of exhaust gas was sampled directly from the particulate dilution tunnel for a period proportional to the appropriate weighting factor for that mode. Sampling time was the same as for the particulate determination because the dilution ratio was the same.
- The sample for each mode was pumped into the bag where it mixed with the other samples giving a cumulative weighted concentration of each species at the end of the test.

- A 1ml sample was then drawn from the bag using a syringe and analysed using a gas chromatograph to determine the species concentrations.

## CHAPTER 5 METHODOLOGY OF THE INVENTORY MODELLING PHASE

### 5.1 DESIGN OF THE MODEL

It was decided to express gross emissions by mass in tons on a per annum basis. This was derived as follows, given that the population has been divided into "n" groups with each arbitrary population group "i" having distinct vehicle characteristics and fuel usage:

- If:
- $PR_i$  = The average rated power of the  $i^{\text{th}}$  population group
  - $PA_i$  = The average power output in service of the  $i^{\text{th}}$  population group
  - $DC_i$  = The duty cycle factor

$$DC_i = \frac{PA_i}{PR_i} \quad \dots(\text{Equation 29})$$

- If:
- $H_i$  = The annual hours of operation of the  $i^{\text{th}}$  population group
  - $E_i$  = Representative test data for the  $i^{\text{th}}$  population group (g/kW.h)
  - $V_i$  = The number of vehicles in the  $i^{\text{th}}$  population group
  - $M_i$  = The annual mileage of the  $i^{\text{th}}$  population group (km)
  - $TAE$  = Total annual emissions for the vehicle population (1,000 tons/annum)
  - $EF_i$  = Emission Factor for the  $i^{\text{th}}$  population group (g/km)

$$TAE = \sum_i^{1 \dots n} \frac{(V_i \times PR_i \times DC_i \times E_i \times H_i)}{1 \times 10^9} \quad \dots(\text{Equation 30})$$

$$EF_i = \frac{(V_i \times PR_i \times DC_i \times E_i \times H_i)}{M_i} \quad \dots(\text{Equation 31})$$

A value of 50% was used as the duty cycle factor ( $DC_i$ ). This can be derived from the European R49 procedure <sup>(93,98)</sup> applied in Phase 2 of the VEP. Duty cycle factor was not determined from real operating cycles in the South African marketplace. This would be a considerable undertaking in its own right. The R49 procedure has been based on a representative operating cycle for Europe and if we assume the applicability of the emissions data derived from it on our emissions model it is proposed that it is an equally

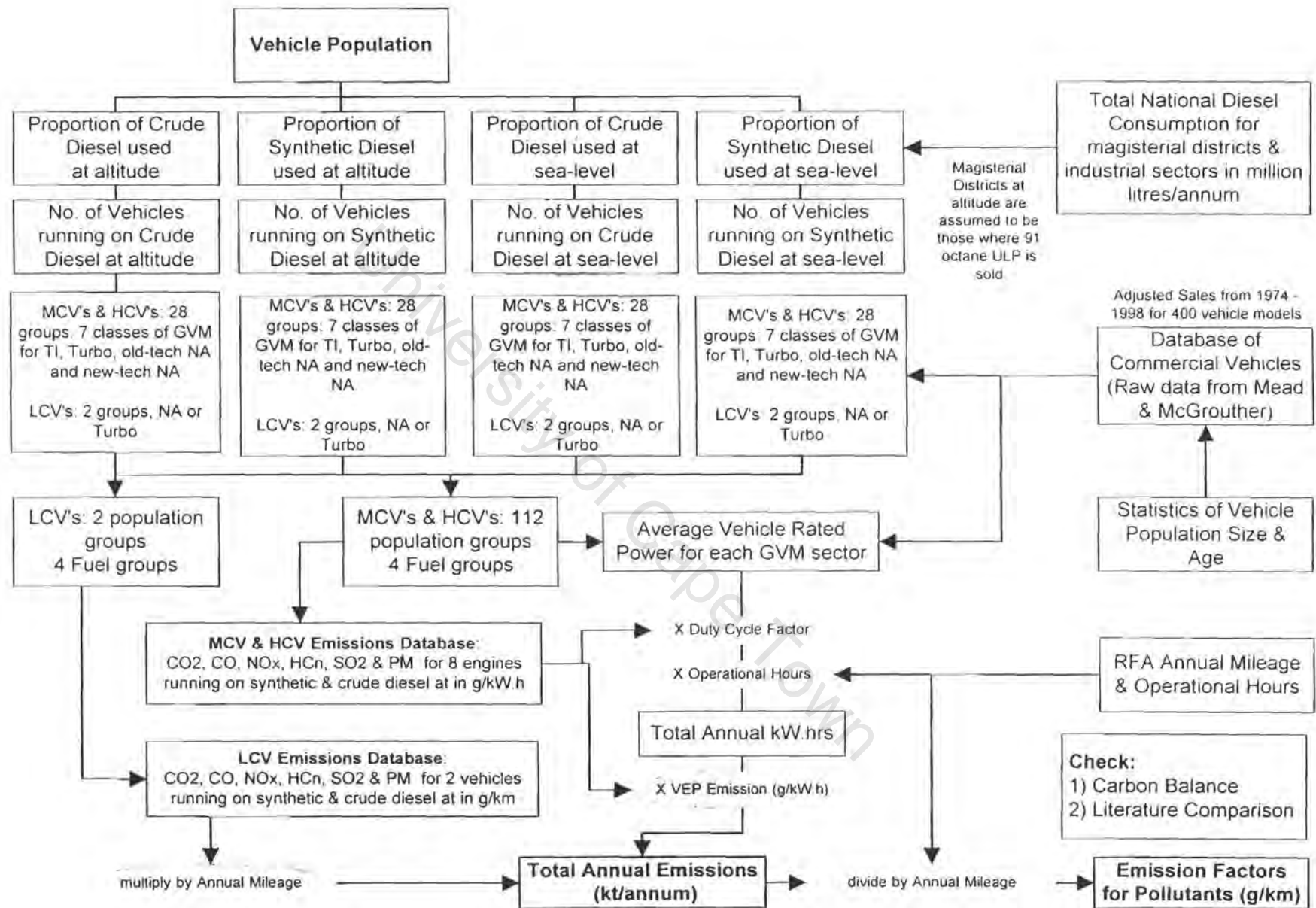
valid assumption to apply the duty cycle factor. The European COPERT emissions factor model <sup>(74)</sup> applies a correction to this 50% duty cycle factor for heavy vehicles. This correction is discussed in detail in **APPENDIX F**. The worked example suggests that, given the validity of such a correction, the errors of assuming a 50% duty cycle are likely to be small. The 50% assumption has been shown to be more or less valid for lighter commercial vehicles <sup>(74)</sup>.

To account for the second objective of the study a more challenging exercise must be undertaken to quantify each of the variables defined for each combination of fuel and engine type. This was attempted by making use of databases external to the experimental work to achieve the following:

- Characterisation of diesel fuel use patterns in South Africa by feedstock, consumer and altitude.
- Characterisation of the diesel engine commercial vehicle population by disaggregating it into groups that can be matched to the experimental data.

This process is described and linked to the equations above by the flowchart presented in **Figure 38** below. The calculation process for light-duty commercial vehicles is different, as shown. The input data to this sub-model were not measured in the experimental phase of this study, but formed part of the light-duty VEP study <sup>(109)</sup>. These emissions data are expressed in units of grams per kilometre and need only to be multiplied by annual mileage to yield TAE defined above. The accuracy of the model is therefore highly dependent on the degree to which the vehicle population can be broken down and matched to appropriate emissions data, particularly in the case of light commercial vehicles.

Figure 38: Schematic Representation of Proposed Emission Inventory Model based on VEP Data for South African Diesel Commercial Vehicles



## 5.2 CHARACTERISING THE DIESEL FUEL CONSUMPTION OF COMMERCIAL VEHICLES IN SOUTH AFRICA

To derive a solution from the model described by **Figure 38** the following must be estimated:

- Total fuel consumption. This allows a carbon balance to be performed to check the model result and, if necessary, proportion the model accordingly.
- The proportion of fuel used at altitude conditions.
- The proportion of synthetic fuel used at altitude and sea level.

Two primary resources were applied to the above. The total fuel consumption of the diesel commercial vehicle park alone and the altitude proportion of diesel consumed were calculated from the database of sectoral fuel sales for magisterial districts in South Africa. This is compiled for the oil industry by Caltex, and was made available for this study by the Department of Minerals and Energy <sup>(21)</sup>. To make a regional distinction of what constitutes altitude versus sea-level conditions, these terms had to be defined. The term *sea level* is of course self-explanatory. A useful definition of *altitude conditions* for the purposes of modelling would simply be those areas where the reduction in ambient air density is such that the exhaust emissions of a heavy-duty diesel engine will deviate significantly from those emitted when operating at sea level. Topography in the field is, however, almost infinitely variable so that a model designed according to this definition would require extensive tests at a variety of altitudes instead of the single site used for the VEP. A more practical definition was therefore derived that could be applied to the resources available:

*Regions that constitute "altitude conditions" are regions where 91 octane unleaded petrol is sold by fuel vendors.*

The criteria applied by the oil industry to determine where 91 octane unleaded petrol is sold is an altitude of 1,200 meters above sea level <sup>(28)</sup>. This is arguably a crude distinction for the complex reality of vehicle operation. The experimental dataset, however, only includes data from one high altitude location at about 1,650 meters, so in terms of a first approximation it was deemed an acceptable criterion for this study. A more rigorous approach would be to match a database of magisterial district altitudes to the fuels sales database. This would, however, require additional test data indicating a correlation

between emissions and altitude so that the contribution of each district to total emissions could then be appropriately weighted. **Table 21** below summarises sectoral diesel consumptions, the estimated allocation to commercial vehicles and the estimated altitude consumed proportion according to the above definition:

**Table 21:** Sectoral Breakdown of South African Diesel Consumption for 1998 <sup>(21)</sup>

Sector	Sectoral Consumption (litres)	Sectoral Consumption (%)	Altitude Consumption (litres)	Proportion Consumed Altitude (%)	Estimated Usage Factor	Estimated CV Consumption (litres)
Road Haulage	9.21E+08	15.4%	6.40E+08	69.5%	1	9.21E+08
Retail Garages	1.38E+09	23.0%	8.43E+08	61.2%	1	1.38E+09
Construction	2.70E+08	4.5%	1.98E+08	73.6%	0.9	2.43E+08
Agricultural Co-ops	3.70E+08	6.2%	2.56E+08	69.3%	0.5	1.85E+08
Pub. Trans. NL Auth.	2.04E+08	3.4%	1.36E+08	66.6%	1	2.04E+08
Government	8.00E+07	1.3%	4.49E+07	56.1%	1	8.00E+07
Farmers	7.43E+08	12.4%	4.79E+08	64.5%	0.5	3.71E+08
Mining	5.22E+08	8.7%	4.38E+08	83.9%	0.7	3.66E+08
Rem. Gen. Trade	6.95E+08	11.6%	4.82E+08	69.3%	1	6.95E+08
Transnet Total	2.28E+08	3.8%	1.39E+08	60.9%	1	2.28E+08
(Trans. Diesel Locos)	1.90E+08	3.2%			-1	-1.90E+08
(Transnet Marine)	1.05E+07	0.2%			-1	-1.05E+07
General dealers	3.72E+08	6.2%	3.01E+08	80.7%	1	3.72E+08
Loc. Mar. Fish	8.57E+07	1.4%	2.88E+06	3.4%	0.5	4.29E+07
Local Authorities	1.06E+08	1.8%	7.79E+07	73.5%	1	1.06E+08
<b>TOTAL</b>	<b>5.97E+09</b>	<b>100.0%</b>	<b>4.04E+09</b>			<b>4.99E+09</b>
<b>AVERAGE</b>				<b>67.6%</b>		

The usage figures indicated in **Table 21** above are estimates of the proportion of diesel used by commercial vehicles in each sector, as opposed to stationary engines driving compressors or generators and diesel-powered marine craft. These factors are all assumed. Indeed, accurate verification would constitute an exhaustive study on its own. Only the factor for Local Marine Fishing has its basis in anecdotal reports from the oil industry staff that compile these figures that a large portion of the fishing industry's energy consumption is road transport-based. These estimates account for lesser percentages of total consumption though, with the exception of farming sector consumption. Despite these conjectures it is proposed that this approach is an improvement on that of the UK's National Atmospheric Emissions Inventory that assumes all national diesel consumption is road transport-based <sup>(68,69)</sup>.

The proportion of synthetic diesel used was estimated using refinery capacities obtained from the South African Petroleum Industry Association (Sapia) yearbook <sup>(92)</sup>. Two

assumptions were made, first that the Secunda Sasol refinery operates near full capacity for economic reasons and secondly that all production of this refinery is used at altitude conditions and all production of the Moss gas refinery is used at sea-level conditions. **Table 22** below presents the estimated breakdown of diesel consumption by refinery and feedstock:

**Table 22:** Estimated SA Refinery Production of Diesel in Million Litres for 1998 <sup>(92)</sup>

REFINERY	CAPACITY	CAPACITY	SOLD IN LOCAL INLAND MARKET	SOLD IN LOCAL INLAND MARKET
	(barrels/day)	(%)	(million litres)	(%)
Sapref	180000	27.0%	1480	24.8%
Enref	105000	15.8%	863	14.5%
Calref	100000	15.0%	822	13.8%
Natref	86000	12.9%	707	11.9%
Sasol	150000	22.5%	1718 <sup>(38)</sup>	28.8%
Mossgas	45000	6.8%	370	6.2%
<b>TOTAL</b>	<b>666000</b>	<b>100%</b>	<b>5959</b>	<b>100%</b>

*Note: Above assumes Local Sales proportional to Capacity except for Sasol which is reported by Howells <sup>(38)</sup>.*

The data from **Table 21** and **Table 22** can now be combined to generate the first tier of the model in **Figure 38**, the proportions of synthetic and crude-derived fuel used by the vehicle population at altitude and sea level respectively. These proportions are presented below in **Table 23**. The assumption was made that the proportion of actual vehicles using a particular fuel at a certain altitude condition was identical to the proportion of the fuel sold at that altitude of the total fuel market.

**Table 23:** Estimated Proportions for Fuel and Altitude Usage of SA Diesel Commercial Vehicles

Fuel:	Crude	Synthetic	Crude	Synthetic	TOTAL
Area:	Sea-Level	Sea-Level	Altitude	Altitude	
Proportion:	26.20%	6.20%	38.80%	28.80%	100%

### 5.3 CHARACTERISING THE DIESEL COMMERCIAL VEHICLE POPULATION

Solving the model in **Figure 38** further requires characterising the diesel commercial vehicle population by making the following estimates:

- A proportional breakdown of the vehicle population into established weight categories that can be matched to the data set of engine capacities.
- The breakdown of the naturally aspirated population into old and new technology categories.
- The average power of each of the population groups.
- The average operating hours and mileage of vehicles in these categories.

Published data that accounted for all the above was not found, therefore a database had to be created that related engine characteristics to incidence in the population. The "Commercial Vehicle Data Digest", published by Mead & McGrouther<sup>(13,14)</sup>, was selected as a basis for this database. This source combines the required engine and vehicle data with sales data for most of the models sold in South Africa for the last 20 years, with some coverage of the period 20 to 35 from the present. Later editions are conveniently compiled in a Microsoft Access Database that reduces the onerous task of large-scale manual data entry. The major shortcoming being that at the time of writing the available editions only included data for years of sale up to 1998, which limited the calculation of all results for the entire emissions database to that year.

The primary impediment to applying the Mead & McGrouther database in its raw form to an emissions model is that the total annual sales figures obtained from the digest do not give a proportional representation of a model in the marketplace. It is proposed, however, that there is a relationship defined by a finite probability of a vehicle being scrapped that increases with every year that passes since the year of sale. This applies especially in the case of large vehicle samples. The relationship between the number of vehicles sold in a particular year and the number of vehicles remaining in the vehicle park in a later year was defined as follows:

If:  $Y_S$  = The year of sale

$Y_P$  = The year for which the vehicle park is being characterised

$V_P$  = The number of vehicles in the vehicle park in year  $Y_P$  sold in year  $Y_S$

$V_S$  = The number of vehicles sold in year  $Y_S$

$f(Y_P - Y_S)$  = A function that is solved as a "scrapping factor"

$$V_P = f(Y_P - Y_S) V_S \quad \dots(\text{Equation 32})$$

The scrapping factor function is certainly non-linear, as at the very least the probabilities of scrapping a vehicle compound for successive years. Accelerated deterioration of the vehicle will further compound an increased rate of scrapping with the passage of time from the year of sale.

Verburgh <sup>(105)</sup> has proposed scrapping factors for use in modelling the vehicle park for the purpose of stock control in the auto spares industry. **Figure 39** below presents these factors for gasoline passenger vehicles as determined for 1989.

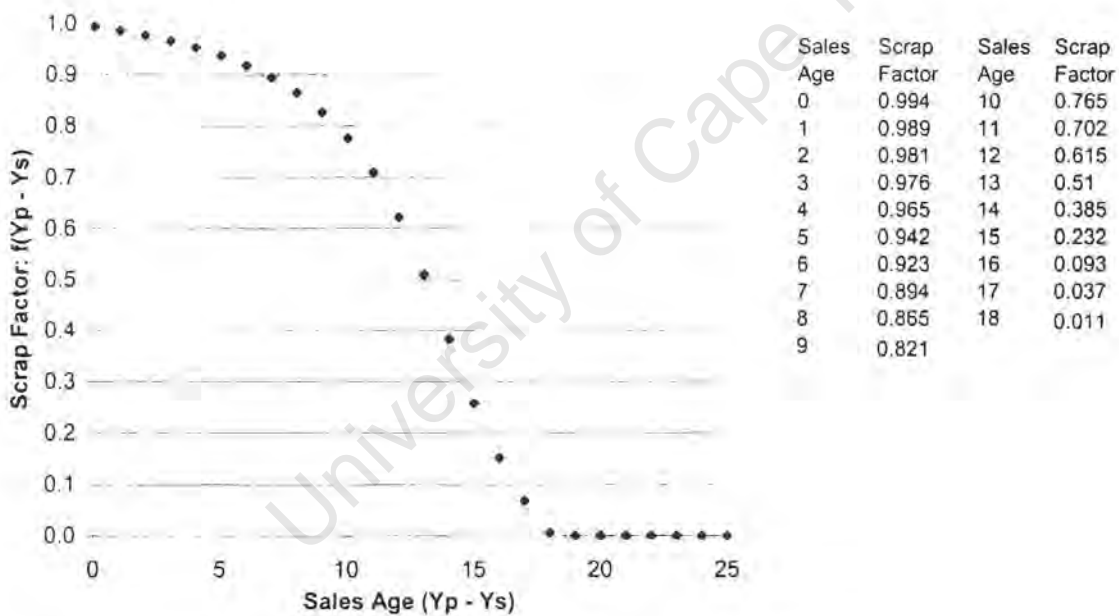


Figure 39: Scrapping factors for Gasoline Passenger Vehicles as Proposed by Verburgh <sup>(105)</sup>

As discussed in **Section 3.10.2**, such component lifecycle curves are typically characterised by a Weibull distribution. The manipulation of two constants allows a suitable distribution to correlate with the size of the population and to some degree average age statistics. It was decided, however, to attempt a novel approach in this study using a four constant function that offered more flexibility and the possibility of smoothing sales data to exactly match population size, average age and median age. Using

Verburgh's <sup>(105)</sup> figures as an example, the factors presented in **Figure 39** can be fitted to a curve of the following form:

If:  $A, B, C$  &  $D$  are constants

$$f(Y_P - Y_S) = A(\arctan(B(Y_P - Y_S) + C)) + D \quad \dots(\text{Equation 33})$$

Clearly  $f(Y_P - Y_S)$  must approach zero as a limit as negative scrapping factors will cause negative populations. This mathematical requirement can be dealt with by defining a final scrapping factor "SF" as follows:

$$SF = \frac{f(Y_P - Y_S) + ABS(f(Y_P - Y_S))}{2} \quad \dots(\text{Equation 34})$$

Verburgh's scrapping factors for gasoline vehicles can therefore be defined by the following constants from **Equation 33** for an  $R^2$  correlation coefficient of 0.9986:

- $A = -0.4496$
- $B = 0.2885$
- $C = -4.006$
- $D = 0.3979$

These scrapping factors are likely to be influenced by a number of factors, but mainly by consumer behaviour, economic pressures and vehicle application. In the case of diesel engines, longer engine life and the commercial application are likely to result in a slower rate of scrapping than that for gasoline passenger vehicles. How then does one determine appropriate scrapping factors with which to relate vehicle sales and actual incidence in the diesel commercial vehicle population?

A solution was proposed whereby **Equation 32** – using scrapping factors defined by **Equations 33** and **34** – was applied to the NAAMSA total annual sales data <sup>(43)</sup> for commercial vehicles over a 30-year period. The constants of **Equation 33** were adjusted until a total population was yielded of a quantity that corresponded with available statistics of the number of vehicles on the road and their average age. These characteristics of the estimated population can be defined as follows:

- If:  $V_T$  = The total size of the vehicle park in year 1
- $A_V$  = The average age of the vehicle park in year 1
- $SF_i$  = Scrapping Factor for  $i^{th}$  year (**Equation 34**)
- $V_i$  = Number of vehicles sold in  $i^{th}$  year (NAAMSA) <sup>(43)</sup>

$$V_T = \sum_i^{1...n} (SF_i \times V_i) \quad \dots(\text{Equation 35})$$

where  $SF_n$  has approached zero, that is, all vehicles sold in year n are scrapped:

$$A_V = \frac{\sum_i^{1...n} SF_i \times V_i \times i}{V_T} \quad \dots(\text{Equation 36})$$

Statistics of median age were also compared, although these are more qualitative as the latest available figures found were for 1989 and had to be extrapolated to the present <sup>(17)</sup>.

**Table 24** below lists different sources for total commercial vehicle population, average age and median age <sup>(5,17,61,72)</sup>.

**Table 24:** Commercial Vehicle Population Size & Age Characteristics

Source (at Year end)	Total CV	MCV & HCV	LCV	Total CV	MCV & HCV	LCV	Total CV
	<i>Popl.</i>	<i>Popl.</i>	<i>Popl.</i>	<i>Avg. Age</i>	<i>Avg. Age</i>	<i>Avg. Age</i>	<i>Median Age</i>
CSS (Extrapolated data)(1998) <sup>(17)</sup>	1 504 749			11.8			12.1
Automobile Association (1998) <sup>(5)</sup>	1 561 207	276 977	1 284 230				
NaTIS (1999) <sup>(72)</sup>	1 489 283	227 468	1 261 815				
Marketing Shop (1998) <sup>(61)</sup>	2 079 819	268 156	1 811 663	9.6	11.9	9.3	
Marketing Shop (2000) <sup>(61)</sup>	2 203 172	272 061	1 931 111				

*Note: Marketing Shop statistics were supplied with permission by Dave Scott & Associates*

**Equations 34, 35 and 36** were applied to 30 years of sales figures for light commercial vehicles and combined medium and heavy commercials, such that the resulting

population was in agreement with data from Reference 61 in Table 24. Calculations were for the year 2000, assuming age data was roughly unchanged since 1998. This source was selected in preference to the National Traffic Information System (NaTIS) registration-based statistics, as the figures from Reference 61 are a complete set including both population and age data. Reference 61 is widely used in industry for this type of data. The resulting scrapping factor curves are presented in Figure 40 below, compared to those proposed by Verburgh for gasoline vehicles in 1989 <sup>(29)</sup>. The coefficients, NAAMSA sales data, adjusted sales and resulting population, average age and median age data are presented in Table 25. The scrapping factors themselves are not shown but can be easily calculated using the coefficients shown.

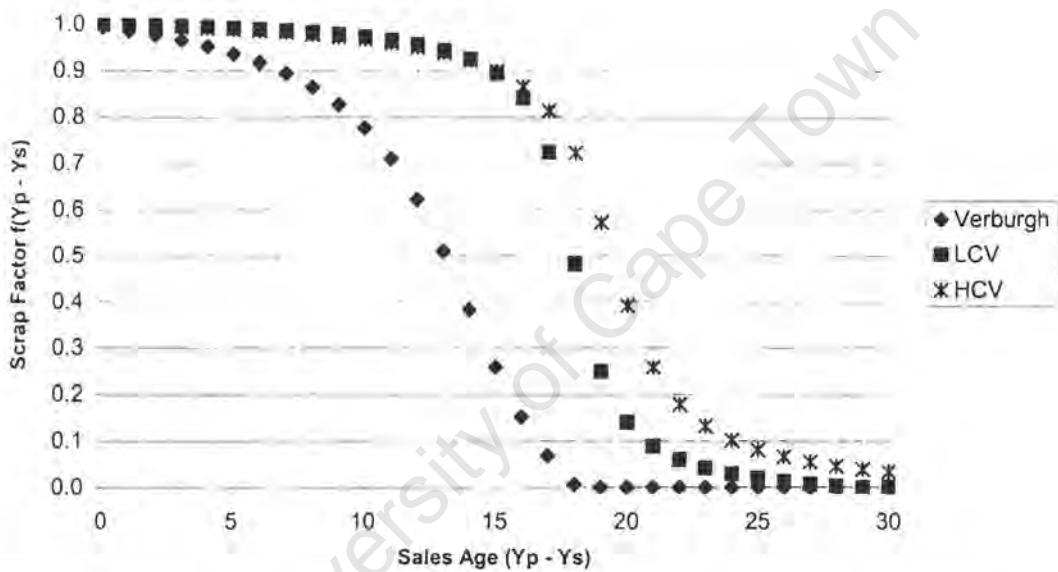


Figure 40: Estimated Scrapping Factors for SA Commercial Vehicles

Table 25: Characterisation of SA Commercial Vehicle Population using Scrapping Factors (2000)

	Coefficients for Equation 32				Sales <sup>(43)</sup> (1970-2000)	Predicted Population	Predicted Avg. Age	Predicted Median Age
	A	B	C	D				
<b>LCV</b>	-0.3369	0.8520	-15.30	0.4931	3 089 128	1 931 265	9.3	9.07
<b>MCV &amp; HCV</b>	-0.3356	0.5546	-10.75	0.5041	475 977	272 066	11.9	12.3

The scrapping factors calculated enabled the proportional adjustment of the Mead & McGrouther database sales to vehicle quantities proportional to actual numbers of vehicles in the population. The characteristics of vehicle mass, power, aspiration and so forth will therefore be more proportionally represented in the emissions database. **Figure**

41 and Figure 42 below show the estimated population from each sales year compared to the adjusted vehicle numbers in the emissions database for Light Commercial Vehicles (LCVs) and combined Medium and Heavy Commercial Vehicles (MCVs & HCVs) respectively.



Figure 41: 1998 Estimated Population Compared to Adjusted Emissions Database Sales Figures: LCVs



Figure 42: 1998 Estimated Population Compared to Adjusted Emissions Database Sales Figures: MCVs & HCVs

Database raw sales figures were not increased by more than 20% to conform to a fixed proportion of the estimated population to prevent excessive distortions of certain models. In some cases, as can be seen above, under-reporting in the Mead & McGrouther figures was such that it was not practical to smooth the database population and include this point. For example, Mead & McGrouther completely omit any sales for light commercial vehicles in 1980.

Other relevant data was listed with each database entry, along with the adjusted sales described above. These included power, gross vehicle mass, aspiration, engine type and whether in the case of ADE engines the engine was old or new technology according to the VEP engine sample. Once the numbers sold of each database entry were adjusted to be proportional to the actual vehicle park, this data could be derived as proportions and averages for the entire population.

**Table 26** below presents the selected results of this exercise combined with other externally referenced data. Annual mileages were allocated based on vehicle weight using figures published by the Road Freight Association (RFA) <sup>(79)</sup>. The average operating hours were then calculated using assumed average speeds. In the absence of a detailed national traffic speed study, lighter vehicles were assumed to have the same average speed as the combined European Urban and Highway light duty emissions cycle of 46.5km/h <sup>(27)</sup>. The average speed for heavy vehicles was obtained from results of the University of Natal's SIMTRANS computer simulation of a long-haul truck trip from Durban to Johannesburg <sup>(100)</sup>. The average speed of the 17,000kg to 20,000kg gross vehicle mass category was assumed to be the average of the light vehicles and long-haul vehicles to reflect the probability of mixed usage.

The RFA mileage figures are derived from a cost calculation for new vehicles and do not necessarily hold for vehicles over the entire 30-year age span of the emissions model. Indeed, use of this data in its raw form yielded results with excessive carbon output relative to the known fuel consumption from SAPIA. The RFA mileages were therefore multiplied by a factor of 0.832 such that the model carbon and SAPIA consumption balanced. This is common practice in inventory modelling <sup>(15)</sup>.

**Table 26:** Selected Estimated Diesel Commercial Vehicle (CV) Population Characteristics from Emissions model (1998)

LCV	Average	Turbo		Total	Average	Annual	Annual	Diesel	No. of	Popl.	Energy
GVM	Power*	Fraction		No. of	Speed	Mile.	Service	LCV	Diesel	Cap.***	Cap.****
(kg)	(kW)	(%)		LCV	(km/h)	(km)	(hrs)	(%)	LCV	(GW)	(TW.h)
LCV < 3500	55.8	14.0%		1 811 663	46.5	30000	645	20.9%	377 964	21.09	13.61
M&HCV	Average	Turbo	TI**	% ADE	Average	Annual	Annual	Popl.	No. of	Park	Energy
GVM	Power*	Fraction	Fraction	Engines	V. Speed	Mile.	Service	Fraction	Vehicles	Cap.	Cap.
(kg)	(kW)	(%)	(%)	(%)	(km/hr)	(km)	(hrs)	(%)		(GW)	(TW.h)
3501-7500	68	8.0%	7.8%	74.7%	46.5	39 909	858.3	19.8%	53 184	3.6	3.1
7501-10 000	89	2.7%	0.0%	56.6%	46.5	39 909	858.3	10.7%	28 804	2.6	2.2
10 001-12 500	95	0.0%	0.0%	72.4%	46.5	39 909	858.3	18.4%	49 456	4.7	4.0
12 501-15 000	106	39.6%	0.4%	76.0%	46.5	38 662	831.4	24.4%	65 398	6.9	5.8
15 001-17 500	161	42.5%	3.5%	51.6%	46.5	51 718	1112.2	4.4%	11 768	1.9	2.1
17 501-20000	202	55.6%	4.8%	98.8%	56.0	63 527	1134.4	2.4%	6 448	1.3	1.5
Over 20 000	231	57.5%	14.5%	58.6%	65.5	87 145	1331.5	19.8%	53 097	12.3	16.3
<b>AVERAGE</b>	<b>124</b>	<b>26.1%</b>	<b>4.8%</b>	<b>69.0%</b>	<b>50.5</b>	<b>50 074</b>	<b>963</b>				
<b>TOTAL</b>								<b>100.0%</b>	<b>268 155</b>	<b>33.3</b>	<b>35.1</b>
<b>POPL. AVG.</b>	<b>84</b>				<b>48</b>	<b>38 331</b>	<b>777</b>				
<b>POPL. TOT.</b>									<b>646 119</b>	<b>54.4</b>	<b>48.7</b>

Note: Annual mileages have been proportioned relative to RFA figures<sup>(79)</sup> but factored by 0.832 so that carbon is balanced.

\*: This is the population weighted average rated power (the maximum power the engines are rated for by the manufacturers).

\*\* : TI: Turbo-intercooled engines

\*\* : Popl. Cap.: Cumulative Population Engine Power Capacity (the sum of the rated powers)

\*\*\* : Energy Cap.: Cumulative Population Capacity for Energy Output per Annum

The above figures were used directly in the calculation of Total Annual Emissions as described by the model depicted in **Figure 38** above.

## 5.4 SCENARIO MODELLING

A number of scenarios were modelled by adjusting the engine emission data input to the model. These were as follows:

### i. No Synthetic Fuel Industry

This scenario was modelled by simply substituting the emission data for crude-derived fuel into the data fields formerly containing the synthetic fuel emission data for altitude and sea level conditions respectively. A formula toggle was programmed in the spreadsheet model so that cutting and pasting operations were unnecessary.

### ii. The Conversion of all MCVs and HCVs to Turbo-intercooled Engines

Proportions of vehicles allocated to the different types of engine aspiration as presented in **Table 26** were all changed to reflect a 100% turbo-intercooled population. This was only applied to MCVs and HCVs as no turbo-intercooled data was available for LCVs.

The vehicle population was kept the same for this exercise, but clearly the increased capacity of the vehicle park will require less trips to transport the same freight. Therefore the operating hours were adjusted so that the MCV and HCV "Energy Capacity" shown in **Table 26** was the same as the baseline of 48.7 Terawatt hours (TW.h). This is simply the product of the park capacity in GigaWatts (GW) and the annual operating hours and represents the vehicle park energy output assuming constant operation at rated conditions. Thus the scenario and the baseline are compared assuming the same annual output, given that duty cycle factors (**Equation 29**) remain constant for both.

**iii. The Conversion of all Naturally Aspirated MCVs and HCVs to Turbocharged Engines**

The methodology for modelling this scenario was identical to that for turbo-intercooled conversion described above. Although turbo-charged data was available for LCVs they were not included so that the results would be comparative to the turbo-intercooled conversion scenario.

**iv. Meeting all South Africa's Goods Transport Needs with Heavy Vehicles of Gross Vehicle Mass greater than 20,000kg**

The objective of this scenario was to simulate the effect of using only large vehicles to meet the country's goods transport needs. In other words, transport the annual commercial road freight of the country in larger loads on larger vehicles with fewer total trips. In this case the total population was reduced to take account of the very much larger power per vehicle of the 20,000+kg Gross Vehicle Mass class. Simply put, 144,017 of these vehicles have approximately the same capacity as the Medium and Heavy Commercial population of the baseline model, shown in **Table 26** above (33.3GW). Annual vehicle operational hours were again reduced so that the estimated annual energy output was the same as the baseline model.

**v. The Reduction of the Regulated Limit for Diesel Fuel Sulphur**

Five scenarios were modelled to estimate the effect on commercial vehicle emissions of reducing the regulated diesel fuel sulphur limit of 0.55% down to 0.3%, 0.2%, 0.1%, 0.05% and 0.005%. Diesel fuel sulphur level has a direct and quantifiable effect on PM and SO<sub>2</sub> emissions. In the case of SO<sub>2</sub>, emissions were assumed to be directly proportional to fuel sulphur by a linear relationship through the origin. Thus the test data for SO<sub>2</sub> was simply adjusted by interpolating linearly for the fuel sulphur level being

evaluated between the fuel sulphur level of the test fuel and zero. That is to say, for zero fuel sulphur the interpolation will return a value of zero SO<sub>2</sub>.

The relationship between fuel sulphur level and PM is discussed in detail in **Section 3.6.1** of **CHAPTER 3** as regards findings in the literature and in **Section 7.1.6** of **CHAPTER 7** as regards findings specific to this study. It was decided to compare three models of the fuel sulphur effect on PM emissions from heavy-duty diesel engines. Light-duty diesel emissions were modelled with **Equation 26** for all scenarios. The heavy-duty models applied were **Equation 25** (COPERT III), **Equation 24** (AVL) and the seven equations derived from the experimental study and presented in **Figure 52**. The comparative results from these three models are presented below in **Figure 49**.

**vi. A Regulation Compliant Vehicle Park (Euro 1 –3)**

This scenario modelled the effect of importing European regulation compliant vehicles. Three tiers of regulation were assessed, the so-called Euro I, II and III limits <sup>(27,40,98)</sup> for both heavy-duty commercials (load specific limits in g/kW.h) and light commercials (distance-specific emissions in g/km). The heavy-duty limits are presented in **APPENDIX D1**. A formula toggle in the model allowed the test data from the baseline model to be simply substituted with the limit values, but only if smaller than the test data. It is of course true that vehicle ageing effects are not taken into account in any comparison of these scenarios with the baseline. It was assumed though that similar ageing effects would influence the population once compliant vehicles have replaced the current population and that a relative comparison (percentage difference) taking no account of ageing is thus approximately valid.

**vii. Conversion of the Vehicle Park to CNG-Fuelled Engines**

This scenario was viewed as of great strategic importance in the light of the rapid growth of the Natural Gas industry in South Africa <sup>(39)</sup> and the growth in gas vehicle conversion in general, although this has been mostly light-duty conversions to LPG. LPG is an oil refining by-product that is mostly pentane and butane. A current surplus and low retail price have made it an attractive fuel for captive fleets. CNG has, however, become the alternative fuel of choice for heavy-duty gas applications globally. The data set used to model this scenario was not rigorous and was generated from data for only one engine reported by MAN for their 11.97 litre natural gas engine <sup>(57)</sup>. This data is presented in **Table 8** in **Section 3.5** which deals with the effects of engine technology on emissions.

This MAN engine has the same displacement and block design as the 4-series ADE engines tested for the VEP emissions data set used to calculate the baseline. The 4-series engines represent larger engine displacements in the VEP data. ADE 3-series engines accounted for the smaller engine displacement sample. The MAN data were also determined using the European R49 test cycle.

CO<sub>2</sub> emissions were estimated using a figure of 35% efficiency loss observed by MAN relative to diesel for CNG engines in operation. Estimated data was generated for 3-series engines, light commercials and altitude conditions for all engine categories by simply adjusting the MAN data in proportion to the average differences between engines and fuels in the original VEP data set. The altitude effect and the engine displacement effect on emissions were therefore modelled as being the same as for the baseline model.

## CHAPTER 6 RESULTS

### 6.1 RESULTS OF THE EXPERIMENTAL PHASE

The results have been presented in tabular form in this section. Graphical representations showing trends and comparisons are displayed in **APPENDIX Q** and referred to where relevant in the text.

For purposes of simplicity, presentation of the results has been split between those for the regulated emissions plus CO<sub>2</sub> and SO<sub>2</sub> and those for the VOCs (aldehydes and hydrocarbons). The former category is the more relevant to emissions legislation and is discussed first. Problems with adapting R49 to the measurement of the VOCs and also their low concentrations in diesel engine emissions have caused these results to be of questionable quantitative validity. This is discussed more fully in **Section 7.1.7**.

#### 6.1.1 RESULTS FOR REGULATED EMISSIONS, CO<sub>2</sub> AND SO<sub>2</sub>

##### 6.1.1.1 COASTAL PROGRAMME RESULTS

**Table 27** and **Table 28** below list the results for the regulated emissions plus CO<sub>2</sub> and SO<sub>2</sub> for the two test fuels. These results are represented graphically in **Figure Q - 1** to **Figure Q - 6** in **APPENDIX Q**.

**Table 27:** Coastal Programme Results of Regulated Emissions, CO<sub>2</sub> and SO<sub>2</sub> with Coastal Diesel A

ENGINE	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
314N	1.44	3.09	11.65	2.66	813	0.80
364N	1.30	3.26	11.62	2.67	764	0.91
364T	0.66	2.33	14.38	2.24	735	0.71
407N	0.85	3.24	19.28	1.98	813	0.47
447N	0.57	2.57	12.62	2.37	769	0.59
447T	0.27	0.58	16.94	1.84	708	0.26

**Table 28:** Coastal Programme Results of Regulated Emissions, CO<sub>2</sub> and SO<sub>2</sub> with Reference Diesel RF-03

ENGINE	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
314N	1.32	2.80	10.73	1.44	832	0.50
364N	1.13	2.85	10.28	1.40	748	0.57
364T	0.67	2.17	13.67	1.18	727	0.48
407N	0.96	2.55	17.98	1.04	785	0.26
447N	0.47	3.03	12.01	1.14	755	0.38
447T	0.30	0.57	14.43	1.13	690	0.14

### 6.1.1.2 HIGHVELD PROGRAMME RESULTS

Table 29, Table 30 and Table 31 below list the results for the regulated emissions plus CO<sub>2</sub> and SO<sub>2</sub> for the three test fuels. These results are represented graphically in Figure Q - 7 to Figure Q - 12 in APPENDIX Q.

**Table 29:** Altitude Programme Results of Regulated Emissions, CO<sub>2</sub> And SO<sub>2</sub> with Highveld Diesel C

ENGINE	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
314N	2.11	4.13	9.51	2.66	844	0.91
364N	1.18	6.52	9.04	2.60	770	1.48
364T	0.51	4.65	12.14	2.44	722	0.83
407N	0.85	12.83	15.23	2.58	834	1.39
447N	0.54	15.54	8.87	2.83	767	3.24
447T	0.19	0.93	13.71	2.13	650	0.26

**Table 30:** Altitude Programme Results of Regulated Emissions, CO<sub>2</sub> and SO<sub>2</sub> with Reference Diesel RF-03

ENGINE	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
314N	1.74	3.80	9.56	1.54	812.	0.58
364N	1.07	5.25	8.76	1.34	739	0.87
364T	0.52	4.31	12.43	1.39	725	0.68
407N	1.01	12.76	15.12	1.39	796	1.07
447N	0.49	14.79	8.66	1.41	772	2.67
447T	0.23	0.83	12.91	1.05	686	0.19

**Table 31:** Altitude Programme Results of Regulated Emissions, CO<sub>2</sub> and SO<sub>2</sub> with Highveld Diesel B

ENGINE	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
314N	1.78	3.84	11.00	0.02	834	0.50
364N	1.15	4.63	8.89	0.07	741	0.82
364T	0.53	4.33	12.68	0.11	743	0.62
407N	0.99	10.44	16.11	0.06	818	0.93
447N	0.56	13.90	9.16	0.09	784	2.53
447T	0.28	0.87	13.67	0.07	668	0.20

### 6.1.2 RESULTS FOR MEASUREMENT OF VOLATILE ORGANIC COMPOUNDS

The VOCs measured were the aldehydes; formaldehyde and acetaldehyde and the hydrocarbons; methane, benzene and 1,3 butadiene. No aldehyde results are reported for the coastal programme, but are presented for the highveld programme.

#### 6.1.2.1 COASTAL PROGRAMME RESULTS

The emissions measured for the organic species, methane (CH<sub>4</sub>), butadiene (C<sub>4</sub>H<sub>6</sub>) and benzene (C<sub>6</sub>H<sub>6</sub>), are listed below in **Table 32**. The quantities of emissions measured were very low and close to the limit of resolution of the gas chromatograph. The quantitative validity of these results is thus questionable and they should be used with caution.

**Table 32:** Coastal Programme Results of Methane, Butadiene and Benzene Emissions

ENGINE	DIESEL A			RF-03-A-84		
	CH <sub>4</sub> g/kW.h	C <sub>4</sub> H <sub>6</sub> g/kW.h	C <sub>6</sub> H <sub>6</sub> g/kW.h	CH <sub>4</sub> g/kW.h	C <sub>4</sub> H <sub>6</sub> g/kW.h	C <sub>6</sub> H <sub>6</sub> g/kW.h
314N	0.13	0.02	0.02	0.17	0.02	0.02
364N	0.25	0.009	0.007	0.26	0.009	0.003
364T	0.11	0.008	0.007	0.11	0.01	0.008
407N	0.21	0.004	0.01	0.18	0.009	0.006
447N	0.20	0.007	0.01	0.19	0.007	0.01
447T	0.15	0	0.003	0.17	0.002	0.004

These values are expressed as a fraction of total hydrocarbons in **APPENDIX O1**.

### 6.1.2.2 HIGHVELD PROGRAMME RESULTS

The emissions measured for the VOCs, formaldehyde ( $\text{CH}_2\text{O}$ ), acetaldehyde ( $\text{C}_2\text{H}_4\text{O}$ ), methane ( $\text{CH}_4$ ), butadiene ( $\text{C}_4\text{H}_6$ ) and benzene ( $\text{C}_6\text{H}_6$ ) are listed below in **Table 33**, **Table 34** and **Table 35** for the three test fuels. The measurements of hydrocarbon species were again close to the limit of resolution of the chromatograph. Resolution of the aldehyde measurements was, however, relatively good, the laboratory reporting the sample aldehyde content to the nearest  $0.1\mu\text{g}$ . The quantitative validity of the aldehyde results is thus far greater than for the hydrocarbon species results, although as discussed in **Section 7.1.7** the stability of the formaldehyde derivative is a significant source of error.

**Table 33:** Altitude Programme Results of Organic Species Emissions with Diesel C

ENGINE	$\text{CH}_2\text{O}$ g/kW.h	$\text{C}_2\text{H}_4\text{O}$ g/kW.h	$\text{CH}_4$ g/kW.h	$\text{C}_4\text{H}_6$ g/kW.h	$\text{C}_6\text{H}_6$ g/kW.h
314N	0.033	0.020	0.20	0	0
364N	0.021	0.019	0.16	0.02	0
364T	0.012	0.006	0.07	0.01	0
407N	0.018	0.016	0.11	0	0
447N	0.027	0.012	0.07	0	0
447T	0.002	0.001	0.02	0	0

**Table 34:** Altitude Programme Results of Organic Species Emissions with Diesel B

ENGINE	$\text{CH}_2\text{O}$ g/kW.h	$\text{C}_2\text{H}_4\text{O}$ g/kW.h	$\text{CH}_4$ g/kW.h	$\text{C}_4\text{H}_6$ g/kW.h	$\text{C}_6\text{H}_6$ g/kW.h
314N	0.022	0.012	0.27	0	0
364N	0.020	0.010	0.07	0	0
364T	0.004	0.002	0.10	0	0.06
407N	0.011	0.007	0.11	0.005	0
447N	0.015	0.012	0.05	0	0
447T	0.004	0.004	0.01	0.003	0

**Table 35:** Altitude Programme Results of Organic Species Emissions with Reference Diesel RF-03

ENGINE	CH <sub>2</sub> O g/kW.h	C <sub>2</sub> H <sub>4</sub> O g/kW.h	CH <sub>4</sub> g/kW.h	C <sub>4</sub> H <sub>6</sub> g/kW.h	C <sub>6</sub> H <sub>6</sub> g/kW.h
314N	0.022	0.019	0.82	0.1	0
364N	0.028	0.019	0.10	0	0
364T	0.022	0.011	0.06	0	0
407N	0.022	0.015	0.07	0	0
447N	0.039	0.016	0.04	0	0
447T	0.003	0.001	0.03	0	0

These values are expressed as a percentage of total hydrocarbons in **APPENDIX O1**.

### 6.1.3 RESULTS SUPPLEMENTARY TO THE VEHICLE EMISSIONS PROJECT

The test equipment used for the diesel phase of the VEP was used both before and after its completion to undertake other studies. The results of these studies provided valuable supplementary information required to compile an emissions inventory representative of the vehicle population. The scope of the VEP omitted tests on Coastal Synthetic fuel and turbo-intercooled engines, both of which were included in these supplementary studies.

The emissions performance of South African coastal synthetic diesel was compared to coastal crude diesel in tests on an ADE 364N only. These results provide some indication though of likely emissions of the whole engine set, given operation with coastal synthetic diesel. The published data <sup>(26)</sup> are presented below in **Table 36**. These were the first tests attempted prior to the bulk of the study, and some discrepancies with the VEP data are evident for HC<sub>n</sub> and NO<sub>x</sub> emissions. These are discussed below in **CHAPTER 7**.

**Table 36:** ADE 364N Emissions for Operation on Coastal Synthetic, Coastal Crude and Reference Diesel at Sea-level Conditions <sup>(26)</sup>

FUEL	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	PM g/kW.h
Crude	0.41	3.53	7.67	0.937
Synthetic	0.39	2.63	6.25	0.471
RF-03	0.37	2.67	6.97	0.571

After the completion of the VEP, BP Southern Africa commissioned the University of Stellenbosch <sup>(94)</sup> to perform emissions tests on a variety of fuels. The test engine used was a turbo-intercooled ADE 447TI, fortuitously the ideal engine to complete the VEP data set. A total of six fuels were tested the specifications of which are presented in **APPENDIX I**. The results from the confidential report are presented below in **Table 37** by permission of BP Southern Africa and the University of Stellenbosch:

**Table 37:** ADE 447TI Emissions for Operation on Six Test Fuels at Sea Level Conditions <sup>(94)</sup>

FUEL #	HC <sub>n</sub> g/kW.h	CO g/kW.h	NO <sub>x</sub> g/kW.h	SO <sub>2</sub> g/kW.h	CO <sub>2</sub> g/kW.h	PM g/kW.h
1	0.41	0.91	11.05	2.28	634.66	0.27
2	0.42	0.89	11.35	2.27	646.00	0.30
3	0.32	0.87	10.65	1.68	631.41	0.23
4	0.32	0.92	10.90	2.24	633.58	0.28
5	0.47	0.93	10.79	0.98	627.65	0.18
6	0.30	0.82	10.44	0.06	624.75	0.13

\* CO<sub>2</sub> emissions derived from fuel consumption carbon less CO, HC<sub>n</sub> & PM carbon

## 6.2 RESULTS OF THE INVENTORY MODELLING PHASE

The inventory modelling phase entailed first determining a baseline for national diesel vehicle emissions and then altering the model inputs to predict emissions given a number of scenarios for emissions mitigation. The baseline and scenario modelling results are presented separately below, mostly in graphical form. The complete tabulated data is presented in **Table R – 1** to **Table R – 8** in **APPENDIX R**.

### 6.2.1 BASELINE RESULTS

Initially a baseline was calculated to estimate Emission Factors and Total Annual Emissions for 1998. These figures are presented below in **Table 38** and **Table 39**.

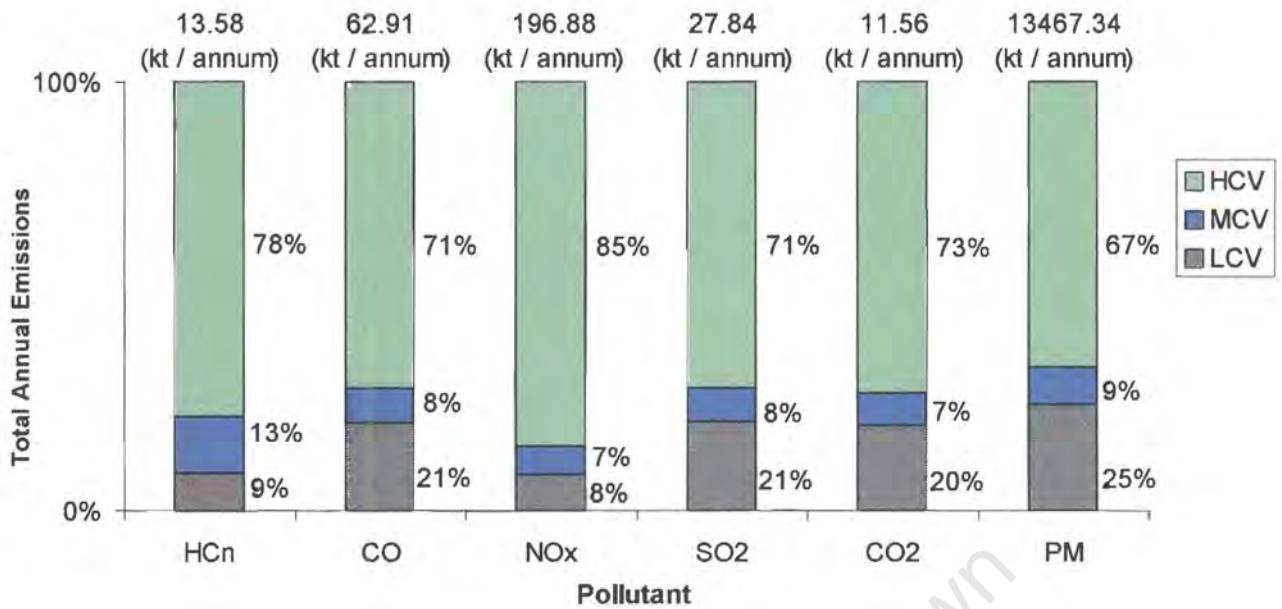
**Table 38:** Estimated Emission Factors for Diesel Commercial Vehicles (1998)

Vehicle Type	Emission Factors (g/km)					
	HC <sub>n</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	CO <sub>2</sub>	PM
LCV	0.10	1.14	1.47	0.51	237	0.25
MCV	0.86	2.41	6.18	1.02	470	0.47
HCV	1.05	3.82	13.0	1.66	809	0.68
M&HCV	1.01	3.54	11.7	1.54	741	0.64
All CV's	0.48	2.14	5.70	0.94	447	0.41

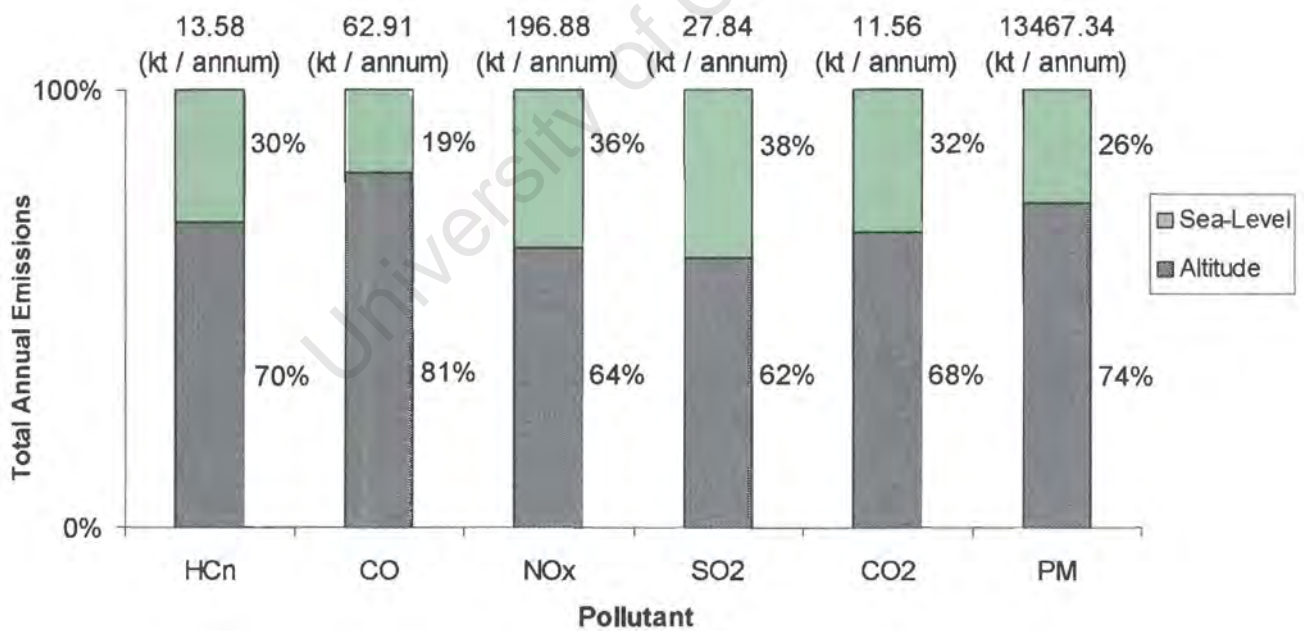
**Table 39:** Estimated Total Annual Emissions for Diesel Commercial Vehicles (1998)

Vehicle Type	Total Annual Emissions (kt/annum)					
	HC <sub>n</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	CO <sub>2</sub>	PM
LCV	1.17	12.92	16.61	5.81	2691	2.84
MCV	1.82	5.13	13.13	2.17	999	1.00
HCV	10.59	44.86	167.14	19.87	9778	7.71
M&HCV	12.41	49.99	180.26	22.03	10777	8.72
All CV's	13.58	62.91	196.88	27.84	13467	11.56

**Figure 43** and **Figure 44** below show the breakdown of emissions according to vehicle type and altitude respectively.



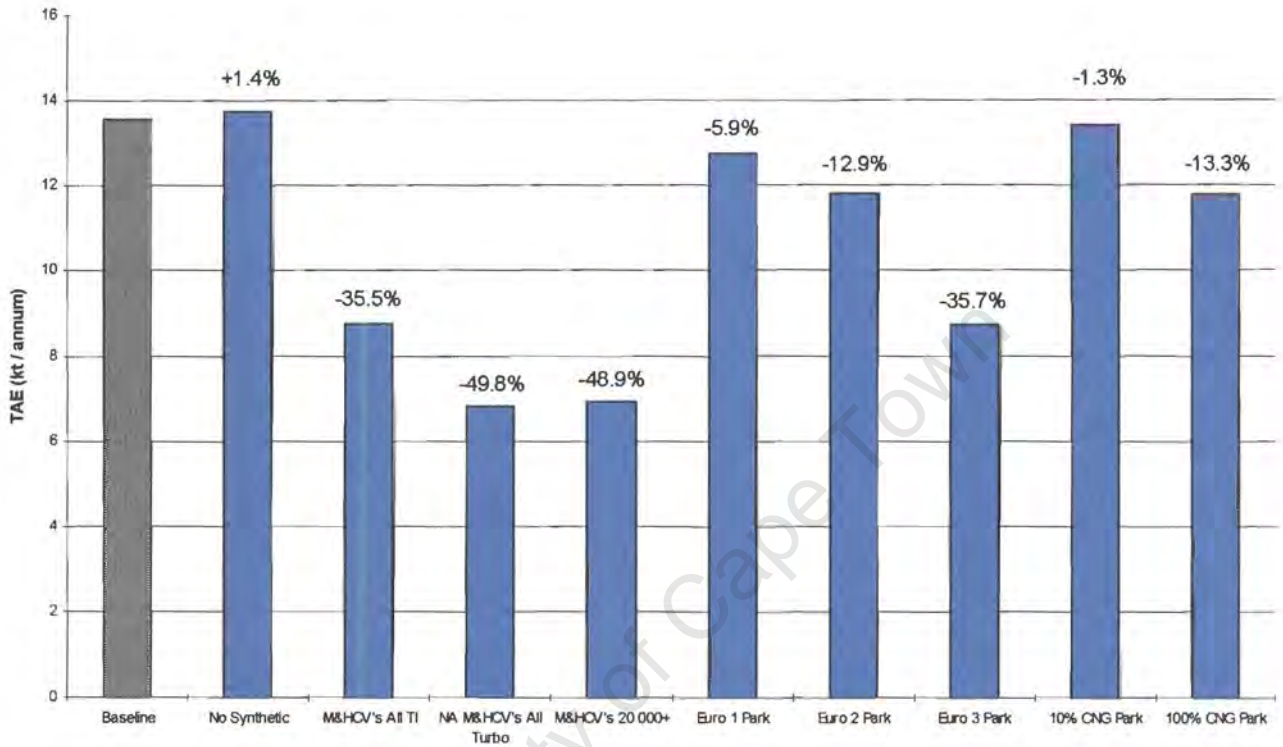
**Figure 43:** 1998 Diesel Commercial Vehicle Park Baseline Emissions from Model: Vehicle Class Breakdown



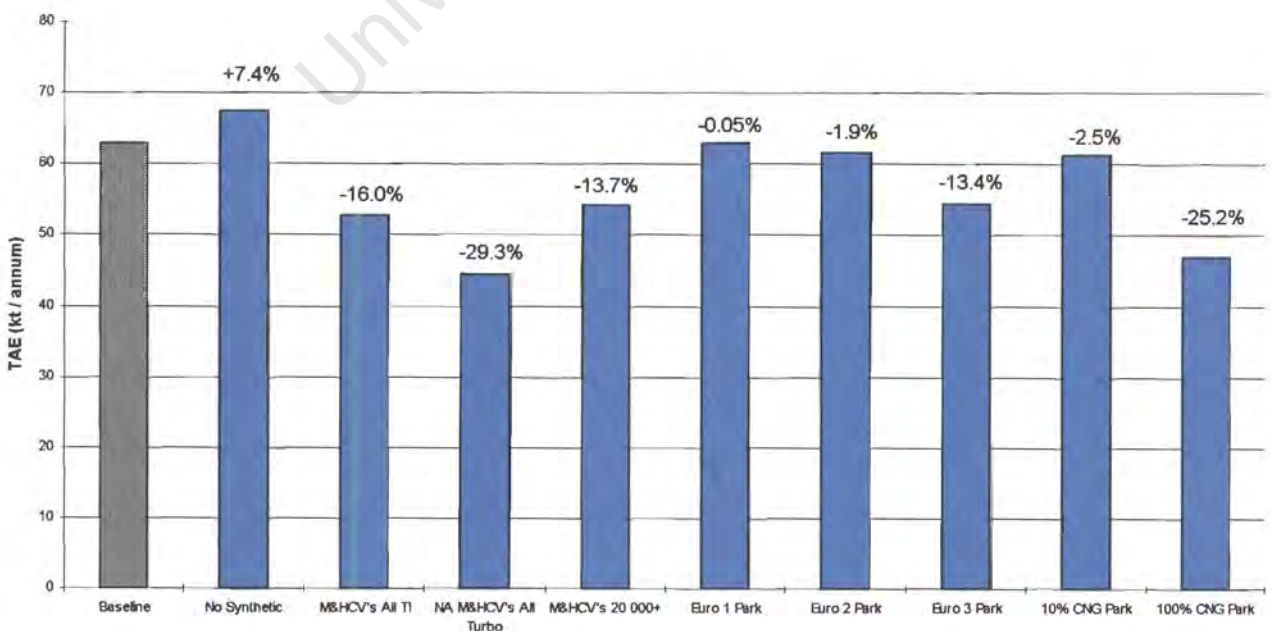
**Figure 44:** 1998 Diesel Commercial Vehicle Park Baseline Emissions from Model: Altitude Breakdown

## 6.2.2 SCENARIO MODELLING RESULTS

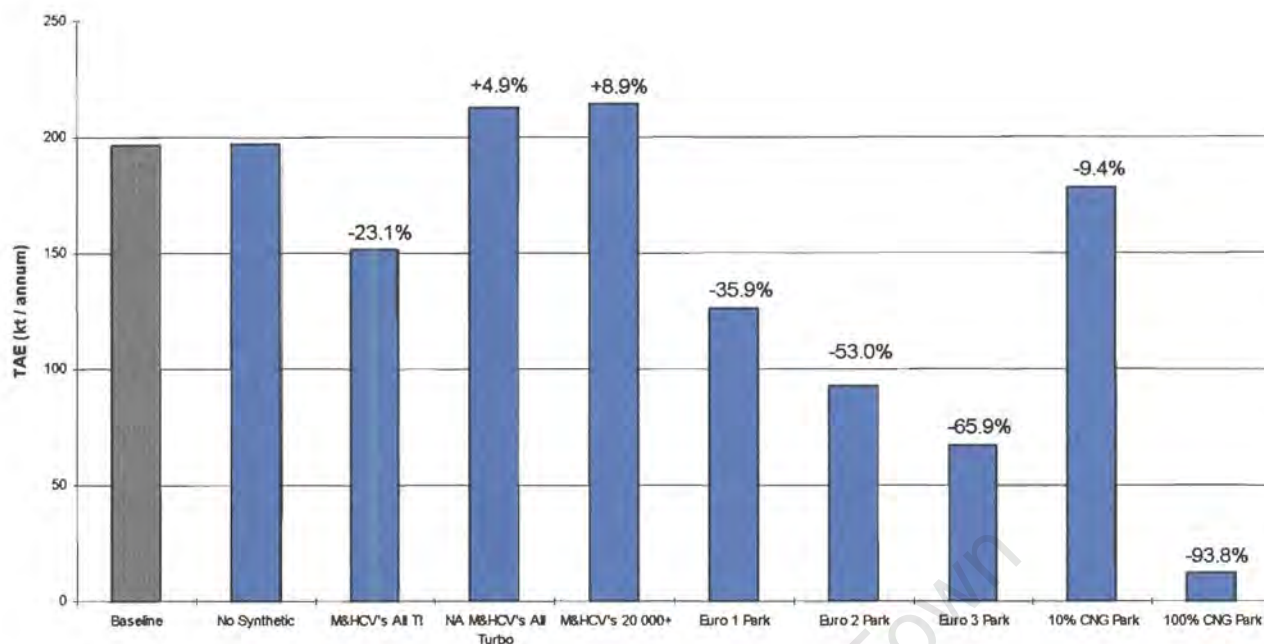
The results of the scenario modelling exercise are presented graphically below in **Figure 45** to **Figure 51**. Each pollutant HC<sub>n</sub>, CO, NO<sub>x</sub>, PM, SO<sub>2</sub> and CO<sub>2</sub> is plotted respectively against the baseline result.



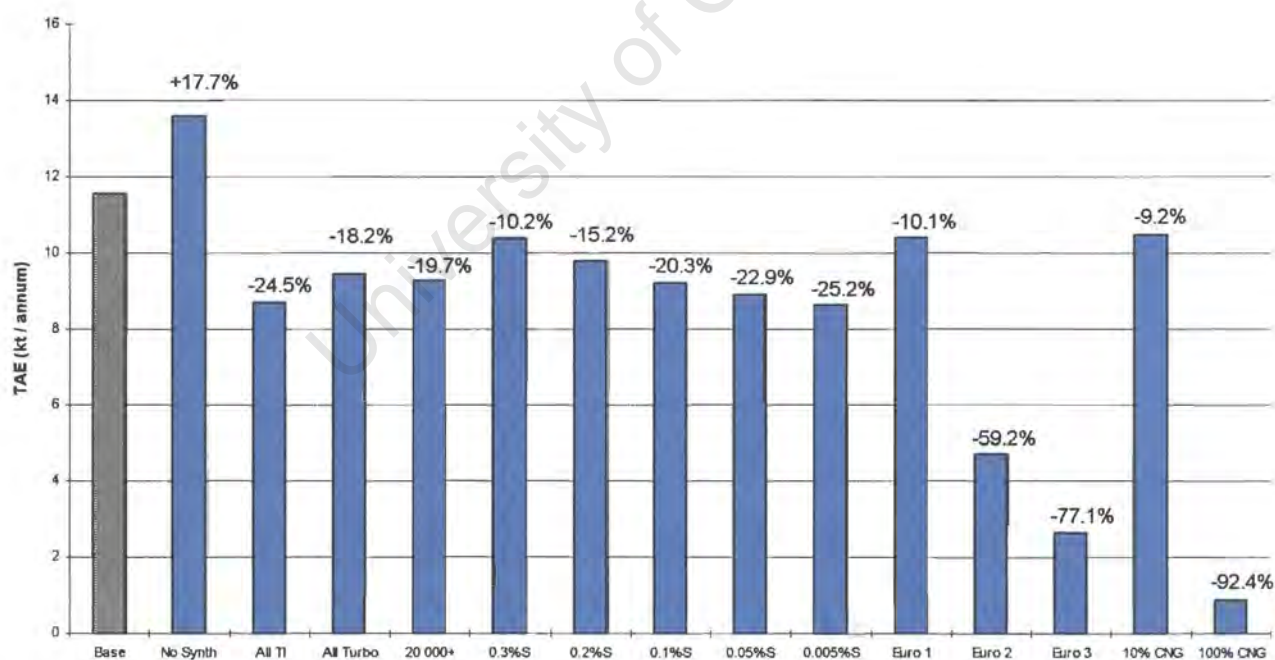
**Figure 45:** 1998 Diesel Commercial Vehicle Park Hydrocarbon (HC<sub>n</sub>) Emissions: Scenarios



**Figure 46:** 1998 Diesel Commercial Vehicle Population Carbon Monoxide (CO) Emissions: Scenarios

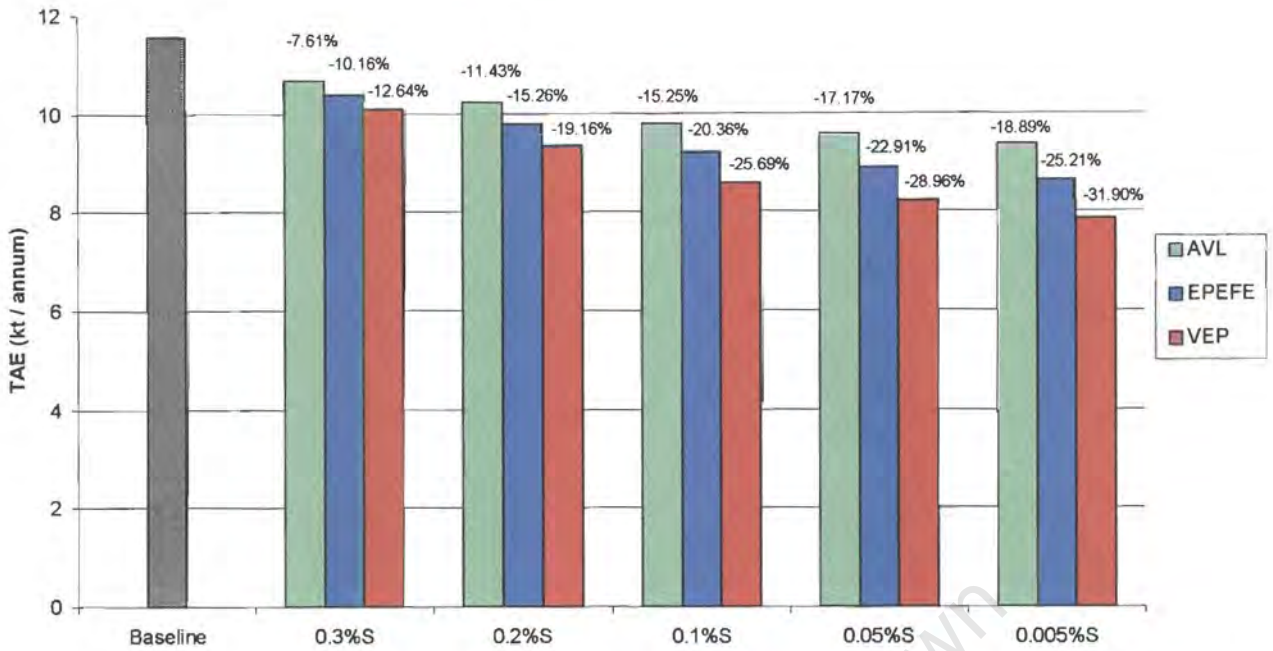


**Figure 47:** 1998 Diesel Commercial Vehicle Population Oxides of Nitrogen (NO<sub>x</sub>) Emissions: Scenarios

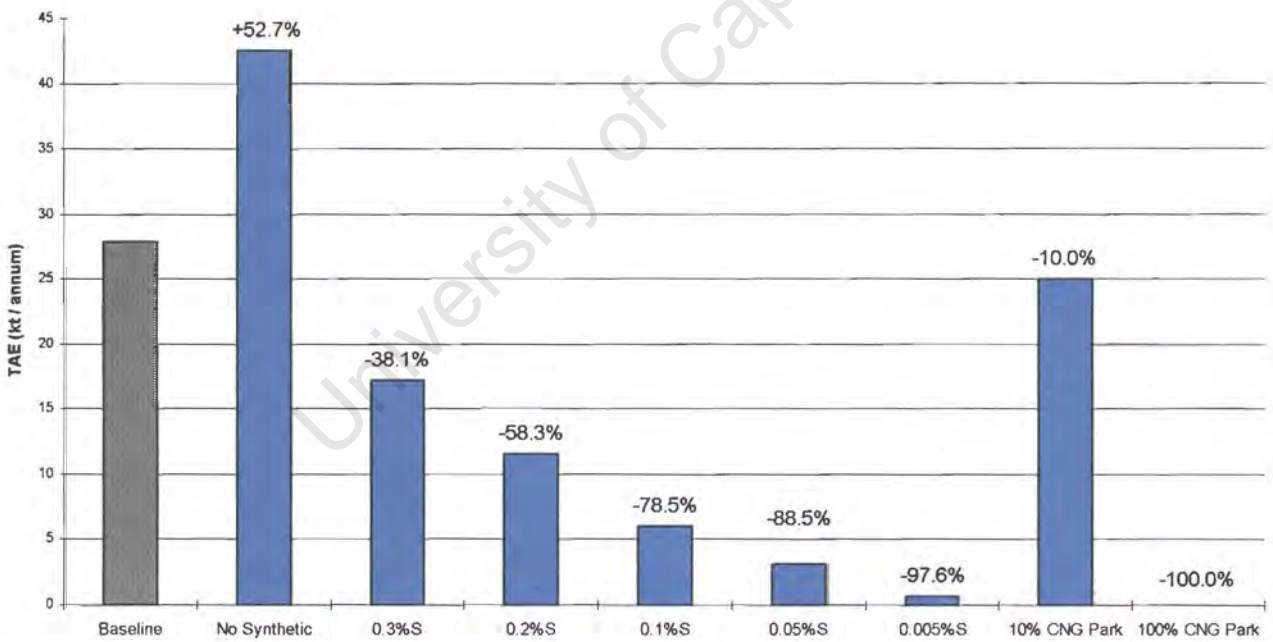


**Figure 48:** 1998 Diesel Commercial Vehicle Population Particulate Matter (PM) Emissions: Scenarios

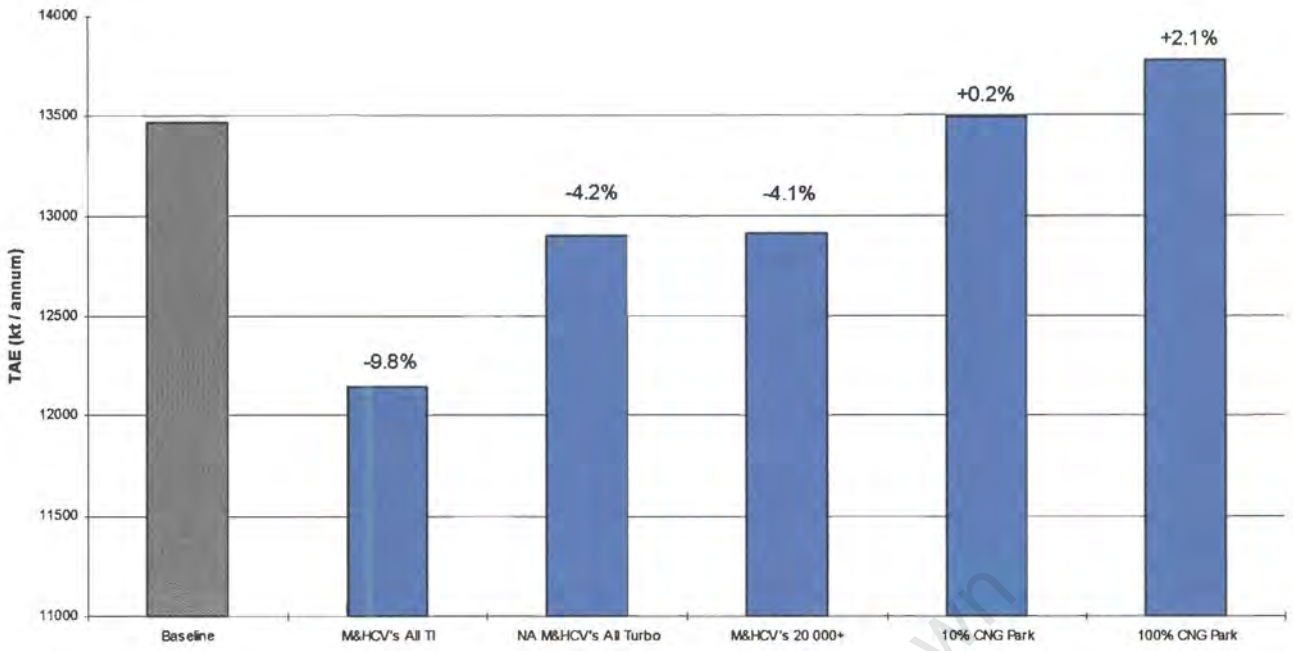
Three models for the effect of fuel sulphur content on PM emissions are compared below in **Figure 49**. Only the results from the model using the EPEFE equations discussed in **Section 3.6.1** are included above in **Figure 48**.



**Figure 49:** Total Annual PM Emissions from SA Diesel Commercial Vehicles: Comparison of Sulphur Models



**Figure 50:** 1998 Diesel Commercial Vehicle Population Sulphur Dioxide (SO<sub>2</sub>) Emissions: Scenarios



**Figure 51:** 1998 Diesel Commercial Vehicle Population Carbon Dioxide (CO<sub>2</sub>) Emissions: Scenarios

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## CHAPTER 7 DISCUSSION

### 7.1 DISCUSSION OF THE EXPERIMENTAL RESULTS

In this section some analysis of the results presented in **Section 6.1** is attempted. A generalised investigation is performed on various factors influencing diesel engine emissions performance, for instance fuel type, engine model and environmental conditions like altitude. Discussion is focussed on the VEP results, with additional reference to the supplementary results where appropriate.

#### 7.1.1 COMPARISON OF RESULTS WITH EUROPEAN REGULATIONS

It is useful to compare the test results with European regulated limits for the ECE R49 test to determine the emissions performance of the engine sample tested relative to manufacturing standards in Europe. Various limits of increasing severity have been promulgated in recent years, therefore given that the engines tested are of imported European technology, it is important that the limits selected correspond to the relevant model year of the test engines as a form of validating the test results. Furthermore as indicated by the vehicle database presented in **APPENDIX M**, engines manufactured by ADE still powered more than two thirds of the country's heavy vehicles in 1998 and presumably must account for at least half at the time of writing. The emissions performance of these engines relative to established norms is therefore still essential to understanding the impact of heavy vehicles on air-quality in South Africa.

According to the manufacturers, the technology level used in this study was subject to legislation preceding that on which the experimental methodology was based, the so-called ECE R24 limits. Current European legislation is three tiers beyond this as discussed in **APPENDIX D1**. ECE R24 and two subsequent tiers of limits are presented below in **Table 40**. Note the absence of particulate limits. At this time smoke was measured by means of an opacity meter and the limit is thus not relevant. The two Regulation 49 based sets of limits are more recent and serve to show how South African technology during the experimental phase of this study compared to more modern standards.

**Table 40:** European Emissions Limits Relevant to the Engine Test Sample and Two Subsequent Tiers

<b>CONFORMITY OF PRODUCTION LIMITS FOR ECE R24</b>					
<b>Effective Date</b>	<b>Engine Power</b>	<b>HC<sub>n</sub></b>	<b>CO</b>	<b>NO<sub>x</sub></b>	<b>PM</b>
		<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>
1.10.90	> 85 kW	2.64	13.2	15.8	-
(all production)	≤ 85 kW	2.64	13.2	15.8	-
<b>CONFORMITY OF PRODUCTION LIMITS FOR ECE R49</b>					
<b>Effective Date</b>	<b>Engine Power</b>	<b>HC<sub>n</sub></b>	<b>CO</b>	<b>NO<sub>x</sub></b>	<b>PM</b>
		<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>
1.10.93	> 85 kW	1.23	4.9	9.0	0.4
(all production)	≤ 85 kW	1.23	4.9	9.0	0.68
<b>CONFORMITY OF PRODUCTION LIMITS FOR ECE R49</b>					
<b>Effective Date</b>	<b>Engine Power</b>	<b>HC<sub>n</sub></b>	<b>CO</b>	<b>NO<sub>x</sub></b>	<b>PM</b>
		<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>	<b>g/kW.h</b>
1.10.96	> 85 kW	1.1	4.0	7.0	0.15
(all production)	≤ 85 kW	1.1	4.0	7.0	0.26

The specific test engines were randomly selected so the Conformity of Production limits or the limits applicable to any engine off the production line are applicable. These limits are for tests at sea level using the same RF-03-A-84 reference fuel used for this project, so a direct comparison with the reference fuel results at sea-level is valid. Comparison of **Table 28** in **Section 6.1.1.1** with the ECE R24 limits shows that all the engines are well within the regulated limits applicable to their technology level except for the 407N and 447T, which exceeded the NO<sub>x</sub> limit by 22%, and 7% respectively.

Comparison with 1993 regulations shows that all the engines are within the limits for CO and particulates and that the 314N and 364N exceed the unburned hydrocarbon limit. The NO<sub>x</sub> emissions of all the engines however fall outside the limits by between 14 and 100%.

Comparison with the 1996 regulations is less favourable. All the engines fall outside the NO<sub>x</sub> limit. Similarly, all except the 447T fall outside the particulate limit. All the engines conformed to the CO limits and all but two, the 314N and 364N, conformed to the unburned hydrocarbon limits.

### 7.1.2 MORE RECENT TECHNOLOGY VERSUS OLD TECHNOLOGY

There are two examples where comparisons can be made between old and more recent manufacturing technology; the 314N versus the more recent 364N and the 407N versus the more recent 447N. In general the trends were similar. **Table 41** and **Table 42** below compare the regulated and CO<sub>2</sub> emissions for the Coastal and Highveld Programmes respectively.

**Table 41:** Comparison of Old and New ADE Technology Tested: Coastal Programme

	314N Avg.	364N Avg.	% Diff.	407N Avg.	447N Avg.	% Diff.
HC <sub>n</sub>	1.38	1.21	-12	0.90	0.52	-42
CO	2.95	3.05	3	2.89	2.80	-3
NO <sub>x</sub>	11.19	10.95	-2	18.63	12.31	-34
PM	0.65	0.74	14	0.36	0.48	33
CO <sub>2</sub>	822	756	-8	799	762	-5

314N & 407N: Old Technology Engines

364N & 447N: More Recent Technology Engines

**Table 42:** Comparison of Old and New ADE Technology Tested: Altitude Programme

	314N Avg.	364N Avg.	% Diff.	407N Avg.	447N Avg.	% Diff.
HC <sub>n</sub>	1.88	1.13	-40	0.95	0.53	-44
CO	3.92	5.46	+39	12.01	14.75	+23
NO <sub>x</sub>	10.03	8.90	-11	15.49	8.90	-43
PM	0.67	1.06	+58	1.13	2.81	+149
CO <sub>2</sub>	829.96	749.75	-10	815.87	774.37	-5

% Diff = (More recent - Old) / Old \* 100

To summarise the above, it is evident that the more recent technology engines emit lower HC<sub>n</sub> and NO<sub>x</sub> as well as CO<sub>2</sub>, indicating improved fuel economy. In contrast they emit significantly higher PM emissions and higher CO at high altitude. Both the CO and PM emissions from the new technology engines at sea level are still within (or close to) the 1993 regulation limits shown in **Table 40** above.

It is not necessarily contradictory that HC<sub>n</sub> emissions are lower for the more recent technology engines despite the higher CO emissions, as this may be the result of

reduced cylinder crevice volumes and improved bowl-in piston technology that promotes mixing and reduces wetting of the cylinder walls and piston surface. This could well reduce the amount of unburned fuel, despite an overall increase in zones of rich but still relatively complete combustion. Unusually PM emissions are higher in spite of higher thermal efficiency, as indicated by the lower CO<sub>2</sub> emissions. There may be less oxidation of PM formed at the beginning of combustion, in the late burning phase with the new technology engines due to a longer period of injection.

### 7.1.3 EFFECT OF TURBOCHARGING

Table 43 and Table 44 below compare the averaged emissions of the turbocharged (turbo) engines (364T & 447T) to their Naturally Aspirated (NA) versions (364N & 447N) for the Coastal and Altitude Programmes respectively:

Table 43: Comparison of Turbo & NA Engines For Coastal Programme

	364N Avg.	364T Avg.	% Diff.	447N Avg.	447T Avg.	% Diff.
HC <sub>n</sub>	1.21	0.66	-45	0.52	0.29	-44
CO	3.05	2.25	-26	2.80	0.58	-79
NO <sub>x</sub>	10.95	14.02	28	12.31	15.69	27
Parts	0.74	0.59	-20	0.48	0.20	-58
CO <sub>2</sub>	756	731	-3	762	699	-8

$$\% \text{ Diff} = (\text{turbo} - \text{NA}) / \text{NA} * 100$$

Table 44: Comparison of Turbo & NA Engines For Altitude Programme

	364N Avg.	364T Avg.	% Diff.	447N Avg.	447T Avg.	% Diff.
HC <sub>n</sub>	1.13	0.52	-54	0.53	0.24	-55
CO	5.46	4.43	-19	14.75	0.88	-94
NO <sub>x</sub>	8.90	12.41	39	8.90	13.43	51
Parts	1.06	0.71	-33	1.13	0.22	-81
CO <sub>2</sub>	750	730	-3	816	668	-18

$$\% \text{ Diff} = (\text{turbo} - \text{NA}) / \text{NA} * 100$$

These results are as expected. Energy is recovered from the exhaust by a turbine that drives a compressor that in turn boosts the intake air charge of the turbocharged engine. This increases the density of air drawn into the cylinder considerably, thus increasing volumetric efficiency and promoting mixing of the fuel droplets with air during diffuse

combustion. Typically HC<sub>n</sub>, CO and PM emissions are reduced as a result. The increased volumetric efficiency improves fuel economy, reflected in reduced CO<sub>2</sub> emissions.

The penalty of turbocharging though is that the temperature of the boosted intake charge air increases according to the gas law. Typical intake air temperatures are of the order of 200°C instead of the near ambient temperature air charging a naturally aspirated engine. This increased temperature at the start of combustion, combined with the effect of higher thermal efficiency and increased power density of the engine, result in higher peak flame temperatures on which NO<sub>x</sub> emissions are strongly dependent, the higher temperature causing more dissociation of nitrogen into NO<sub>x</sub>.

The problem can be resolved by cooling the air between the turbocharger compressor and the engine. This is termed intercooling or sometimes aftercooling and is discussed in detail in **Section 3.5**. **Table 45** below compares emissions data from the VEP and supplementary programme for a naturally aspirated, a turbocharged and a turbo-intercooled engine from the ADE 447 range of engines.

**Table 45:** Effect of Turbo-intercooling on PM and NO<sub>x</sub> emissions

ENGINE	ASPIRATION	Fuel	Fuel Sulphur (%)	PM (g/kW.h)	NO <sub>x</sub> (g/kW.h)
ADE 447N	Natural	SA Crude	0.45	0.59	12.62
ADE 447T	Turbo	SA Crude	0.45	0.26	16.94
ADE 447TI	Turbo-Intercooled	SA Crude	0.51	0.27	11.05

**Table 45** shows that turbo-intercooling can reduce NO<sub>x</sub> emissions to below those of a naturally aspirated engine. In this case particulates were the same within the limits of uncertainty but turbo-intercooling usually reduces particulates as well due to the increased density of the combustion air. The absence of this effect in **Table 45** is probably accounted for by the fact that although the fuels used were from the same refinery the turbo-intercooled engine was operated on fuel with a sulphur content of 0.51% while the VEP test fuel had a fuel sulphur content of 0.45%. Increased fuel sulphur causes increased particulate emissions. Turbo-intercooling therefore offers reductions in particulate emissions without the penalty of higher NO<sub>x</sub> emissions and the sensitivity to

altitude of naturally aspirated engines. Combined with this is improved fuel economy that benefits the consumer.

#### 7.1.4 EFFECT OF ALTITUDE

The effect of the transition to high altitude conditions on emissions can be examined by comparing the results for the Coastal and Highveld programmes of the VEP for the Reference Fuel. This comparison is presented graphically in **Figure Q - 13** to **Figure Q - 18** in **APPENDIX Q**. **Table 46** below shows the effect of the altitude transition as a percentage change of the emission.

**Table 46:** Effect of Altitude Increase on Emissions: A Comparison Based on Reference Fuel Results

ENGINE	HC <sub>n</sub>	CO	NO <sub>x</sub>	PM	CO <sub>2</sub>	SO <sub>2</sub>
	% Diff.	% Diff.	% Diff.	% Diff.	% Diff.	% Diff.
314N	32	36	-11	16	-2	7
364N	-5	84	-15	51	-1	-4
364T	-22	99	-9	43	0	17
407N	6	401	-16	310	1	34
447N	5	388	-28	603	2	24
447T	-24	45	-11	35	-1	-7
<b>AVERAGE</b>	-1	176	-15	177	0	12

$\% \text{ Diff} = (\text{Highveld} - \text{Coast}) / \text{Coast} * 100$

The data in **Table 46** shows good agreement with data reported by the South West Research Institute (SWRI) presented in **Table 7**. HC<sub>n</sub> emissions did not, however, show any altitude sensitivity in the VEP compared to a 334% increase for naturally aspirated engines and a 20% increase for turbocharged engines reported by the SWRI. There is excellent agreement for the other pollutants, except for the very large 603% increase in PM emissions for the 447N.

The most notable effect was for CO and particulate emissions where there was a severe increase at the higher altitude, particularly for the naturally aspirated (NA) 4-series engines. This is a direct result of the overall increase in the ratio of fuel to air in the engine due to the roughly 15% drop in ambient air density that occurred with the transition from sea-level to the altitude of 1488 metres at the altitude programme test site.

The diesel engine is a constant-volume machine; in other words at a constant speed it will always draw in an identical volume of air during every combustion cycle. Thus, in the case of naturally aspirated engines it will draw in a lower mass of air per combustion cycle at the higher altitude, the drop being directly proportional to the change in ambient air density. At the extremes of altitude that characterised the programme this resulted in emissions consistent with incomplete combustion from over-fuelling. CO and particulates form in the fuel rich zones of the diesel flame, CO emissions in particular being very strongly dependent on the ratio of fuel to air in a hydrocarbon flame, and are thus most severely affected by the altitude transition.

Turbocharging does in general lessen these effects by boosting the inlet air pressure as is evident in the comparison of the 447N and 447T. The boost of the turbocharger is, however, dependent on engine speed and in the case of the 364T that fared less well, the boost at intermediate speed is only of the order of 0.3bar. The R49 procedure is heavily biased toward intermediate speed and idle (combined weighting of 82%) and thus turbocharged engines without wastegating or variable geometry are not particularly favoured (discussed in **Section 1.1** and **Section 3.5**). The 447T has the added feature of a compensated fuel pump governor that reduces the fuel pump delivery proportionally to the inlet air pressure, which accounts for the less severe impact of altitude.

Also consistent with the lower air density at high altitude was the consistent drop in NO<sub>x</sub> emissions. This is due to lower peak cylinder pressure corresponding to lower peak flame temperature on which NO<sub>x</sub> is strongly dependent. This is the converse effect of that of turbocharging described above in **Section 7.1.3**. A slightly lean (more air available for combustion) flame also favours high flame temperature and thus high NO<sub>x</sub> emissions. Therefore the overall enrichment (less air available for combustion) of the combustion process can reduce NO<sub>x</sub> emissions as well.

The changes in HC<sub>n</sub> and SO<sub>2</sub> emissions are more erratic and in the case of HC<sub>n</sub> average out to negligible change, the test-to-test variations being probably more a result of individual engine characteristics than any effect of altitude. There is possibly a trend indicated of increased SO<sub>2</sub> formation with the engines where CO increases and hence overfuelling was greatest.

Scrutiny of **Figure Q - 14** (altitude effect on CO) and **Figure Q - 16** (altitude effect on particulates) highlight an apparent anomaly between the 407N and 447N. The transition to high altitude was accompanied by very similar increases in CO indicating a similar level of overfuelling that should correspond to similar increases in particulate emissions. Particulate emissions for the 407N increased by only half the percentage increase of the 447N, though. The answer to this lies in the NO<sub>x</sub> emissions, which are 75% higher for the 407N indicating significantly higher peak flame temperatures. Higher peak flame temperatures result in greater oxidation of the particulate matter formed at the beginning of combustion due to pyrolysis of the injected fuel, thus reducing the mass of particulate matter emitted. The cause of the higher flame temperature whether the result of design or engine malfunction was not investigated.

### 7.1.5 SMALL BORE VERSUS LARGE BORE COMPARISON

The choice of test engines that include an old technology, a more recent technology and a turbocharged engine in both the 3-series (1 litre per cylinder) and 4-series (2 litre per cylinder) ranges allows for a direct comparison based on cylinder capacity that includes all the engines. **Table 47** and **Table 48** below illustrate this comparison for the coastal and highveld programmes respectively. Averages are taken using all the test fuels.

**Table 47:** Comparison of Emissions between one and two litre per cylinder ADE Engines: Coastal Programme

ENGINE	3-Series Avg. g/kW.h	4-Series Avg. g/kW.h	% Diff. of 4-Series %
HC <sub>n</sub>	1.08	0.57	-47
CO	2.75	2.09	-24
NO <sub>x</sub>	12.06	15.54	+29
PM	0.66	0.35	-47
CO <sub>2</sub>	770	754	-2
SO <sub>2</sub>	1.93	1.58	-18

*% Difference of 4-series = (4-series - 3-series) / 3-series \* 100*

**Table 48:** Comparison of Emissions between one and two litre per cylinder ADE Engines:  
Altitude Programme

ENGINE	3-Series Avg. g/kW.h	4-Series Avg. g/kW.h	% Diff. of 4-Series %
HC <sub>n</sub>	1.18	0.57	-52
CO	4.61	9.21	+100
NO <sub>x</sub>	10.45	12.60	+21
PM	0.81	1.39	+72
CO <sub>2</sub>	770	753	-2
SO <sub>2</sub>	1.35	1.29	-4

*% Diff. Of 4-series = (4-series - 3-series) / 3series \* 100*

Some trends are evident from the above. Unburned hydrocarbons are consistently lower for the 4-series engines. There are a number of possible reasons for this:

- The rated engine speed is lower for the 4-series engines (2100 rpm vs. 2800 rpm). This allows more absolute time for the fuel to mix to within combustible limits before the end of the combustion process.
- There is a lower ratio of crevice volume to cylinder volume in the larger engines, a phenomenon that simply results from the circular geometry of the cylinder. Crevice volume is not however as critical in HC<sub>n</sub> formation in diesel engines as it is in spark ignition engines because most of the fuel is concentrated in the middle of the cylinder around the injector.

NO<sub>x</sub> is also consistently higher for the 4-series engines although this result is biased by the very high NO<sub>x</sub> emissions of the 407N.

At coast the 4-series engines emitted lower CO and particulates consistent with the higher NO<sub>x</sub> levels that indicate more pre-mixed combustion and less fuel rich diffusion combustion. However, the results for the highveld tests show a reversal of this trend with the 4-series engines emitting much higher CO and particulates mostly as a result of the massive increases on these emissions for the 407N and 447N with the transition to altitude. This possibly indicates that pump timing and delivery settings for the 4-series engine sample that were specific to coastal conditions.

Similarly SO<sub>2</sub> emissions are lower for the 4-series at coast but again this improvement seems to be negated by severe over-fuelling at highveld conditions in the case of the 447N and 407N. There is little difference in CO<sub>2</sub> emissions with marginally improved fuel economy indicated for the 4-series engines.

### 7.1.6 FUEL EFFECTS ON EMISSIONS

The general impact of local pump fuels on heavy-duty diesel emissions was evaluated in the VEP by the comparison of pump fuel results to those measured from operation with the reference diesel. The fuel specifications of the VEP test fuels as well as those used in the BP Southern Africa supplementary study are presented in **APPENDIX I. Table 49** below compares Coastal Pump Diesel A from the VEP, a fuel fairly representative of crude-based diesel sold at coast, with the reference diesel.

**Table 49:** Comparison of Diesel A Emissions with Reference Diesel Emissions (Coastal Programme)

ENGINE	HC <sub>n</sub> % Diff.	CO % Diff.	NO <sub>x</sub> % Diff.	PM % Diff.	CO <sub>2</sub> % Diff.	SO <sub>2</sub> % Diff.
314N	+9	+11	+9	+59	-2	+85
364N	+15	+15	+13	+58	+2	+91
364T	-1	+8	+5	+48	+1	+89
407N	-11	+27	+7	+80	+4	+91
447N	+21	-15	+5	+57	+2	+108
447T	-10	+2	+17	+86	+3	+63
<b>AVERAGE</b>	<b>+4</b>	<b>+8</b>	<b>+9</b>	<b>+65</b>	<b>+2</b>	<b>+88</b>

% Diff. = (Diesel A - Reference) / Reference \* 100

The most significant difference between these fuels is the higher sulphur content of the Coastal Diesel A, quite clearly illustrated by the very much higher SO<sub>2</sub> and particulate emissions. Particulate emissions have been strongly related to fuel sulphur content. General findings and numerical relations from the literature are discussed in detail in **Section 3.6.1**. There are somewhat less severe increases in CO and NO<sub>x</sub> also evident with Diesel A, the NO<sub>x</sub> increase possibly being related to higher cetane number. There are marginal increases in HC<sub>n</sub> and CO<sub>2</sub> emissions with Diesel A as well.

**Table 50** below shows a similar comparison of the crude based Diesel C and the synthetic Diesel B with the Reference Diesel for the Vehicle Emissions Programme. These fuels account for most of the diesel fuel sold at high altitude conditions.

**Table 50:** Comparison of Diesel B and C Emissions with Reference Diesel Emissions (Altitude Programme)

ENGINE	HC <sub>n</sub>		CO		NO <sub>x</sub>		Parts		CO <sub>2</sub>		SO <sub>2</sub>	
	%Δ C	%Δ B	%Δ C	%Δ B	%Δ C	%Δ B	%Δ C	%Δ B	%Δ C	%Δ B	%Δ C	%Δ B
314N	+21	+2	+9	+1	-1	+15	+56	-14	+4	+3	+73	-99
364N	+11	+7	+24	-12	+3	+1	+71	-6	+4	0	+94	-95
364T	-1	+2	+8	0	-2	+2	+21	-9	0	+2	+76	-92
407N	-16	-2	+1	-18	+1	+7	+30	-13	+5	+3	+85	-96
447N	+10	+15	+5	-6	+2	+6	+21	-5	-1	+2	+100	-94
447T	-17	+24	+12	+4	+6	+6	+40	+9	-5	-3	+103	-94
<b>AVERAGE</b>	<b>+1</b>	<b>+8</b>	<b>+10</b>	<b>-5</b>	<b>+2</b>	<b>+6</b>	<b>+40</b>	<b>-6</b>	<b>+1</b>	<b>+1</b>	<b>+88</b>	<b>-95</b>

$$\% \Delta C = (\text{Diesel C} - \text{Reference}) / \text{Reference} * 100$$

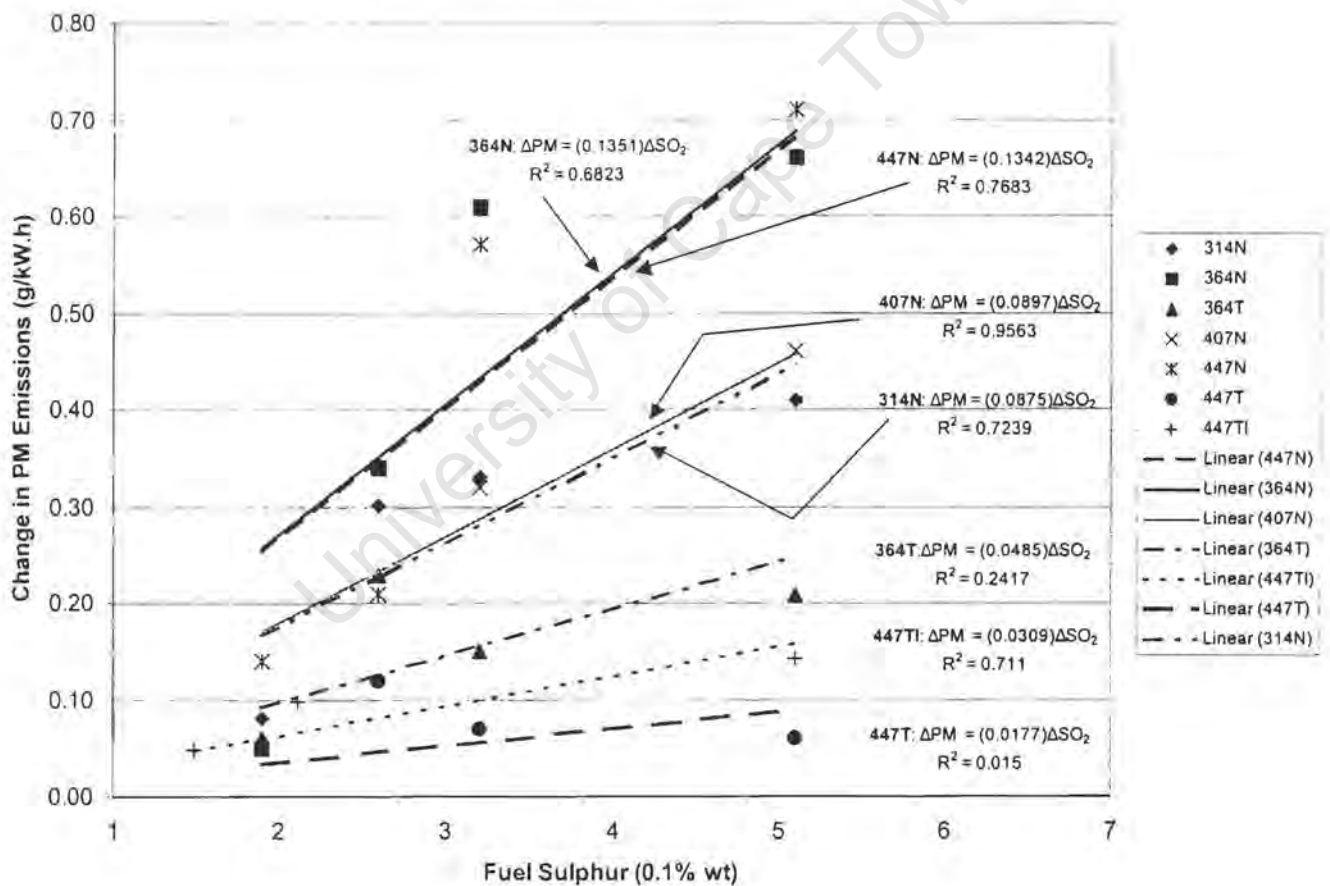
$$\% \Delta B = (\text{Diesel B} - \text{Reference}) / \text{Reference} * 100$$

Here again the much higher SO<sub>2</sub> and particulates of the crude-based Diesel C are the most striking fuel effects. Conversely SO<sub>2</sub> emissions with the synthetic Diesel B approach zero due to the very low trace concentrations of sulphur in this fuel. The potential benefit of low particulates is, however, not as large as might be expected with only a marginal improvement on the reference fuel being evident. This may be a result of the influence of other fuel properties, for instance a higher proportion of poly-aromatics in Diesel B and a higher 95% distillation temperature. The other contrasting emissions properties of the fuels relative to the Reference Diesel are marginal and were not deemed significant in the light of possible test error and individual engine characteristics.

The effect of fuel sulphur on particulate emissions was identified as a scenario for the modelling phase of this study as discussed in **Section 5.4**. A number of numerical relationships have been derived for quantifying this effect in the literature. It was attempted to derive a correlation from the combined VEP and BP Southern Africa experimental results to augment these derivations and perhaps provide an alternative model more representative of local engines and fuels. It is important to note that the fuel matrix used in the experimental study did not include any test fuels where properties were decoupled and therefore density, polyaromatic content and cetane number are bound to have some confounding effect. While this casts some doubt on any fuel sulphur

particulate matter relation derived from the experimental data, it must be borne in mind that the range of effect of fuel sulphur is significantly greater than other properties (**Figure 26**) and fuel sulphur content itself varies to a large degree in the fuel matrix, ranging from 0 ppm to 5130 ppm. In contrast, density, polyaromatic content and cetane number variation was small within the test fuel matrix as can be seen from the fuel specifications presented in **APPENDIX I**.

The experimental data was arranged into 20 pairwise comparisons of change in particulate matter emission versus change in fuel sulphur content. It was found that the test data was very scattered such that a linear regression like that used by AVL <sup>(112)</sup> to derive **Equation 22** provided a poor fit. Linear regression on an engine for engine basis however yielded far more coherent results as indicated below in **Figure 52**:



**Figure 52:** Experimental Correlation of Change in PM Emissions with Fuel Sulphur Content

The following is evident from the above findings:

- There is good agreement between the correlations derived for turbocharged engines and those in the literature. European studies typically involve turbocharged and turbo-intercooled engines that are specific to that market. The engine sample for the particular EPEFE study reported on in **Section 3.6.1** consisted entirely of 5 turbo-intercooled engines <sup>(88)</sup>. The results presented in **Figure 52** above strongly indicate that the application of correlations derived from such engine samples to old technology markets like that in South Africa may significantly underestimate the impact of fuel sulphur content on particulate matter emissions.
- The correlations for the two old-technology naturally aspirated engines, the 314N and the 407N, lie one on top of the other as do the correlations for the newer-technology naturally aspirated engines, the 364N and the 447N. This adds to the plausibility of a link between engine technology and the sensitivity of particulate matter emissions to changes in fuel sulphur content.

#### 7.1.7 QUANTITATIVE VALIDITY OF THE VOLATILE ORGANIC COMPOUND RESULTS

The sampling of VOC species requires either sample dilution or sample heating to prevent condensation of the species themselves or absorption into condensed water. The convenience of the particulate dilution tunnel (**Section 3.8.2**) made measurement of a dilute sample the obvious choice especially for the hydrocarbons methane, butadiene and benzene for which the sample had to be stored in a bag for the duration of the test.

The use of this method resulted in severe resolution problems because diesel exhaust is already diluted compared to typical spark-ignition engine exhaust, hydrocarbon emissions being typically a factor of five lower. The problem was exacerbated in the Highveld Programme because conditions required the dilution tunnel to be set at dilution ratios about 20% lower than coast. This is clearly seen in the altitude results where in most cases no butadiene or benzene was detected at all. These results in particular should be viewed with limited confidence. In fact all the gas chromatograph traces for the methane,

butadiene and benzene measurements at coast and highveld were barely above noise level and so should be viewed more qualitatively than quantitatively.

An aldehyde measurement method was only developed in time for the Highveld Programme, hence the lack of aldehyde results for the Coastal Tests. Although resolution was good, it was not always possible for the lab to extract the sample immediately and so test samples remained in the refrigerator in certain cases over an entire weekend. Tests to determine the effect of this showed a 30% lower formaldehyde result. The formaldehyde derivative is known to be unstable so these results should be used with caution in any analysis.

Possibly the best method of quantitative analysis in this case, is to view the results as a percentage of the total hydrocarbon results, which should highlight serious errors. This data is presented in **Table O - 1** to **Table O - 4** in **APPENDIX O1**. Certainly some consistencies are evident and some confidence can be placed in the averages for all six engines as a general quantity for diesel engines in the case of the aldehyde measurements and possibly methane.

Of the non-oxygenated VOCs, methane provided the most robust readings, accounting for between 12% and 26% of total hydrocarbon emissions. This can be compared to the results of CORINAIR (see **APPENDIX F**) emissions inventories for heavy-duty vehicles operating in European countries as presented in **Table G - 7** in **APPENDIX G**. These figures indicate that methane emissions were estimated at around 3.2%, 3% and 10% of total VOC emissions for France, Germany and Sweden respectively. The experimental results obtained for methane are therefore relatively high. Given the concerns already raised concerning methodology there are however no grounds to dispute the European data on this basis.

The VOC percentage data in **APPENDIX O1** can also be critically compared to the emission factors for VOCs published by the European Environment Agency <sup>(2,74)</sup> for their COPERT mobile source emission factor programme. These are expressed in similar terms as a percentage of total non-methane VOC emissions. Both COPERT II and III propose high formaldehyde emission for heavy-duty diesel engines ranging from 6% to 8.4% of total non-methane VOC emissions. The results of the experimental study indicated far lower values, except in the case of the 447N test engine, for which

measurements indicated consistently elevated formaldehyde emissions, particularly when fuelled by Highveld Diesel C and the Reference Fuel. Acetaldehyde emissions were also somewhat lower than predicted by COPERT except again for the case of the 447N.

Overall, while a useful learning process was undertaken, none of the VOC speciation results obtained show the potential to offer more reliable estimates than those in the literature. Certainly unless the lessons learned are applied in a revised national programme to generate new data, inventory modellers could do worse than apply the COPERT emission factors discussed above.

## 7.2 DISCUSSION OF THE INVENTORY MODELLING RESULTS

### 7.2.1 DISCUSSION OF THE BASELINE RESULTS

Balancing carbon gives a very general validation of the baseline results of an inventory model but a more specific measure of the quality of the data can perhaps be sought by comparison with results calculated by other researchers in other countries. Clearly though, given that absolute emissions will vary, they must be reduced to specific units to facilitate comparison. The most convenient method is by expressing total emissions in fuel specific units. **Table 51** below presents the baseline emissions expressed in fuel specific units of kilotons emission per megaton diesel fuel consumed:

**Table 51:** Baseline Model Results in Fuel Specific Units: SA Diesel Commercial Vehicles (1998)

Vehicle Type	Total Annual Emissions (kt/Mt Diesel)					
	HC <sub>n</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	CO <sub>2</sub>	PM
LCV	1.39	15.30	19.67	6.88	3186.21	3.36
MCV	5.80	16.36	41.88	6.92	3186.21	3.19
HCV	3.45	14.62	54.46	6.47	3186.21	2.51
M&HCV	3.67	14.78	53.29	6.51	3186.21	2.58
All CV's	3.21	14.88	46.58	6.59	3186.21	2.74

The above can now be compared with international results. **Table 52** below compares the results of the modelling study for all diesel commercial vehicles with European results from the CORINAIR programme as presented in **APPENDIX G**.

**Table 52:** Comparison of Baseline Results with European CORINAIR Results

Country	Year	Total Annual Emissions (kt/Mt Diesel)				
		HC <sub>n</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	PM
SA	1998	3.21	14.88	46.58	6.59	2.74
UK	1990	12.23		50.42		4.23
UK	1996	6.26		29.44		2.57
France	1996	6.96	28.98	41.92	5.58	
Germany	1996	4.82	10.47	34.78	2.10	
Sweden	1996	6.06	18.77	63.18	0.59	

*HC<sub>n</sub> emissions are NMVOCs for CORINAIR results*

*Diesel consumption was estimated from CO<sub>2</sub> emissions for all data*

*UK data is for all diesel vehicles*

*Data for France, Germany and Sweden is for diesel vehicles > 3500 kg*

The following is evident from **Table 52**:

- HC<sub>n</sub> emissions seem substantially underestimated. 1998 South African emissions can be assumed to be similar to UK 1990 emissions or indeed higher, given the technology mix. Comparison of the emission factors derived in the modelling study as presented in **Section 6.2.1** with international emissions factors as presented in **APPENDIX G** indicates good agreement with the tables of CORINAIR data (**Table G - 1**), European data reported by Faiz (**Table G - 8**) and French data reported by Faiz (**Table G - 10**). US and Dutch data reported by Faiz indicate emission factors 2 to 3 fold higher (**Table G - 9** and **Table G - 11**). The general agreement would suggest therefore that the discrepancy seen in **Table 52** above results mostly from the fact that ageing effects were not taken into account in the modelling study. The sensitivity of hydrocarbon emissions to road type which is accounted for by CORINAIR but which was not reflected in this study may also contribute to the discrepancy.
- While PM emissions are close to UK 1996 levels, the above observations probably hold for PM emissions too. It should be borne in mind that technology mix, high sulphur fuel and the profound altitude effects observed should result in PM specific emissions well in excess of UK 1990 levels. As discussed in **Section 3.10.2** the UK's NAEI <sup>(68,69)</sup> inventory assumes a 100% increase in PM emissions over 80,000 km. Given the age of the South African population this implies that the total PM

emissions calculated by the modelling study would at least double if ageing effects were accounted for. This brings the result more in line with UK 1990 levels plus 30%, which is a more likely scenario. As is the case with HC<sub>n</sub> emissions the emissions factors calculated show good agreement with most international data presented in **APPENDIX G**.

- CO emissions fall within the range of CORINAIR data presented but again are probably underestimated for the same reasons as discussed for PM and HC<sub>n</sub> emissions.
- There is good agreement between the NO<sub>x</sub> emissions calculated and the CORINAIR results. Ageing and poor maintenance effects are not as profound in the case of NO<sub>x</sub> emissions as for other emissions. This is discussed in more detail in **Section 3.7.5**. The total NO<sub>x</sub> emissions calculated can therefore be viewed with a relatively high degree of confidence.
- SO<sub>2</sub> emissions are fuel derived and are therefore also likely to be reliable. Comparison of the total SO<sub>2</sub> emissions calculated in the modelling study with the CORINAIR data above reflect the differing legislated fuel sulphur levels in those countries. Sweden has a very low legislated fuel sulphur level of 0.005% weight as compared with 0.55% in South Africa (somewhat mitigated by synthetic fuel). This accounts for the large discrepancy with the Swedish inventory results.

## **7.2.2 DISCUSSION OF THE SCENARIO MODELLING**

The results of modelling the effect of various scenarios on the national emission inventory for commercial vehicles are presented in **Section 6.2.2**. These results are discussed respectively below:

### **7.2.2.1 EFFECT OF THE SYNTHETIC FUEL INDUSTRY**

South Africa is an acknowledged world leader in this industry. Currently this has a very emissions positive effect as indicated by the modelling results. This is primarily due to the very low sulphur levels of synthetic fuels. Although this effect will diminish with reduced crude-derived sulphur levels, the synthetic industry has made further strides in the

provision of special low emission diesel fuels, for example Sasol's Slurry Phase Distillate an ultra-high cetane fuel that offers significantly lower emissions even relative to European low emission diesels (**Section 3.6.1**). The lifecycle emissions of synthetic fuels were not investigated in this study.

#### **7.2.2.2 ENGINE TYPE VARIATION**

Turbocharging is clearly the most certain route for reducing commercial vehicle emissions as there is the added incentive of reduced running costs. The high proportion of activity at altitude conditions makes turbocharging a particularly effective measure for emissions reduction. Intercooling is however essential to prevent NO<sub>x</sub> penalties as shown in **Figure 47**.

#### **7.2.2.3 VEHICLE SIZE**

Larger diesel engines are more efficient due to a lower surface area to volume ratio and lower friction due to lower running speeds. While light vehicles are convenient for the consumer they are not desirable from an environmental or fuel economy perspective, although in the case of NO<sub>x</sub> emissions the model shows penalties for large vehicle use. Clearly though the economic necessity for South Africa to create a small and medium business focussed economy will tend to drive the continued popularity of light commercial vehicles. Consumer behaviour could perhaps be modified in cities like Cape Town by fostering urban delivery subcontractors that use larger vehicles and serve many businesses. The practicality of this and costs to the ratepayer of damage to the roads are unlikely to make this an attractive option.

#### **7.2.2.4 FUEL SULPHUR LEVEL**

The direct relationship between fuel sulphur and particulate matter and sulphur dioxide emissions results in a continuing reduction as fuel sulphur is reduced. This is particularly the case for SO<sub>2</sub>, which although not regulated due to its purely fuel-derived nature, is a serious threat to human health (**Section 3.3.5**). Particulate matter reductions are significant but not large. Therefore one must carefully balance the very high costs of sulphur reduction with the emissions gains. Molden <sup>(64)</sup> has estimated the cost of reducing diesel sulphur from the new limit of 3000 ppm to an even lower 500 ppm at R3 billion. Of concern are also refinery emissions themselves, particularly CO<sub>2</sub> emissions which can be expected to increase <sup>(18,29)</sup>. Ultimately fuel sulphur reduction is likely to be determined not

by emissions impact but by the minimum requirements of engines currently being imported.

#### **7.2.2.5 REGULATION COMPLIANCE**

The results show that given good vehicle park maintenance and lower fuel sulphur (0.2%), the South African commercial vehicle park should approach the equivalent of Euro 1 emissions compliance at present. It should be borne in mind however that the age effect on the baseline emissions would in all probability be very profound if it could be modelled although this can be balanced against the fact that new engines being imported have emissions far lower than Euro 1 levels. In contrast Euro 2 and Euro 3 compliance imply very extensive changes to the vehicle population. Given the characteristics of the population discussed in this study, significant market penetration will require at least a decade of selective importing of engines and vehicles meeting these standards. This is discussed in detail below in **Section 7.2.3**. Certainly significant improvements in air quality can be expected given that these engines are operated at the emission regulation fuelling strategies and with exhaust treatment devices like particulate traps fully functional. The temptation in the kilowatt-hungry South African market is to alter fuelling strategies to appeal to consumers that regularly overload vehicles for short-term economic returns. Distributors and CKD assemblers may also disable or omit exhaust after-treatment devices (see **Section 3.5**) to firm up small profit margins in depressed markets.

#### **7.2.2.6 CNG / LPG CONVERSION**

This is probably the best medium term measure to reduce emissions of particulates, oxides of nitrogen and sulphur dioxide especially in urban environments. Although thermal efficiency is lower than for compression ignition engines running on diesel, CNG is a low carbon fuel so CO<sub>2</sub> penalties are marginal as shown in **Figure 51**. The supply of CNG to Sasolburg and the mooted pipeline from the Kudu Gas fields to Cape Town could drive a rapid development of a vehicle gas industry. Given the capacity of the commercial vehicle population estimated by this paper at some 55 GW or the equivalent of 14 large highveld coal fired power stations, potential gains for fuel suppliers are great even given a duty cycle of only 30% and limited market penetration. Fuelling a large percentage of new vehicles on CNG will slow up the demand for increased refinery capacity for diesel while allowing oil companies to diversify into a new energy source market. The State has

openly stated its interest in offering incentives <sup>(169)</sup> and it is to be hoped that this far-sighted approach is matched by industry.

### 7.2.3 ANALYSIS OF TRENDS IN THE VEHICLE POPULATION

Identifying trends in vehicle population growth and composition is essential if the scenario results discussed above are to be interpreted in a realistic context. The creation of a methodology for modelling the rate of scrapping of vehicles enabled the prediction of a number of scenarios for population growth and the rate of penetration of new technologies into the market. It was found that the erratic sales for heavy vehicles of the last twenty years as shown by **Figure 42** above in **CHAPTER 5**, necessitates a radical change in the characteristics of that population. As discussed in **CHAPTER 5** the rate at which vehicles are scrapped can be modelled by an s-shaped curve that converges to zero vehicles remaining on the x-axis of year of sale. **Figure 42** illustrates how the steep section of the curve where the rate of scrapping accelerates sharply has approached the large block of vehicles sold in the early 80's. If the projected rate of scrapping is maintained this large block of vehicles will disappear over the next 5 years.

**Figure 53** below illustrates how the population would drop if the current rate of scrapping is maintained and sales continue the trend of the last ten years. This is compared to the more likely scenario of the total heavy-duty population growing at the rate sustained over much of the last decade. This rate extrapolated from CSIR data <sup>(165)</sup> is around 2% and therefore roughly similar to South Africa's economic growth rate.

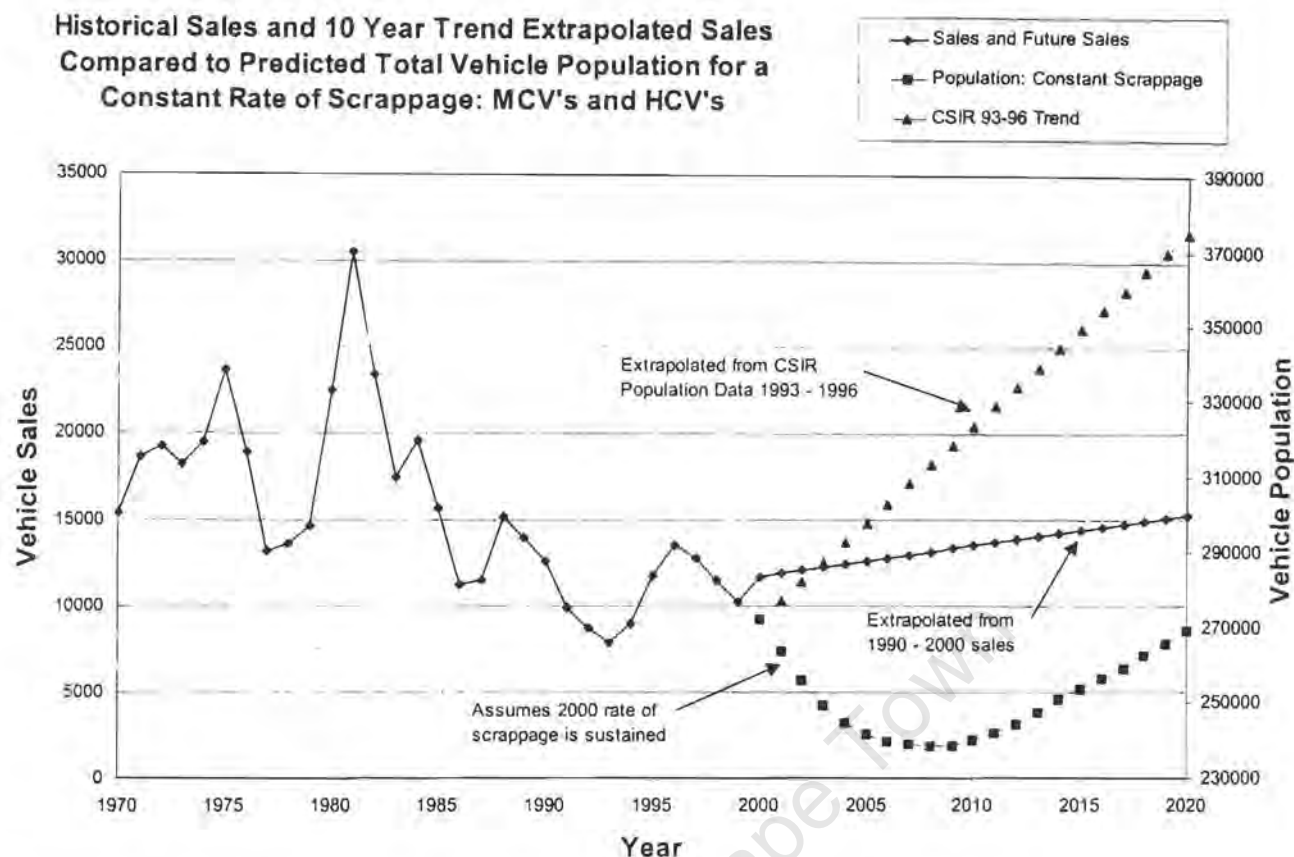


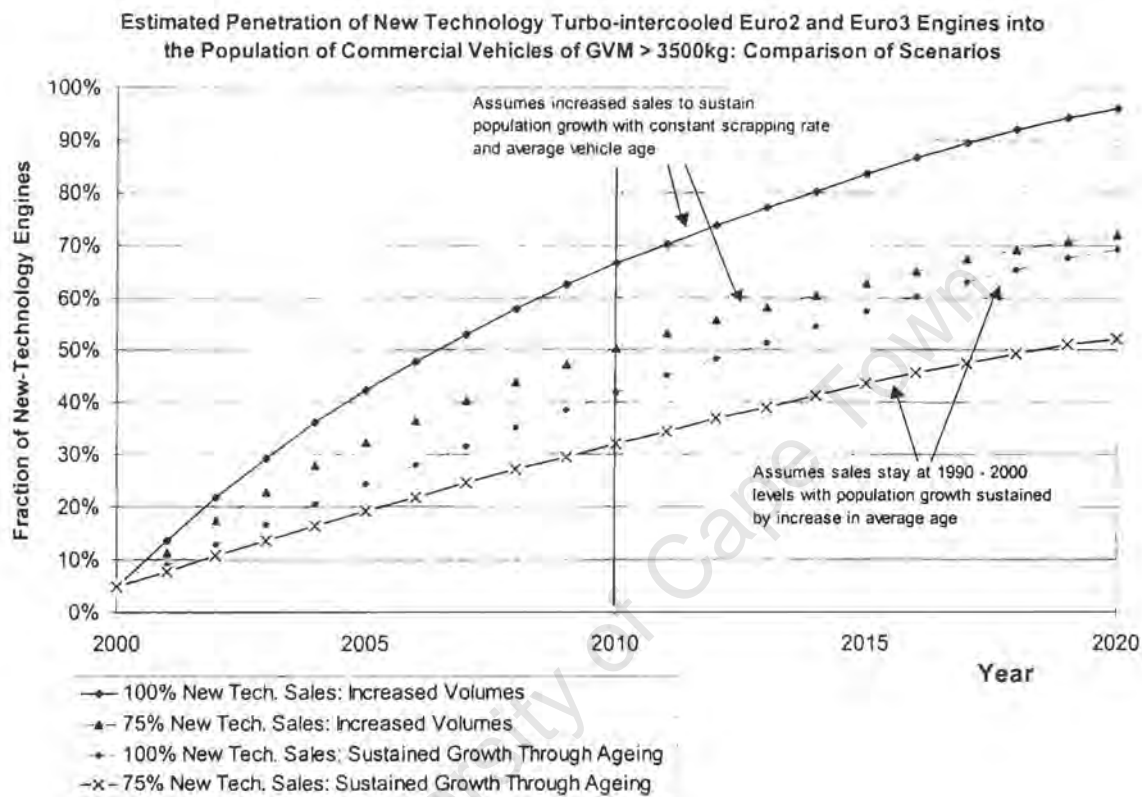
Figure 53: Population Growth Scenarios for South African Vehicles > 3500 kg GVM

Clearly, given that the heavy-vehicle population is likely to continue increasing in proportion to economic growth, two contrasting scenarios or combination of scenarios are possible, both of which would have a profound effect on vehicle emissions:

1. The economy cannot finance the sustained growth with significantly increased sales of new vehicles. As a result average vehicle age increases dramatically along with the contribution of old and obsolete vehicles to emissions. Compromised vehicle performance will also begin to reduce the efficiency of the transport network.
2. Sales of new vehicles increase dramatically to replace the old vehicles that have reached the end of their useful life. New technologies therefore enter the country at an accelerated rate. These would be mostly Euro 3 vehicles. This modelling phase of this study has indicated that this is the most effective strategy for emissions mitigation.

We can assume that the future will be some combination of these two scenarios. **Figure 54** below indicates their contrasting effects on the penetration of new technology into the marketplace. Total sales were modelled as either being 100% new technology or 75%

new technology and 25% old stock. The starting point was assumed to be the 4.79% turbo-intercooled portion of the population calculated for 1998. Given that the formerly market dominant local diesel engine manufacturer ADE closed at the end of 1999 and stock has remained in the market until well into 2001, it is not unreasonable to assume that the population composition changed little until 2000.



**Figure 54:** Scenarios for the Penetration of New Technology into the South African Heavy-duty Vehicle Population

The data from **Figure 53** and **Figure 54** are presented in tabular form in **Appendix P**. **Figure 54** indicates that the scenarios identified for growth of the heavy commercial vehicle population give rise to highly divergent possibilities for the vehicle population composition. If we assume however a compromise between the extremes of possibility, the following can be proposed perhaps with some element of confidence:

- New technology turbo-intercooled engines should power about a third of the heavy vehicle population by 2006 – 2007.
- New technology turbo-intercooled engines should power about half of the heavy vehicle population by 2012.

- By 2020 it is likely that a quarter of the heavy vehicle population will still be powered by technology that is already viewed as obsolete today like naturally aspirated engines or turbocharged engines without intercooling. This is however a more speculative prediction than numbers 1 and 2.

#### 7.2.4 WEAKNESSES OF THE MODEL

The model has definite shortcomings that in most cases can be improved upon. These can be summarised as follows:

- The emission data set does not take account of ageing effects on vehicle emissions. Vehicle emissions can be assumed to deteriorate seriously with age particularly if maintenance is poor.
- The emissions data set does not take account of new technology entering the marketplace, specifically electronic control, common rail injection and variable geometry turbo-charging. The emissions data consists of measurements from ADE engines only and while this may be representative of 1998, the year of calculation for this study for which an ADE content of 69% was calculated, the incidence of ADE engines in the population will already be much diluted by new engines. It should be stressed that using the regulated emissions limits from the country of origin for imported engines is not a solution as the actual emissions are often far lower especially in the case of unburned hydrocarbon and carbon monoxide emissions. Furthermore this does not take local fuel effects into account.
- The Mead & McGrouther vehicle database has a highly suitable format and concept for the purpose of vehicle park modelling but sales data is partial and the published database is updated slowly, the latest figures at the time of writing being for 1998. Certain engine data is missing for some models which requires great effort to make estimates or corrections

- The VEP emissions data for diesel light commercial vehicles is very limited and highly unrepresentative of technology. For instance the turbocharged vehicle model tested had higher particulate emissions than the naturally aspirated vehicle.
- The adjustment of average vehicle mileages by carbon balance is assumed and needs to be verified by more accurate data from the field if baseline accuracy is required. For comparative purposes however this is probably not necessary.
- The turbo-intercooled data available is insufficient to evaluate this technology. This is especially true for LCVs where no data was available.
- No data is available for diesel passenger cars that are an increasing presence in the marketplace and should be included either in a passenger car database or with the commercial vehicles in a diesel fuel specific database. Rayner <sup>(78)</sup> has predicted a sustained increase in the proportion of diesel passenger cars and measures will have to be taken to take account of their emissions.

Since the time of Phase 2 of the VEP programme, considerable world class emissions testing infrastructure has developed in South Africa, specifically at the Eurotype Test Centre (Pty) Ltd in East London, the Volkswagen South Africa emissions test facility in Port Elizabeth and the Sasol Oil test facility in Sasolburg. There is no reason why the data availability shortcomings described above cannot be resolved by a sustained and continually updated programme that obtains data from all or some of these facilities. Certainly regular testing offers an improved economy of scale and ensures that expertise and equipment is maintained which unfortunately was not the case with the VEP contractors.

## CHAPTER 8 CONCLUSIONS

Some conclusions drawn from the experimental and inventory modelling studies are presented below:

- The Vehicle Emissions Project results indicated that emissions from naturally aspirated diesel engines deteriorate severely with increase in altitude to elevation typical of the South African Highveld. Turbocharged engines are far less sensitive to altitude change.
- Correlation of diesel fuel sulphur level with particulate matter (PM) emissions suggested strongly that pre-Euro I naturally aspirated engines are far more sensitive to diesel fuel sulphur level than indicated by numerical relations derived in Europe and published in the literature. These engines will constitute a significant sector of the vehicle population for some time to come, a situation likely to be even more pronounced in developing countries with poorer or more diverse economies. This finding is therefore highly significant for those undertaking inventory modelling in the developing world, particularly for the purpose of evaluating the effects of reductions in the legislated diesel sulphur limit.
- A simple emissions inventory model of the vehicle population is a useful tool for estimating the impact of fuel and technology changes on air quality.
- The South African vehicle population and fuel supply chain can be adequately modelled using available databases at low cost. Improvements to the vehicle population database should however be encouraged.
- An arc-tan function distribution can be used in place of the traditional Weibull distribution to model the rate of scrapping in the vehicle population. In this way, too rapid conversion to 100% scrappage that underestimates the older population can be avoided without splicing two functions together as is done in some inventory models.
- The inventory modelling study found that Heavy Commercial Vehicles account for the greater part of emissions from diesel commercial vehicles in South Africa, accounting for between 67% and 85% of the regulated pollutants, SO<sub>2</sub> and CO<sub>2</sub>. Medium

Commercials account for 7% to 13% of total diesel commercial vehicle emissions while diesel Light Commercial Vehicles account for 8% to 25%.

- The inventory modelling study found that most pollutants from diesel commercial vehicles are emitted at high altitude, around and above 1200m. Emissions of the regulated pollutants, SO<sub>2</sub> and CO<sub>2</sub> at this elevation accounted for 62% to 81% of the total emissions predicted by the model.
- A healthy synthetic fuel industry and reduced crude-derived fuel sulphur will have a very positive effect on air quality as regards emissions of particulates (PM) and sulphur dioxide (SO<sub>2</sub>). The primary gain for particulate emission reductions with reduced fuel sulphur will be through the enabling of exhaust after-treatment technology like particulate traps which are not currently fuel sulphur tolerant.
- New engine technologies should improve air quality substantially. Naturally aspirated diesel engines are not positive from an emissions perspective especially given the considerable economic activity at high altitude.
- Small business growth and a concomitant growth in light commercial vehicles will impact air quality negatively. Efforts to optimise the emissions of these vehicles should be undertaken.
- The inventory model indicated significant reductions in particulate matter (PM) and SO<sub>2</sub> emissions for reductions in fuel sulphur level. Particulate matter reduction was modelled using three correlations, two from European studies and the third from the experimental phase of this study that indicated the greatest reductions. For the recently agreed new fuel sulphur limit of 0.3% these correlations predicted a reduction in particulate matter emissions of 7.6%, 10.2% and 12.6%. A reduction in SO<sub>2</sub> emissions of 38.1% was indicated. For a fuel sulphur limit of 0.05% typical of Europe, reductions in particulate matter emissions of 17.2%, 22.9% and 29.0% were predicted for the three correlations. A reduction in SO<sub>2</sub> emissions of 88.5% was indicated.
- The import of Euro 2 and Euro 3 compliant vehicles will have a highly significant impact on air quality. Regulatory bodies need to ensure that these engines are sold

into the market operating as designed. The rate of market penetration of these vehicles will be slow if vehicle sales continue on the trend of the last ten years.

- New technology turbo-intercooled engines should power about a third of the heavy vehicle population by 2006 – 2007.
- New technology turbo-intercooled engines should power about half of the heavy vehicle population by 2012.
- By 2020 it is likely that a quarter of the heavy vehicle population will still be powered by technology that is already viewed as obsolete today like naturally aspirated engines or turbocharged engines without intercooling.
- Local manufacturers and distributors should be encouraged to begin gas vehicle demonstrator projects to raise consumer awareness and begin negotiation of such vehicles from parent companies at an affordable cost. Government needs to finalise and guarantee incentive schemes to promote the use of CNG and LPG. Efforts should be made to incorporate vehicles as a significant consumer of the Kudu Gas pipeline to assist in justifying the economics of installation.
- Engine emission data for South African commercial vehicles is outdated and limited in model coverage. Testing should be routine to maintain economic testing volumes and thus sustain measurement quality.

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## APPENDIX A WORLD-WIDE FUEL CHARTER DIESEL SPECIFICATIONS

Table A - 1: Category 2 Diesel Fuel Specifications; Markets with stringent requirements for Emissions Controls or other Market Demands <sup>(110)</sup>

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	53 <sup>(1)</sup>	--
Cetane Index	-	50 <sup>(2)</sup>	--
Density @ 15°C	kg/m <sup>3</sup>	820 <sup>(3)</sup>	850
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>(4)</sup>	4.0
Sulfur content	% m/m	--	0.030 <sup>(5)</sup>
Total aromatics content	% m/m	--	25
Polyaromatics content (di+tri+)	% m/m	--	5
T90 <sup>(6)</sup>	°C	--	340
T95 <sup>(6)</sup>	°C	--	355
Final Boiling Point	°C	--	365
Flash point	°C	55	--
Carbon residue	% m/m	--	0.30
CFPP <sup>(7)</sup> or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	200
Oxidation stability	g/m <sup>3</sup>	--	25
Biological growth	-	--	'Zero' content
Vegetable Derived Esters	% m/m	--	See Footnote <sup>(8)</sup>
Total acid number	mg KOH/g	--	0.08
Corrosion performance	-	--	Light rusting or less
Copper corrosion	merit	--	Class I
Ash content	% m/m	--	0.01
Particulates	mg/l	--	24
Injector cleanliness I	% air flow loss	--	85
Injector cleanliness II	Average Plunger Deposit Rating	--	10.0
	% flow loss	--	5.0
Lubricity (HFRR scar dia. @ 60°C)	micron	--	400

**Table A - 2:** Category 4 Diesel Fuel Specifications; Markets with Further Advanced Requirements for Emission Control, to enable sophisticated NO<sub>x</sub> and PM aftertreatment technologies <sup>(110)</sup>

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	55 (1)	--
Cetane Index	-	52 (2)	--
Density @ 15°C	kg/m <sup>3</sup>	820 (3)	840
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 (4)	4.0
Sulfur content	% m/m	--	Sulfur-Free (5)
Total aromatics content	% m/m	--	15
Polyaromatics content (di+tri+)	% m/m	--	2.0
T90 (6)	°C	--	320
T95 (6)	°C	--	340
Final Boiling Point	°C	--	350
Flash point	°C	55	--
Carbon residue	% m/m	--	0.20
CFPP (7) or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg	--	200
Oxidation stability	g/m <sup>3</sup>	--	25
Foam volume	ml	--	100
Foam vanishing time	sec.	--	15
Biological growth	-	--	'Zero' content
Vegetable Derived Esters	% m/m	--	Non-detectable
Total acid number	mg KOH/g	--	0.08
Corrosion performance	-	--	Light rusting or less
Copper corrosion	merit	--	Class I
Ash content	% m/m	--	0.01
Particulates	mg/l	--	24
Injector cleanliness I	% air flow loss	--	85
Injector cleanliness II	Average Plunger Deposit Rating	--	10.0
	% flow loss	--	5.0
Lubricity ( HFRR scar dia. @ 60°C )	micron	--	400

## APPENDIX B LIFECYCLE EMISSIONS ESTIMATES FOR VARIOUS FUELS

**Table B - 1:** Lifecycle Emissions (g/km) for Various Fuels as determined for heavy-duty bus operation, estimated by the CSIRO Australia <sup>(8)</sup>

		(g/km)										
		Diesel	LSD	*LSD+ W5	ULS Diesel	*ULS+ W5	LPG	CNG	LNG	E95 (wood)	BD20	BD100
<b>CO<sub>2</sub></b>	Precombustion	227	246	231	274	249	210	144	234	744	300	708
	Fossil fuel Combustion	1413	1404	1409	1406	1411	1310	1336	1326	73	1050	0
	Total	1640	1650	1640	1680	1660	1520	1480	1560	817	1350	708
	Renewable combustion									1394	262	1306
	Grand total	1640	1650	1640	1680	1660	1520	1480	1560	2211	1612	2004
<b>CH<sub>4</sub></b>	Precombustion	0.69	0.70	0.65	0.73	0.67	0.64	0.26	2.54	0.11	0.48	0.20
	Fossil fuel Combustion	0.02	0.01	0.01	0.01	0.01	0.12	2.50	2.23	0.00	0.00	0.00
	Total	0.71	0.71	0.66	0.74	0.68	0.76	2.76	4.77	0.11	0.48	0.20
	Renewable combustion									0.10	0.00	0.02
	Grand total	0.71	0.71	0.66	0.74	0.68	0.76	2.76	4.77	0.21	0.48	0.22
<b>N<sub>2</sub>O</b>	Precombustion	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.08	0.42
	Fossil fuel Combustion	0.04	0.04	0.04	0.04	0.04	0.01	0.02	0.02		0.02	0.00
	Total	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.00	0.10	0.42
	Renewable combustion									0.02	0.005	0.025
	Grand total	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.105	0.445
<b>CO</b>	Precombustion	3.73	3.74	3.5	3.89	3.54	3.45	0.09	2.85	2.00	3.01	3.52
	Combustion	1.88	1.32	1.34	1.41	1.38	0.12	0.66	9.05	14.60	4.28	7.68
	Total	5.61	5.06	4.84	5.30	5.01	3.57	0.75	11.90	16.60	7.29	11.20
<b>NO<sub>x</sub></b>	Precombustion	1.10	1.18	1.10	1.28	1.16	1.02	0.63	1.60	0.34	1.19	2.70
	Combustion	15.00	14.72	14.53	14.32	13.80	5.31	9.87	32.50	7.83	23.51	17.20
	Total	16.10	15.90	15.63	15.60	14.96	6.33	10.50	34.10	8.17	24.70	19.90
<b>NM VOC</b>	Precombustion	2.00	2.01	1.87	2.09	1.90	1.85	0.28	2.84	0.38	1.64	2.02
	Combustion	1.10	0.50	0.53	0.52	0.54	0.02	2.75	2.45	4.85	1.05	0.84
	Total	3.10	2.51	2.40	2.61	2.44	1.87	3.03	5.29	5.33	2.69	2.86
<b>Particles</b>	Precombustion	0.16	0.17	0.16	0.26	0.24	0.14	0.01	0.08	0.15	0.25	0.84
	Combustion	0.47	0.22	0.24	0.16	0.17	0.02	0.05	0.01	0.21	0.38	0.60
	Total	0.62	0.39	0.40	0.42	0.41	0.16	0.06	0.09	0.36	0.63	1.44

<sup>8</sup> Based on a 5% blend of waste oil with the specified fuel. Calculations based on weighting emissions from waste oil by 5% and that from the diesel by 95%.

LSD: Low Sulphur Diesel (0.05% wt)  
 ULSD: Ultra Low Sulphur Diesel (0.001% wt)  
 E95: Ethanol  
 CNG: Compressed natural gas  
 LNG: Liquid natural Gas

WS: 5% waste oil added  
 LPG: Liquid Petroleum Gas  
 BD20: 20% biodiesel / 80% diesel blend  
 BD100: 100% biodiesel

### APPENDIX C EFFECT OF VEHICLE SPEED ON EMISSIONS OF HEAVY VEHICLES

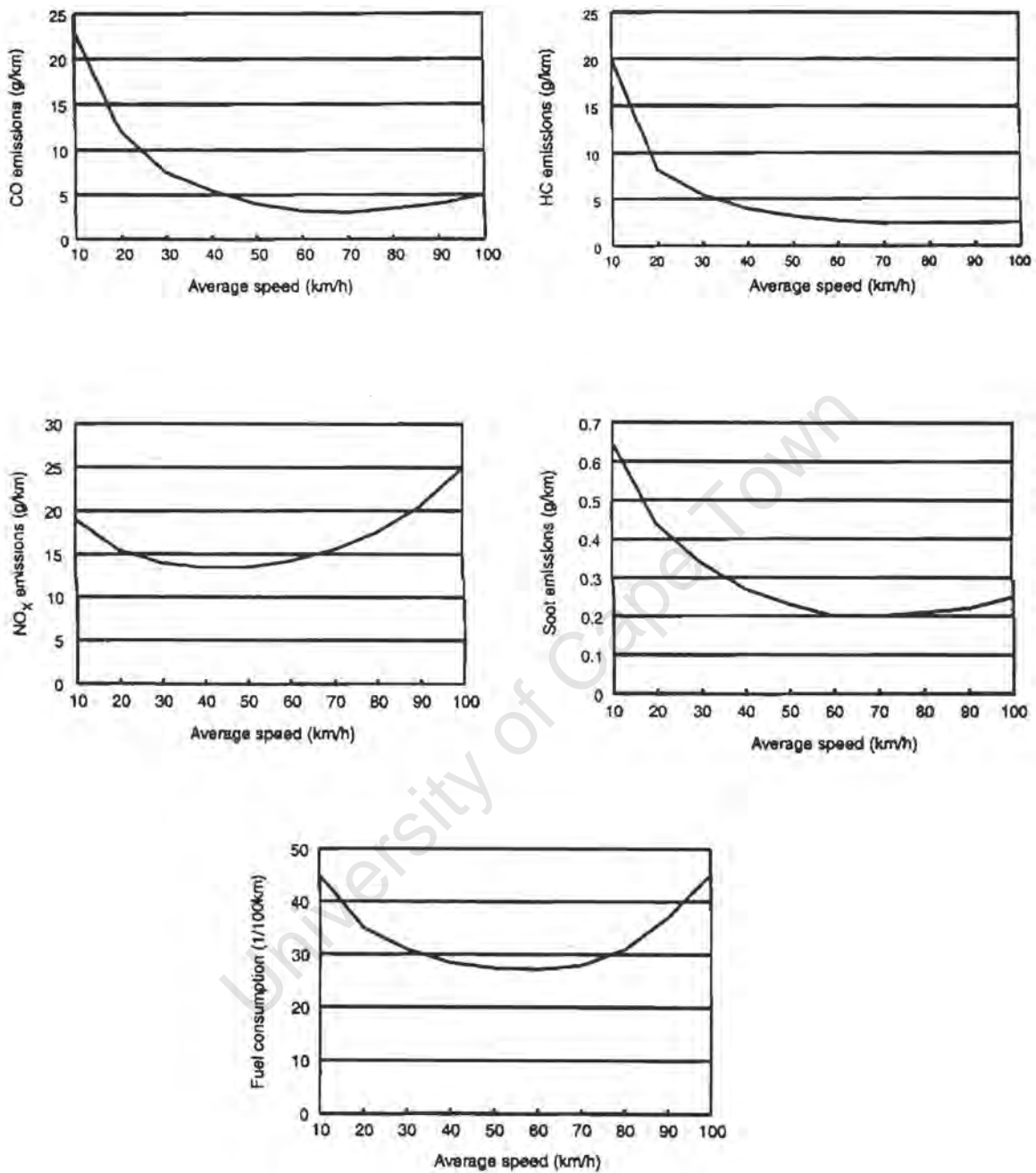


Figure C - 1: Effect of Average Speed on Emissions and Fuel Consumption for Swiss Heavy Vehicles <sup>(27)</sup>

## APPENDIX D EUROPEAN AND US EMISSIONS CYCLES AND REGULATED LIMITS

The heavy-duty diesel test cycles applied in Europe and the US are presented below along with the regulated limits that pertain to them.

### APPENDIX D1 EUROPEAN CYCLES AND LIMITS

European regulated emissions limits have been steadily lowered and lower limits are proposed for the future. These Tiers of regulations have become known as “Euro” standards and are numbered as shown below in **Table D - 1** according to their date of implementation. Test cycles have also been updated and now include transient testing for which limits are shown below in **Table D - 2**. The indicated test cycles are discussed below.

**Table D - 1:** European Union Steady-State Emissions Standards for Heavy Duty Diesel Engines <sup>(40)</sup>

Tier	Date & Category	Test Cycle	g/kWh (smoke in m <sup>-1</sup> )				
			CO	HC	NOx	PM	Smoke
Euro I	1992, <85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992, >85 kW		4.5	1.1	8.0	0.36	
Euro II	1996.10		4.0	1.1	7.0	0.25	
	1998.10		4.0	1.1	7.0	0.15	
Euro III	1999.10, EEVs only	ESC & ELR	1.5	0.25	2.0	0.02	0.15
	2000.10	ESC & ELR	2.1	0.66	5.0	0.10 0.13*	0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02	0.5
Euro V	2008.10		1.5	0.46	2.0	0.02	0.5

\* - for engines of less than 0.75 dm<sup>3</sup> swept volume per cylinder and a rated power speed of more than 3000 min<sup>-1</sup>

**Table D - 2:** European Union Transient Emissions Standards for Heavy Duty Diesel Engines <sup>(40)</sup>

			g/kWh				
Tier	Date & Category	Test Cycle	CO	NMHC	CH <sub>4</sub> <sup>a</sup>	NOx	PM <sup>b</sup>
Euro III	1999.10, EEVs only	ETC	3.0	0.40	0.65	2.0	0.02
	2000.10	ETC	5.45	0.78	1.6	5.0	0.16 0.21 <sup>c</sup>
Euro IV	2005.10	ETC	4.0	0.55	1.1	3.5	0.03
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03

*a - for natural gas engines only*  
*b - not applicable for gas-fuelled engines at the year 2000 and 2005 stages*  
*c - for engines of less than 0.75 dm<sup>3</sup> swept volume per cylinder and a rated power speed of more than 3000 min<sup>-1</sup>*

The **ECE-R49** test is a steady state test consisting of 13 modes of different speeds and loads, although three of the modes are idle. The modes are unequally weighted with the weighting favouring the maximum torque condition, rated condition and idle. This test method was used in the experimental phase of this study and is discussed in detail above in **CHAPTER 4**.

The **European Stationary Cycle (ESC)** is a modified 13-mode steady state test. The speed and load conditions for each mode and their weightings are indicated below in **Table D - 3**

The test engine speeds shown in **Table D - 3** below are defined as follows:

1. The high speed  $n_{hi}$  is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as  $n_{hi}$ .
2. The low speed  $n_{lo}$  is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as  $n_{lo}$ .
3. The engine speeds A, B, and C to be used during the test are then calculated from the following formulas:

$$A = n_{lo} + 0.25(n_{hi} - n_{lo})$$

$$B = n_{lo} + 0.50(n_{hi} - n_{lo})$$

$$C = n_{lo} + 0.75(n_{hi} - n_{lo})$$

**Table D - 3: Engine Conditions and Weighting Factors for Modes of ESC Test <sup>(40)</sup>**

Mode	Engine Speed	% Load	Weight factor, %	Duration
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

The **European Load Response Cycle (ELR)** was introduced into the Euro III regulation tier for the purpose of smoke opacity measurement from heavy-duty diesel engines. The test consists of a sequence of three load steps at each of the three engine speeds A (cycle 1), B (cycle 2) and C (cycle 3), followed by cycle 4 at a speed between speed A and speed C and a load between 10% and 100%, selected by the certification personnel. Speeds A, B, and C are the same as for the ESC Cycle above. The load and speed profile of the test engine are shown below in **Figure D - 1**.

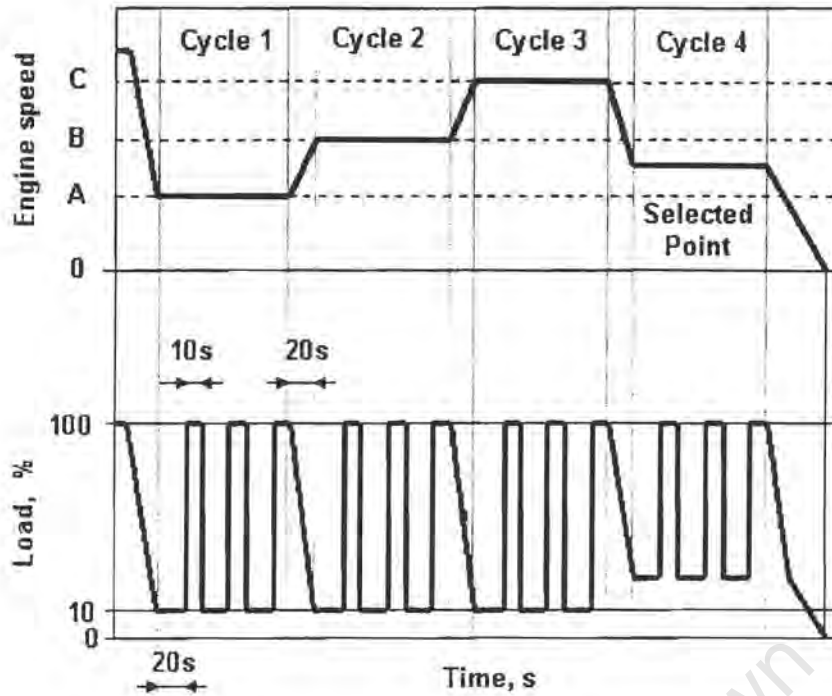


Figure D - 1: Operating Profile of the ELR Smoke Opacity Cycle for Heavy-Duty Diesel Engines <sup>(40)</sup>

The **European Transient Cycle (ETC)** cycle has been based on real road cycle measurements of heavy-duty vehicles <sup>(40)</sup>. Different driving conditions are represented by three parts of the ETC cycle, including urban, rural and motorway driving. The duration of the entire cycle is 1800s. The duration of each part is 600s.

- Part one represents city driving with a maximum speed of 50km/h, frequent starts, stops, and idling.
- Part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h
- Part three is motorway driving with average speed of about 88km/h.

The cycle has been developed in two variants: as a chassis and an engine dynamometer test. For the purpose of engine certification, the ETC cycle is performed on an engine dynamometer. The pertinent engine speed and torque curves are shown in **Figure D - 2** and **Figure D - 3**. Vehicle speed vs. time over the duration of the cycle is shown in **Figure D - 4**.

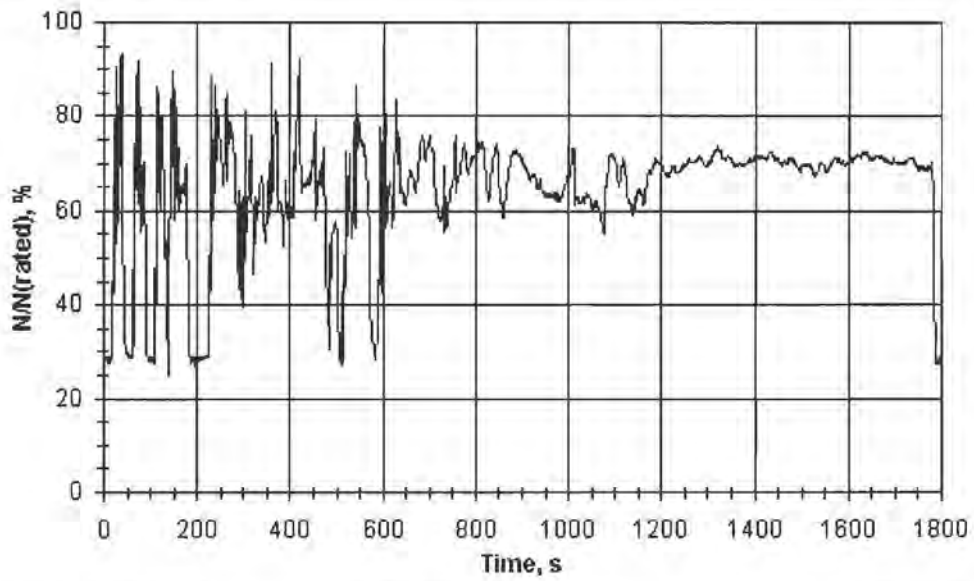


Figure D - 2: ETC Transient Cycle for Heavy-Duty Diesel Engines: Speed profile <sup>(40)</sup>

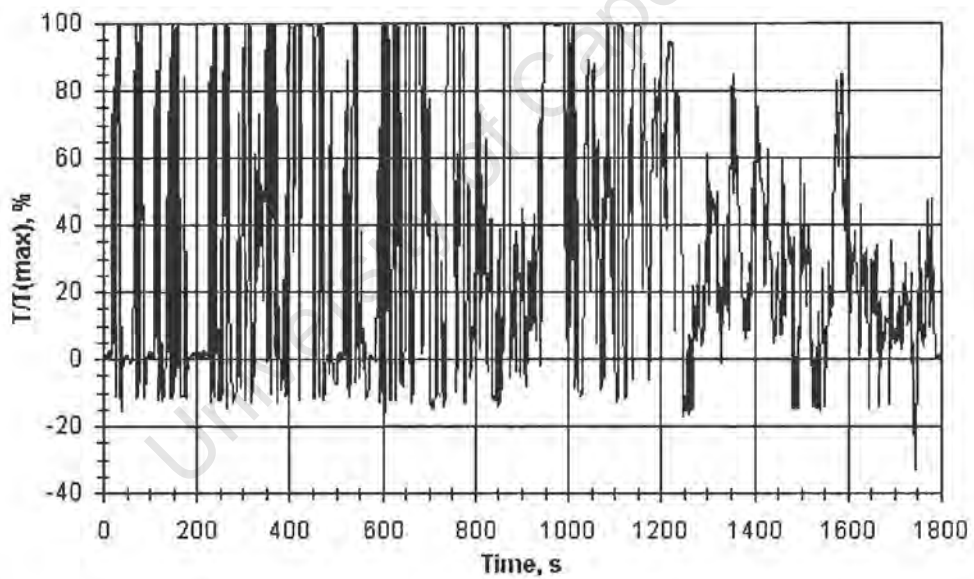


Figure D - 3: ETC Transient Cycle for Heavy-Duty Diesel Engines: Torque profile <sup>(40)</sup>

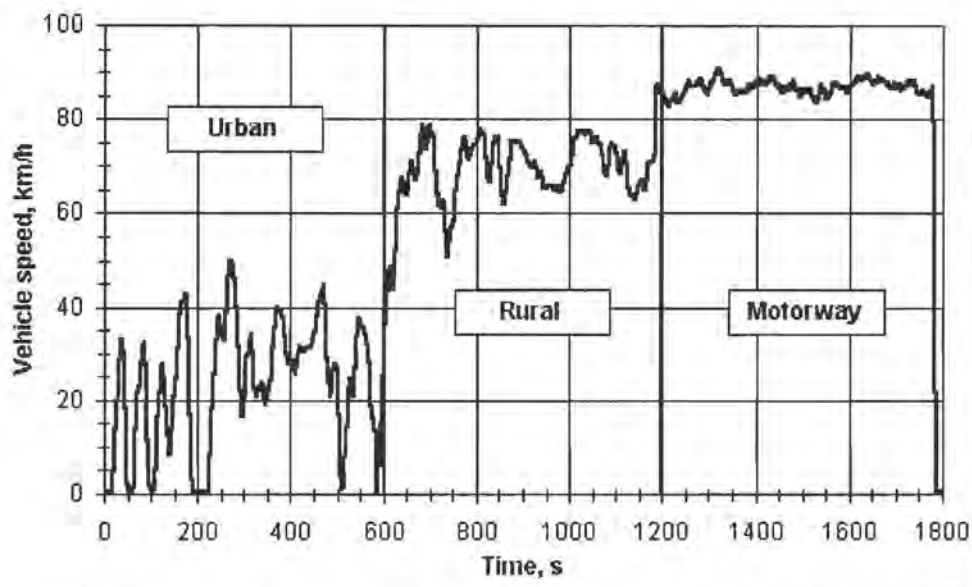


Figure D - 4: ETC Transient Cycle for Heavy-Duty Diesel Engines: Chassis Dynamometer Vehicle Speed profile <sup>(40)</sup>

## APPENDIX D2 CYCLES AND LIMITS IN THE UNITED STATES

Transient testing was adopted as the sole method of evaluating heavy-duty diesel engines in 1985 <sup>(83)</sup>. The regulated limits for the Environmental Protection Agency (EPA) Federal Test Procedure (FTP) for heavy-duty engines are shown below in **Table D - 4**.

Table D - 4: US EPA Regulated Emissions Limits for heavy-duty vehicles <sup>(41)</sup>

Year	HC	CO	NO <sub>x</sub>	PM
<b>Heavy-Duty Diesel Truck Engines (g/bhp.h)</b>				
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
<b>Urban Bus Engines (g/bhp.h)</b>				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.05*

\* - in-use PM standard 0.07

The 1998 limits above are valid until 2003 at which time an addendum will be enforced. Manufacturers will have the choice of two regulatory options as shown below in **Table D - 5**. All other limits from the 1998 regulatory tier will apply.

**Table D - 5:** 2004 Addendum to US FTP Regulated Emissions Limits for Heavy-Duty Vehicles <sup>(41)</sup>

Option	Regulated Limit (g/bhp.h)	
	NMHC + NO <sub>x</sub>	NMHC
1	2.4	n/a
2	2.5	0.5

*NMHC: Non methane hydrocarbons*

The FTP transient cycle used to apply the above limits consists of four phases: the first is a NYNF (New York Non Freeway) phase typical of light urban traffic with frequent stops and starts, the second is LANF (Los Angeles Non Freeway) phase typical of crowded urban traffic with few stops, the third is a LAFY (Los Angeles Freeway) phase simulating crowded expressway traffic in Los Angeles, and the fourth phase repeats the first NYNF phase <sup>(41,83)</sup>.

It comprises a cold start followed by idling, acceleration and deceleration phases, and various speeds and loads sequenced to simulate the running of the vehicle that corresponds to the engine being tested. There are few stabilized running conditions, and the average load factor is about 20 to 25% of the maximum horsepower available at a given speed.

The cycle is carried out twice and the second repetition is made with a warm start after a stop of 1200 seconds after completion of the first cycle. This is often distinguished as the FTP "Hot Start" test as opposed to the "Cold Start" section. The equivalent average speed of the cycle is about 30 km/h and the equivalent distance travelled is 10.3 km for a running time of 1200 s. The speed and torque profile during the cycle are shown below in **Figure D - 5**.

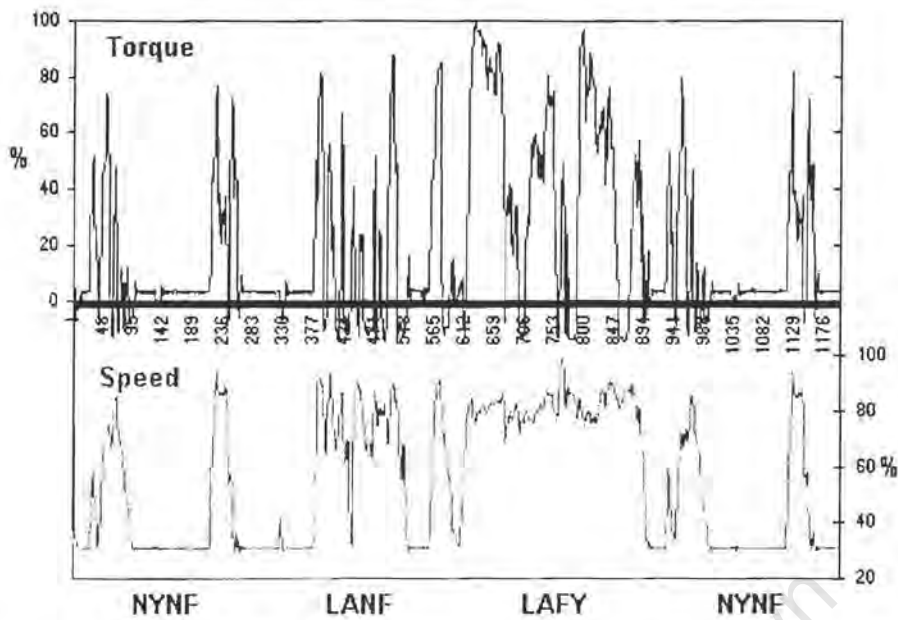


Figure D - 5: Speed and Load Profiles for US FTP Emissions Testing Cycle for Heavy-Duty Engines <sup>(41)</sup>

A typical test facility design used for the FTP procedure is shown in Figure D - 6 below.

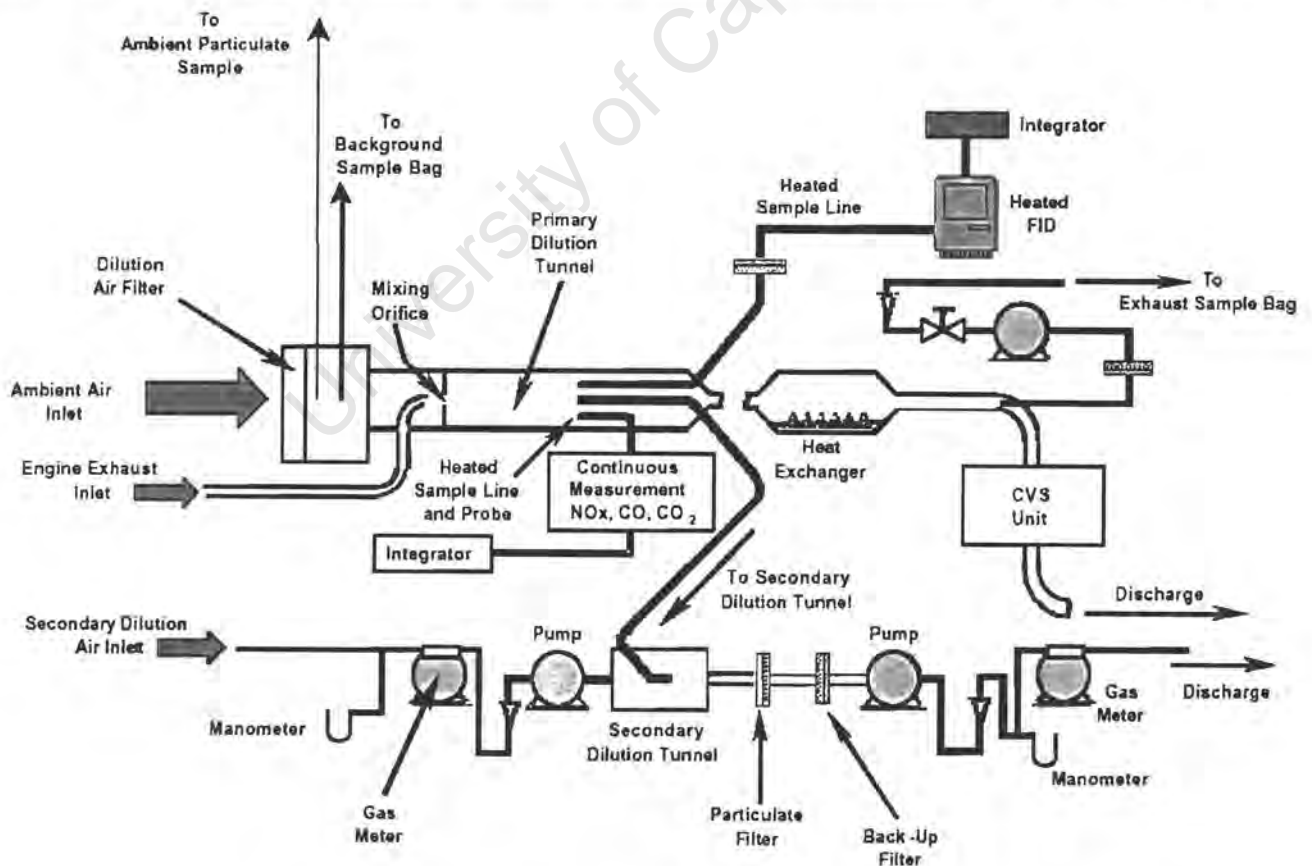


Figure D - 6: Typical Test facility Design for US FTP Emissions Testing (Double Dilution Tunnel) <sup>(83)</sup>

## APPENDIX E UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA) MOBILE6 EMISSIONS FACTOR MODEL: HEAVY-DUTY METHODOLOGY

“Mobile 6” is a desktop computer based atmospheric emissions factor model for mobile emission sources designed by the United States’ EPA. It has been developed as a tool for predicting HC<sub>n</sub>, CO and NO<sub>x</sub> emissions from cars trucks and motorcycles under various conditions <sup>(7,103)</sup>. The current model does not evaluate particulate matter, toxics including speciated volatile organic compounds or greenhouse gases but the intention to release versions 6.1, 6.2 and 6.3, addressing these three emission categories, was announced by EPA early in 2001 <sup>(7)</sup>. Mobile 6 is not a classical inventory model that calculates gross annual emissions. Rather a composite emission factor is derived according to the specification of the user that can then be directly applied to the building of an emissions inventory as a separate exercise.

The model has the capability to make calculations retrospectively as well as predict emissions in the future, given scenarios defined by the user. **Figure E - 1** below presents an example that compares the predictions of Mobile 6 with the older version Mobile 5, for NO<sub>x</sub> emissions from all highway vehicles <sup>(7)</sup>.

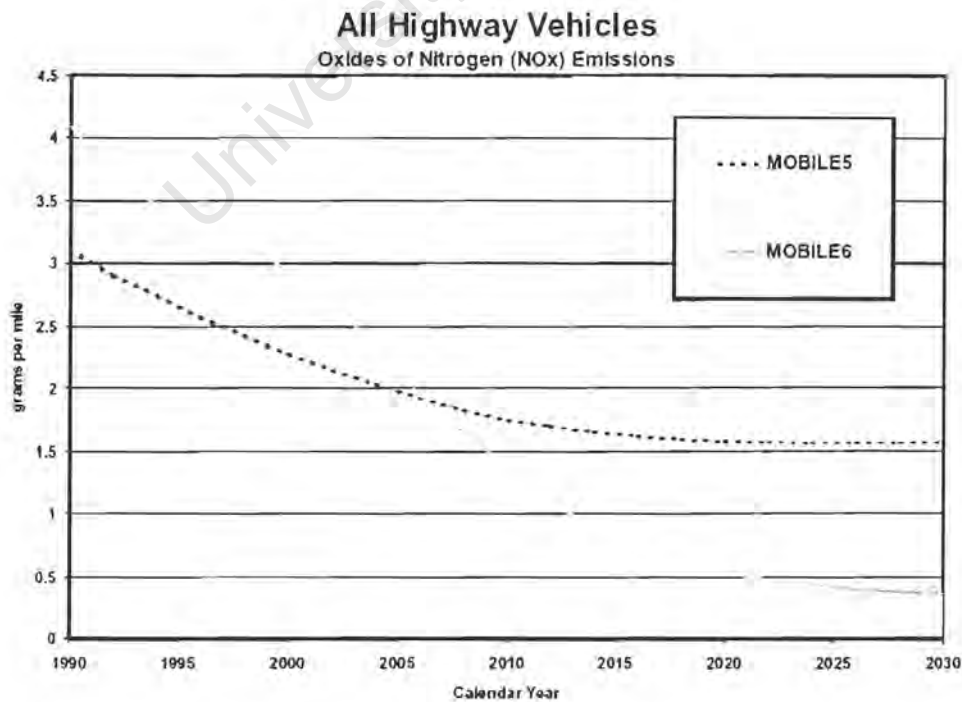


Figure E - 1: Example of EPA Mobile 6 output for NO<sub>x</sub> Emissions <sup>(7)</sup>

Mobile 6 is an average speed approach (ASA) type model as discussed in **Section 3.10.1 of CHAPTER 3**, but can disaggregate mobile sources by a number of other criteria, for example the following:

- 28 individual vehicle categories
- Altitude of operation
- Vehicle speed
- Ambient temperature
- Fuel properties
- Mode of operation
- Mileage accrual rate
- Inspection and maintenance programmes
- Deterioration of emissions with age of the vehicle

Cold start and evaporative emissions are also taken into account. The approach with heavy-duty vehicles is work specific rather than directly vehicle speed based as is the case with light duty vehicles. This facilitates the use of work specific test data measured for regulatory purposes. The calculation procedure is expressed below by **Equation 37** (51).

If:  $EF$  = Emissions Factor (grams/mile)  
 $E$  = Work Specific Emissions (grams/bhp.h)  
 $C$  = Conversion Factor (bhp.h/mile)

$$EF = E X C \quad \dots(\text{Equation 37})$$

The conversion factor is related to operational duty cycle and vehicle speed. Mobile 6 vehicle category numbers 14 - 23 and 26 - 28 are diesel vehicles. **Table E - 1** below indicates their vehicle mass criteria and the default annual mileages assigned to each category. These are used to estimate parameters like the number of cold starts per day. The mileages shown are for the year 2000. Mobile6 does however allow age related mileage accrual to be modelled. Annual mileages are presumed to diminish with age according to a curve. Deterioration of emissions with age is modelled by defining a deterioration rate in units of grams per brake horsepower per 10 000 miles, using experimental data (51).

**Table E - 1:** EPA Mobile6 Diesel Vehicle Categories and Default Annual Mileages for year 2000 <sup>(103)</sup>

Category Number	Vehicle Code	Default Annual Mileage (km)	Vehicle Type	Gross Vehicle Mass (kg)
14	LDDV	11,050	Light-Duty Diesel Passenger Cars	
15	LDDT12	5,805	Light-Duty Diesel Trucks 1 and 2	0 – 2 722 kg
16	HDDV2B	25,195	Class 2b Heavy-Duty Diesel Vehicles	3 857 – 4 536 kg
17	HDDV3	27,010	Class 3 Heavy Duty Diesel Vehicles	4 537 – 6 350 kg
18	HDDV4	34,901	Class 4 Heavy Duty Diesel Vehicles	6 351 – 7 258 kg
19	HDDV5	36,560	Class 5 Heavy Duty Diesel Vehicles	7 259 – 8 845 kg
20	HDDV6	35,990	Class 6 Heavy Duty Diesel Vehicles	8 846 – 11 794 kg
21	HDDV7	34,136	Class 7 Heavy Duty Diesel Vehicles	11 795 - 14969 kg
22	HDDT8A	59,973	Class 8a Heavy Duty Diesel Vehicles	14 970 – 27 216 kg
23	HDDT8B	93,242	Class 8b Heavy Duty Diesel Vehicles	> 27 216 kg
26	HDDBT	55,741	Diesel Transit and Urban Buses	
27	HDDBS	15,902	Diesel School Buses	
28	LDDT34	24,979	Light-Duty Diesel Trucks 3 and 4	2 723 – 3 856 kg

Mobile 6 assumes a mathematical distribution of vehicle population for each category that is a function in vehicle age. This is similar to the technique of scrapping factors applied in this study. Examples of these curves are presented below in **Table E - 2**.

Table E - 2: Age dependent curves fitted to the US Vehicle Population for the Mobile6 Model <sup>(104)</sup>

Aggregate Vehicle Category	Equation	Vehicle Ages
Light-duty vehicle	$y = (8,517,910 * e^{-(age/16.10050554)^{4.45489164}})$ $y = 112855609.5568e^{(-0.2321*age)}$	1-12 13-25
Light-duty truck 0-6,000 lbs	$y = (3.386,682 * e^{-(age/14.38211814)^{3.04037069}})$ $y = 805298.7399e^{(-0.0409*age)}$	1-18 19-25
Light-duty trucks 6,001-8,500 lbs	$y = 1305324.4e^{(-0.070863*age)}$	1-25
Heavy-duty vehicles classes 2B-3	$y = 732326.5e^{(-0.09455*age)}$	1-25
Heavy-duty vehicles classes 4-8	$y = 404143.88e^{(-0.066843*age)}$	1-25
Heavy-duty school buses	$y = 38982e^{(-0.068092*age)}$	1-25
Heavy-duty transit buses	$y = (3462 * e^{-(age/17.16909475)^{12.53214119}})$ $y = 24987.0776 e^{(-0.2000*age)}$	1-17 18-25

University of Cape Town

## APPENDIX F EUROPEAN ENVIRONMENT AGENCY (EEA) COPERT III EMISSIONS FACTOR MODEL: HEAVY-DUTY METHODOLOGY

The European Environment Agency (EEA) is a European Union organisation that was established in 1990. Its stated mission is as follows:

*"...to support sustainable development and to help to achieve significant and measurable improvements in Europe's environment through the provision of timely, targeted, relevant and reliable information to policy-making agents and the public."*

In 1994 the EEA in turn appointed the European Topic Centre for Air Emissions (ETC/AE) to act on its behalf as a centre of technical expertise on atmospheric emissions. The ETC/AE has in this capacity designed the COPERT III computer model, a Microsoft™ Windows® supported application developed to calculate emissions factors from mobile sources. The EEA provides this software to European Union member states as part of its CORINAIR (CORe INventory for AIR Emissions) database initiative. This is a database of emission inventories for Europe maintained by ETC/AE. European Union members are required by law to submit emissions inventories conforming to standard categories of pollutants and sources.

COPERT III applies a continually revised empirical database of actual emissions measurements to an extensive disaggregation of the vehicle population based on technological and operational factors. The model separately estimates the emissions of vehicle categories with a hot engine, after cold starting and evaporative emissions from the fuel system. The basic methodology is shown below in **Figure F - 1**:

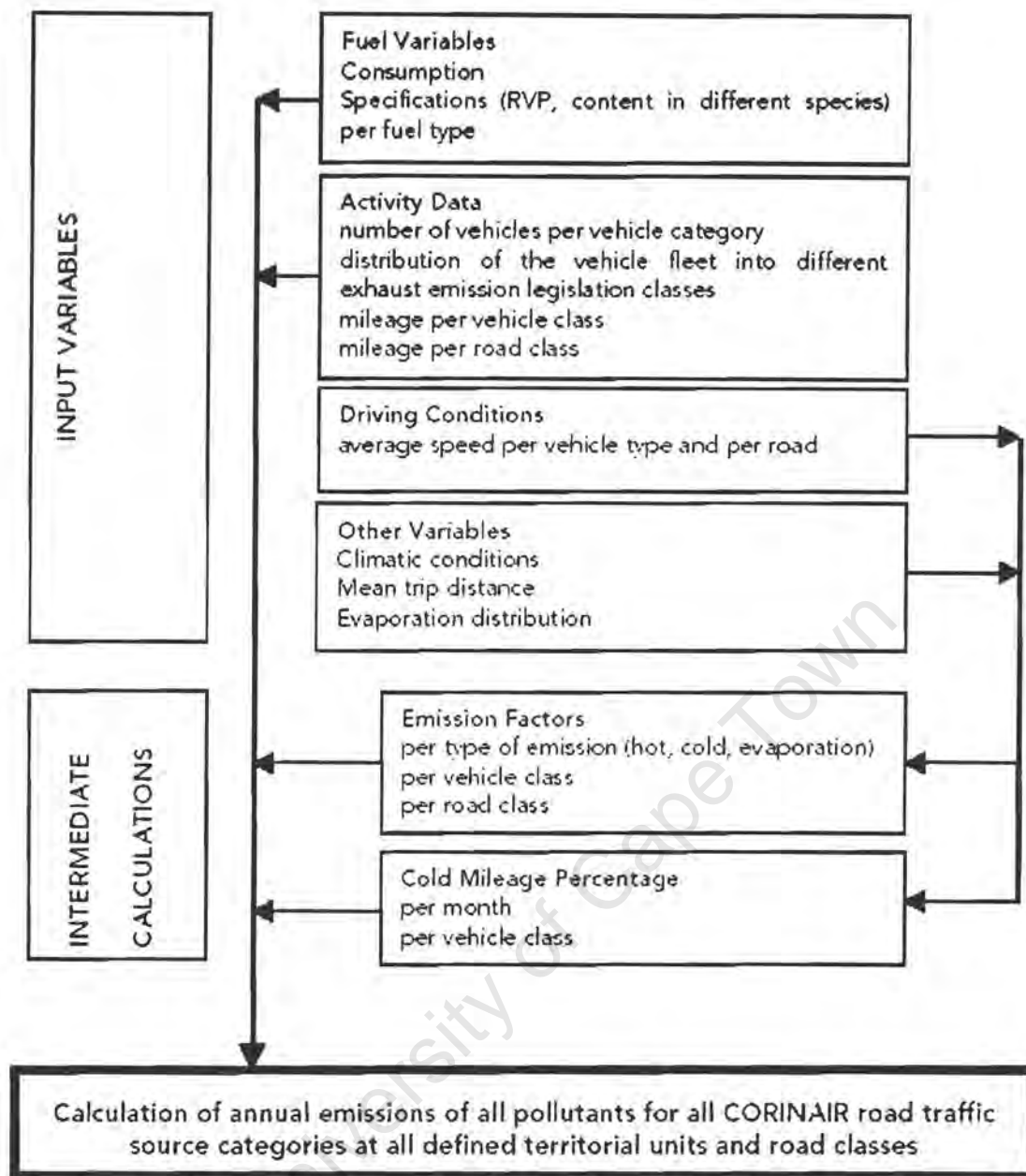


Figure F - 1: Schematic of the COPERT III Model Methodology <sup>(74)</sup>

As indicated in the third tier of the Input Variables of **Figure F - 1** above, the COPERT III model derives emission factors for mobile sources using an Average Speed Approach (ASA) method like the EPA Mobile6 (**APPENDIX E**) and IPIECA models. This approach is discussed in **Section 3.10.1** of **CHAPTER 3**. Baseline emission factors are calculated using speed dependent equations derived from empirical data. The equations applied to heavy-duty diesel engines are presented below in **Table F - 1**.

**Table F - 1:** COPERT III Speed Dependent Emission and Fuel Consumption Factors for Heavy-duty Vehicles with Vehicle Mass > 3.5 tons

Pollutant	Weight Class	Speed Range [km/h]	Emission Factor [g/km]	R <sup>2</sup>
CO	All Weight Categories	0-100	$37,280V^{-0,6945}$	0,880
	Weight<7,5t	0 - 46,7	$50,305V^{-0,7708}$	0,902
NO <sub>x</sub>	Weight<7,5t	46,7 - 100	$0,0014V^2 - 0,1737V + 7,5506$	0,260
		7,5<Weight<16t	0 - 58,8	$92,584V^{-0,7993}$
	16<Weight<32t	58,8 - 100	$0,0006V^2 - 0,0941V + 7,7785$	0,440
		0 - 100	$108,36V^{-0,6061}$	0,650
	Weight>32t	0 - 100	$132,88V^{-0,5581}$	0,894
VOC	All Weight Categories	0-100	$40,120V^{-0,8774}$	0,976
	Weight<7,5t	0 - 100	$4,5563V^{-0,7070}$	0,944
PM	7,5<Weight<16t	0 - 100	$9,6037V^{-0,7259}$	0,974
	16<Weight<32t	0 - 100	$10,890V^{-0,7105}$	0,946
	Weight>32t	0 - 100	$11,028V^{-0,6960}$	0,961
	Weight<7,5t	0 - 47	$1425,2V^{-0,7993}$	0,990
		47 - 100	$0,0082V^2 - 0,0430V + 60,12$	0,798
Fuel Consumption	7,5<Weight<16t	0 - 59	$1068,4V^{-0,4905}$	0,628
		59 - 100	$0,0126V^2 - 0,6589V + 141,18$	0,037
	16<Weight<32t	0 - 59	$1595,1V^{-0,4744}$	0,628
		59 - 100	$0,0382V^2 - 5,1630V + 399,3$	0,037
	Weight>32t	0 - 58	$1855,7V^{-0,4367}$	0,914
58 - 100	$0,0765V^2 - 11,414V + 720,9$	0,187		

The first level of disaggregation is therefore the type of roads used by vehicles and the average vehicle speed estimated for that road type so that the equations in **Figure F - 1** can be applied. A number of correction factors are then applied to the emission factors calculated by the speed dependent equations to account for the following:

- Technology level of the vehicle (regulation compliance, Euro I, Euro II etc.)
- Fuel properties
- Vehicle Age distribution
- Road Gradient
- Load Factor (commercial vehicles)
- Effect of Inspection and Maintenance schemes
- Estimated number of cold starts

The methodology for fuel property correction of emissions by the COPERT III equations is described below. The equations for heavy-duty diesel emissions are presented in **Figure F - 2** and for light-duty diesel emissions in **Figure F - 3**.

**Figure F - 2:** COPERT III Correction Factors for the Effect of Fuel Properties on Heavy-duty Diesel Emissions <sup>(74)</sup>

Pollutant	Correction factor equation
CO	$FCorr = 2,24407 - 0,0011 \cdot DEN + 0,00007 \cdot PAH - 0,00768 \cdot CN - 0,00087 \cdot T_{95}$
VOC	$FCorr = 1,61466 - 0,00123 \cdot DEN + 0,00133 \cdot PAH - 0,00181 \cdot CN - 0,00068 \cdot T_{95}$
NO <sub>x</sub>	$FCorr = -1,75444 + 0,00906 \cdot DEN - 0,0163 \cdot PAH + 0,00493 \cdot CN + 0,00266 \cdot T_{95}$
PM	$FCorr = [0,06959 + 0,00006 \cdot DEN + 0,00065 \cdot PAH - 0,00001 \cdot CN] \cdot [1 - 0,0086 \cdot (450 - S)/100]$

- DEN = Density at 15°C [kg/m<sup>3</sup>]
- S = Sulphur content in ppm
- PAH = Polycyclic aromatics content in %
- CN = Cetane number
- T<sub>95</sub> = Back end distillation in °C

**Figure F - 3:** COPERT III Correction Factors for the Effect of Fuel Properties on Light-duty Diesel Emissions <sup>(74)</sup>

Pollutant	Correction factor equation
CO	$FCorr = -1,3250726 + 0,003037 \cdot DEN - 0,0025643 \cdot PAH - 0,015856 \cdot CN + 0,0001706 \cdot T_{95}$
VOC	$FCorr = -0,293192 + 0,0006759 \cdot DEN - 0,0007306 \cdot PAH - 0,0032733 \cdot CN - 0,000038 \cdot T_{95}$
NO <sub>x</sub>	$FCorr = 1,0039726 - 0,0003113 \cdot DEN + 0,0027263 \cdot PAH - 0,0000883 \cdot CN - 0,0005805 \cdot T_{95}$
PM	$FCorr = (-0,3879873 + 0,0004677 \cdot DEN + 0,0004488 \cdot PAH + 0,0004098 \cdot CN + 0,0000788 \cdot T_{95}) \cdot [1 - 0,015 \cdot (450 - S)/100]$

DEN = Density at 15°C [kg/m<sup>3</sup>]  
 S = Sulphur content in ppm  
 PAH = Polycyclic aromatics content in %

CN = Cetane number  
 T<sub>95</sub> = Back end distillation in °C

The baseline emissions are corrected for variations in fuel properties by solving "FCorr" independently for both the baseline fuel and the new fuel, and then multiplying the baseline emission by the ratio of the two as follows <sup>(74)</sup>:

- If:
- E = Baseline Emission
  - E<sub>c</sub> = Corrected Emission
  - FCorr<sub>B</sub> = Correction factor for baseline fuel properties
  - FCorr<sub>C</sub> = Correction factor for new fuel

$$E_C = \left( \frac{FCorr_C}{FCorr_B} \right) \cdot E \quad \dots(\text{Equation 38})$$

Load factor (defined as Duty Cycle Factor in this study) is another parameter that can be assumed to have a significant effect on South African mobile source emissions due to reported overloading <sup>(95)</sup> and the variable topography of the country. The COPERT III load factor corrections are presented below in **Table F - 2**. These corrections assume baseline emission factors are measured from a test with a 50% duty cycle factor.

**Table F - 2:** COPERT III Load Correction Factors for Heavy-duty Vehicles <sup>(74)</sup>

Pollutant	Load Factor (Correction)
CO	0,21
NO <sub>x</sub>	0,18
VOC	0,00
PM	0,08
Fuel Consumption	0,18

The corrected emission factor is calculated as follows using the above correction factors:

- If:
- EF<sub>c,i</sub> = Corrected Emission Factor for i<sup>th</sup> vehicle group
  - EF<sub>i</sub> = Uncorrected Emission Factor for i<sup>th</sup> vehicle group
  - C<sub>f</sub> = Correction factor from **Table F - 2** above
  - DC<sub>i</sub> = Estimated Duty Cycle Factor (Load factor) in % of Full Load for ith vehicle group

$$EF_{c,i} = EF_i \times \left( 1 + \frac{2C_f \times (DC_i - 50)}{100} \right) \quad \dots(\text{Equation 39})$$

For example the University of Natal's SIMTRANS simulation has calculated a duty cycle factor of 55.6% for long haul commercial vehicle powered by a 320 kW ADE 442T travelling from Durban to Johannesburg <sup>(100)</sup>. If this was taken as representative of a South African vehicle group the particulate matter emission factor derived from the R49 test as used in this study which has a duty cycle factor of 50% would be corrected as follows:

If: PM = Measured emissions of particulate matter

$$EF_{c,i} = PM \times \left( 1 + \frac{2 \times 0.08 \times (55.6 - 50)}{100} \right)$$

$$EF_{c,i} = 1.00896 \bullet PM \quad \text{about 0.9\% increase in PM emissions}$$

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## APPENDIX G EMISSION INVENTORY AND EMISSION FACTOR DATA FROM THE LITERATURE

The results of the modelling phase of this study can be compared to other work in South Africa and elsewhere. Such data is presented below.

### APPENDIX G1 THE UK NATIONAL ATMOSPHERIC EMISSIONS INVENTORY (NAEI)

The NAEI <sup>(68,69)</sup> has a high degree of disaggregation for road transport emissions factors, particularly as regards the type of road on which the vehicle operates. Typically these are obtained from the EEA's COPERT programme (**APPENDIX F**). Those that apply to diesel commercial vehicles are presented below:

**Table G - 1:** NAEI Emission Factors for NMVOC (g/km) <sup>(68)</sup>

Emission Standard		Urban	Rural single c/way	Rural dual c/way	Motorway
Diesel LGV	Pre-Euro I	0.30	0.16	0.19	0.18
	Euro I	0.23	0.13	0.10	0.10
	Euro II	0.16	0.09	0.07	0.07
Rigid HGVs	Old	6.42	3.21	3.21	3.21
	Pre-Euro I	1.84	1.44	1.39	1.39
	Euro I	1.08	0.71	0.59	0.57
	Euro II	1.00	0.65	0.53	0.52
Artic HGVs	Old	6.78	3.21	3.21	3.21
	Pre-Euro I	1.63	1.05	0.86	0.83
	Euro I	0.97	0.68	0.59	0.57
	Euro II	0.89	0.61	0.51	0.49

LGV: Light Goods Vehicle

HGV: Heavy Goods Vehicle

Artic: Articulated chassis

NMVOC: Non-methane Volatile Organic Compounds (broadly equivalent to unburned hydrocarbons less methane)

Euro II: Manufactured to 1996 European emissions standards

Euro I: Manufactured to 1992 European emissions standards

C/way: Carriageway

**Table G - 2:** NAEI Emission Factors for CO (g/km) <sup>(68)</sup>

Emission Standard		Urban	Rural single c/way	Rural dual c/way	Motorway
Diesel LGV	Pre-Euro I	1.09	0.84	1.36	1.29
	Euro I	0.82	0.57	0.80	0.76
	Euro II	0.57	0.40	0.56	0.54
Rigid HGVs	Old	6.00	2.90	2.90	2.90
	Pre-Euro I	2.64	2.12	1.99	1.97
	Euro I	1.66	1.16	0.97	0.95
	Euro II	1.45	1.07	0.92	0.90
Artic HGVs	Old	7.30	3.70	3.70	3.10
	Pre-Euro I	3.06	2.48	2.46	2.47
	Euro I	1.67	1.23	1.07	1.05
	Euro II	1.39	1.15	1.07	1.05

**Table G - 3:** NAEI Emission Factors for NO<sub>x</sub> (g/km) <sup>(68)</sup>

Emission Standard		Urban	Rural single c/way	Rural dual c/way	Motorway
Diesel LGV	Pre-Euro I	1.22	1.15	1.53	1.48
	Euro I	0.54	0.31	0.41	0.39
	Euro II	0.38	0.21	0.28	0.27
Rigid HGVs	Old	11.80	14.40	14.40	14.40
	Pre-Euro I	5.02	4.96	5.65	5.91
	Euro I	3.94	3.24	3.38	3.47
	Euro II	3.16	2.51	2.59	2.65
Artic HGVs	Old	18.20	24.10	24.10	19.80
	Pre-Euro I	16.93	12.93	11.69	11.52
	Euro I	9.14	6.82	5.98	5.86
	Euro II	7.48	5.58	4.89	4.79

**Table G - 4:** NAEI Emissions Factors for PM10 (g/km) <sup>(68)</sup>

Emission Standard		Urban	Rural single c/way	Rural dual c/way	Motorway
Diesel LGV	Pre-Euro I	0.361	0.304	0.453	0.433
	Euro I	0.109	0.082	0.158	0.148
	Euro II	0.065	0.049	0.095	0.089
Rigid HGVs	Old	1.831	1.129	1.033	1.033
	Pre-Euro I	0.534	0.415	0.406	0.408
	Euro I	0.352	0.241	0.204	0.199
	Euro II	0.171	0.118	0.099	0.097
Artic HGVs	Old	1.520	0.910	0.710	0.710
	Pre-Euro I	0.785	0.579	0.517	0.508
	Euro I	0.538	0.372	0.316	0.308
	Euro II	0.207	0.143	0.121	0.118

The total annual emissions in the United Kingdom are reported by the NAEI for all the pollutants that were assessed locally for this study. Diesel and petrol emissions are reported separately as sub sections of total Road Transport for the 1996 report <sup>(69)</sup> but from 1997 until the latest 1999 report <sup>(68)</sup>, only total Road Transport is reported although diesel and petrol are still disaggregated in the calculations. The results for Road Transport and those available for diesel vehicles only are presented below in **Table G - 5** and compared to the total diesel and petrol consumption for the United Kingdom.

Table G - 5: Total Annual Road Transport Emissions for the United Kingdom (NAEI) <sup>(68,69)</sup>

		Year											
		1970	1980	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
CO <sub>2</sub> (Mt C)	Road Trans. Total	16.3	21.2	29.7	29.5	29.9	30.3	30.4	30.1	31.3	31.7	31.5	31.2
	Diesel Veh. Only	4.3	5	9.1			10.1	11.1	11.5	12.3			
PM <sub>10</sub> (kt)	Road Trans. Total	44	53	59	58	55	53	52	47	44	39	35	32
	Diesel Veh. Only	33	37	45			43	43	40	37			
CO (kt)	Road Trans. Total	5427	5378	5235	5072	4855	4525	4268	4003	3961	3726	3507	3293
	Diesel Veh. Only												
NO <sub>x</sub> (kt)	Road Trans. Total	769	989	1306	1275	1225	1147	1084	997	956	880	786	714
	Diesel Veh. Only	364	427	536			494	484	448	423			
SO <sub>2</sub> (kt)	Road Trans. Total	44	42	63	58	62	59	63	51	37	27	23	12
	Diesel Veh. Only												
NMVOC (kt)	Road Trans. Total	523	601	698	680	648	601	563	515	479	434	389	351
	Diesel Veh. Only	104	117	130			114	109	98	90			
UK Diesel Cons. (Mt)		<i>5.02*</i>	<i>5.84</i>	<i>10.63</i>			<i>11.80</i>	<i>12.97</i>	<i>13.44</i>	<i>14.37</i>	<i>14.98</i>	<i>15.14</i>	<i>15.2</i>
UK Petrol Cons. (Mt)		<i>14.15</i>	<i>19.11</i>	<i>24.30</i>			<i>23.83</i>	<i>22.76</i>	<i>21.94</i>	<i>22.41</i>	<i>22.25</i>	<i>21.85</i>	<i>21.5</i>
Diesel Pass. Cars (% pop.)				3%						10%	11%	11%	12%

\*: *Data in small font italics are calculated from CO<sub>2</sub> emissions*

Mt C: *tons X 10<sup>6</sup> of carbon equivalent*

kt: *tons X 10<sup>3</sup>*

## APPENDIX G2 SOUTH AFRICAN TRANSPORT EMISSIONS MODELLED BY GERSON

Gerson <sup>(30)</sup> used emission factors for diesel fuel usage to calculate South African transport emissions as part of an emissions inventory of the energy sector. The emission factors were referenced to Ledbetter (1972) and therefore almost certainly represent an outdated appraisal of probable emissions. The emission factors and Gerson's inventory for the total transport sector including petrol use for 1989 are presented below in Table G - 6.

Table G - 6: Emission Factors and Inventory for South African Transport Sector (1989) estimated by Gerson <sup>(30)</sup>

Pollutant	HC <sub>n</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	PM
Emission Factors (kg / 1000 litres diesel)	16.3	7.2	26.6	4.8	13.2
Total Transport Sector Emissions (kt)	276	2356	236	39	61

## APPENDIX G3 EUROPEAN CORINAIR RESULTS FOR 1994

The European Environment Agency (EEA) keeps annual emissions inventories for European countries in its CORINAIR database. The heavy vehicle (> 3.5 tons) contribution to the 1994 inventories for France, Germany and Sweden <sup>(70)</sup> are presented below in **Table G - 7**:

**Table G - 7:** CORINAIR Emissions Inventory Contribution of Heavy Vehicles > 3.5t for 1994 <sup>(70)</sup>

COUNTRY	Total Emissions in tons/annum (CO <sub>2</sub> in kt/annum)					
	SO <sub>2</sub>	NO <sub>x</sub>	NM VOC	CO	CO <sub>2</sub>	CH <sub>4</sub>
France	41 226	309 557	51 378	213 984	23 530	1711
Germany	27 447	455 175	63 127	137 078	41 696	1953
Sweden	629	67 220	6 449	19 967	3 390	720

## APPENDIX G4 VARIOUS INTERNATIONAL DIESEL VEHICLE EMISSION FACTORS

Faiz et al <sup>(27)</sup> (Pg 41, pp 57-61) have reviewed various emissions factors for diesel vehicles derived for the European and US transport sectors. A selection of this data is presented below:

**Table G - 8:** Diesel Vehicle Emission Factors for Europe <sup>(27)</sup>

### Estimated Emissions, European Medium- to Heavy-Duty Vehicles (grams per kilometer)

Vehicle type	Carbon monoxide	Hydrocarbons	Nitrogen oxides	Particulate matter	CH <sub>4</sub>	N <sub>2</sub> O	NH <sub>3</sub>	Fuel consumption (liters/100km)
<b>Urban</b>								
3.5-16.0 tons	18.8	2.79	8.7	0.95	0.085	0.030	0.003	27.03
More than 16.0 tons	18.8	5.78	16.2	1.60	0.175	0.030	0.003	43.48
<b>Rural</b>								
3.5-16.0 tons	7.3	0.76	7.4	0.82	0.010	0.030	0.003	22.22
More than 16.0 tons	7.3	2.58	14.8	1.40	0.080	0.030	0.003	38.46
<b>Motorway</b>								
3.5-16.0 tons	4.2	0.62	6.0	1.67	0.020	0.030	0.003	18.18
More than 16.0 tons	4.2	2.27	13.5	1.25	0.070	0.030	0.003	34.48

**Notes:**

\* Average driving speed for urban: 25 km/h; rural: 75 km/h; and highway: 100 km/h.

\* Emission factors in g/km are derived from the COPERT model for 1990, utilizing the CORINAIR methodology for road traffic emissions. The pollutants included are: CO, NO<sub>x</sub>, TPM. Fuel consumption is also estimated.

Source: Samaras 1992

### Exhaust Emissions, European Heavy-Duty Vehicles

(grams per kilometer)

Engine type and vehicle loading	Carbon monoxide	Hydrocarbons	Nitrogen oxides	Particulate matter
Natural aspiration, 3.5-16.0 tons	3.41	0.61	6.58	0.55
<b>Turbo-charged</b>				
3.5-16.0 tons	2.00	0.57	13.07	0.37
16.0-38.0 tons	4.21	1.06	26.90	0.71
Turbo-charged with inter-cooling, 16.0-38.0 tons	5.37	1.00	16.90	0.61

Source: Sawyer 1986

Table G - 9: Diesel Vehicle Emission Factors for the United States <sup>(27)</sup>**Estimated Emission and Fuel Consumption Factors for U.S. Heavy-Duty Diesel-Fueled Trucks and Buses***(grams per kilometer)*

<i>Vehicle type</i>	<i>Carbon monoxide</i>	<i>Hydrocarbons</i>	<i>Nitrogen oxides</i>	<i>Particulate matter</i>	<i>Carbon dioxide</i>	<i>Fuel consumption (liters/100 km)</i>
<b>U.S. heavy-duty diesel trucks</b>						
Advanced control	6.33	1.32	5.09	—	982	35.7
Moderate control	7.24	1.72	11.56	—	991	35.7
Uncontrolled	7.31	2.52	15.55	—	1,249	45.5
<b>U.S. 1984 measurements</b>						
Single-axle tractors	3.75	1.94	9.37	1.07	1,056	—
Double-axle tractors	7.19	1.74	17.0	1.47	1,464	—
Buses	27.40	1.71	12.40	2.46	1,233	—
<b>New York City vehicles</b>						
Medium-heavy trucks	—	2.84	23.28	2.46	—	53.8
Transit buses	—	5.22	34.89	2.66	—	80.7

— Not applicable

Note: MOBILE5 estimates.

Source: Chan and Reale 1994; Weaver and Turner 1991; Weaver and Klausmeier 1988

Table G - 10: Diesel Vehicle Emission Factors for France <sup>(27)</sup>**Exhaust Emissions and Fuel Consumption, Utility and Heavy-Duty Trucks, France***(grams per kilometer)*

<i>Vehicle type</i>	<i>Avg. Speed km/h</i>	<i>Fuel Consmp. km/l</i>	<i>Carbon monoxide</i>	<i>Hydrocarbons</i>	<i>Nitrogen oxides</i>	<i>Particulate matter</i>
<b>Empty</b>						
Utility truck (3.5t), IDI	76.5	11.0	1.0	0.6	1.6	0.5
	123.7	6.1	1.7	1.6	1.9	2.0
Heavy-duty truck (19t), DI	68.9	4.3	2.6	0.8	15.5	0.5
	88.4	3.9	2.8	0.7	12.0	0.4
Semi-trailer (40t), DI	69.2	4.0	1.9	1.1	6.7	0.9
	88.0	3.7	1.7	1.0	7.4	0.9
<b>Loaded</b>						
Utility truck (3.5t), IDI	74.2	9.3	1.2	0.9	1.6	0.9
	117.7	5.8	1.7	1.8	1.9	2.3
Heavy-duty truck (19t), DI	66.8	3.5	3.1	0.8	16.4	0.5
	84.7	3.4	3.8	0.7	13.4	0.5
Semi-trailer (40t), DI	62.2	2.3	3.2	1.1	10.7	1.4
	75.6	2.4	3.0	1.0	10.1	1.3

Source: Roumegoux 1995

Table G - 11: Diesel Vehicle Emission Factors for the Netherlands<sup>(27)</sup>

**Exhaust Emissions, Utility and Heavy-Duty Vehicles, Netherlands**  
(grams per kilometer)

<i>Testing procedure and loading</i>	<i>Carbon monoxide</i>	<i>Hydrocarbons</i>	<i>Nitrogen oxides</i>	<i>Particulate matter</i>
<b>Urban</b>				
Less than 3.5 tons	3.0	1.3	1.3	1.2
3.5-5.5 tons	4.0	2.0	6.0	1.5
5.5-12.0 tons	10.0	7.0	10.0	3.5
12.0-15.0 tons	13.0	9.0	13.0	5.0
More than 15.0 tons	16.0	12.0	20.0	7.0
<b>Rural</b>				
Less than 3.5 tons	1.5	0.7	1.3	0.6
3.5-5.5 tons	2.0	1.0	6.0	1.0
5.5-12.0 tons	4.0	2.5	10.0	2.0
12.0-15.0 tons	4.5	3.0	13.0	2.5
More than 15.0 tons	5.0	3.5	20.0	3.0
<b>Highway</b>				
Less than 3.5 tons	0.9	0.5	1.4	0.5
3.5-5.5 tons	1.0	0.8	7.0	0.9
5.5-12.0 tons	1.5	2.0	13.0	1.8
12.0-15.0 tons	2.0	2.3	15.0	2.0
More than 15.0 tons	2.0	2.5	25.0	2.5

Source: Veidt 1986

## APPENDIX H TEST ENGINE SPECIFICATIONS

Table H - 1 below lists some important basic specifications for the test engines:

Table H - 1: VEP Programme and BP Africa Supplementary Data: Test Engine Specifications

ADE (SA) Name:	TEST ENGINE						
	314N	364N	364T	407N	447N	447T	447TI
European Equiv.:	OM 314	OM 364	OM364A	OM407	OM447	OM447A	OM447LA
NO. OF CYLINDERS	4	4	4	6	6	6	6
CYLINDER BORE	97 mm	97.5 mm	97.5 mm	125 mm	128 mm	128 mm	128 mm
PISTON STROKE	128 mm	133 mm	133 mm	155 mm	155 mm	155 mm	155 mm
TOTAL PISTON DISPLACEMENT	3784 cm <sup>3</sup>	3972 cm <sup>3</sup>	3972 cm <sup>3</sup>	11 410 cm <sup>3</sup>	11 967 cm <sup>3</sup>	11 967 cm <sup>3</sup>	11 967 cm <sup>3</sup>
CYLINDER DEAD SPACE	59.1 cm <sup>3</sup>	61 cm <sup>3</sup>	64 cm <sup>3</sup>	123 cm <sup>3</sup>	129 cm <sup>3</sup>	130.8 cm <sup>3</sup>	133.0 cm <sup>3</sup>
COMPRESSION RATIO	17:1	17.25:1	16.5:1	16.5:1	16.5:1	16.25:1	16.25:1
MAXIMUM TORQUE	235 N.m	268 N.m	387 N.m	835 N.m	894 N.m	1290 N.m	1700 N.m
RATED POWER	58 kW	66 kW	85 kW	149 kW	177 kW	213 kW	294 kW
RATED SPEED	2800 rpm	2800 rpm	2800 rpm	2200 rpm	2200 rpm	2100 rpm	2100 rpm
ASPIRATION	Natural	Natural	Turbo	Natural	Natural	Turbo	Turbo-intercooled

NOTE: All the above engines were of the 4-stroke, direct injection type. All the engines were water cooled with cooling water controlled at 85°C for the duration of the tests.

## APPENDIX I TEST FUEL SPECIFICATIONS

Table I - 1: Fuel Specifications: Diesel A Coastal Fuel and Reference Diesel

PROPERTY	UNITS	Diesel A	RF-03-A-84
Acid Number (Total)	mg KOH/g	0.036	0.011
Ash	mass %	<0.01	<0.01
Cetane Number		53	50.7
Carbon Residue	mass %	0.11	0.06
Cloud Point	deg C	4	-8
Cold Filter Plugging Point	deg C	-6	-18
Copper corrosion	3 h @ 100 deg C	1a	1a
Density at 15 deg C	kg/l	0.8507	0.8363
Density at 20 deg C	kg/l	0.8474	0.8329
<b>Distillation</b>			
Initial Boiling Point	deg C	189	186
5%	deg C	219	207
10%	deg C	236	217
20%	deg C	258	232
30%	deg C	273	244
40%	deg C	285	256
50%	deg C	296	267
60%	deg C	308	280
70%	deg C	321	294
80%	deg C	335	310
90%	deg C	355	332
95%	deg C	371	351
Final Boiling Point	deg C	386	362
Recovery	vol %	98	98
Residue	vol %	1.2	1.5
Water Coulometric	mg/kg	150	40
Flash Point PMCC	deg C	72	70
Sulphur	mass %	0.45	0.19
Viscosity kinematic	cSt	3.867	2.803
Calorific Value	MJ/kg	42.6	42.8
Nitrogen	mg/l		71
Carbon	mass %	87	86
Hydrogen	mass %	13	14
Oxygen	mass %		
Total Aromatics	mass %	39	
Polynuclear Aromatics	mass %	5	
Additives	ppm v/v		none

Table I - 2: Fuel Specifications: Altitude Fuels Diesel B and Diesel C

PROPERTY	UNITS	Diesel B	Diesel C
Acid Number (Total)	mg KOH/g	0.02	0.05
Ash	mass %	<0.01	<0.01
Cetane Number		53	52
Carbon Residue	mass %	0.075	0.08
Cloud Point	deg C	-1	6
Cold Filter Plugging Point	deg C	-8	-6
Copper corrosion	3 h @ 100 deg C	1b	1b
Density at 15 deg C	kg/l	0.8322	0.8517
Density at 20 deg C	kg/l	0.8287	0.8483
<b>Distillation</b>			
Initial Boiling Point:	deg C	175	187
5%	deg C	193	212
10%	deg C	200	228
20%	deg C	211	251
30%	deg C	221	269
40%	deg C	231	283
50%	deg C	242	296
60%	deg C	254	308
70%	deg C	271	322
80%	deg C	293	338
90%	deg C	330	359
95%	deg C	362	375
Final Boiling Point	deg C	>365	382
Recovery	vol %	98	98
Residue	vol %	1.5	1.1
Water Coulometric	mg/kg	130	160
Flash Point PMCC	deg C	67	79
Sulphur	mass %	<0.01	0.51
Viscosity kinematic	cSt	2.255	3.915
Calorific Value	MJ/kg	45.9	45.7
Nitrogen	mg/l	4	195
Carbon	mass %	87	87
Hydrogen	mass %	13	13
Oxygen	mass %	<0.01	<0.1
Total Aromatics	mass %	33.1	31.6
Polynuclear Aromatics	mass %	0.3	2
Additives	ppm v/v	Yes	Yes

**Table I - 3:** BP Africa Supplementary Data: Test Fuel Specifications

TEST	UNIT	Test Fuel Number					
		1	2	3	4	5	6
Density @ 20°C	Kg/L	0.8599	0.8599	0.8433	0.8598	0.845	0.8050
Flash Point(PMCC)	°C	83	83	83	80	80	91
Cetane Index	calc.	49	49	54	49	53	58.5
Sulphur	% mass	0.513	0.511	0.362	0.509	0.3	0.0011
Distillation: IBP	°C	214	213	214	212	215	219
10 % vol. rec. @	°C	260	260	260	260	238	228
50 % vol. rec. @	°C	304	303	302	303	252	251
90 % vol. rec. @	°C	358	358	358	358	330	328
FBP	°C	382	382	382	383	370	371
Res./Loss	% vol.	2.0/0.8	1.5/1.0	1.5/1.0	1.5/1.0	2.0/0.1	2.0/0.1
Evap. @ 262°C	% vol.	92	92	92	92		

**Key to Table I - 3**

Test Fuel Number	Product
1	Coastal Crude 1
2	Coastal Crude 2
3	Blend of Coastal Crude and Synthetic
4	Coastal Crude 3
5	Low Sulphur Coastal Crude
6	Highveld Synthetic

## APPENDIX J CALCULATIONS USED TO DETERMINE THE EMISSIONS

### APPENDIX J1 CALCULATION OF THE CO, HC<sub>N</sub>, NO<sub>x</sub>, CO<sub>2</sub> AND SO<sub>2</sub> EMISSIONS

Each 13-mode test yielded 13 different concentrations for each of these gaseous species. The concentrations then had to be converted to one weighted power specific result as follows:

- If:  $\theta_i$  = The concentration of the pollutant in the exhaust gas as measured by the analyser for the  $i$ th mode of 13
- $\theta_{f,i}$  = Mass flow rate of the pollutant for the  $i$ th mode of 13
- $G_{EXH}$  = Exhaust gas mass flowrate
- $W_i$  = Weighting factor for the  $i$ th mode of 13 as stipulated by Regulation 49 <sup>(98)</sup>
- $M_\theta$  = Molar mass of the pollutant
- $M_{EXH}$  = Molar mass of the exhaust gas
- $P_i$  = Engine power measured in  $i$ th mode
- $E$  = Weighted power specific emissions of the pollutant for the test (typical units are g/kW.h)

$$\theta_{f,i} = \frac{M_\theta}{M_{EXH}} \times \theta_i \times G_{EXH} \quad \dots(\text{Equation 40})$$

$$E = \frac{\sum_{i=1 \dots 13} (\theta_{f,i} \times W_i)}{\sum_{i=1 \dots 13} (P_i \times W_i)} \quad \dots(\text{Equation 41})$$

The ECE R49 procedure <sup>(98)</sup> prescribes an approximation for  $M_{EXH}$  for all 13 modes of 29 grams/mole. This is roughly equivalent to exhaust gas that is a mixture of 1% carbon dioxide (CO<sub>2</sub>) and 99% air. This approximation was applied in all calculations as the scope of work for the experimental phase of this study stipulated strict adherence to European standards. At rated conditions CO<sub>2</sub> concentrations can however be as high as 12% which implies that  $\theta_{f,i}$  is calculated around 5% too high using **Equation 40**.

## APPENDIX J2 CALCULATIONS RELEVANT TO THE CALCULATION OF THE PARTICULATE MATTER EMISSIONS

The particulate sample was drawn from a dilution tunnel that diluted a portion of the exhaust gas. The dilution ratio was determined by measuring the CO<sub>2</sub> concentrations in the raw exhaust, dilution tunnel and ambient dilution air. The following equation as specified by ECE R49 <sup>(98)</sup> was applied:

If  $q$  = dilution ratio  
 $CO_{2A}$  = concentration of CO<sub>2</sub> in ambient dilution air  
 $CO_{2R}$  = concentration of CO<sub>2</sub> in raw exhaust  
 $CO_{2D}$  = concentration of CO<sub>2</sub> in dilution tunnel

$$q = \frac{CO_{2R} - CO_{2A}}{CO_{2D} - CO_{2A}} \quad \dots(\text{Equation 42})$$

Two properties of the sampling system had to be controlled so that each mode was properly weighted and the stipulations of Regulation 49 were met. These were dilution ratio ( $q$ ) and the mass of diluted gas sampled through the filters for each mode ( $M_{SAM}$ ). The profound effect on particulate mass of dilution ratio has been discussed in **Section 3.1**. In the field the critical dilution stage is as the exhaust gas leaves the exhaust pipe in the period before dispersion when hydrocarbons are adsorbed onto the carbonaceous core of particulate matter. The dilution of exhaust gas upon leaving the exhaust pipe, is greater for low exhaust gas flow rates at say idle conditions than for high exhaust gas flow rates at say rated conditions. This is simulated in the test procedure by keeping the product of exhaust gas flowrate and dilution ratio, called the equivalent diluted mass flow rate, more or less constant within a band of 7% either side of the mean product. This can be expressed as follows:

If:  $G_{EXH}$  = Exhaust gas mass flowrate  
 $G_{EDF}$  = Equivalent diluted mass flow rate  
 $G_{EDF,i}$  =  $G_{EDF}$  for the  $i$ th mode of 13  
 $G_{EDF,m}$  = Mean  $G_{EDF}$  for the 13 modes

$$G_{EDF} = q \times G_{EXH} \quad \dots(\text{Equation 43})$$

$$G_{EDF,m} - (0.07 \times G_{EDF,m}) < G_{EDFi} < G_{EDF,m} + (0.07 \times G_{EDF,m}) \quad \dots(\text{Equation 44})$$

Therefore given that exhaust gas flowrate is fixed for an engine, dilution ratio (q) had to be controlled such that **Equation 44** above was satisfied. The weighting factors shown in were essentially attained by control of the sample mass  $M_{SAM}$ , although they are also a function of equivalent diluted mass flow rate to take account of relative dilution and varying exhaust gas flowrate as follows:

- If:  $M_{SAM}$  = Total mass of diluted gas sampled through filters for all 13 modes
- $M_{SAM,i}$  = Sample mass for ith mode of 13
- $W_{E,i}$  = Equivalent weighting factor for ith mode of 13. These must be within a tolerance of 0.003 of the weighting factors ( $W_i$ ) stipulated by Regulation 49 shown in **Table 20** for each mode of a test
- $W_i$  = Weighting factor for the ith mode of 13 as stipulated by Regulation 49 <sup>(98)</sup>

$$W_{E,i} = \frac{M_{SAM,i} \times \sum_{i=1 \dots 13} (G_{EDF,i} \times W_i)}{M_{SAM} \times G_{EDF,i}} \quad \dots(\text{Equation 45})$$

Therefore the modes can be weighted by controlling the mass sampled per mode for a known set of 13 dilution ratios. This gave rise to a number of practical requirements as follows:

- Each engine reacted to the exhaust sampling system in a different way. Total exhaust back pressure and critical speed effects varied. This required first commissioning the system to attain a set of 13 dilution ratios that satisfied **Equation 44** above.
- Attaining the correct equivalent weighting factors required sampling a known mass of gas. The means of measuring the amount of gas sampled was volumetric corrected by temperature. This required an entire 13-mode test to be run as part of

commissioning, using the dilution ratios determined above, so that the gas temperatures could be determined as these varied for every set-up.

The amount of gas sampled per mode for the commissioning test was taken as a volumetric proportion of the weighting factors. These then had to be corrected to mass proportional samples using measured gas temperature and dilution ratio data and recalculated to give the correct volume proportional values for use in the actual tests. An iterative process was applied using a derivation of the equations discussed above as follows:

If:  $A$  = a constant for each mode

$$A = \frac{W_i \times \sum_{i=1 \dots n} G_{EDF,i}}{G_{EDF,i}} \quad \dots(\text{Equation 46})$$

$$M_{SAM,i} = \frac{W_i \left( \sum_j^{j=1 \dots i-1} M_{SAM,j} + \sum_k^{k=i+1 \dots 13} M_{SAM,k} \right)}{(A - W_i)} \quad \dots(\text{Equation 47})$$

**Equation 47** above was applied to the commissioning data for each mode in turn until convergence occurred. The resulting set of sample masses was converted back to volume using the gas temperatures measured. The effect of varying ambient conditions on sample gas temperatures in subsequent tests was not taken into account. It must be borne in mind though that the heating effect of the engine in the test cell kept ambient temperature within a narrow band. Such errors that arose did not in general cause the equivalent weighting factors measured for a test to deviate from the stipulated weighting factors by more than the 0.003 tolerance allowed by Regulation 49. In the case where such errors caused a test to be invalid, **Equation 47** above was applied to the new data to re-correct the volumetric sample size for each mode.

Once the test was complete and the filtrate of particulate matter was weighed the particulate emissions were calculated in absolute and specific units as follows:

- If:  $M_f$  = Mass of particulate matter filtrate  
 $P_i$  = Engine power measured in  $i$ th mode  
 $PM_f$  = Weighted particulate matter emission mass flow rate for the test  
 $PM$  = Weighted power specific particulate matter emissions for the test  
 (typical units are g/kW.h)

$$PM_f = \frac{M_f \times \sum_{i=1 \dots 13} (G_{EDF,i} \times W_i)}{M_{SAM}} \quad \dots(\text{Equation 48})$$

$$PM = \frac{PM_f}{\sum_{i=1 \dots 13} (P_i \times W_i)} \quad \dots(\text{Equation 49})$$

### APPENDIX J3 CALCULATION OF THE ALDEHYDE AND HYDROCARBON SPECIES EMISSIONS

The method of calculating the aldehyde and hydrocarbon species emissions was similar to that applied to the particulate emissions discussed above in **APPENDIX J2**. In all three cases the 13-mode test yielded one composite result weighted by proportional sampling.

In the case of the aldehyde measurements, the mass of hydrozone derivatives detected by chromatography was converted to a mass of aldehyde. This could then be applied to **Equation 48** and **Equation 49** with the mass of aldehyde replacing the mass of particulate matter filtrate ( $M_f$ ). The mass sampled per mode ( $M_{SAM,i}$ ) was completely different though and in different proportions to the particulate samples. The aldehyde sample was not diluted and therefore dilution ratio ( $q$ ) was effectively a value of 1. This was applied to **Equations 45 – 47** to calculate the correct sample size for each mode. Clearly the equivalent diluted mass flow  $G_{EDF}$  was not at all constant in this instance as is required with particulate measurement. It must be remembered though that the mass of aldehyde is not affected by adsorption phenomena dependent on dilution ratio as is the case with particulate matter. Loss of aldehyde itself to possible adsorption on particulate matter was precluded by filtering out the particulate matter before sampling.

The hydrocarbon species were sampled from the particulate dilution tunnel and therefore the samples taken for each mode were an exact proportion of those taken for particulate matter measurements in order to correctly weight the result. The only difference in calculation method stems from the result being a concentration of the pollutant in the sample bag rather than the mass of a filtrate. This concentration then simply replaces the ratio of filtrate mass to sample mass ( $M_f / M_{SAM}$  term) in **Equation 48** above so that hydrocarbon species emissions can be calculated.

APPENDIX K SAMPLING EQUIPMENT DRAWINGS AND PHOTOGRAPHS

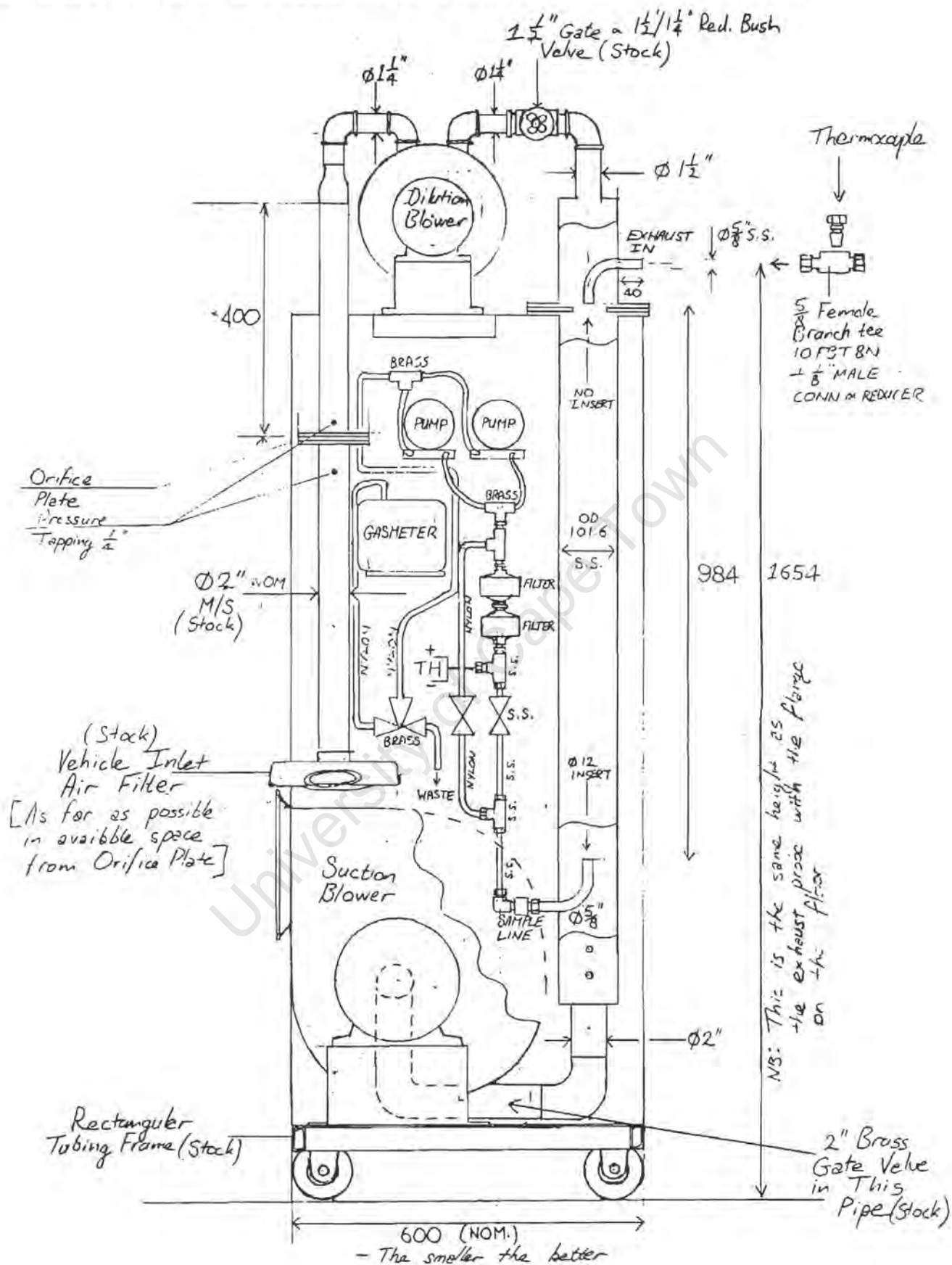


Figure K - 1:

Dimensioned Layout of VEP Partial Flow Dilution Tunnel

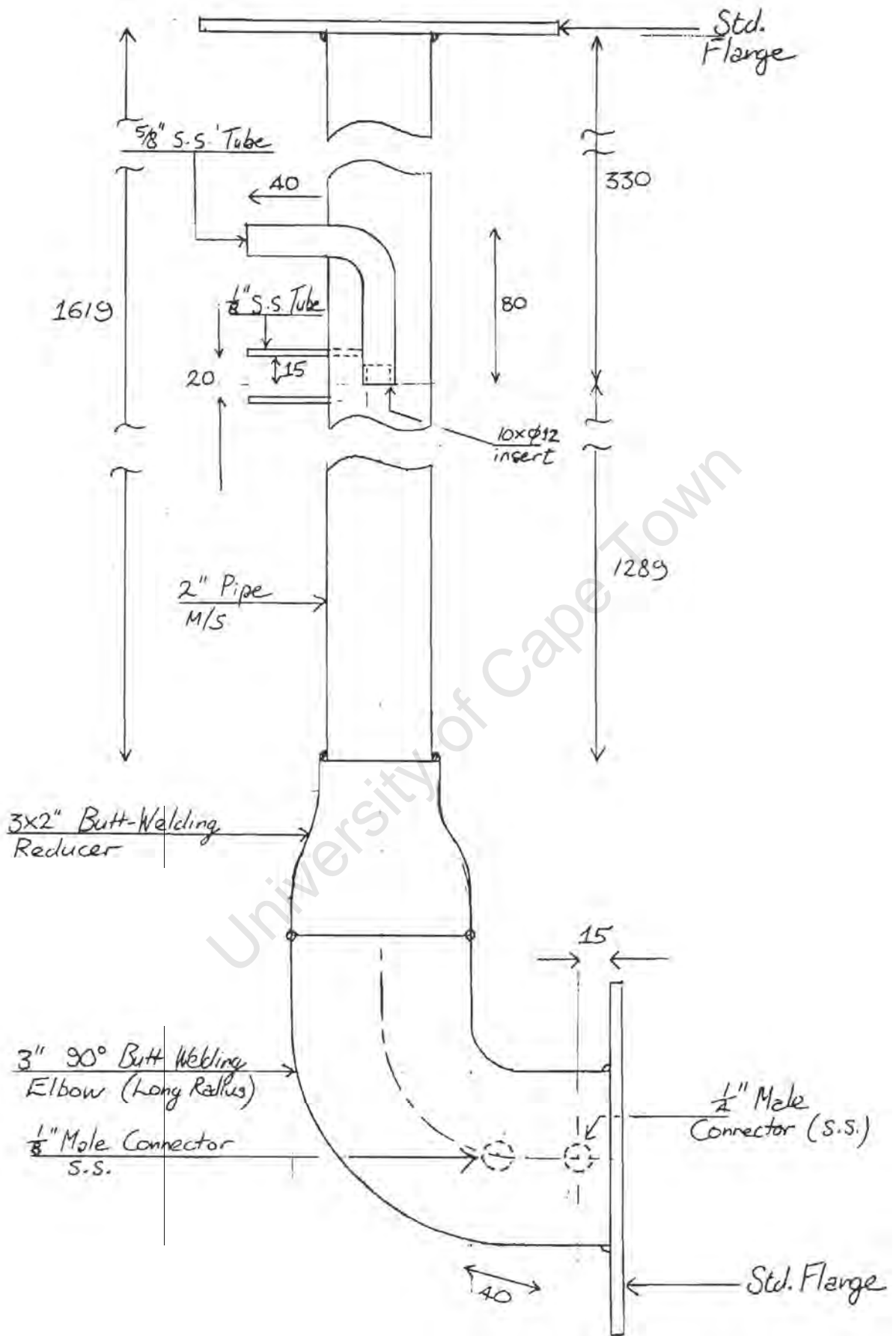


Figure K - 2: Assembly Drawing of Sampling Exhaust Section for 1 litre per cylinder ADE Engines

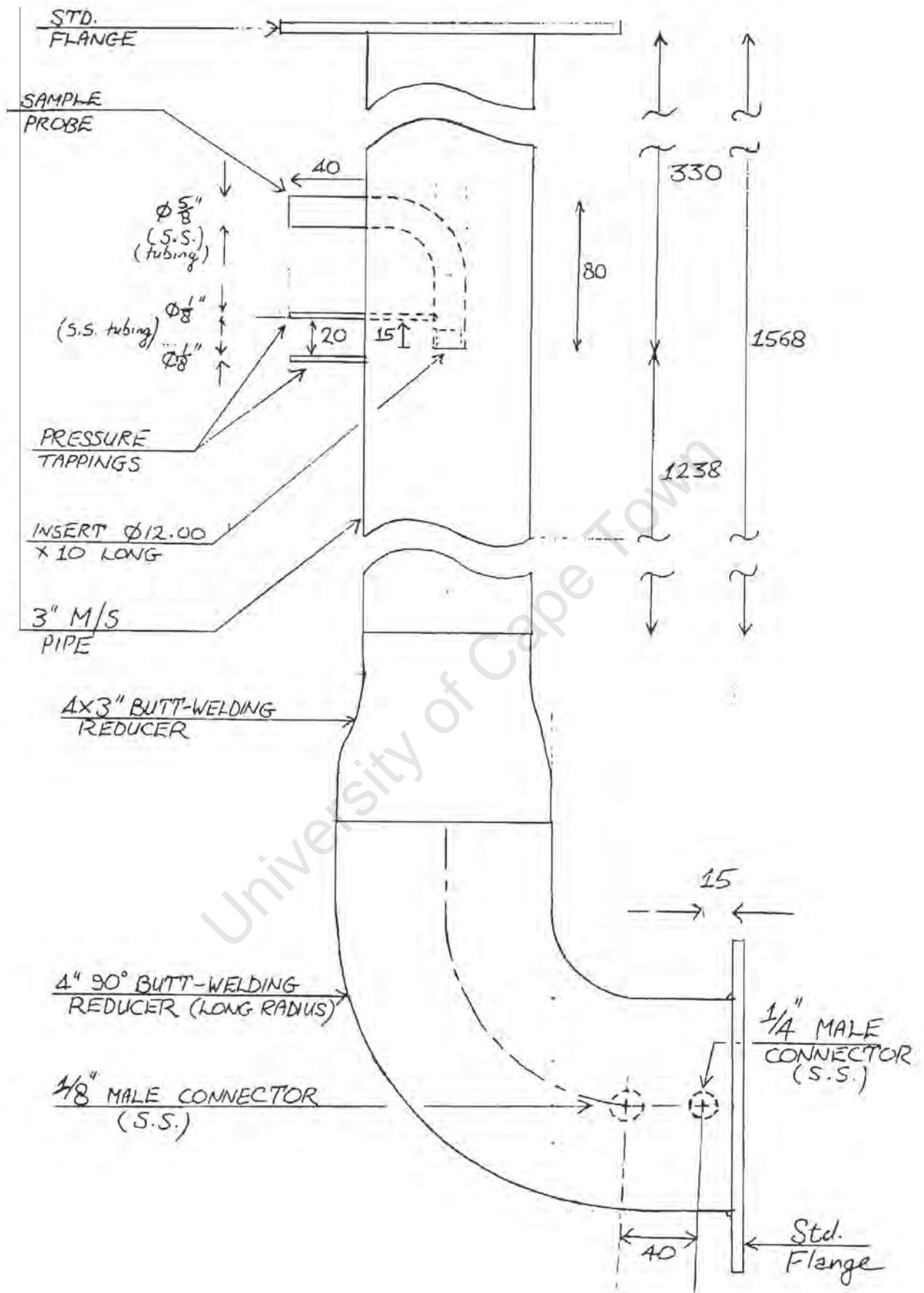


Figure K - 3: Assembly Drawing of Sampling Exhaust Section for 2 litre per cylinder ADE Engines

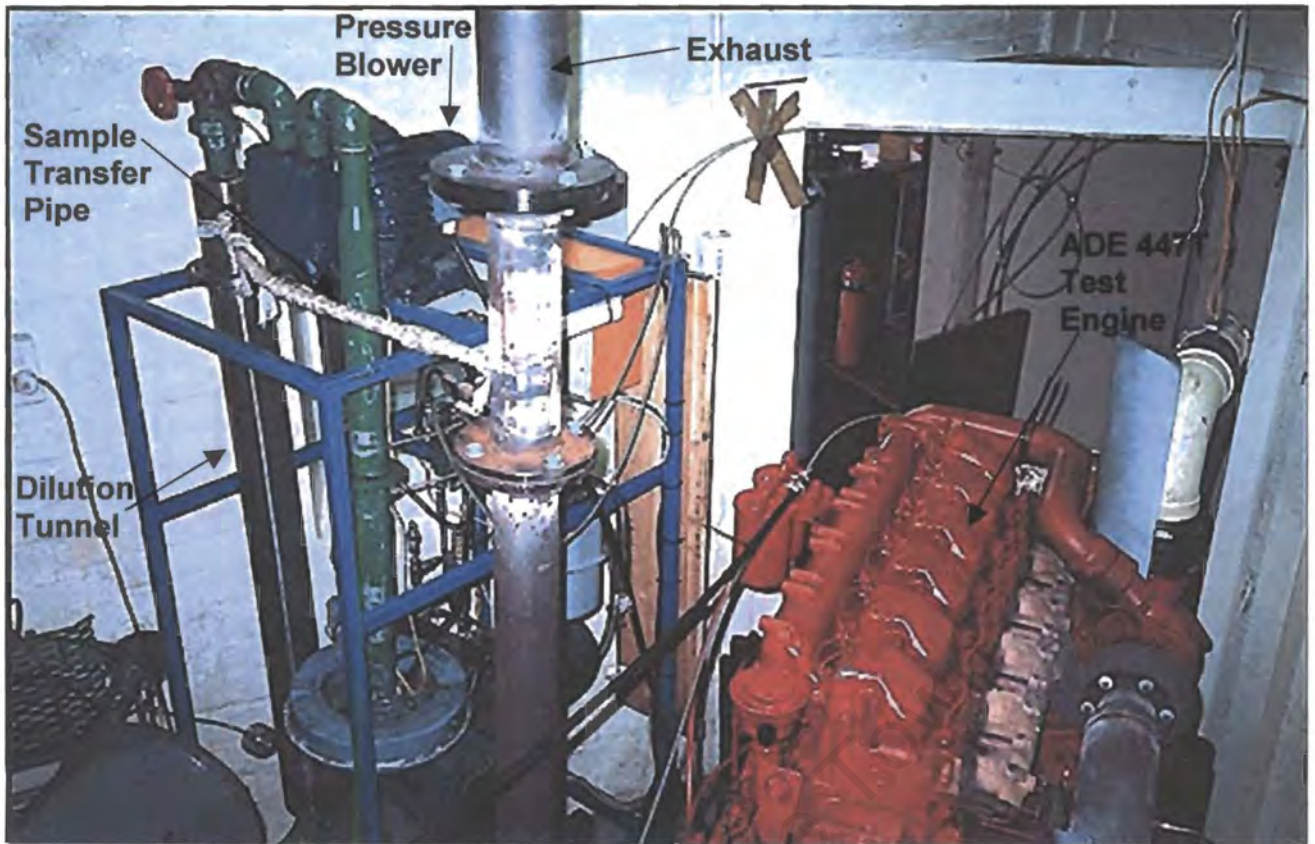


Figure K - 4: Partial Flow Dilution Tunnel Set-up: Oblique View

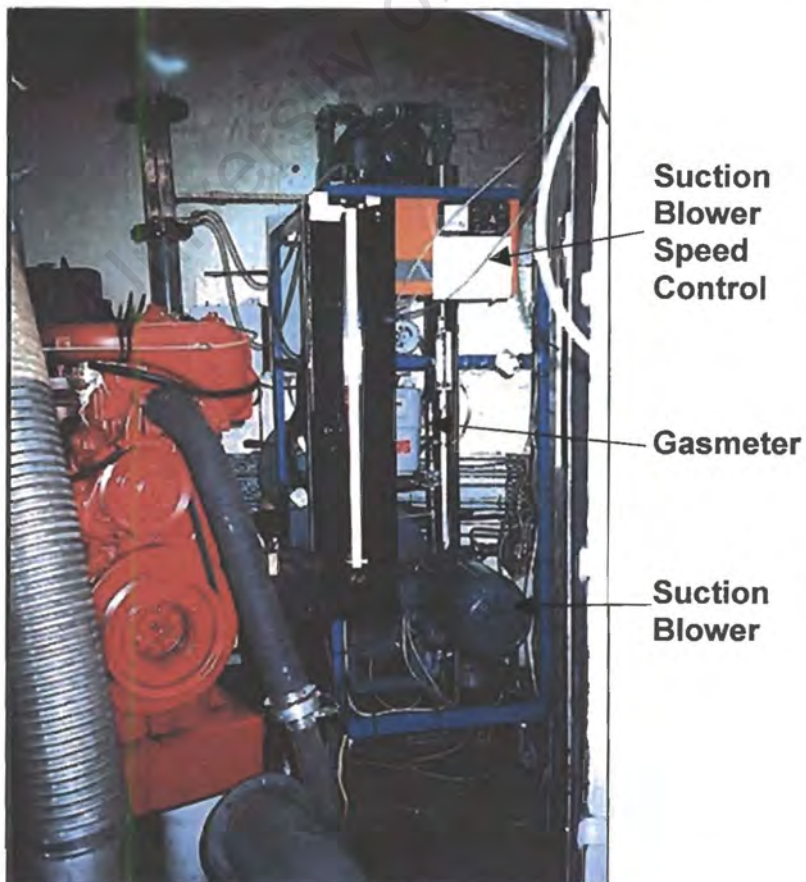


Figure K - 5: Partial Flow Dilution Tunnel Set-up: Front View

## **APPENDIX L ANALYSER CALIBRATION DETAILS**

### **APPENDIX L1 CROSS CORRELATION OF CALIBRATION GAS BOTTLES**

This procedure was used to ensure a constant standard of instrument calibration. When a “new” replacement bottle was found to be different from the “old” one, correlation factors were worked out to calibrate the analyser to the original standard. This means that the test results are based on the original “reference” bottles, some of which were correlated to the available Gold Standard calibration bottles. This procedure was carried out in both the Highveld and Coastal Programmes.

The correlation procedure was as follows. The analyser was calibrated for zero and then spanned with the “reference” gas bottle. Once the analyser was calibrated, the analyser then measured the concentration of the calibration bottle to be correlated to the “reference” bottle. In the case of the diesel tests, given that the ‘new’ bottle’s measured concentration was reasonably close to its supplier-certified concentration, the ‘new’ bottle was simply marked with this same concentration, measured relative to the ‘reference’ bottle. Hereafter this new value was taken as the calibration value for spanning the analyser.

### **APPENDIX L2 GOLD STANDARD CALIBRATION**

With the assistance of the Cape Town City Council, all the NO<sub>x</sub> and SO<sub>2</sub> calibration gas bottles were correlated to the Gold Standard calibration gas bottles. The calibration bottles for other gases were cross-correlated to “reference” bottles as described above

### **APPENDIX L3 CALIBRATION SPANS FOR THE DIESEL TESTS**

**Table L - 1** below lists the correlated concentrations of the calibration gases used to span the gas analysers for the diesel tests:

Table L - 1: Span Gas Concentrations for Experimental Study (VEP Data)

<b>Pollutant</b>	<b>Coastal</b>	<b>Altitude</b>
<b>HC<sub>n</sub></b>	330 ppmC	330 ppmC
<b>CO</b>	900 ppm	925 ppm
<b>NO<sub>x</sub></b>	1545 ppm	1350 ppm
<b>CO<sub>2</sub></b>	15.1%	15.1%
<b>SO<sub>2</sub></b>	368.4 ppm	368.4 ppm
<b>Methane</b>	15 ppm	15 ppm
<b>Butadiene</b>	30.3 ppm	30.3 ppm
<b>Benzene</b>	28.8 ppm	28.8 ppm

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## APPENDIX M VEHICLE DATABASE

Table M - 1: Database of Light Commercial Vehicles (LCV): < 3500 kg GVM

Vehicle Model	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration (Diesel)	Engine Type	Diesel Proportion	Diesel Weighted Power (kW)	Diesel Turbo Proportion	Diesel NA Proportion	Diesel Wgt. Turbo Power (kW)	Diesel Wgt. NA Power (kW)
COLT 1600 SWB	2350	55	94 - 97	2887		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2000 LWB	2459	70	94 - 98	4007		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2000 LWB 98 on	2595	78	98 - p	49		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2000i HI-LINE	2645	90	98 - p	77		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2400i HI-LINE & 4X4		97	98 - p	104		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2500 D	2385	55	95 - 98	8370	NA	Diesel	0.0058	0.3213	0.0000	0.0058	0.0000	0.3213
COLT 2500 D LWB & HI-LINE	1430	57	98 - p	115	NA	Diesel	0.0001	0.0046	0.0000	0.0001	0.0000	0.0046
COLT 2500 TURBO DIESEL 4X4	2765	62	97 - 98	815	Turbo	Diesel	0.0006	0.0353	0.0006	0.0000	0.0353	0.0000
COLT 2600 PETROL HI-LINE		79	95 - p	2531		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2800 D HI-LINE	2845	71	99 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 2800 TD RODEO	2950	92	99 - p	0	Turbo	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 3000 V6 RODEO 4x4	2690	109	94 - p	4712		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COLT 3000i V6 RODEO 4X4	2905	133	98 - p	342		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DACIA ELAN P/U & D/S	2320	54	96 - 97	335		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DACIA MAGIC DOUBLE CAB	1900	54	96 - 97	209		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DAIHATSU MOVE PANEL VAN		34	97 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FIAT ESPRESSO PANEL VAN	1200	41	93 - 96	2713		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1300 P/U	1532	48	83 - 86	8798		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1300	1577	50	94 - 96	5149		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1400	1545	55	86 - 94	11492		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1600 94-96	1614	60	94 - 96	3384		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1600	1550	63	84 - 94	21953		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD BANTAM 1600i	1611	77	94 - 96	2285		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD 1600 1 TONNER	2204	50	77 - 86	27647		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD 2400 DIESEL 1 TONNER	2245	45.2	82 - 85	1721	NA	Diesel	0.0012	0.0543	0.0000	0.0012	0.0000	0.0543
FORD 3000 1 TONNER	1000	101.5	77 - 86	35664		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 1600	400	53	86 - 91	8801		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 1800	2400	64	91 - 96	9076		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 2000 LWB.	2400	66	86 - 91	8846		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 2200	2430	48	86 - 96	6279	NA	Diesel	0.0044	0.2103	0.0000	0.0044	0.0000	0.2103
FORD COURIER 2200 91-96	2400	77	91 - 96	6576		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 2,5 TURBO DIESEL	2580	80	97 - p	2279	Turbo	Diesel	0.0016	0.1272	0.0016	0.0000	0.1272	0.0000
FORD COURIER 2,5 DIESEL	2580	64	97 - p	2614	NA	Diesel	0.0018	0.1167	0.0000	0.0018	0.0000	0.1167
FORD COURIER V6	2455	103	86 - 90	7521		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 3000 V6 4x2	2755	104	90 - 96	4456		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER V6 4x4	2755	97	90 - 96	4293		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD COURIER 3,4	2455	108	97 - p	1741		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD RANGER 1800	2400	64	00 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD RANGER 2200	2400	77	00 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD RANGER 2500 D	2580	64	00 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD RANGER 2500 TD	2580	80	00 - p	0	Turbo	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

FORD RANCHERO GLI & OUTBACK UTE	2300	157	97 - p	588		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD RANCHERO XR6 UTE	2062	164	97 - p	192		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD HUSKY ONE TON PICK-UP		60	85 - 87	1114		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD HUSKY 2.0 PICK-UP	2300	74	87 - 96	2953		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD HUSKY PANEL VAN	2205	74	85 - 90	908		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD SPECTRON PANEL VAN	2750	77	96 - p	427		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD TRITON 0510 & 0610	5500	76	85 - 86	128		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD TRITON 0608	6000	58	86 - 87	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FORD TRITON 0608 87-96	6000	58	87 - 96	1417	NA	Diesel	0.0010	0.0573	0.0000	0.0010	0.0000	0.0573
FORD TRITON 0610	500	76	87 - 96	1338		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HYUNDAI BAKKIE 2,5 TD	2701	62.5	97 - p	0	Turbo	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HYUNDAI BAKKIE 2,6i	2689	62.5	97 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HYUNDAI 2,6i PANEL VAN	2830	62.5	97 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 21-22 & KB 26-27	2350	54	81 - 89	18081		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 21 & FLEETSIDE	2238	58	87 - 89	6766		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 24 & LE, KB 29, KB 44 & LE	2238	70	87 - 89	6508		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 41/42 1800 & KBD41/42	2350	62	81 - 89	6787		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KBD 22/LE, KBD 27 & KBD 42	2350	44	83 - 89	11529	NA	Diesel	0.0080	0.3540	0.0000	0.0080	0.0000	0.3540
ISUZU KBD 28 & 23 LE	2350	50	87 - 89	6236	NA	Diesel	0.0044	0.2176	0.0000	0.0044	0.0000	0.2176
ISUZU KB 160 (Uprated 1993)	2450	52	93 - 94	526		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 160 FLEETSIDE	2450	60	89 - 95	8985		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB200 FLEETSIDE	2450	70	94 - 97	5824		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 230 SWB & LWB	2450	70	89 - 95	12229		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 230 4x4 PICK-UP	2450	70	89 - 92	3292		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 250 D SWB & LWB	2450	52	89 - 96	36515	NA	Diesel	0.0255	1.3251	0.0000	0.0255	0.0000	1.3251
ISUZU KB 250 D 4x4 PICK-UP	2450	52	89 - 93	2502	NA	Diesel	0.0017	0.0908	0.0000	0.0017	0.0000	0.0908
ISUZU KB 260 SWB & LWB	2450	78	92 - 96	8914		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 260 4X4 LWB	2450	78	92 - 96	2268		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 260 D/C 4X4		80	93 - 96	956		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 280 DT LE (SWB/LWB)		64	93 - 96	12631	Turbo	Diesel	0.0088	0.5641	0.0088	0.0000	0.5641	0.0000
ISUZU KB 280 DT 4X4 & LE		64	93 - 96	2378	Turbo	Diesel	0.0017	0.1062	0.0017	0.0000	0.1062	0.0000
ISUZU KB 280 DT D/C LE		64	93 - 96	3640	Turbo	Diesel	0.0025	0.1626	0.0025	0.0000	0.1626	0.0000
ISUZU KB 200 SWB & LWB	2450	70	97 - p	3869		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 250 SWB & LWB	2450	52	97 - p	7804	NA	Diesel	0.0054	0.2832	0.0000	0.0054	0.0000	0.2832
ISUZU KB 260 PETROL	2450	80	97 - p	2938		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU KB 280 DT	2550	74	97 - p	11668	Turbo	Diesel	0.0081	0.6025	0.0081	0.0000	0.6025	0.0000
ISUZU KB 320 V6	2450	140	98 - p	1387		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU WFR 11 FVX PANEL VAN	2550	69	83 - 89	2569		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISUZU TLD24	4200	55	77 - 88	1278	NA	Diesel	0.0009	0.0491	0.0000	0.0009	0.0000	0.0491
ISUZU TLD44-A & TLD54-A	4800	55	77 - 89	8500	NA	Diesel	0.0059	0.3263	0.0000	0.0059	0.0000	0.3263
KIA CERES 2.4	2695	53	98 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER DEFENDER 110 TD5 PU		90	99 - p	0	Turbo	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER SERIES III PETROL P-U	2681	82	81 - 86	1757		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER SERIES III ADE DIESEL P-U	2681	55	82 - 94	1617	NA	Diesel	0.0011	0.0621	0.0000	0.0011	0.0000	0.0621
LAND ROVER 88" PETROL		60.4	65 - 80	445		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER 109" DIESEL		53	65 - 80	249	NA	Diesel	0.0002	0.0092	0.0000	0.0002	0.0000	0.0092
LAND ROVER 109" 6 CYL. PETROL		64	68 - 80	1134		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER PUP 110 V8 P/U	3050	64.6	84 - 96	2961		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LAND ROVER DEFENDER 90/110/130 TDI	240	83	95 - p	3267	Turbo	Diesel	0.0023	0.1892	0.0023	0.0000	0.1892	0.0000



NISSAN / DATSUN HARDBODY 2000	2605	70	00 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN HARDBODY 2400i	2702	88	00 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN HARDBODY 2700D	2683	64	00 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN 1 TONNER 2,7 TD	2733	76	97 - p	2538	Turbo	Diesel	0.0018	0.1346	0.0018	0.0000	0.1346	0.0000
NISSAN / DATSUN HARDBODY 3000i	261	110.3	00 - p	0		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN HARDBODY 3200D	2730	76	00 - p	0	NA	Diesel	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN 1800 E20 EKONOVAN	2398	61	81 - 96	19766		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN 1 TONNER 3000 LWB 4x2 & 4x4	261	110.3	90 - 96	12467		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN SAFARI 4x4 P-U	2859	92	82 - 90	4563		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NISSAN / DATSUN CABSTAR	4400	92	84 - 90	3825		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OPEL CORSA 130i UTILITY	1560	58	97 - p	6666		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OPEL CORSA 140i		65	00 - p	0			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OPEL CORSA 160i UTILITY	1560	70	97 - p	3626		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OPEL CORSA 170D		42	99 - p	0			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RENAULT R5 PANEL VAN	1185	34	80 - 85	1289		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SUZUKI SJ 410 V-Q	1250	33.5	83 - 89	3956		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SUZUKI SJ 413	1340	47	86 - 89	385		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SVM 3000 4x4	1640	103	87 - 92	176		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA TUV 1300	1875	41.8	82 - 87	9962		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA STALLION 3/4 PICK-UP	1850	46	87 - 92	16798		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA STALLION 1800 P/V	1960	65	92 - 96	2455		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA STALLION 1800 P/U	1960	65	91 - 96	4276		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA 1800 P/V	2080	65	94 - 96	238		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA STALLION 2,4 DIESEL P/U	1980	61	95 - 96	112	NA	Diesel	0.0001	0.0048	0.0000	0.0001	0.0000	0.0048
TOYOTA CONQUEST 130 CARRI	1450	55	98 - p	634		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA COROLLA 1600 P/V		55	83 - 89	4902		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 1600	1406	50	79 - 87	57335		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 1800 S & SR	2480	59	87 - 96	81065		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2000	2470	63	79 - 87	18563		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2000 4x4	2470	63	80 - 86	17760		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2200 DIESEL	2470	47.1	80 - 86	29412	NA	Diesel	0.0205	0.9667	0.0000	0.0205	0.0000	0.9667
TOYOTA HI-LUX 2200 4x4	2480	70	85 - 86	4597		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2200 & SRX	2480	70	87 - 96	32171		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2200 4x4 & DOUBLE CAB	2480	70	87 - 94	27217		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2400 DIESEL	2480	55	85 - 96	61285	NA	Diesel	0.0428	2.3523	0.0000	0.0428	0.0000	2.3523
TOYOTA HI-LUX 2400 DIESEL 4x4 PICK-UP	2480	55	89 - 96	2085	NA	Diesel	0.0015	0.0800	0.0000	0.0015	0.0000	0.0800
TOYOTA HI-LUX 2400 S PETROL	2480	80	94 - 96	1138		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2400 RAIDER PETROL	2480	80	94 - 96	6262		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2.8 DIESEL P/U	2480	65	95 - 96	1393	NA	Diesel	0.0010	0.0632	0.0000	0.0010	0.0000	0.0632
TOYOTA HI-LUX 1800 SWB	2580	65	98 - p	4828		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2000 98-On	2580	68	98 - p	902		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 2400D	2580	61	98 - p	886	NA	Diesel	0.0006	0.0377	0.0000	0.0006	0.0000	0.0377
TOYOTA HI-LUX 2700i RAIDER & SRX	2590	108	98 - p	1415		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-LUX 3000D	2590	67	98 - p	2106	NA	Diesel	0.0015	0.0985	0.0000	0.0015	0.0000	0.0985
TOYOTA HI-ACE 1800 PANEL VAN (FULL BLIND)	2500	58	84 - 85	462		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-ACE WAGON LS & PANEL VAN	2300	58	87 - 90	1500		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-ACE 2000 PANEL VAN AND COMMUTER 16		65	84 - 87	6613		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA HI-ACE 16 SEATER COMMUTER	2650	70	87 - 96	41249		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA STOUT	3400	63	66 - 89	9059		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TOYOTA DYNA PETROL	4300	59	78 - 86	7834		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA DYNA PETROL ONLY - L.W.B.	7000	64	85 - 95	3534		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA DYNA 6-094	5800	70	94 - 96	454		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA LAND CRUISER PETROL	3040	97	81 - 85	4010		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA LAND CRUISER PETROL 81-85	3035	145	97 - p	407		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA LAND CRUISER DIESEL 81-85	3040	78.4	81 - 85	2612	NA	Diesel	0.0018	0.1429	0.0000	0.0018	0.0000	0.1429
TOYOTA LAND CRUISER DIESEL	3035	96	97 - p	2159	NA	Diesel	0.0015	0.1446	0.0000	0.0015	0.0000	0.1446
TOYOTA LAND CRUISER DLX	3035	103	85 - 94	3567		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOYOTA LAND CRUISER DLX DIESEL	3035	55	85 - 94	1758	NA	Diesel	0.0012	0.0675	0.0000	0.0012	0.0000	0.0675
VOLKSWAGEN KOMBI 1800 & PANEL VAN	2400	70	89 - 93	4650		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
VOLKSWAGEN PANEL VAN 1.8	2400	72	95 - 98	862		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
VOLKSWAGEN WATER COOLED 1.9 L COMMERCIALS	2390	57	83 - 89	3048		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
VOLKSWAGEN PICK-UP (PETROL)		63	81 - 96	13564		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
VOLKSWAGEN PICK-UP (DIESEL)		40	81 - 87	3126	NA	Diesel	0.0022	0.0873	0.0000	0.0022	0.0000	0.0873
VOLKSWAGEN SPORT PICK-UP		70	89 - 95	3604		Petrol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOTALS				1 432 943			20.86%	55.8	2.92%	17.95%	70.8	53.4
								Diesel	Diesel	Diesel	Diesel	Diesel
Vehicle Model	GVM	Engine	Vintage	Adjusted	Aspiration	Engine	Diesel	Weighted	Turbo	NA	Wgt. Turbo	Wgt. NA
	(kg)	Power (kW)	(yy - yy)	Sales	(Diesel)	Type	Proportion	Power (kW)	Proportion	Proportion	Power (kW)	Power (kW)

Table M - 2: Database of Medium Commercial Vehicles (MCV): 3501 - 7500 kg GVM

Vehicle Model	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
Toyota Dyna 4-ton	7080	62	83 - 93	14020	Natural	ADE 314	OLD	0.412	25.53	0.000	0.000	0.412	0.412	0.412	0.000	0.000	25.535
Toyota Dyna 5-084	5035	66	94 - 94	3612	Natural	ADE 364N	NEW	0.106	7.00	0.000	0.000	0.106	0.106	0.000	0.000	0.000	7.003
Nissan Cabstar	6500	87	92 - 95	2085	Turbo	Nissan FD35T		0.061	5.33	0.061	0.000	0.000	0.000	0.000	5.329	0.000	0.000
Isuzu N 4000 D (FT)	7000	70	89 - 95	3120	Natural	ADE 364C	NEW	0.092	6.42	0.000	0.000	0.092	0.092	0.000	0.000	0.000	6.417
Isuzu N 3500 D (FN)	6000	62	89 - 95	2289	Natural	ADE 314	OLD	0.067	4.17	0.000	0.000	0.067	0.067	0.067	0.000	0.000	4.168
MB 308D	3550	72	96 - p	233	TI	OM 601 LA		0.007	0.49	0.000	0.007	0.000	0.000	0.000	0.000	0.493	0.000
MB 312D	3550	90	96 - p	1341	TI	OM 602 LA		0.039	3.54	0.000	0.039	0.000	0.000	0.000	0.000	3.544	0.000
MB 412D	4600	90	96 - p	760	TI	OM 602 LA		0.022	2.01	0.000	0.022	0.000	0.000	0.000	0.000	2.008	0.000
MB 609/42	6700	85	89 - 93	644	Turbo	ADE 364T	NEW	0.019	1.61	0.019	0.000	0.019	0.000	0.000	1.609	0.000	0.000
MB L608D/41	6500	62	79 - 89	1000	Natural	ADE 314	OLD	0.029	1.82	0.000	0.000	0.029	0.029	0.029	0.000	0.000	1.822
Iveco Turbodaily	+5600	86.5	98 - p	318	TI	IVECO		0.009	0.81	0.000	0.009	0.000	0.000	0.000	0.000	0.809	0.000
Nissan Cabstar 35/40/40L	+6500	90	97 - p	1152	Natural	Nissan FD 46		0.034	3.04	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.045
Mitsubishi Canter 3.6 FE	6000	81.5	97 - p	246	Natural	Mit. 4D 32-2A		0.007	0.59	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.588
Leyland Terrier 750 pre 82	7500	72	79 - 82	142	Natural	Leyland 6-98DV		0.004	0.30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300
Leyland Terrier 750 post 82	7500	87.5	82 - 85	64	Natural	ADE 354	OLD	0.002	0.17	0.000	0.000	0.002	0.002	0.002	0.000	0.000	0.165
LDV VH400ET	3500	81.5	96 - 98	248	Natural	Peugeot ET70		0.007	0.59	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.595
Ford DO 607	5600	56.2	74 - 82	1135	Natural	Ford 255		0.033	1.87	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.874
Ford DO 807	7500	56.2	73 - 82	968	Natural	Ford 255		0.028	1.60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.598
Ford Cargo 0608	6100	55	82 - 86	339	Natural	ADE 236	OLD	0.010	0.55	0.000	0.000	0.010	0.010	0.010	0.000	0.000	0.547

Ford Cargo 0808	7500	55	82 - 86	326	Natural	ADE 236	OLD	0.010	0.53	0.000	0.000	0.010	0.010	0.000	0.000	0.526	
<b>TOTALS</b>				<b>34 041</b>				<b>1</b>	<b>67.974</b>	<b>8.0%</b>	<b>7.8%</b>	<b>74.7%</b>	<b>72.8%</b>	<b>53.0%</b>	<b>86.5</b>	<b>88.0</b>	<b>64.4</b>

**Table M - 3:** Database of Heavy Commercial Vehicles (HCV) Weight Class 1: 7501 - 10 000 kg GVM

Vehicle Model	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
Isuzu FRR 500	9900	129	97 - 98	157	Natural	Isuzu 6 HH1-N		0.009	1.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.098
Isuzu F5000 (FN)	9200	94	89 - 95	1068	Natural	ADE 352	OLD	0.058	5.44	0.000	0.000	0.058	0.058	0.058	0.000	0.000	5.445
Isuzu SBR 422BA	+9800	94	82 - 88	1444	Natural	ADE 352	OLD	0.078	7.36	0.000	0.000	0.078	0.078	0.078	0.000	0.000	7.361
Isuzu SBR 422	9000	98	76 - 83	2719	Natural	Isuzu-6 BBI		0.147	14.45	0.000	0.000	0.000	0.000	0.000	0.000	0.000	14.451
Ford DO 910	9200	76.6	72 - 82	2370	Natural	Ford 360		0.129	9.85	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.846
Ford cargo 0912	9450	87.5	82 - 86	714	Natural	ADE 354	OLD	0.039	3.39	0.000	0.000	0.039	0.039	0.039	0.000	0.000	3.389
Hino FD 10-135	9900	94	83 - 94	2693	Natural	ADE 352	OLD	0.146	13.73	0.000	0.000	0.146	0.146	0.146	0.000	0.000	13.731
Hino KL 340 & 360	9900	94	72 - 83	1450	Natural	Hino EC 100		0.079	7.39	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.391
MB 0811/42	8500	85	89 - 93	489	Turbo	ADE 364T	NEW	0.027	2.25	0.027	0.000	0.027	0.000	0.000	2.254	0.000	0.000
MB L1013B/48	10000	94	81 - 87	727	Natural	ADE 352	OLD	0.039	3.71	0.000	0.000	0.039	0.039	0.039	0.000	0.000	3.706
Bedford J5LC5	9860	73	69 - 80	1305	Natural	GM 330		0.071	5.17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.168
Mitsubishi FK 115J/K	+10000	87.5	80 - 86	1483	Natural	ADE 354	OLD	0.080	7.04	0.000	0.000	0.080	0.080	0.080	0.000	0.000	7.041
Nissan CM 8F Pre 93	8800	62	87 - 92	443	Natural	ADE 314N	OLD	0.024	1.49	0.000	0.000	0.024	0.024	0.024	0.000	0.000	1.491
Nissan CM 8F Post 93	8800	66	93 - 94	139	Natural	ADE 364N	NEW	0.008	0.50	0.000	0.000	0.008	0.008	0.000	0.000	0.000	0.496
Nissan CM 10 F Pre 93	9900	94	87 - 92	741	Natural	ADE 352	OLD	0.040	3.78	0.000	0.000	0.040	0.040	0.040	0.000	0.000	3.779
Nissan CM 10 F Post 93	9900	100	93 - 95	495	Natural	ADE 366	NEW	0.027	2.69	0.000	0.000	0.027	0.027	0.000	0.000	0.000	2.687
<b>TOTALS</b>				<b>18 437</b>				<b>1</b>	<b>89.3</b>	<b>2.7%</b>	<b>0.0%</b>	<b>56.6%</b>	<b>54.0%</b>	<b>50.5%</b>	<b>85.0</b>	<b>N/A</b>	<b>89.5</b>

**Table M - 4:** Database of Heavy Commercial Vehicles (HCV) Weight Class 2: 10 001 - 12 500 kg GVM

Vehicle Model	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
Hino 10-145/6	10400	100	94 - 95	514	Natural	ADE 366N	NEW	0.016	1.62	0.000	0.000	0.016	0.016	0.000	0.000	0.000	1.623
Nissan DU 780 Pre 82	11804	98	77 - 81	2797	Natural	Nissan ND6		0.088	8.66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8.659
Nissan DU 780 82 - 91	11804	94	82 - 91	5242	Natural	ADE 352	OLD	0.166	15.57	0.000	0.000	0.166	0.166	0.166	0.000	0.000	15.567
Nissan DU 780 Post 91	11804	100	91 - 95	1284	Natural	ADE 366N	NEW	0.041	4.06	0.000	0.000	0.041	0.041	0.000	0.000	0.000	4.056
Nissan UD 55	10400	113	98 - p	56	Natural	Nissan FE 6A		0.002	0.20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200
MB 1014/48	11250	100	95 - p	325	Natural	ADE 366N	NEW	0.010	1.03	0.000	0.000	0.010	0.010	0.000	0.000	0.000	1.028
Isuzu F 6500 (FN)	11000	94	89 - 95	1059	Natural	ADE 352	OLD	0.033	3.14	0.000	0.000	0.033	0.033	0.033	0.000	0.000	3.144
Isuzu TXD 45 Pre 82	12200	106	80 - 81	228	Natural	Isuzu 6 BDI		0.007	0.76	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.763
Isuzu TXD 45 Post 82	12200	94	82 - 86	425	Natural	ADE 352	OLD	0.013	1.26	0.000	0.000	0.013	0.013	0.013	0.000	0.000	1.261

Isuzu SBR 422 B	10500	98	81 - 83	539	Natural	Isuzu 6 BBI		0.017	1.67	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.670
Isuzu FSR 700	12000	129	97 - p	141	Natural	Isuzu 6 HH1-N		0.004	0.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.573
Toyota DA 110/116 Pre 82	12000	107	78 - 81	2761	Natural	Toyota 2D		0.087	9.33	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.331
Toyota DA 110/116 Pos 82	12000	94	82 - 95	6428	Natural	ADE 352	OLD	0.203	19.09	0.000	0.000	0.203	0.203	0.203	0.000	0.000	19.087
Toyota DA 13-133/135/136	12500	100	97 - p	357	Natural	ADE 366N	NEW	0.011	1.13	0.000	0.000	0.011	0.011	0.000	0.000	0.000	1.127
Ford D 1010	10300	76.6	71 - 82	672	Natural	Ford 360		0.021	1.63	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.627
Ford D1211	12200	84.7	78 - 82	1248	Natural	Ford 380		0.039	3.34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.340
Ford Cargo 1112 & 1113	11500	90.75	82 - 86	390	Natural	ADE 354,352N	OLD	0.012	1.12	0.000	0.000	0.012	0.012	0.012	0.000	0.000	1.117
Ford Cargo 1212 & 1213	12300	90.75	82 - 85	153	Natural	ADE 354,352N	OLD	0.005	0.44	0.000	0.000	0.005	0.005	0.005	0.000	0.000	0.439
Leyland Boxer 1000 Pre 82	+10300	81	73 - 82	294	Natural	Leyland 6-98 NV		0.009	0.75	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.753
Leyland Boxer 1000 Pos 82	+10300	87.5	82 - 86	183	Natural	ADE 354	OLD	0.006	0.50	0.000	0.000	0.006	0.006	0.006	0.000	0.000	0.505
MB L1113B/48	11300	94	76 - 94	4705	Natural	ADE 352	OLD	0.149	13.97	0.000	0.000	0.149	0.149	0.149	0.000	0.000	13.974
MB LA1113/42	11300	94	73 - 83	447	Natural	ADE 352	OLD	0.014	1.33	0.000	0.000	0.014	0.014	0.014	0.000	0.000	1.327
MB LA1213B/42	11500	94	78 - 89	1210	Natural	ADE 352	OLD	0.038	3.59	0.000	0.000	0.038	0.038	0.038	0.000	0.000	3.592
SAMAG 130-12 FK/FL	12200	94	83 - 87	155	Natural	ADE 352	OLD	0.005	0.46	0.000	0.000	0.005	0.005	0.005	0.000	0.000	0.462
Vetsak 125/94	12500	94	85	43	Natural	ADE 352	OLD	0.001	0.13	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.127
TOTALS				31 655				1	95.4	0.0%	0.0%	72.4%	72.4%	64.6%	0.0%	0.0%	95.4

Table M - 5: Database of Heavy Commercial Vehicles (HCV) Weight Class 3: 12 501 - 15 000 kg GVM

Vehicle Model	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
Nissan UD 90/95	+14850	136	98 - p	120	Turbo	Nissan FE 6T		0.003	0.39	0.003	0.000	0.000	0.000	0.000	0.390	0.000	0.000
Nissan CK 10 K/A	13000	94	74 - 86	1799	Natural	ADE 352	OLD	0.043	4.04	0.000	0.000	0.043	0.043	0.043	0.000	0.000	4.040
Nissan CM 12 E/L	13000	94	87 - 95	1838	Natural	ADE 352	OLD	0.044	4.13	0.000	0.000	0.044	0.044	0.044	0.000	0.000	4.126
Nissan CM 16N	15000	100	90 - 95	856	Natural	ADE 366C	NEW	0.020	2.05	0.000	0.000	0.020	0.020	0.000	0.000	0.000	2.046
Nissan CM 15 E	14700	125	87 - 92	906	Turbo	ADE 352/366T	NEW	0.022	2.70	0.022	0.000	0.022	0.000	0.000	2.704	0.000	0.000
MB 1214/48	14000	100	94 - p	1959	Natural	ADE 366N	NEW	0.047	4.65	0.000	0.000	0.047	0.047	0.000	0.000	0.000	4.681
MB 1414K/36	15000	100	93 - p	285	Natural	ADE 366N	NEW	0.007	0.68	0.000	0.000	0.007	0.007	0.000	0.000	0.000	0.680
MB 1414/48	15000	100	92 - p	454	Natural	ADE 366N	NEW	0.011	1.08	0.000	0.000	0.011	0.011	0.000	0.000	0.000	1.084
MB 1213/42	13300	94	79 - 94	3156	Natural	ADE 352	OLD	0.075	7.09	0.000	0.000	0.075	0.075	0.075	0.000	0.000	7.088
MB L1413/51 & 36	13500	96	76 - 83	844	Natural	OM 352		0.020	1.93	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.935
MB LK1413/48 & 32	14500	94	82 - 93	1389	Natural	ADE 352	OLD	0.033	3.12	0.000	0.000	0.033	0.033	0.033	0.000	0.000	3.120
MB 1417	14500	124	80 - 92	2893	Turbo	ADE 352T	OLD	0.069	8.57	0.069	0.000	0.069	0.000	0.000	8.568	0.000	0.000
MB LAK 1517	14800	124	75 - 94	1842	Turbo	ADE 352T	OLD	0.044	5.46	0.044	0.000	0.044	0.000	0.000	5.455	0.000	0.000
MB 1419S/32 & 48 LC	14500	138	77 - 88	908	Natural	ADE 409	OLD	0.022	2.99	0.000	0.000	0.022	0.022	0.022	0.000	0.000	2.993
Iveco Cargo 13.14	13200	90	98 - p	42	Natural	Iveco 8060.05		0.001	0.09	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.090
Iveco ML150E18	15000	130	98 - p	41	TI	Iveco 8060.45 B		0.001	0.13	0.000	0.001	0.000	0.000	0.000	0.000	0.128	0.000
Isuzu FTR 800	14000	147	97 - p	239	Turbo	Isuzu 6HH1-S		0.006	0.84	0.006	0.000	0.000	0.000	0.000	0.839	0.000	0.000
Isuzu FTR 800 T	14000	169	97 - p	109	TI	Isuzu 6 HE1-T		0.003	0.44	0.000	0.003	0.000	0.000	0.000	0.000	0.439	0.000
Isuzu F 9000 (TT)	15000	124	89 - 95	300	Turbo	ADE 352T	OLD	0.007	0.89	0.007	0.000	0.007	0.000	0.000	0.890	0.000	0.000
Isuzu F8000 (TN)	+13350	109	89 - 95	1829	Turbo	ADE 352T	OLD	0.044	4.76	0.044	0.000	0.044	0.000	0.000	4.762	0.000	0.000
Isuzu JCR 360 TA	13500	124	82 - 86	2212	Turbo	ADE 352T	OLD	0.053	6.55	0.053	0.000	0.053	0.000	0.000	6.553	0.000	0.000
Isuzu JCR 360	+13000	106	79 - 84	382	Natural	Isuzu 6 BDI		0.009	0.97	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.968
MAN 14-192 Pre 83	14000	141	77 - 82	172	Natural	MAN D2565M		0.004	0.58	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.580

MAN 14-192 Pre 83	14000	138	83 - 84	41	Natural	ADE 409	OLD	0.001	0.14	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.135
MAN 15.192 FT/S	15000	138	82 - 86	91	Natural	ADE 409	OLD	0.002	0.30	0.000	0.000	0.002	0.002	0.002	0.000	0.000	0.299
MAN 14.130 FT/FK/FL	14000	109	85 - 87	66	Natural	ADE 352N	OLD	0.002	0.17	0.000	0.000	0.002	0.002	0.002	0.000	0.000	0.173
MAN 15-223 LCR	14600	151	97 - p	139	Turbo	MAN D0826L		0.003	0.50	0.003	0.000	0.000	0.000	0.000	0.502	0.000	0.000
Hino F14-146	14450	100	94 - p	397	Natural	ADE 366N	NEW	0.009	0.95	0.000	0.000	0.009	0.009	0.000	0.000	0.000	0.948
Hino F14-176	14200	125	98 - p	42	Turbo	ADE 366T	NEW	0.001	0.13	0.001	0.000	0.001	0.000	0.000	0.125	0.000	0.000
Hino FF 13-133	13000	94	83 - 94	1594	Natural	ADE 352N	OLD	0.038	3.58	0.000	0.000	0.038	0.038	0.038	0.000	0.000	3.579
Hino KR 320	12700	90	74 - 84	2127	Natural	Hino EH 100		0.051	4.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.573
Hino FG 14-173	14500	124	84 - 94	2039	Turbo	ADE 352T	OLD	0.049	6.04	0.049	0.000	0.049	0.000	0.000	6.039	0.000	0.000
Freightliner FL70	14973	119	97 - p	24	TI	Cummins B5.9		0.001	0.07	0.000	0.001	0.000	0.000	0.000	0.000	0.069	0.000
Vetsak 125/94	12500	94	85 - 85	43	Natural	ADE 352N	OLD	0.001	0.10	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.096
Vetsak 130/124	13000	124	85 - 85	57	Turbo	ADE 352T	OLD	0.001	0.17	0.001	0.000	0.001	0.000	0.000	0.169	0.000	0.000
Mitsubishi FM 215 F/L	14030	94	79 - 86	2846	Natural	ADE 352	OLD	0.068	6.39	0.000	0.000	0.068	0.068	0.068	0.000	0.000	6.392
Ley. Boxer 1200 Pre 82	12550	81	73 - 82	804	Natural	Leyland 6-98NV		0.019	1.56	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.557
Ley. Boxer 1200 Pos 82	12550	87.5	83 - 86	378	Natural	ADE 354	OLD	0.009	0.79	0.000	0.000	0.009	0.009	0.009	0.000	0.000	0.790
Ley. Boxer 1300 Pre 82	13210	81	73 - 82	794	Natural	Leyland 6-98NV		0.019	1.54	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.537
Ley. Boxer 1300 Pos 82	13210	103	82 - 85	174	Turbo	ADE 352T	OLD	0.004	0.43	0.004	0.000	0.004	0.000	0.000	0.427	0.000	0.000
Ley. Chieftain CH 4013	+14000	94	79 - 86	403	Natural	ADE 352	OLD	0.010	0.90	0.000	0.000	0.010	0.010	0.010	0.000	0.000	0.904
Ley. Eland Pre 82	14500	115	73 - 82	1093	Turbo	Leyland 411		0.026	3.00	0.026	0.000	0.000	0.000	0.000	3.002	0.000	0.000
Ley. Eland Post 82	14500	124	83 - 85	140	Turbo	ADE 352T	OLD	0.003	0.41	0.003	0.000	0.003	0.000	0.000	0.414	0.000	0.000
International Acco 1840D	13650	127	79 - 83	1184	Turbo	Int. D-358		0.028	3.59	0.028	0.000	0.000	0.000	0.000	3.594	0.000	0.000
Ford D 1311	13200	84.7	71 - 82	1036	Natural	Ford 380		0.025	2.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.096
Ford D 1414	14500	106	72 - 82	880	Turbo	Ford 360T		0.021	2.23	0.021	0.000	0.000	0.000	0.000	2.229	0.000	0.000
Ford Cargo 1312 & 1313	13200	90.75	82 - 86	414	Natural	ADE 354/352	OLD	0.010	0.90	0.000	0.000	0.010	0.010	0.010	0.000	0.000	0.897
Ford Cargo 1317	13200	124	84 - 86	206	Turbo	ADE 352T	OLD	0.005	0.61	0.005	0.000	0.005	0.000	0.000	0.610	0.000	0.000
Ford Cargo 1517	15000	124	82 - 86	223	Turbo	ADE 352T	OLD	0.005	0.66	0.005	0.000	0.005	0.000	0.000	0.659	0.000	0.000
Ford Cargo 2217	14500	124	82 - 86	51	Turbo	ADE 352T	OLD	0.001	0.15	0.001	0.000	0.001	0.000	0.000	0.151	0.000	0.000
<b>TOTALS</b>				<b>41 859</b>				<b>1</b>	<b>106.1</b>	<b>39.6%</b>	<b>0.4%</b>	<b>76.0%</b>	<b>45.2%</b>	<b>35.8%</b>	<b>121.5</b>	<b>152.8</b>	<b>95.7</b>

Table M - 6: Database of Heavy Commercial Vehicles (HCV) Weight Class 4: 15 001 - 17 500 kg GVM

Vehicle	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
MAN 16-223 LCR/LCKR	15990	151	97 - p	68	Turbo	MAN D0826 L		0.009	1.37	0.009	0.000	0.000	0.000	0.000	1.366	0.000	0.000
MAN 16.282 FT	15950	213	96 - p	38	Turbo	ADE 447T	NEW	0.005	1.08	0.005	0.000	0.005	0.000	0.000	1.083	0.000	0.000
MAN 16-352 FTS	15950	308	97 - p	24	TI	MAN D2866 LF		0.003	0.97	0.000	0.003	0.000	0.000	0.000	0.974	0.000	0.000
MAN 16-240 HT/HL Pre 82	15950	177	76 - 81	194	Natural	MAN D2566 M		0.026	4.55	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.553
MAN 16-240 HT/HL Post 82	15950	174	82 - 89	320	Natural	ADE 407N	OLD	0.042	7.39	0.000	0.000	0.042	0.042	0.042	0.000	0.000	7.392
MAN 16.240 HAK Pre 82	15950	177	76 - 81	32	Natural	MAN D2566 M		0.004	0.75	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.750
MAN 16.240 HAK Post 82	15950	174	82 - 90	218	Natural	ADE 407N	OLD	0.029	5.04	0.000	0.000	0.029	0.029	0.029	0.000	0.000	5.038
MAN16.240 FT/FTS Pre 82	15950	177	77 - 81	103	Natural	MAN D2566 M		0.014	2.42	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.419
MAN16.240 FT/FTS post 82	15950	174	82 - 89	229	Natural	ADE 407N	OLD	0.030	5.29	0.000	0.000	0.030	0.030	0.030	0.000	0.000	5.294
Isuzu SHR 361 TA	16000	206	83 -86	136	Turbo	ADE 407T	OLD	0.018	3.72	0.018	0.000	0.018	0.000	0.000	3.725	0.000	0.000
Isuzu FVR 900T	15999	199	97 - p	90	Turbo	Isuzu 6SD1-TC		0.012	2.39	0.012	0.000	0.000	0.000	0.000	2.386	0.000	0.000
Iveco Eurocargo	16000	130	98 - p	55	TI	Iveco 8060.25V		0.007	0.94	0.000	0.007	0.000	0.000	0.000	0.941	0.000	0.000

Hino 41-260F	16200	188	80 - 84	234	Natural	Hino EK 100		0.031	5.85	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	5.851
Hino F16-177	15500	125	94 - p	1277	Turbo	ADE 366T	NEW	0.169	21.18	0.169	0.000	0.169	0.000	0.000	0.000	21.184	0.000	0.000
MB 1735S/35	17000	260	92 - p	346	Turbo	ADE 442T	NEW	0.046	11.93	0.046	0.000	0.046	0.000	0.000	0.000	11.933	0.000	0.000
MB 1729S/32	17000	213	94 - p	361	Natural	ADE 442N	NEW	0.048	10.22	0.000	0.000	0.048	0.048	0.000	0.000	0.000	0.000	10.215
MB 1617/48, 52 & K36	15950	125	92 - p	208	Turbo	ADE 366T	NEW	0.028	3.46	0.028	0.000	0.028	0.000	0.000	0.000	3.455	0.000	0.000
MB 1623S/36	15950	150	96 - p	188	TI	ADE 366TI	NEW	0.025	3.74	0.000	0.025	0.025	0.000	0.000	0.000	0.000	3.737	0.000
International 4900 4X2	15880	186	93 - 95	125	Turbo	Int. DT 466E		0.017	3.08	0.017	0.000	0.000	0.000	0.000	0.000	3.082	0.000	0.000
Leyland Marathon II	17000	196	76 - 83	139	Turbo	Leyland TL 12		0.018	3.62	0.018	0.000	0.000	0.000	0.000	0.000	3.617	0.000	0.000
Nissan CK 20 D/L/N	15600	133	73 - 83	2056	Natural	Nissan PD6		0.273	36.31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	36.310
Nissan CK 25D/N	16000	174	83 - 84	226	Natural	ADE 407N	OLD	0.030	5.23	0.000	0.000	0.030	0.030	0.030	0.000	0.000	0.000	5.230
Nissan CK 41CT	17500	191	80 - 85	526	Turbo	Nissan PD6T		0.070	13.33	0.070	0.000	0.000	0.000	0.000	0.000	13.327	0.000	0.000
SAMAG 168-16 K/L	16500	124	83 - 87	171	Turbo	ADE 352T	OLD	0.023	2.82	0.023	0.000	0.023	0.000	0.000	0.000	2.821	0.000	0.000
SAMAG 240-16 L/S/K	16500	174	83 - 87	94	Natural	ADE 407N	OLD	0.012	2.17	0.000	0.000	0.012	0.012	0.012	0.000	0.000	0.000	2.171
SAMAG 280-16S	16500	206	83 - 87	74	Turbo	ADE 407T	OLD	0.010	2.03	0.010	0.000	0.010	0.000	0.000	0.000	2.028	0.000	0.000
TOTALS				7 532				1	160.9	42.5%	3.5%	51.6%	19.2%	14.4%	164.9	160.0	157.8	

Table M - 7: Database of Heavy Commercial vehicles (HCV) Weight Class 5: 17 501kg - 20000 kg GVM

Vehicle	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
MAN 19-280 FT/FTS	19000	206	78 - 90	738	Turbo	ADE 407T	OLD	0.179	36.84	0.179	0.000	0.179	0.000	0.000	36.835	0.000	0.000
MAN 19.300/321	19000	235	85 - 90	180	TI	ADE 407TI	OLD	0.044	10.25	0.000	0.044	0.044	0.000	0.000	0.000	10.251	0.000
MAN 19-292 FT/FTS	19000	213	90 - 94	147	Natural	ADE 442N	NEW	0.036	7.57	0.000	0.000	0.036	0.036	0.000	0.000	0.000	7.571
MAN 19-362 FTS	19000	260	90 - 93	61	Turbo	ADE 442T	NEW	0.015	3.83	0.015	0.000	0.015	0.000	0.000	3.833	0.000	0.000
Fiat 619T1	19000	194	69 - 80	32	Natural	Fiat 8210.02		0.008	1.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.503
MB 1924/48 38 & 32	19000	174	81 - 93	1039	Natural	ADE 407N	OLD	0.252	43.81	0.000	0.000	0.252	0.252	0.252	0.000	0.000	43.812
MB LS 1928S/32 & 55	19000	206	81 - 90	1309	Turbo	ADE 407T	OLD	0.317	65.32	0.317	0.000	0.317	0.000	0.000	65.324	0.000	0.000
MB 1928S/32 & 55 V	19000	202	87 - 92	413	Natural	ADE 422N	OLD	0.100	20.24	0.000	0.000	0.100	0.100	0.100	0.000	0.000	20.235
MB 1933/35 V8 LC	19000	243	87 - 90	189	Turbo	ADE 422T	OLD	0.046	11.12	0.046	0.000	0.046	0.000	0.000	11.122	0.000	0.000
MB 1831S/35	18000	250	97 - p	19	TI	OM 441LA		0.005	1.17	0.000	0.005	0.000	0.000	0.000	0.000	1.173	0.000
TOTALS				4 127				1	201.7	55.6%	4.8%	98.8%	38.8%	35.2%	210.5	236.5	185.0

Table M - 8: Database of Heavy Commercial Vehicles (HCV) Weight Class 6: Over 20 000 kg GVM

Vehicle	GVM (kg)	Engine Power (kW)	Vintage (yy - yy)	Adjusted Sales	Aspiration	Engine Model	Engine Tech.	Sample Prop.	Weighted Power	Turbo Prop.	TI Prop.	ADE Prop.	NA ADE Prop.	Old NA ADE Prop.	Turbo Power	TI Power	NA Power
MB 2426B/32 & 52	26000	213	92 - p	446	Natural	ADE 442N	NEW	0.013	2.80	0.000	0.000	0.013	0.013	0.000	0.000	0.000	2.796
MB 2535S/32	25500	260	94 - p	631	Turbo	ADE 442T	NEW	0.019	4.83	0.019	0.000	0.019	0.000	0.000	4.826	0.000	0.000
MB 2545S/32	27500	320	96 - p	363	TI	ADE 442TI	NEW	0.011	3.42	0.000	0.011	0.011	0.000	0.000	0.000	3.415	0.000

MB 2629	33000	213	92 - p	584	Natural	ADE 442N	NEW	0.017	3.66	0.000	0.000	0.017	0.017	0.000	0.000	0.000	3.661
MB 2635	26000	260	92 - p	964	Turbo	ADE 442T	NEW	0.028	7.37	0.028	0.000	0.028	0.000	0.000	0.000	7.375	0.000
MB 2638S/32	33000	260	95 - p	196	Turbo	OM 442A		0.006	1.50	0.006	0.000	0.000	0.000	0.000	0.000	1.499	0.000
MB 2644S/32	26000	320	94 - p	293	TI	ADE 442TI	NEW	0.009	2.76	0.000	0.009	0.009	0.000	0.000	0.000	2.757	0.000
Nissan UD 430 WT	26000	315	98-p	25	Turbo	Nissan RF8TC		0.001	0.23	0.001	0.000	0.000	0.000	0.000	0.000	0.232	0.000
Scania R144GA	28500	369	96 - p	377	TI	Sc. DSC 14-		0.011	4.09	0.000	0.011	0.000	0.000	0.000	0.000	4.087	0.000
MAN 26.402 DFTS	26000	308	93 - p	644	TI	MAN D2866 LF		0.019	5.84	0.000	0.019	0.000	0.000	0.000	0.000	5.840	0.000
MAN 26-422 DFTS	26000	308	97 - p	242	TI	MAN D2866 LF		0.007	2.19	0.000	0.007	0.000	0.000	0.000	0.000	2.195	0.000
MAN 26.552 DFTS	26000	401	95 - p	150	TI	ADE 443TI	NEW	0.004	1.77	0.000	0.004	0.004	0.000	0.000	0.000	1.774	0.000
Iveco Eurotrækker	33000	270	98 - p	37	TI	IVECO		0.001	0.29	0.000	0.001	0.000	0.000	0.000	0.000	0.292	0.000
International 9800	25900	343	98 - p	368	TI	Cummins N14		0.011	3.72	0.000	0.011	0.000	0.000	0.000	0.000	3.717	0.000
MB 2219	22500	138	78 - 93	1059	Natural	ADE 409N	OLD	0.031	4.30	0.000	0.000	0.031	0.031	0.031	0.000	4.301	0.000
MB2225	26000	202	87 - 93	402	Natural	ADE 422D	OLD	0.012	2.39	0.000	0.000	0.012	0.012	0.012	0.000	2.387	0.000
MB 2233S/30	22500	243	82 - 86	206	Turbo	OM 422A		0.006	1.47	0.006	0.000	0.000	0.000	0.000	0.000	1.470	0.000
MB 2624	26000	174	81 - 88	987	Natural	ADE 407	OLD	0.029	5.05	0.000	0.000	0.029	0.029	0.029	0.000	5.051	0.000
MB 2628K/32 SC	26000	202	87 - 93	564	Natural	ADE 422N	OLD	0.017	3.35	0.000	0.000	0.017	0.017	0.017	0.000	3.353	0.000
MB 2628/41 & 32	26000	206	81 - 93	2575	Turbo	ADE 407T	OLD	0.076	15.61	0.076	0.000	0.076	0.000	0.000	0.000	15.610	0.000
MB 2632/L41 & S/32	26000	235	75 - 83	730	Natural	OM 403		0.021	5.05	0.000	0.000	0.000	0.000	0.000	0.000	5.051	0.000
MB 2633S/32	26000	243	83 - 92	2076	Turbo	OM 422A		0.061	14.84	0.061	0.000	0.000	0.000	0.000	0.000	14.840	0.000
MB 2633/45	26000	243	86 - 92	100	Turbo	ADE 422T	OLD	0.003	0.72	0.003	0.000	0.003	0.000	0.000	0.000	0.718	0.000
MB 2636S/32 V10	26000	254	86 - 93	1889	Natural	ADE 423N	OLD	0.056	14.12	0.000	0.000	0.056	0.056	0.056	0.000	14.118	0.000
MB 2638S/32 V8	26000	243	87 - 91	406	Turbo	ADE 422T	OLD	0.012	2.90	0.012	0.000	0.012	0.000	0.000	0.000	2.900	0.000
Nissan CW 290	26000	213	93 - 95	132	Turbo	ADE 447T	NEW	0.004	0.83	0.004	0.000	0.004	0.000	0.000	0.000	0.829	0.000
Nissan CW 41 H/P	25000	191	77 - 85	2101	Turbo	PD6 T		0.062	11.81	0.062	0.000	0.000	0.000	0.000	0.000	11.810	0.000
Nissan CW 45 HD/PA	25000	206	82 - 89	1048	Turbo	ADE 407T	OLD	0.031	6.35	0.031	0.000	0.031	0.000	0.000	0.000	6.350	0.000
Nissan CW 55	26000	243	89 - 94	182	Turbo	ADE 422T	OLD	0.005	1.30	0.005	0.000	0.005	0.000	0.000	0.000	1.299	0.000
Nissan CW 46	26000	206	89 - 93	748	Turbo	ADE 407T	OLD	0.022	4.53	0.022	0.000	0.022	0.000	0.000	0.000	4.532	0.000
Nissan CW 47	26000	213	93 - 94	108	Turbo	ADE 447T	NEW	0.003	0.68	0.003	0.000	0.003	0.000	0.000	0.000	0.678	0.000
Nissan CW 350	26000	260	93 - 95	109	Turbo	ADE 442T	NEW	0.003	0.83	0.003	0.000	0.003	0.000	0.000	0.000	0.831	0.000
Oshkosh 1344	26000	216	78 - 83	319	Turbo	CAT 3406		0.009	2.03	0.009	0.000	0.000	0.000	0.000	0.000	2.028	0.000
Oshkosh E 1446 T350	27000	261	80 - 83	40	TI	CAT 3406-350HP		0.001	0.31	0.000	0.001	0.000	0.000	0.000	0.000	0.306	0.000
Samag 240-26 K/L	26000	174	83 - 87	292	Natural	ADE 407N	OLD	0.009	1.50	0.000	0.000	0.009	0.009	0.009	0.000	1.497	0.000
Samag 280-26 K/S	26000	206	83 - 87	164	Turbo	ADE 407T	OLD	0.005	0.99	0.005	0.000	0.005	0.000	0.000	0.000	0.995	0.000
Scania 112	+25000	224	82 - 87	224	Turbo	Sc 1115L		0.007	1.48	0.007	0.000	0.000	0.000	0.000	0.000	1.475	0.000
Scania P142H	+25000	285	82 - 87	580	Turbo	Sc DS 14		0.017	4.87	0.017	0.000	0.000	0.000	0.000	0.000	4.868	0.000
MAN 22/24-192	+23000	138	76 - 87	286	Natural	ADE 409N	OLD	0.008	1.16	0.000	0.000	0.008	0.008	0.008	0.000	1.163	0.000
MAN 26.362	26000	260	90 - 95	402	Turbo	ADE 442T	NEW	0.012	3.08	0.012	0.000	0.012	0.000	0.000	0.000	3.076	0.000
MAN 26-372 DFT/DFTS	26000	265	90 - 95	189	Natural	ADE 443N	NEW	0.006	1.48	0.000	0.000	0.006	0.006	0.000	0.000	1.475	0.000
MAN 26-442	26000	320	90 - 95	508	TI	ADE 442TI	NEW	0.015	4.78	0.000	0.015	0.015	0.000	0.000	0.000	4.780	0.000
MAN 30.240 Pre 82	30000	177	76 - 81	232	Natural	MAN D 2566 M		0.007	1.21	0.000	0.000	0.000	0.000	0.000	0.000	1.211	0.000
MAN 30.240 Post 82	30000	174	82 - 90	369	Natural	ADE 407N	OLD	0.011	1.89	0.000	0.000	0.011	0.011	0.011	0.000	1.890	0.000
MAN 30.330	+30000	260	84 - 89	666	Turbo	ADE 442T	NEW	0.020	5.10	0.020	0.000	0.020	0.000	0.000	0.000	5.097	0.000
MAN 30.365	29500	254	86 - 89	230	Natural	ADE 423N	OLD	0.007	1.72	0.000	0.000	0.007	0.007	0.007	0.000	1.720	0.000
MAN 30.380	29500	320	84 - 89	357	TI	ADE 442TI	NEW	0.010	3.36	0.000	0.010	0.010	0.000	0.000	0.000	3.359	0.000
Isuzu SPZ 451	24000	174	80 - 88	607	Natural	ADE 407N	OLD	0.018	3.11	0.000	0.000	0.018	0.018	0.018	0.000	3.106	0.000
Isuzu VPZ 441S	24000	206	80 - 86	210	Turbo	ADE 407T	OLD	0.006	1.27	0.006	0.000	0.006	0.000	0.000	0.000	1.272	0.000
International 9700	25400	343	93 - 94	971	TI	Cummins N14		0.029	9.80	0.000	0.029	0.000	0.000	0.000	0.000	9.800	0.000
International 4900 6X4	25200	186	93 - 94	672	Turbo	Int. DT 466E		0.020	3.69	0.020	0.000	0.000	0.000	0.000	0.000	3.685	0.000
International F 5070/350	+25000	258	73 - 84	771	Turbo	Cummins 290/350		0.023	5.86	0.023	0.000	0.000	0.000	0.000	0.000	5.860	0.000
International S2670 Pre 84	23200	258	80 - 83	384	Turbo	Cummins 290/350		0.011	2.92	0.011	0.000	0.000	0.000	0.000	0.000	2.916	0.000
International S2670 Post 84	23200	206	84 - 85	222	Turbo	ADE 407T	OLD	0.007	1.35	0.007	0.000	0.007	0.000	0.000	0.000	1.347	0.000
Volvo FL10 & FH12	20-34000	259	95 - p	82	TI	Volvo		0.002	0.63	0.000	0.002	0.000	0.000	0.000	0.000	0.629	0.000

Hino 39-260	26000	188	79 - 84	534	Natural	Hino EK100		0.016	2.95	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.952
Hino 26-290	26000	206	85 - 94	917	Turbo	ADE 407T	OLD	0.027	5.56	0.027	0.000	0.027	0.000	0.000	5.557	0.000	0.000
Hino 35-293	26000	213	94 - 95	87	Turbo	ADE 447T	NEW	0.003	0.55	0.003	0.000	0.003	0.000	0.000	0.546	0.000	0.000
Hino 55/350	26000	243	89 - 94	293	Turbo	ADE 422T	OLD	0.009	2.09	0.009	0.000	0.009	0.000	0.000	2.093	0.000	0.000
Ford LNT 9000-350	24100	261	76 - 84	1049	Turbo	Cummins NTC		0.031	8.05	0.031	0.000	0.000	0.000	0.000	8.054	0.000	0.000
Fiat 697N & 697T	+25000	194	71 - 81	102	Natural	Fiat 8210.02		0.003	0.58	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.584
Freightliner FL80, FLB 75 /90	27494	254	97 - p	500	TI	Cummins		0.015	3.74	0.000	0.015	0.000	0.000	0.000	0.000	3.735	0.000
Leyland 22.12 pre 82	22675	115	75 - 82	471	Turbo	Leyland 411		0.014	1.59	0.014	0.000	0.000	0.000	0.000	1.595	0.000	0.000
Leyland 22.12 post 82	22675	124	82 - 85	372	Turbo	ADE 352T	OLD	0.011	1.36	0.011	0.000	0.011	0.000	0.000	1.359	0.000	0.000
Leyland Landtrain	30000	196	81 - 84	140	Turbo	Leyland TL 12		0.004	0.81	0.004	0.000	0.000	0.000	0.000	0.808	0.000	0.000
<b>TOTALS</b>				<b>33 986</b>				<b>1</b>	<b>231.4</b>	<b>57.5%</b>	<b>14.5%</b>	<b>58.6%</b>	<b>23.3%</b>	<b>19.7%</b>	<b>223.3</b>	<b>321.7</b>	<b>201.4</b>
<b>Vehicle</b>	<b>GVM</b>	<b>Engine</b>	<b>Vintage</b>	<b>Adjusted</b>	<b>Aspiration</b>	<b>Engine</b>	<b>Engine</b>	<b>Sample</b>	<b>Weighted</b>	<b>Turbo</b>	<b>TI</b>	<b>ADE</b>	<b>NA ADE</b>	<b>Old NA</b>	<b>Turbo</b>	<b>TI</b>	<b>NA</b>
	<b>(kg)</b>	<b>Power (kW)</b>	<b>(yy - yy)</b>	<b>Sales</b>		<b>Model</b>	<b>Tech.</b>	<b>Prop.</b>	<b>Power</b>	<b>Prop.</b>	<b>Prop.</b>	<b>Prop.</b>	<b>Prop.</b>	<b>ADE Prop.</b>	<b>Power</b>	<b>Power</b>	<b>Power</b>

## APPENDIX N TEST DATA AND CARBON BALANCES: REGULATED EMISSIONS, CO<sub>2</sub> AND SO<sub>2</sub>

### APPENDIX N1 SEA-LEVEL TESTS

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 314N

Fuel: Coastal Diesel A

#### Uncorrected Modal Concentrations

MODE	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	329.82	1.52	278.16	191.55	63.46
2	370.58	2.34	352.63	213.15	81.70
3	376.85	3.31	386.39	338.92	102.36
4	309.91	5.05	365.72	620.05	140.25
5	224.68	7.07	351.97	1069.66	193.75
6	293.61	9.50	373.19	1306.34	244.25
7	293.89	1.52	238.80	186.04	62.47
8	590.02	10.29	310.99	1282.49	263.53
9	677.96	7.60	340.39	835.77	204.68
10	518.62	5.63	363.69	592.76	152.32
11	554.40	4.04	375.27	343.85	113.91
12	591.29	2.94	400.00	216.99	94.19
13	289.74	1.52	261.44	179.44	60.85

#### Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	10.80	90.75	19.9
1850	22	41.50	232.94	20.2
1850	55	57.60	232.07	20.8
1850	110	88.20	231.62	21.1
1850	165	124.50	230.90	21.6
1850	220	156.40	226.73	22.1
600	4	10.00	89.55	22.0
2800	197	235.50	311.84	23.3
2800	148	179.80	316.12	23.7
2800	99	130.80	317.59	23.8
2800	49	91.80	316.82	23.3
2800	20	69.70	316.59	23.4
600	4	11.00	88.79	23.3

#### Final Specific Results

HCn' =	1.51 g/kW.h	SO <sub>2</sub> =	3.29 g/kW.h
CO' =	3.09 g/kW.h	CO <sub>2</sub> =	813.04 g/kW.h
NO <sub>x</sub> =	11.67 g/kW.h	Parts =	0.80 g/kWh

#### Weighted Average Specific Fuel Consumption

251.29 g/kW.h

#### Carbon Balance

1.1) In from Fuel Cons. =	218.51	gC/kW.h
<b>Total =</b>	<b>218.51</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.33	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	221.89	gC/kW.h
2.3) Out from HC emiss. =	1.31	gC/kW.h
2.4) Out from Part. emiss. =	0.80	gC/kW.h
<b>Total =</b>	<b>225.33</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>3.12</b>	<b>%</b>

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 314N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

MODE	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>
	ppm	%	ppm	ppm	ppm
1	218.96	1.47	213.76	133.34	48.65
2	288.15	2.30	271.84	187.13	59.20
3	305.49	3.23	299.27	287.22	69.26
4	253.68	4.88	286.38	518.87	89.00
5	213.91	6.74	276.36	879.76	110.09
6	237.57	9.22	326.96	1138.87	142.54
7	214.87	1.46	240.31	163.97	47.37
8	585.79	9.78	313.10	1112.26	149.17
9	638.18	7.63	335.07	737.23	120.99
10	479.97	5.65	369.04	540.41	96.05
11	475.56	3.87	394.30	300.60	74.87
12	490.59	2.93	400.00	190.35	63.91
13	199.97	1.48	230.33	151.00	46.17

Engine Test Data

Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
rpm	N.m	g/min	kg/h	deg. C
600	4	10.50	88.57	23.6
1850	21	39.60	231.33	23.5
1850	51	54.80	231.46	23.4
1850	103	81.60	230.48	24.1
1850	154	110.30	229.79	24.6
1850	205	154.00	228.96	25.2
600	4	9.50	91.25	25.0
2800	192	233.00	311.76	25.8
2800	144	174.20	310.83	26.3
2800	96	131.60	311.37	26.0
2800	48	96.10	311.36	26.0
2800	19	68.60	312.47	25.4
600	4	9.50	90.96	25.5

Final Specific Results

HCr' =	1.39 g/kW.h	SO <sub>2</sub> =	2.11 g/kW.h
CO' =	2.80 g/kW.h	CO <sub>2</sub> =	831.87 g/kW.h
NO <sub>x</sub> =	10.75 g/kW.h	Parts =	0.50 g/kWh

Weighted Average Specific Fuel Consumption  
257.30 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. =	223.74	gC/kW.h
<b>Total =</b>	<b>223.74</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.20	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	227.03	gC/kW.h
2.3) Out from HC emiss. =	1.21	gC/kW.h
2.4) Out from Part. emiss. =	0.50	gC/kW.h
<b>Total =</b>	<b>229.95</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>2.77</b>	<b>%</b>

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 364N

Fuel: Coastal Diesel A

Uncorrected Modal Concentrations

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	384.06	1.46	304.97	221.09	51.47
2	411.60	2.17	336.30	200.40	69.64
3	378.55	3.19	348.86	337.30	91.60
4	289.72	5.32	411.61	677.13	135.36
5	265.70	7.67	385.13	1069.84	193.23
6	318.35	10.70	375.47	1579.27	276.69
7	324.21	1.43	297.85	210.11	53.69
8	1000.90	11.71	333.32	1102.10	313.51
9	485.54	8.98	340.73	887.53	237.40
10	517.05	6.19	380.38	482.56	165.99
11	523.00	4.09	372.27	272.80	114.04
12	665.70	2.87	552.71	137.04	88.15
13	335.30	1.53	322.91	215.95	52.54

Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	10.20	88.34	29.0
1680	26	36.30	212.48	30.0
1680	65	52.40	211.24	31.0
1680	130	86.50	208.41	32.0
1680	194	119.00	207.21	33.0
1680	259	162.70	203.65	36.0
600	4	9.80	86.32	33.0
2800	236	285.30	323.42	37.0
2800	177	208.00	317.93	40.0
2800	118	145.00	317.94	40.0
2800	59	96.40	319.78	39.0
2800	24	68.30	321.63	38.0
600	4	11.30	84.86	36.0

Final Specific Results

HCn' =	1.34 g/kW.h	SO <sub>2</sub> =	3.00 g/kW.h
CO' =	3.20 g/kW.h	CO <sub>2</sub> =	757.31 g/kW.h
NO <sub>x</sub> =	11.62 g/kW.h	Parts =	0.91 g/kWh

Weighted Average Specific Fuel Consumption

239.96 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 208.66 gC/kW.h

Total = 208.66 gC/kW.h

2.1) Out from CO emiss. = 1.37 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 206.68 gC/kW.h

2.3) Out from HC emiss. = 1.17 gC/kW.h

2.4) Out from Part. emiss. = 0.91 gC/kW.h

Total = 210.13 gC/kW.h

% diff. = -0.71 %

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 364N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	259.15	1.51	230.08	197.92	36.53
2	277.99	2.15	289.00	159.44	45.58
3	301.92	3.17	309.57	281.37	57.85
4	259.70	5.13	341.88	572.29	80.85
5	216.87	7.45	323.53	961.46	107.44
6	232.48	9.96	319.49	1424.80	141.10
7	238.63	1.38	263.94	170.57	34.26
8	950.24	10.89	283.46	942.04	156.68
9	460.90	8.14	326.30	681.98	119.50
10	406.55	5.87	341.17	407.15	86.63
11	494.27	3.80	394.67	191.36	63.04
12	594.16	2.84	553.63	104.53	50.93
13	248.70	1.49	282.94	175.26	34.25

Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	10.40	86.37	33.0
1680	25	31.10	208.97	33.0
1680	63	50.80	208.97	33.0
1680	126	80.60	207.75	34.0
1680	188	115.00	207.75	34.0
1680	251	156.00	203.79	36.0
600	4	10.40	85.38	35.0
2800	223	274.00	321.75	38.0
2800	167	195.00	318.09	40.0
2800	112	136.00	318.09	40.0
2800	56	91.10	319.91	39.0
2800	22	70.10	321.75	38.0
600	4	10.50	85.87	34.0

Final Specific Results

HCn' =	1.21 g/kW.h	SO <sub>2</sub> =	1.67 g/kW.h
CO' =	2.79 g/kW.h	CO <sub>2</sub> =	741.75 g/kW.h
NO <sub>x</sub> =	10.28 g/kW.h	Parts =	0.57 g/kW.h

Weighted Average Specific Fuel Consumption  
238.79 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. =	207.64	gC/kW.h
<b>Total =</b>	<b>207.64</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.20	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	202.43	gC/kW.h
2.3) Out from HC emiss. =	1.05	gC/kW.h
2.4) Out from Part. emiss. =	0.57	gC/kW.h
<b>Total =</b>	<b>205.26</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>1.15</b>	<b>%</b>

**PROJECT: DIESEL VEP TESTING WITH R49  
METHOD**

**ENGINE: ADE 364T**

**Fuel: Coastal Diesel A**

**Uncorrected Modal Concentrations**

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	199.77	1.46	160.24	247.45	62.09
2	301.17	2.82	259.76	258.90	89.88
3	261.83	4.50	255.09	528.31	121.22
4	156.87	7.10	250.95	1088.72	176.28
5	182.95	9.37	198.31	1847.74	227.14
6	401.16	11.19	185.53	2335.16	269.43
7	168.04	1.44	159.20	269.31	64.00
8	609.40	8.90	173.52	1435.08	218.32
9	508.49	7.56	212.26	1045.35	192.42
10	510.57	6.30	237.98	633.03	166.48
11	389.32	4.64	299.76	348.62	130.52
12	476.56	3.44	372.97	200.66	105.29
13	191.01	1.43	189.23	246.06	59.61

**Engine Test Data**

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	9.00	94.14	16.6
1680	40	45.00	208.83	16.7
1680	101	74.90	215.96	16.7
1680	202	129.90	238.78	16.9
1680	303	185.90	265.97	17.6
1680	404	245.70	296.74	17.1
600	4	11.20	93.67	17.4
2800	309	356.40	537.27	17.4
2800	232	273.40	486.46	17.4
2800	155	202.40	428.28	17.4
2800	77	129.60	367.76	17.4
2800	31	88.70	335.69	16.9
600	4	10.70	93.83	17.1

**Final Specific Results**

HCn' =	0.68 g/kW.h	SO <sub>2</sub> =	2.73 g/kW.h
CO' =	2.33 g/kW.h	CO <sub>2</sub> =	736.96 g/kW.h
NO <sub>x</sub> =	14.40 g/kW.h	Parts =	0.71 g/kWh

**Weighted Average Specific Fuel Consumption**  
228.94 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. =	199.08	gC/kW.h
<b>Total =</b>	<b>199.08</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.00	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	201.13	gC/kW.h
2.3) Out from HC emiss. =	0.59	gC/kW.h
2.4) Out from Part. emiss. =	0.71	gC/kW.h
<b>Total =</b>	<b>203.43</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>-2.18</b>	<b>%</b>

**PROJECT: DIESEL VEP TESTING WITH R49  
METHOD**

**ENGINE: ADE 364T**

**Fuel: Reference Diesel RF-03**

**Uncorrected Modal Concentrations**

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	154.90	1.45	138.63	243.11	47.26
2	241.30	2.85	205.27	265.31	64.43
3	238.07	4.54	226.30	555.62	82.90
4	139.63	6.95	225.11	1133.83	110.26
5	174.22	9.21	206.09	1827.88	134.09
6	348.73	10.89	209.76	2247.97	150.64
7	141.67	1.46	140.74	220.97	43.92
8	608.73	8.81	183.61	1341.94	124.05
9	503.21	7.56	210.02	960.95	110.51
10	457.91	6.28	228.83	604.04	97.76
11	374.56	4.66	312.29	288.91	78.27
12	434.11	3.45	387.94	149.84	65.03
13	153.29	1.45	169.46	198.90	41.49

**Engine Test Data**

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	10.10	93.57	18.2
1680	41	44.10	211.00	18.4
1680	102	75.40	221.35	18.6
1680	203	125.90	239.43	18.3
1680	305	181.50	264.58	19.1
1680	396	234.90	293.93	19.3
600	4	9.60	93.35	18.6
2800	307	349.00	538.19	18.8
2800	233	271.00	481.46	18.6
2800	156	197.90	428.73	19.2
2800	78	128.80	369.63	18.0
2800	31	87.40	337.05	18.6
600	4	10.00	93.52	18.3

**Final Specific Results**

HCr' =	0.69 g/kW.h	SO <sub>2</sub> =	1.61 g/kW.h
CO' =	2.17 g/kW.h	CO <sub>2</sub> =	729.90 g/kW.h
NO <sub>x</sub> =	13.70 g/kW.h	Parts =	0.48 g/kWh

**Weighted Average Specific Fuel Consumption**  
223.98 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. =	194.76	gC/kW.h
<b>Total =</b>	<b>194.76</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	0.93	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	199.20	gC/kW.h
2.3) Out from HC emiss. =	0.60	gC/kW.h
2.4) Out from Part. emiss. =	0.48	gC/kW.h
<b>Total =</b>	<b>201.21</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>-3.31</b>	<b>%</b>

**PROJECT: DIESEL VEP TESTING WITH R49  
METHOD**

**ENGINE: ADE 407N**

**Fuel: Coastal Diesel A**

**Uncorrected Modal Concentrations**

MODE	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	355.76	1.35	212.07	215.81	51.14
2	319.92	2.31	206.26	304.17	67.83
3	298.96	3.36	197.02	558.59	80.53
4	226.14	5.39	226.33	1082.34	106.17
5	124.99	7.62	210.50	1732.89	144.89
6	487.84	10.30	227.81	2364.63	205.86
7	374.76	1.35	288.27	218.11	50.87
8	928.25	10.89	256.39	2143.05	228.45
9	160.23	8.34	253.41	1761.83	172.73
10	191.98	6.05	233.97	1099.43	128.32
11	251.85	4.10	192.40	622.49	92.66
12	338.23	3.07	227.36	366.08	75.51
13	337.36	1.35	256.89	222.57	45.50

**Engine Test Data**

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	20.90	226.01	14.7
1500	71	97.50	585.05	14.5
1500	177	139.20	584.00	14.8
1500	355	219.30	579.28	14.7
1500	532	304.60	573.49	14.9
1500	709	418.40	564.93	15.9
600	4	20.60	223.87	16.3
2200	647	608.10	746.21	20.0
2200	485	456.30	743.09	20.7
2200	324	332.10	746.46	21.0
2200	162	224.60	749.21	20.4
2200	65	165.80	747.71	19.7
600	4	22.00	223.52	16.6

**Final Specific Results**

HCr' =	0.94 g/kW.h	SO <sub>2</sub> =	2.56 g/kW.h
CO' =	3.24 g/kW.h	CO <sub>2</sub> =	815.66 g/kW.h
NO <sub>x</sub> =	19.37 g/kW.h	Parts =	0.47 g/kW.h

**Weighted Average Specific Fuel Consumption  
247.51 g/kW.h**

**Carbon Balance**

1.1) In from Fuel Cons. =	215.23	gC/kW.h
<b>Total =</b>	<b>215.23</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.39	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	222.61	gC/kW.h
2.3) Out from HC emiss. =	0.82	gC/kW.h
2.4) Out from Part. emiss. =	0.47	gC/kW.h
<b>Total =</b>	<b>225.28</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>-4.67</b>	<b>%</b>

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD

ENGINE: ADE 407N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

MODE	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	242.82	1.26	192.18	203.00	37.43
2	257.80	2.27	213.97	288.92	46.90
3	243.90	3.30	203.40	526.00	54.04
4	188.63	5.28	236.48	1001.73	68.43
5	110.65	7.50	239.47	1619.65	88.71
6	387.73	9.93	248.49	2158.46	112.86
7	231.29	1.25	219.67	197.27	34.62
8	758.48	10.42	293.57	1990.50	123.81
9	155.77	8.03	292.20	1597.73	98.03
10	167.97	5.86	257.08	1005.45	75.09
11	205.18	4.00	215.54	580.46	56.60
12	263.96	3.06	245.78	340.62	47.58
13	207.23	1.29	197.30	194.51	31.12

Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	21.10	224.06	18.7
1500	70	93.70	571.92	20.1
1500	176	134.80	571.06	19.4
1500	352	215.50	568.10	19.3
1500	528	297.90	558.43	20.2
1500	704	408.00	561.73	20.2
600	4	20.30	222.04	20.2
2200	629	593.00	722.96	23.8
2200	472	438.00	730.63	25.2
2200	315	324.80	736.90	25.5
2200	157	221.50	737.63	24.3
2200	63	165.70	733.50	24.2
600	4	20.30	223.25	20.6

Final Specific Results

HCr' =	0.99 g/kW.h	SO <sub>2</sub> =	1.49 g/kW.h
CO' =	2.56 g/kW.h	CO <sub>2</sub> =	785.23 g/kW.h
NO <sub>x</sub> =	18.03 g/kW.h	Parts =	0.26 g/kWh

Weighted Average Specific Fuel Consumption  
244.76 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. =	212.84	gC/kW.h
<b>Total =</b>	<b>212.84</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.10	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	214.30	gC/kW.h
2.3) Out from HC emiss. =	0.86	gC/kW.h
2.4) Out from Part. emiss. =	0.26	gC/kW.h
<b>Total =</b>	<b>216.52</b>	<b>gC/kW.h</b>
<b>% dfff. =</b>	<b>-1.73</b>	<b>%</b>

**PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL**

**ENGINE: ADE 447N**

**Fuel: Coastal Diesel A**

**Uncorrected Modal Concentrations**

MODE	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>
	ppm	%	ppm	ppm	ppm
1	313.99	1.24	170.47	148.58	54.65
2	498.94	2.36	244.13	250.56	73.30
3	385.95	3.66	239.22	501.64	88.37
4	165.43	6.01	229.70	990.75	124.25
5	46.59	8.61	177.65	1617.73	179.97
6	467.71	12.50	143.79	1787.10	291.41
7	334.80	1.25	212.31	141.01	59.60
8	756.50	12.59	106.73	1558.60	307.73
9	154.17	8.97	161.32	1401.15	216.26
10	239.83	6.50	168.11	950.33	152.94
11	352.51	4.22	180.70	563.45	106.44
12	455.40	3.05	193.56	322.68	85.43
13	310.45	1.25	204.18	151.82	52.01

**Engine Test Data**

Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
rpm	N.m	g/min	kg/h	deg. C
600	4	18.80	229.61	21.9
1500	81	91.60	545.41	21.9
1500	202	148.00	544.37	22.2
1500	405	235.00	537.53	22.8
1500	607	334.00	534.26	23.8
1500	833	487.97	524.62	24.3
600	4	17.90	227.15	23.6
2200	749	706.60	749.96	23.9
2200	552	498.00	754.24	23.6
2200	368	363.00	756.27	23.8
2200	184	234.00	761.66	22.6
2200	74	171.00	762.03	22.5
600	4	18.90	228.79	22.3

**Final Specific Results**

HCn' =	0.60 g/kW.h	SO <sub>2</sub> =	2.74 g/kW.h
CO' =	2.57 g/kW.h	CO <sub>2</sub> =	769.07 g/kW.h
NO <sub>x</sub> =	12.66 g/kW.h	Parts =	0.59 g/kWh

**Weighted Average Specific Fuel Consumption**

240.31 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. = 208.97 gC/kW.h

**Total = 208.97 gC/kW.h**

2.1) Out from CO emiss. = 1.10 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 209.89 gC/kW.h

2.3) Out from HC emiss. = 0.52 gC/kW.h

2.4) Out from Part. emiss. = 0.59 gC/kW.h

**Total = 212.11 gC/kW.h**

**% dff. = -1.50 %**

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 447N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

MODE	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	228.12	1.08	148.67	139.31	42.62
2	433.46	2.34	197.11	237.81	54.18
3	338.09	3.60	180.80	476.10	62.26
4	197.91	5.93	183.62	927.74	78.35
5	110.25	8.59	150.68	1545.24	103.62
6	685.34	12.06	128.38	1715.09	161.42
7	270.14	1.09	186.87	131.13	40.50
8	937.03	12.24	81.61	1373.59	160.94
9	166.54	8.89	153.06	1180.25	119.48
10	215.87	6.38	162.57	801.20	88.47
11	287.89	4.18	167.93	478.06	65.49
12	374.60	2.94	181.45	263.70	54.07
13	210.13	1.12	171.21	128.86	37.42

Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	19.30	221.95	22.6
1500	82	90.00	543.38	22.2
1500	204	145.00	546.97	22.1
1500	409	227.00	540.84	23.0
1500	613	322.40	532.52	23.6
1500	814	471.00	521.13	25.2
600	4	19.60	221.09	23.3
2200	726	682.00	741.08	26.4
2200	551	485.00	746.15	26.6
2200	367	356.00	757.03	25.5
2200	184	225.90	757.52	25.4
2200	73	164.00	761.65	24.5
600	4	19.60	219.71	24.4

Final Specific Results

HCn' =	0.51 g/kW.h	SO <sub>2</sub> =	1.59 g/kW.h
CO' =	3.03 g/kW.h	CO <sub>2</sub> =	755.47 g/kW.h
NO <sub>x</sub> =	12.04 g/kW.h	Parts =	0.38 g/kWh

Weighted Average Specific Fuel Consumption

236.41 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. =	205.58	gC/kW.h
<b>Total =</b>	<b>205.58</b>	<b>gC/kW.h</b>
2.1) Out from CO emiss. =	1.30	gC/kW.h
2.2) Out from CO <sub>2</sub> emiss. =	206.18	gC/kW.h
2.3) Out from HC emiss. =	0.44	gC/kW.h
2.4) Out from Part. emiss. =	0.38	gC/kW.h
<b>Total =</b>	<b>208.30</b>	<b>gC/kW.h</b>
<b>% diff. =</b>	<b>-1.32</b>	<b>%</b>

**PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL**

**ENGINE: ADE 447T**

**Fuel: Coastal Diesel A**

**Uncorrected Modal Concentrations**

**Engine Test Data**

MODE	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm	rpm	N.m	g/min	kg/h	deg. C
1	122.43	1.10	100.96	122.31	14.05	600	4	20.20	225.05	20.0
2	197.12	2.73	112.00	255.49	44.14	1500	123	119.20	551.87	19.0
3	146.33	4.41	86.04	526.98	74.07	1500	307	203.20	590.33	20.0
4	49.33	6.80	70.98	1179.91	124.42	1500	614	348.50	663.85	21.4
5	43.50	8.68	80.00	1854.82	153.95	1500	920	494.40	751.28	23.7
6	105.41	10.66	96.44	2439.78	188.47	1500	1227	680.30	847.26	26.0
7	129.16	1.13	123.77	115.84	18.52	600	4	21.10	216.06	24.2
8	89.33	9.19	101.77	2102.16	157.29	2100	960	802.30	1138.85	26.3
9	49.42	7.95	89.37	1425.73	145.56	2100	720	614.90	1002.03	26.8
10	61.09	6.56	89.20	929.82	130.47	2100	480	449.00	856.10	25.9
11	121.72	4.76	79.92	471.67	90.65	2100	240	285.50	781.78	24.1
12	171.79	3.30	103.49	270.49	61.05	2100	96	179.60	725.17	23.5
13	115.28	1.12	115.62	118.30	14.24	600	4	20.40	220.95	23.0

**Final Specific Results**

HCn' = 0.30 g/kW.h      SO<sub>2</sub> = 1.84 g/kW.h  
 CO' = 0.58 g/kW.h      CO<sub>2</sub> = 708.18 g/kW.h  
 NO<sub>x</sub> = 17.03 g/kW.h      Parts = 0.26 g/kWh

**Weighted Average Specific Fuel Consumption**

225.76 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. = 196.31 gC/kW.h

**Total = 196.31 gC/kW.h**

2.1) Out from CO emiss. = 0.25 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 193.27 gC/kW.h

2.3) Out from HC emiss. = 0.26 gC/kW.h

2.4) Out from Part. emiss. = 0.26 gC/kW.h

**Total = 194.04 gC/kW.h**

% diff. = 1.16 %

PROJECT: DIESEL VEP TESTING WITH R49  
METHOD AT SEA-LEVEL

ENGINE: ADE 447T

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

MODE	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm
1	114.05	1.11	88.63	121.18	11.27
2	190.05	2.78	97.56	237.48	35.87
3	151.54	4.35	82.29	468.85	54.33
4	51.16	6.79	77.64	1049.07	84.69
5	48.24	8.74	95.95	1720.55	96.43
6	91.88	10.21	114.97	2026.33	106.93
7	106.92	1.12	119.01	103.30	14.02
8	96.31	8.87	101.19	1837.67	101.50
9	59.04	7.71	89.37	1354.90	79.92
10	74.11	6.47	90.13	761.17	75.35
11	141.42	4.56	95.18	392.19	52.33
12	193.11	3.35	119.87	236.56	35.69
13	105.57	1.12	108.92	104.61	10.87

Engine Test Data

Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
600	4	21.00	223.99	20.9
1500	121	119.00	550.70	21.4
1500	304	196.80	588.52	22.4
1500	607	347.40	669.20	24.0
1500	911	496.00	745.41	25.1
1500	1214	640.90	826.90	26.2
600	4	20.90	209.09	24.5
2100	936	753.20	1126.07	24.7
2100	702	596.30	1006.66	25.2
2100	468	441.20	867.46	25.9
2100	234	267.10	782.35	24.0
2100	94	178.70	727.40	23.0
600	4	21.00	220.42	23.4

Final Specific Results

HCn' = 0.33 g/kW.h      SO<sub>2</sub> = 1.13 g/kW.h  
CO' = 0.57 g/kW.h      CO<sub>2</sub> = 690.10 g/kW.h  
NO<sub>x</sub> = 14.50 g/kW.h      Parts = 0.14 g/kWh

Weighted Average Specific Fuel Consumption

219.40 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 190.78 gC/kW.h

Total = 190.78 gC/kW.h

2.1) Out from CO emiss. = 0.24 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 188.34 gC/kW.h

2.3) Out from HC emiss. = 0.28 gC/kW.h

2.4) Out from Part. emiss. = 0.14 gC/kW.h

Total = 189.01 gC/kW.h

% diff. = 0.93 %

## APPENDIX N2 ALTITUDE TESTS

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 314N

Fuel: Reference Diesel RF-03

## Uncorrected Modal Concentrations

## Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	336.00	1.31	546.00	137.00	58.30	700	4	9.58	74.60	20
2	513.00	2.31	573.00	176.00	69.49	1850	19	41.00	202.22	18
3	467.00	3.35	519.00	298.10	79.60	1850	48	57.00	200.97	19
4	355.00	5.22	486.00	561.00	97.60	1850	99	85.00	199.74	20
5	265.00	7.09	429.00	862.00	116.00	1850	145	111.00	197.99	19
6	245.00	9.55	366.00	1165.00	148.00	1850	195	154.00	199.18	18
7	293.00	1.34	594.00	128.00	54.00	700	4	9.58	74.41	17
8	1003.00	10.97	204.00	1109.00	165.20	2800	181	228.00	266.78	17
9	575.00	7.96	346.80	808.00	127.50	2800	134	175.00	268.05	18
10	600.00	5.79	477.00	573.00	101.40	2800	89	127.00	272.59	17
11	806.10	3.99	630.00	304.00	82.50	2800	45	91.00	267.63	20
12	925.50	3.01	846.00	196.00	75.01	2800	18	69.70	269.41	18
13	325.30	1.33	525.00	142.00	53.94	700	4	9.58	74.95	19

## Final Specific Results

HCn' =	1.74 g/kW.h	SO <sub>2</sub> =	1.54 g/kW.h
CO' =	3.80 g/kW.h	CO <sub>2</sub> =	812.01 g/kW.h
NO <sub>x</sub> =	9.56 g/kW.h	Parts =	0.58 g/kWh

## Weighted Average Specific Fuel Consumption

271.48 g/kW.h

## Carbon Balance

1.1) In from Fuel Cons. = 236.07 gC/kW.h

Total = 236.07 gC/kW.h

2.1) Out from CO emiss. = 1.63 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 221.61 gC/kW.h

2.3) Out from HC emiss. = 1.51 gC/kW.h

2.4) Out from Part. emiss. = 0.58 gC/kW.h

Total = 225.34 gC/kW.h

% diff. = -4.54 %

**PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE**

**ENGINE: ADE 314N**

**Fuel: Highveld Diesel B**

**Uncorrected Modal Concentrations**

**Engine Test Data**

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	339.00	1.37	600.00	169.00	42.60	700	4	10.00	74.07	21
2	510.00	2.47	600.00	220.00	43.10	1850	21	40.00	206.45	18
3	467.00	3.48	540.00	362.00	42.50	1850	52	56.00	206.45	18
4	346.00	5.40	480.00	692.00	41.80	1850	104	85.00	205.20	19
5	224.00	7.60	420.00	1149.00	30.00	1850	156	115.00	203.95	20
6	311.00	10.49	420.00	1507.00	40.00	1850	208	156.00	204.74	17
7	287.00	1.37	600.00	144.00	41.30	700	4	11.00	75.42	18
8	1060.00	11.07	210.00	1368.00	42.09	2800	187	228.00	270.89	18
9	630.00	8.27	390.00	949.00	38.58	2800	140	176.00	275.47	17
10	577.00	5.99	480.00	685.00	38.00	2800	94	127.00	276.70	18
11	822.00	4.19	690.00	353.00	41.90	2800	47	92.00	278.39	17
12	978.00	3.09	960.00	218.00	43.20	2800	19	71.00	278.38	17
13	321.00	1.45	600.00	156.00	40.78	700	4	11.00	75.88	17

**Final Specific Results**

HCn' =	1.78 g/kW.h	SO <sub>2</sub> =	0.02 g/kW.h
CO' =	3.84 g/kW.h	CO <sub>2</sub> =	834.27 g/kW.h
NO <sub>x</sub> =	11.00 g/kW.h	Parts =	0.50 g/kWh

**Weighted Average Specific Fuel Consumption**

259.34 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. = 225.51 gC/kW.h

Total = 225.51 gC/kW.h

2.1) Out from CO emiss. = 1.65 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 227.69 gC/kW.h

2.3) Out from HC emiss. = 1.55 gC/kW.h

2.4) Out from Part. emiss. = 0.50 gC/kW.h

Total = 231.39 gC/kW.h

% diff. = 2.60 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 314N

Fuel: Highveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	357.00	1.36	546.00	140.00	62.19	700	4	10.00	76.67	16
2	535.00	2.46	583.20	181.40	88.10	1850	21	41.00	207.28	18
3	492.00	3.52	534.00	307.10	110.40	1850	52	57.00	209.81	16
4	399.00	5.44	540.60	558.00	144.00	1850	104	85.00	209.79	16
5	274.00	7.63	483.00	902.00	201.00	1850	156	114.00	208.27	16
6	282.00	9.82	468.00	1141.00	239.00	1850	198	161.85	206.99	17
7	354.00	1.39	639.00	129.00	66.90	700	4	9.00	76.16	17
8	1062.00	10.86	267.00	1028.00	278.00	2800	178	236.55	275.20	16
9	739.00	8.13	410.70	735.00	217.18	2800	134	176.00	276.44	17
10	647.00	5.95	543.00	504.00	165.20	2800	89	128.00	277.65	18
11	810.00	4.15	693.00	275.00	128.10	2800	45	89.00	274.49	19
12	894.00	3.15	915.00	176.00	109.00	2800	18	70.00	271.36	20
13	380.00	1.38	675.00	114.30	68.40	700	4	9.00	74.74	20

Final Specific Results

HCn' =	2.11 g/kW.h	SO <sub>2</sub> =	2.66 g/kW.h
CO' =	4.13 g/kW.h	CO <sub>2</sub> =	843.61 g/kW.h
NO <sub>x</sub> =	9.51 g/kW.h	Parts =	0.91 g/kWh

Weighted Average Specific Fuel Consumption

274.79 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 238.95 gC/kW.h

Total = 238.95 gC/kW.h

2.1) Out from CO emiss. = 1.77 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 230.23 gC/kW.h

2.3) Out from HC emiss. = 1.83 gC/kW.h

2.4) Out from Part. emiss. = 0.91 gC/kW.h

Total = 234.75 gC/kW.h

% diff. = -1.76 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	430.00	1.29	429.00	140.00	55.60	700	4	10.00	79.78	18
2	555.00	2.12	471.00	152.00	65.90	1680	24	35.00	180.62	17
3	528.00	3.36	408.00	322.00	79.00	1680	60	52.00	181.73	16
4	390.00	5.63	426.00	643.00	103.00	1680	121	82.00	179.13	17
5	290.00	8.26	363.00	982.00	137.00	1680	181	116.00	174.44	20
6	495.00	11.49	291.00	1380.00	179.00	1680	241	156.00	174.67	17
7	392.00	1.34	441.00	155.00	55.90	700	4	10.00	80.77	16
8	2500.00	13.02	111.60	1070.00	204.00	2800	221	274.00	276.21	18
9	369.00	8.59	231.00	806.00	142.00	2800	166	195.00	274.54	19
10	565.00	6.20	357.00	475.00	112.00	2800	111	145.00	280.56	18
11	949.00	3.97	561.00	218.00	87.20	2800	55	97.00	280.82	17
12	1062.00	2.89	1134.00	102.00	78.10	2800	22	73.00	279.37	17
13	355.00	1.22	411.00	118.00	53.80	700	4	10.00	80.27	17

Final Specific Results

HCn' =	1.07 g/kW.h	SO <sub>2</sub> =	1.34 g/kW.h
CO' =	5.25 g/kW.h	CO <sub>2</sub> =	738.73 g/kW.h
NO <sub>x</sub> =	8.76 g/kW.h	Parts =	0.87 g/kWh

Weighted Average Specific Fuel Consumption

247.93 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 215.59 gC/kW.h

Total = 215.59 gC/kW.h

2.1) Out from CO emiss. = 2.25 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 201.61 gC/kW.h

2.3) Out from HC emiss. = 0.93 gC/kW.h

2.4) Out from Part. emiss. = 0.87 gC/kW.h

Total = 205.66 gC/kW.h

% diff. = -4.60 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364N

Fuel: Highveld Diesel B

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	377.00	1.34	492.00	153.00	43.10	700	4	8.00	79.91	16
2	590.00	2.07	645.00	145.00	44.63	1680	24	31.00	177.22	17
3	594.00	3.37	510.00	306.00	44.17	1680	60	48.00	175.45	20
4	422.00	5.70	435.00	671.00	43.20	1680	119	75.00	178.28	16
5	275.00	8.27	357.00	1071.00	43.20	1680	179	107.00	174.64	18
6	514.00	11.47	263.10	1418.00	43.80	1680	238	150.00	171.71	18
7	360.00	1.26	516.00	138.00	42.80	700	4	8.00	77.96	20
8	1800.00	12.88	99.90	1117.00	43.00	2800	218	266.00	271.68	18
9	372.00	9.25	255.30	892.00	42.70	2800	164	190.00	271.66	18
10	615.00	6.48	348.00	510.00	43.00	2800	109	138.00	275.95	18
11	1060.00	4.28	645.00	240.00	45.10	2800	55	94.00	278.79	18
12	1010.00	3.04	963.00	107.00	49.00	2800	22	74.00	276.15	17
13	370.00	1.38	579.00	155.00	43.80	700	4	9.00	79.36	17

Final Specific Results

HCn' =	1.15 g/kW.h	SO <sub>2</sub> =	0.07 g/kW.h
CO' =	4.63 g/kW.h	CO <sub>2</sub> =	740.83 g/kW.h
NO <sub>x</sub> =	8.89 g/kW.h	Parts =	0.82 g/kWh

Weighted Average Specific Fuel Consumption

238.87 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 207.71 gC/kW.h

Total = 207.71 gC/kW.h

2.1) Out from CO emiss. = 1.98 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 202.18 gC/kW.h

2.3) Out from HC emiss. = 1.00 gC/kW.h

2.4) Out from Part. emiss. = 0.82 gC/kW.h

Total = 205.98 gC/kW.h

% diff. = -0.83 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364N

Fuel: Highveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	476.00	1.35	435.00	157.00	69.80	700	4	11.00	79.74	17
2	648.00	2.11	582.00	163.00	89.10	1680	24	35.00	179.39	17
3	566.00	3.46	519.00	345.00	113.00	1680	61	52.00	176.79	18
4	429.00	5.75	564.00	719.00	163.00	1680	121	83.00	173.18	20
5	316.00	8.48	495.00	1118.00	228.00	1680	182	120.00	176.33	17
6	894.00	12.24	345.00	1462.00	322.00	1680	242	164.00	172.29	18
7	558.00	1.30	564.00	148.00	70.90	700	4	10.00	78.21	20
8	3000.00	13.64	150.30	1072.00	362.00	2800	222	283.00	275.65	17
9	416.00	9.45	300.00	876.00	254.00	2800	167	199.00	273.92	18
10	606.00	6.65	438.00	510.00	187.00	2800	111	145.00	278.18	18
11	925.00	4.30	573.00	255.00	137.00	2800	56	99.00	279.83	17
12	1058.00	3.02	963.00	123.00	112.00	2800	22	73.00	275.19	18
13	480.00	1.33	504.00	143.00	69.80	700	4	9.00	78.11	20

Final Specific Results

HCn' =	1.18 g/kW.h	SO <sub>2</sub> =	2.60 g/kW.h
CO' =	6.52 g/kW.h	CO <sub>2</sub> =	769.71 g/kW.h
NO <sub>x</sub> =	9.04 g/kW.h	Parts =	1.48 g/kWh

Weighted Average Specific Fuel Consumption

255.08 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 221.81 gC/kW.h

Total = 221.81 gC/kW.h

2.1) Out from CO emiss. = 2.80 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 210.06 gC/kW.h

2.3) Out from HC emiss. = 1.03 gC/kW.h

2.4) Out from Part. emiss. = 1.48 gC/kW.h

Total = 215.37 gC/kW.h

% diff. = -2.90 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364T

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	181.00	1.49	277.80	236.00	56.10	700	4	8.00	76.35	21
2	360.00	2.99	354.00	305.00	74.10	1680	39	39.00	177.19	19
3	301.00	4.90	330.90	602.00	92.92	1680	98	71.00	187.05	18
4	150.00	7.71	251.10	1266.00	126.80	1680	195	123.00	200.90	21
5	378.00	10.14	177.90	1856.00	157.20	1680	293	184.00	232.29	19
6	1400.00	11.79	117.90	2057.00	181.30	1680	376	236.00	261.06	19
7	162.00	1.51	213.90	242.00	55.00	700	4	10.00	78.19	17
8	813.00	9.61	97.44	1416.00	154.60	2800	292	338.00	465.30	19
9	867.00	8.06	195.90	1026.00	136.00	2800	219	264.00	421.48	19
10	648.00	6.59	225.60	615.00	118.01	2800	146	190.00	368.13	18
11	533.00	4.91	387.00	333.00	98.13	2800	73	126.00	320.99	16
12	627.00	3.71	525.00	196.00	84.60	2800	29	85.00	283.85	19
13	189.00	1.49	281.04	226.00	55.94	700	4	10.00	77.21	19

Final Specific Results

HCn' =	0.52 g/kW.h	SO <sub>2</sub> =	1.39 g/kW.h
CO' =	4.31 g/kW.h	CO <sub>2</sub> =	725.30 g/kW.h
NO <sub>x</sub> =	12.43 g/kW.h	Parts =	0.68 g/kWh

Weighted Average Specific Fuel Consumption

234.40 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 203.82 gC/kW.h

Total = 203.82 gC/kW.h

2.1) Out from CO emiss. = 1.85 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 197.94 gC/kW.h

2.3) Out from HC emiss. = 0.45 gC/kW.h

2.4) Out from Part. emiss. = 0.68 gC/kW.h

Total = 200.93 gC/kW.h

% diff. = -1.42 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364T

Fuel: Highveld Diesel B

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	182.00	1.45	244.80	223.00	48.05	700	4	9.00	77.00	20
2	384.00	3.02	324.00	304.00	52.10	1680	37	43.00	177.64	19
3	299.00	4.90	291.00	627.00	51.23	1680	97	72.00	188.67	17
4	138.00	7.87	225.00	1306.00	54.80	1680	194	123.00	206.57	18
5	410.00	10.31	183.30	1890.00	52.06	1680	291	183.00	234.30	18
6	1400.00	11.95	137.25	2087.00	50.80	1680	383	243.00	263.32	18
7	176.00	1.52	236.40	239.00	41.70	700	4	11.00	78.39	17
8	784.00	9.79	115.86	1452.00	44.75	2800	297	343.00	469.35	18
9	768.00	8.14	201.36	1042.00	44.05	2800	223	273.00	426.53	18
10	652.00	6.61	237.00	614.00	43.69	2800	149	198.00	376.47	16
11	562.00	4.93	357.00	327.00	43.46	2800	74	130.00	317.90	18
12	665.00	3.74	495.00	191.00	43.50	2800	30	90.00	287.75	18
13	177.00	1.49	281.01	220.00	42.10	700	4	10.00	77.41	19

Final Specific Results

HCr <sub>i</sub> =	0.53 g/kW.h	SO <sub>2</sub> =	0.11 g/kW.h
CO <sub>i</sub> =	4.33 g/kW.h	CO <sub>2</sub> =	742.88 g/kW.h
NO <sub>x</sub> =	12.68 g/kW.h	Parts =	0.62 g/kWh

Weighted Average Specific Fuel Consumption

231.77 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 201.54 gC/kW.h

Total = 201.54 gC/kW.h

2.1) Out from CO emiss. = 1.86 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 202.74 gC/kW.h

2.3) Out from HC emiss. = 0.46 gC/kW.h

2.4) Out from Part. emiss. = 0.62 gC/kW.h

Total = 205.69 gC/kW.h

% diff. = 2.06 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 364T

Fuel: Highveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	221.00	1.48	276.00	184.00	75.30	700	4	9.00	77.02	20
2	392.00	3.04	345.30	260.10	108.50	1680	39	42.00	173.69	20
3	332.00	4.96	320.25	557.00	145.10	1680	98	71.00	185.31	20
4	151.00	7.83	237.00	1210.00	211.10	1680	196	123.00	209.17	16
5	355.00	10.23	185.40	1849.00	270.20	1680	294	182.00	237.25	16
6	1600.00	12.02	135.30	2031.00	321.10	1680	392	245.00	266.30	18
7	194.00	1.55	218.40	214.00	75.90	700	4	8.00	78.89	16
8	886.00	9.96	119.10	1456.00	268.29	2800	310	365.00	472.26	18
9	789.00	8.31	197.10	1066.00	231.50	2800	233	283.00	436.29	17
10	789.00	6.71	210.30	600.70	196.00	2800	155	204.00	385.18	16
11	559.00	5.02	330.00	305.00	156.00	2800	78	130.00	322.85	17
12	654.00	3.83	411.00	158.00	128.00	2800	31	94.00	289.63	17
13	223.00	1.74	246.00	237.00	78.00	700	4	10.00	77.91	18

Final Specific Results

HCn' = 0.51 g/kW.h      SO<sub>2</sub> = 2.44 g/kW.h  
CO' = 4.65 g/kW.h      CO<sub>2</sub> = 722.05 g/kW.h  
NO<sub>x</sub> = 12.14 g/kW.h      Parts = 0.83 g/kWh

Weighted Average Specific Fuel Consumption

232.28 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 201.98 gC/kW.h

Total = 201.98 gC/kW.h

2.1) Out from CO emiss. = 1.99 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 197.06 gC/kW.h

2.3) Out from HC emiss. = 0.45 gC/kW.h

2.4) Out from Part. emiss. = 0.83 gC/kW.h

Total = 200.33 gC/kW.h

% diff. = -0.82 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 407N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
	ppm	%	ppm	ppm	ppm					
1	376.00	1.28	264.00	183.00	48.00	600	4	23.00	189.21	20
2	417.00	2.36	321.00	252.00	59.00	1500	67	93.00	490.68	21
3	364.00	3.55	342.00	518.00	70.50	1500	169	135.00	483.74	22
4	243.00	5.81	345.00	1055.00	93.20	1500	337	213.00	483.76	22
5	173.00	8.40	417.00	1748.00	123.00	1500	506	299.00	479.54	23
6	2900.00	11.48	370.20	2056.00	165.00	1500	674	408.00	467.12	26
7	353.00	1.29	372.00	189.00	44.80	600	4	24.00	185.86	23
8	6000.00	12.08	119.70	1820.00	180.55	2200	603	593.00	639.52	29
9	271.00	8.81	363.00	1672.00	130.02	2200	452	428.00	640.50	30
10	213.00	6.25	315.00	1067.00	100.10	2200	302	312.00	649.31	28
11	353.00	4.06	300.30	550.00	73.90	2200	151	207.00	648.64	26
12	506.00	2.92	417.00	310.00	61.80	2200	60	151.00	647.67	25
13	364.00	1.32	375.00	215.00	44.00	600	4	25.00	188.15	21

Final Specific Results

HCr <sub>1</sub> =	1.01 g/kW.h	SO <sub>2</sub> =	1.39 g/kW.h
CO <sub>1</sub> =	12.76 g/kW.h	CO <sub>2</sub> =	795.74 g/kW.h
NO <sub>x</sub> =	15.12 g/kW.h	Parts =	1.07 g/kWh

Weighted Average Specific Fuel Consumption

255.15 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 221.87 gC/kW.h

Total = 221.87 gC/kW.h

2.1) Out from CO emiss. = 5.47 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 217.17 gC/kW.h

2.3) Out from HC emiss. = 0.88 gC/kW.h

2.4) Out from Part. emiss. = 1.07 gC/kW.h

Total = 224.59 gC/kW.h

% diff. = 1.23 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 407N

Fuel: Highveld Diesel B

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	379.00	1.29	357.00	201.00	41.00	600	4	21.00	190.14	19
2	472.00	2.30	381.00	281.00	41.40	1500	66	90.00	484.67	21
3	417.00	3.46	339.00	540.00	40.70	1500	165	132.00	487.56	20
4	256.00	5.80	351.00	1081.00	40.99	1500	330	212.00	481.67	22
5	153.00	8.26	351.00	1826.00	41.10	1500	495	296.00	484.53	21
6	2400.00	11.59	284.10	2118.00	43.40	1500	665	404.00	470.55	24
7	333.00	1.23	300.30	225.00	40.50	600	4	23.00	188.89	20
8	4400.00	12.15	96.15	1914.00	42.60	2200	591	586.00	648.39	26
9	228.00	8.63	297.00	1701.00	41.80	2200	435	423.00	656.73	26
10	215.00	6.13	273.00	1095.00	41.00	2200	290	309.00	656.67	26
11	369.00	4.01	266.10	561.00	40.40	2200	145	207.00	662.37	23
12	528.00	2.90	363.00	320.00	40.40	2200	58	154.00	658.90	22
13	347.00	1.22	296.10	216.00	39.40	600	4	23.00	191.09	18

Final Specific Results

HCn' =	0.99 g/kW.h	SO <sub>2</sub> =	0.06 g/kW.h
CO' =	10.44 g/kW.h	CO <sub>2</sub> =	818.02 g/kW.h
NO <sub>x</sub> =	16.11 g/kW.h	Parts =	0.93 g/kWh

Weighted Average Specific Fuel Consumption

256.84 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 223.34 gC/kW.h

Total = 223.34 gC/kW.h

2.1) Out from CO emiss. = 4.48 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 223.25 gC/kW.h

2.3) Out from HC emiss. = 0.86 gC/kW.h

2.4) Out from Part. emiss. = 0.93 gC/kW.h

Total = 229.52 gC/kW.h

% diff. = 2.77 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 407N

Fuel: Hlghveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	445.00	1.24	324.00	196.00	60.50	600	4	24.00	190.94	18
2	425.00	2.34	321.00	268.00	80.30	1500	68	90.00	483.77	21
3	392.00	3.58	249.00	520.00	103.00	1500	169	135.00	485.11	21
4	252.00	5.95	357.00	1106.00	150.80	1500	338	213.00	485.11	21
5	201.00	8.70	279.30	1819.00	217.00	1500	506	305.58	480.86	22
6	3400.00	12.01	276.00	2023.00	307.00	1500	663	420.58	464.28	26
7	457.00	1.27	297.30	181.00	66.30	600	4	25.00	186.05	21
8	5100.00	12.65	90.30	1830.00	335.00	2200	595	613.47	647.01	28
9	311.00	9.36	268.20	1748.00	24.41	2200	454	426.00	642.93	30
10	218.00	6.56	228.30	1101.00	182.60	2200	303	313.00	657.98	27
11	338.00	4.22	243.90	575.00	130.20	2200	151	208.00	661.38	24
12	466.00	2.99	301.20	329.00	104.20	2200	61	151.00	660.46	23
13	468.00	1.27	348.00	189.00	66.00	600	4	27.00	189.78	19

Final Specific Results

HCn' =	0.85 g/kW.h	SO <sub>2</sub> =	2.58 g/kW.h
CO' =	12.83 g/kW.h	CO <sub>2</sub> =	833.86 g/kW.h
NO <sub>x</sub> =	15.23 g/kW.h	Parts =	1.39 g/kWh

Weighted Average Specific Fuel Consumption

263.70 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 229.30 gC/kW.h

Total = 229.30 gC/kW.h

2.1) Out from CO emiss. = 5.50 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 227.57 gC/kW.h

2.3) Out from HC emiss. = 0.74 gC/kW.h

2.4) Out from Part. emiss. = 1.39 gC/kW.h

Total = 235.21 gC/kW.h

% diff. = 2.57 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 447N

Fuel: Reference Diesel RF-03

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	367.00	1.23	210.00	133.00	52.10	600	4	23.00	190.44	22
2	790.00	2.27	392.40	188.00	67.20	1500	73	90.00	457.99	22
3	606.00	3.59	357.00	391.00	79.00	1500	183	136.00	457.98	22
4	293.00	6.04	320.40	846.00	106.70	1500	365	221.00	457.96	22
5	165.00	8.88	183.00	1380.00	140.50	1500	548	314.00	455.20	23
6	6200.00	13.49	81.00	1198.00	212.00	1500	730	471.00	443.20	26
7	347.00	1.23	186.30	145.00	53.20	600	4	23.00	191.55	21
8	4000.00	13.98	54.30	1084.00	214.80	2200	659	682.00	621.89	29
9	186.00	9.31	130.20	1196.00	148.00	2200	494	452.00	619.38	30
10	272.00	6.37	165.00	814.00	115.00	2200	330	326.00	631.42	28
11	497.00	4.02	237.00	445.00	84.00	2200	165	210.00	636.54	26
12	684.00	2.81	330.00	234.00	72.30	2200	66	150.00	639.33	24
13	345.00	1.08	218.70	141.00	51.90	600	4	21.00	190.36	22

Final Specific Results

HCn' = 0.49 g/kW.h      SO<sub>2</sub> = 1.41 g/kW.h  
 CO' = 14.79 g/kW.h      CO<sub>2</sub> = 772.43 g/kW.h  
 NO<sub>x</sub> = 8.66 g/kW.h      Parts = 2.67 g/kWh

Weighted Average Specific Fuel Consumption

260.16 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 226.23 gC/kW.h

Total = 226.23 gC/kW.h

2.1) Out from CO emiss. = 6.34 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 210.81 gC/kW.h

2.3) Out from HC emiss. = 0.43 gC/kW.h

2.4) Out from Part. emiss. = 2.67 gC/kW.h

Total = 220.24 gC/kW.h

% diff. = -2.65 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 447N

Fuel: Highveid Diesel B

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO ppm	CO <sub>2</sub> %	THC ppm	NO <sub>x</sub> ppm	SO <sub>2</sub> ppm	Speed rpm	Torque N.m	Fuel Cons. g/min	Air Cons. kg/h	Temp. In deg. C
1	393.00	1.05	282.00	140.40	43.00	600	4	21.00	190.44	22
2	866.00	2.23	501.00	196.00	45.90	1500	73	88.00	457.99	22
3	641.00	3.61	390.30	403.00	45.30	1500	183	132.00	457.98	22
4	288.00	6.12	321.00	896.00	44.50	1500	366	219.00	457.96	22
5	146.00	9.01	222.90	1486.00	43.10	1500	548	318.00	455.20	23
6	5400.00	13.73	69.00	1306.00	46.60	1500	731	476.00	443.20	26
7	382.00	1.07	243.18	137.00	39.39	600	4	21.00	191.55	21
8	4300.00	14.18	56.10	1156.00	46.20	2200	662	693.00	621.89	29
9	183.00	9.38	144.03	1287.00	41.20	2200	497	453.00	619.38	30
10	270.00	6.42	172.20	881.00	40.80	2200	331	325.00	631.42	28
11	519.00	4.09	238.20	478.00	40.80	2200	166	211.00	636.54	26
12	765.00	2.84	372.00	246.00	41.20	2200	66	151.00	639.33	24
13	381.00	1.21	282.00	168.00	40.10	600	4	21.00	190.36	22

Final Specific Results

HCn' =	0.56 g/kW.h	SO <sub>2</sub> =	0.09 g/kW.h
CO' =	13.90 g/kW.h	CO <sub>2</sub> =	784.17 g/kW.h
NO <sub>x</sub> =	9.16 g/kW.h	Parts =	2.53 g/kWh

Weighted Average Specific Fuel Consumption

261.21 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 227.14 gC/kW.h

Total = 227.14 gC/kW.h

2.1) Out from CO emiss. = 5.96 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 214.01 gC/kW.h

2.3) Out from HC emiss. = 0.49 gC/kW.h

2.4) Out from Part. emiss. = 2.53 gC/kW.h

Total = 223.00 gC/kW.h

% diff. = -1.82 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 447N

Fuel: Highveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	439.00	1.27	232.05	155.00	67.30	600	4	21.00	191.74	20
2	765.00	2.31	402.00	201.00	91.00	1500	73	90.00	461.79	21
3	576.00	3.64	351.00	412.00	116.00	1500	183	136.00	461.63	22
4	310.00	6.09	360.00	878.00	174.00	1500	365	224.00	458.93	22
5	169.00	8.97	219.00	1437.00	243.00	1500	548	321.00	456.14	23
6	7000.00	13.61	88.50	1257.00	381.00	1500	748	484.00	441.50	26
7	413.00	1.30	204.00	160.00	67.00	600	4	21.00	189.62	23
8	3600.00	14.07	60.00	1141.00	386.00	2200	662	703.00	620.77	29
9	177.00	9.22	132.00	1249.00	253.00	2200	491	455.00	621.75	30
10	287.00	6.38	165.00	848.00	187.00	2200	327	327.00	633.79	28
11	468.00	4.10	211.20	479.00	332.00	2200	164	210.00	638.91	26
12	634.00	2.88	280.80	259.00	104.30	2200	65	152.00	637.86	25
13	422.00	1.16	237.00	135.00	64.00	600	4	21.00	190.39	21

Final Specific Results

HcN' =	0.54 g/kW.h	SO <sub>2</sub> =	2.83 g/kW.h
CO' =	15.54 g/kW.h	CO <sub>2</sub> =	766.51 g/kW.h
NO <sub>x</sub> =	8.87 g/kW.h	Parts =	3.24 g/kWh

Weighted Average Specific Fuel Consumption

262.71 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 228.45 gC/kW.h

Total = 228.45 gC/kW.h

2.1) Out from CO emiss. = 6.67 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 209.19 gC/kW.h

2.3) Out from HC emiss. = 0.47 gC/kW.h

2.4) Out from Part. emiss. = 3.24 gC/kW.h

Total = 219.56 gC/kW.h

% diff. = -3.89 %

**PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE**

**ENGINE: ADE 447T**

**Fuel: Reference Diesel RF-03**

**Uncorrected Modal Concentrations**

**Engine Test Data**

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	199.00	1.09	181.80	115.00	71.80	600	4	21.00	48.15	21
2	352.00	2.95	189.00	272.00	112.00	1500	121	117.00	108.22	22
3	202.00	4.86	126.00	589.00	150.00	1500	314	200.00	114.35	22
4	62.00	7.44	87.00	1221.00	209.00	1500	628	350.00	131.06	24
5	77.00	9.48	87.30	1914.00	255.00	1500	941	510.00	147.98	26
6	235.00	11.18	69.57	2188.00	300.50	1500	1231	656.00	165.97	30
7	184.00	1.10	153.30	122.00	71.10	700	4	21.00	45.47	25
8	132.00	9.62	75.00	2064.00	259.00	2100	941	757.60	216.53	30
9	70.00	8.30	74.10	1570.00	234.00	2100	726	608.00	189.88	32
10	72.00	6.94	75.00	933.00	204.00	2100	487	435.00	164.98	31
11	187.00	4.87	100.80	471.00	156.00	2100	243	267.00	145.48	28
12	289.00	3.36	162.00	262.00	123.00	2100	97	177.00	136.88	26
13	202.00	1.06	177.00	112.00	71.00	700	4	21.00	49.41	22

**Final Specific Results**

HCr <sub>v</sub> =	0.20 g/kW.h	SO <sub>2</sub> =	2.17 g/kW.h
CO <sub>v</sub> =	0.95 g/kW.h	CO <sub>2</sub> =	660.35 g/kW.h
NO <sub>x</sub> =	13.90 g/kW.h	Parts =	0.19 g/kWh

**Weighted Average Specific Fuel Consumption**

218.90 g/kW.h

**Carbon Balance**

1.1) In from Fuel Cons. = 190.35 gC/kW.h

**Total = 190.35 gC/kW.h**

2.1) Out from CO emiss. = 0.41 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 180.22 gC/kW.h

2.3) Out from HC emiss. = 0.17 gC/kW.h

2.4) Out from Part. emiss. = 0.19 gC/kW.h

**Total = 180.99 gC/kW.h**

**% diff. = -4.92 %**

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 447T

Fuel: Highveld Diesel B

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm	rpm	N.m	g/min	kg/h	deg. C
1	165.00	1.14	204.00	116.00	43.00	600	4	21.00	48.23	24
2	350.00	2.96	216.00	287.00	48.00	1500	126	118.00	106.66	25
3	189.00	4.92	141.00	609.00	48.10	1500	314	202.00	114.26	26
4	46.00	7.18	126.00	1188.00	46.00	1500	628	354.00	131.41	26
5	65.00	9.63	117.00	1891.00	44.00	1500	941	515.00	148.15	28
6	208.00	11.29	90.30	2232.00	49.00	1500	1213	655.85	163.83	32
7	140.00	1.16	183.90	124.00	41.10	700	4	22.00	45.06	27
8	125.00	9.54	90.30	2054.00	43.30	2100	925	757.35	208.58	33
9	58.00	8.22	94.80	1550.00	42.70	2100	694	595.00	184.75	34
10	68.00	6.80	102.00	920.00	43.00	2100	463	426.00	161.62	32
11	183.00	4.76	123.30	485.00	43.00	2100	231	266.00	141.96	30
12	300.00	3.28	192.00	264.00	42.00	2100	93	172.00	134.12	28
13	158.00	1.13	207.00	122.00	42.00	700	4	22.00	48.93	24

Final Specific Results

HCr' =	0.28 g/kW.h	SO <sub>2</sub> =	0.07 g/kW.h
CO' =	0.87 g/kW.h	CO <sub>2</sub> =	668.20 g/kW.h
NO <sub>x</sub> =	13.67 g/kW.h	Parts =	0.20 g/kWh

Weighted Average Specific Fuel Consumption

222.08 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 193.12 gC/kW.h

Total = 193.12 gC/kW.h

2.1) Out from CO emiss. = 0.37 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 182.36 gC/kW.h

2.3) Out from HC emiss. = 0.25 gC/kW.h

2.4) Out from Part. emiss. = 0.20 gC/kW.h

Total = 183.18 gC/kW.h

% diff. = -5.14 %

PROJECT: DIESEL VEP TESTING WITH R49 METHOD  
AT ALTITUDE

ENGINE: ADE 447T

Fuel: Highveld Diesel C

Uncorrected Modal Concentrations

Engine Test Data

Mode	CO	CO <sub>2</sub>	THC	NO <sub>x</sub>	SO <sub>2</sub>	Speed	Torque	Fuel Cons.	Air Cons.	Temp. In
	ppm	%	ppm	ppm	ppm					
1	173.00	1.06	201.00	110.00	63.00	600	4	21.00	46.45	21
2	346.00	2.99	192.00	256.00	82.00	1500	126	117.00	108.02	23
3	189.00	4.97	125.40	556.00	99.70	1500	316	205.00	114.84	23
4	47.00	7.70	95.40	1157.00	127.00	1500	632	357.00	132.90	24
5	59.00	9.89	91.20	1802.00	148.00	1500	947	518.00	151.01	27
6	187.00	11.65	75.45	2051.00	172.00	1500	1237	695.00	168.69	31
7	158.00	1.12	174.00	117.00	62.00	700	4	21.00	43.53	26
8	131.00	9.55	79.20	1850.00	150.00	2100	956	795.00	216.57	31
9	63.00	8.37	77.70	1458.00	140.90	2100	731	616.00	188.11	33
10	67.00	6.91	88.80	858.00	126.90	2100	487	440.00	165.80	31
11	178.00	4.81	105.30	443.00	103.00	2100	244	275.00	144.82	29
12	300.00	3.30	174.30	238.00	87.10	2100	97	179.00	121.61	27
13	165.50	1.09	187.50	113.50	62.50	700	4	23.00	47.38	23

Final Specific Results

HCr' =	0.23 g/kW.h	SO <sub>2</sub> =	1.05 g/kW.h
CO' =	0.83 g/kW.h	CO <sub>2</sub> =	684.84 g/kW.h
NO <sub>x</sub> =	12.91 g/kW.h	Parts =	0.26 g/kWh

Weighted Average Specific Fuel Consumption

226.42 g/kW.h

Carbon Balance

1.1) In from Fuel Cons. = 196.89 gC/kW.h

Total = 196.89 gC/kW.h

2.1) Out from CO emiss. = 0.35 gC/kW.h

2.2) Out from CO<sub>2</sub> emiss. = 186.90 gC/kW.h

2.3) Out from HC emiss. = 0.20 gC/kW.h

2.4) Out from Part. emiss. = 0.26 gC/kW.h

Total = 187.72 gC/kW.h

% diff. = -4.66 %

## APPENDIX O VALIDATION OF VOC SPECIES RESULTS

### APPENDIX O1 VOC RESULTS AS A PERCENTAGE OF TOTAL HYDROCARBON RESULTS

Emission factors for speciated VOCs from mobile sources are commonly expressed as a percentage of total hydrocarbon emissions. This is especially useful when building detailed inventories of individual toxic compounds. Some degree of validation is also possible as presumably this percentage should be fairly consistent for similar engines using the same fuel. **Table O - 1** below presents the coastal results for methane (CH<sub>4</sub>), 1,3 butadiene (C<sub>4</sub>H<sub>6</sub>) and benzene (C<sub>6</sub>H<sub>6</sub>) as a percentage of total hydrocarbon emissions:

**Table O - 1:** Methane, 1,3 Butadiene and Benzene Emissions as a fraction of HC<sub>n</sub> Emissions: Coastal Programme

ENGINE	COASTAL DIESEL A			RF-03-A-84		
	CH <sub>4</sub>	C <sub>4</sub> H <sub>6</sub>	C <sub>6</sub> H <sub>6</sub>	CH <sub>4</sub>	C <sub>4</sub> H <sub>6</sub>	C <sub>6</sub> H <sub>6</sub>
	% of THC	% of THC	% of THC	% of THC	% of THC	% of THC
314N	9	1.6	1.5	12	1.4	1.2
364N	19	0.7	0.5	21	0.8	0.3
364T	16	0.8	1.1	16	1.7	1.1
407N	22	0.4	1.1	18	0.9	0.6
447N	33	1.2	1.7	37	1.3	2.6
447T	48	0	1.0	51	0.5	1.3
<b>AVERAGE</b>	25	0.78	1.2	26	1.1	1.2

**Table O - 2**, **Table O - 3** and **Table O - 4** below present the highveld results for the organic species, formaldehyde (CH<sub>2</sub>O), acetaldehyde (C<sub>2</sub>H<sub>4</sub>O), methane (CH<sub>4</sub>), 1,3 butadiene (C<sub>4</sub>H<sub>6</sub>) and benzene (C<sub>6</sub>H<sub>6</sub>) as a percentage of total hydrocarbon emissions for the three test fuels:

**Table O - 2:** Speciated VOC Emissions as a fraction of HC<sub>n</sub> Emissions with Highveld Diesel C

ENGINE	CH <sub>2</sub> O % of THC	C <sub>2</sub> H <sub>4</sub> O % of THC	CH <sub>4</sub> % of THC	C <sub>4</sub> H <sub>6</sub> % of THC	C <sub>6</sub> H <sub>6</sub> % of THC
314N	1.6	1.0	10	0	0
364N	1.8	1.6	13	1.8	0
364T	2.3	1.2	14	1.8	0
407N	2.2	1.9	13	0	0
447N	5.0	2.3	13	0	0
447T	0.8	0.5	24	0	0
<b>AVERAGE</b>	2.3	1.4	14	-	-

**Table O - 3:** Speciated VOC Emissions as a fraction of HC<sub>n</sub> Emissions with Highveld Diesel B

ENGINE	CH <sub>2</sub> O	C <sub>2</sub> H <sub>4</sub> O	CH <sub>4</sub>	C <sub>4</sub> H <sub>6</sub>	C <sub>6</sub> H <sub>6</sub>
	% of THC	% of THC	% of THC	% of THC	% of THC
314N	1.3	0.7	15	0	0
364N	1.7	0.9	6	0	0
364T	0.7	0.3	18	0	11
407N	1.1	0.7	11	0.46	0
447N	2.7	2.2	9	0	0
447T	1.3	1.1	11	2.5	0
<b>AVERAGE</b>	1.5	0.99	12	-	-

**Table O - 4:** Speciated VOC Emissions as a fraction of HC<sub>n</sub> Emissions with Reference Diesel: Highveld Programme

ENGINE	CH <sub>2</sub> O	C <sub>2</sub> H <sub>4</sub> O	CH <sub>4</sub>	C <sub>4</sub> H <sub>6</sub>	C <sub>6</sub> H <sub>6</sub>
	% of THC	% of THC	% of THC	% of THC	% of THC
314N	1.3	1.1	47	8.4	0
364N	2.6	1.8	10	0	0
364T	4.1	2.2	12	0	0
407N	2.2	1.5	7	0	0
447N	7.9	3.3	8	0	0
447T	1.4	0.3	48	0	0
<b>AVERAGE</b>	3.2	1.7	22	-	-

## APPENDIX O2: SPECIATED VOC EMISSIONS FACTORS USED BY THE EUROPEAN ENVIRONMENT AGENCY <sup>(2,74)</sup>

The European Environment Agency has devised a computer model called the COPERT model to generate emission factors for mobile sources. This model is now in the third generation of development, COPERT III. The emission factors calculated are founded on empirical measurements from peer reviewed sources. In the case of speciated VOCs, emission factors are expressed in similar fashion to the results presented above but as fractions of total non-methane VOC emissions rather than of total hydrocarbon emissions. **Table O - 5** and **Table O - 6** below compare the emissions factors from the second generation COPERTII model <sup>(2)</sup> (1996) with those from COPERTIII <sup>(74)</sup> (1998).

**Table O - 5:** COPERT II Emissions Factors for VOC Species (% weight of total non-methane VOC Emissions) <sup>(2)</sup>

Species or group of species	Gasoline			Diesel	LPG
	Exhaust gas		Evaporation		
	4-stroke engine				
	conventional	3-way catalysts			
Ethane	1.4	1.8		1	3
Propane	0,1	1,0	1	1	44
n-Butane	3,1	5,5	20	2	
i-Butane	1,2	1,5	10		
n-Pentane	2,1	3,2	15	2	
i-Pentane	4,3	7,0	25		
Hexane	7,1	6,0	15		
Heptane	4,6	5,0	2		
Octane	7,9	7,0			
Nonane	2,3	2,0			
Alkanes C>10	0,9	3,0		30 <sup>10)</sup>	
Ethylene	7,2	7,0		12	15
Acetylene	4,5	4,5		4	22
Propylene	3,8	2,5		3	10
Propadiene	0,2				
Methylacetylene	0,3	0,2			
1-Butene	1,7	1,5	1		
1,3-Butadiene	0,8	0,5		2	
2-Butene	0,6	0,5	2		
1-Pentene	0,7	0,5	2		
2-Pentene	1,1	1,0	3	1	
1-Hexene	0,6	0,4			
1,3-Hexene	0,6	0,4	1,5		
Alkanes C>7	0,3	0,2		2 <sup>10)</sup>	
Benzene	4,5	3,5	1	2	
Toluene	12,0	7,0	1	1,5	
o-Xylene	2,5	2,0		0,5	
m,p-Xylene	5,6	4,0	0,5	1,5	
Ethylbenzene	2,1	1,5		0,5	
Styrene	0,7	0,5			0,1
1,2,3-Trimethylbenzene	0,5	1,0			
1,2,4-Trimethylbenzene	2,6	4,0			
1,3,5-Trimethylbenzene	0,8	2,0			
Other aromatic compounds C9	3,8	3,0			
Aromatic compounds C>10	4,5	6,0		20 <sup>10)</sup>	
Formaldehyde	1,7	1,1		6	4
Acetaldehyde	0,3	0,5		2	2
Other Aldehydes C4	0,3	0,2		1,5	
Acrolein	0,2	0,2		1,5	
2-Butenal				1,0	
Benzaldehyde	0,4	0,3		0,5	
Acetone	0,1	1,0		1,5	
	100	100	100	100	100

<sup>10)</sup> C13

Table O - 6: COPERT III Emissions Factors for VOC Species (% weight of total non-methane VOC Emissions) <sup>(74)</sup>

Group	Species	NMVOC Fraction (%wt)				
		Gasoline 4 stroke		Diesel PC & LDV HDV	LPG	
		Convent. Euro I & on IDI & DI				
ALKANES	ethane	1,65	3,19	0,33	0,03	2,34
	propane	0,47	0,65	0,11	0,10	49,85
	butane	2,90	5,24	0,11	0,15	15,50
	isobutane	1,29	1,59	0,07	0,14	6,95
	pentane	1,78	2,15	0,04	0,06	0,35
	isopentane	4,86	6,81	0,52		1,26
	hexane	1,29	1,61			
	heptane	0,36	0,74	0,20	0,30	0,18
	octane	0,56	0,53	0,25		0,04
	2-methylhexane	0,80	1,48	0,45	0,63	0,25
	nonane	0,06	0,16	0,67		0,01
	2-methylheptane		0,57	0,12	0,21	0,09
	3-methylhexane	0,56	1,14	0,22	0,35	0,19
	decane	0,22	0,19	1,18	1,79	
	3-methylheptane	0,40	0,54	0,20	0,27	0,08
	Alkanes C10-C12	0,03	1,76	2,15		0,01
	Alkanes C>13	0,06	1,45	17,91		27,50
CYCLOALKANES	All	0,88	1,14	0,65	1,16	0,10
ALKENES	ethylene	8,71	7,30	10,97	7,01	5,20
	propylene	4,87	3,82	3,60	1,32	5,19
	propadiene		0,05			
	1-butene	0,50	0,73			
	isobutene	4,21	2,22	1,11	1,70	0,63
	2-butene	1,27	1,42	0,52		0,53
	1,3-butadiene	1,42	0,91	0,97	3,30	0,15
	1-pentene	0,09	0,11			
	2-pentene	0,23	0,34			
	1-hexene		0,17			
	dimethylhexene		0,15			
ALKINES	1-butine	0,05	0,21			
	propine	0,76	0,08			
	acetylene	5,50	2,81	2,34	1,05	1,28
ALDEHYDES	formaldehyde	2,08	1,70	12,00	8,40	1,56
	acetaldehyde	0,59	0,75	6,47	4,57	1,81
	acrolein	0,16	0,19	3,58	1,77	0,59
	benzaldehyde	0,60	0,22	0,86	1,37	0,03
	crotonaldehyde	0,02	0,04	1,10	1,48	0,36
	methacrolein		0,05	0,77	0,86	0,10
	butyraldehyde		0,05	0,85	0,88	0,11
	isobutanaldehyde			2,09	0,59	
	propionaldehyde	0,11	0,05	1,77	1,25	0,70
	hexanal			0,16	1,42	
	i-valeraldehyde			0,11	0,09	0,01
	valeraldehyde		0,01	0,41	0,40	
	o-tolualdehyde	0,19	0,07	0,24	0,80	
	m-tolualdehyde	0,38	0,13	0,34	0,59	
p-tolualdehyde	0,18	0,06	0,35			
KETONES	acetone	0,21	0,61	2,94		0,78
	methylthioketone	0,11	0,05	1,20		
AROMATICS	toluene	12,84	10,98	0,69	0,01	1,22
	ethylbenzene	4,78	1,89	0,29		0,24
	m,p-xylene	6,66	5,43	0,61	0,98	0,75
	o-xylene	4,52	2,26	0,27	0,40	0,26
	1,2,3 trimethylbenzene	0,59	0,86	0,25	0,30	0,05
	1,2,4 trimethylbenzene	2,53	4,21	0,57	0,86	0,25
	1,3,5 trimethylbenzene	1,11	1,42	0,31	0,45	0,08
	styrene	0,57	1,01	0,37	0,56	0,02
	benzene	6,83	5,61	1,98	0,07	0,63
	C9	3,12	4,21	0,78	1,17	0,25
	C10		3,07			
C>13	6,01	3,46	13,37		20,37	
TOTALS (all NMVOC species)		99,98	99,65	99,42	96,71	99,98

Note: The remaining fraction to reach 100 % of NMVOC speciation is considered to consist of PAHs

## APPENDIX P DATA FOR HEAVY VEHICLE POPULATION GROWTH SCENARIOS

**Table P - 1** below presents the predicted technology composition of the South African commercial vehicle population with mass greater than 3500 kg until the year 2020. These findings are discussed in detail in **Section 7.2.3**.

**Table P - 1:** Scenarios for Market Penetration of New Technology in the Commercial Vehicle Population > 3500 kg

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020		
Year	Sales*																							
2020	15288																						15288	
2019	15111																					15111	15088	
2018	14935																				14935	14912	14884	
2017	14759																				14759	14737	14709	14678
2016	14583																	14583	14561	14534	14503	14468		
2015	14407																14407	14385	14358	14328	14294	14255		
2014	14231															14231	14210	14183	14153	14119	14081	14037		
2013	14055														14055	14034	14007	13978	13945	13907	13863	13813		
2012	13879													13879	13858	13832	13803	13770	13732	13689	13640	13581		
2011	13703												13703	13682	13657	13628	13595	13558	13516	13467	13409	13341		
2010	13527											13527	13507	13481	13453	13421	13384	13342	13294	13237	13169	13088		
2009	13351										13351	13331	13306	13278	13246	13210	13169	13121	13065	12998	12918	12819		
2008	13175									13175	13155	13130	13103	13071	13036	12995	12948	12892	12827	12747	12650	12527		
2007	12999								12999	12979	12955	12928	12897	12862	12822	12775	12720	12655	12577	12481	12360	12203		
2006	12823							12823	12804	12780	12753	12722	12688	12648	12602	12548	12484	12407	12312	12193	12038	11832		
2005	12647						12647	12628	12604	12578	12548	12513	12474	12429	12376	12313	12237	12143	12025	11873	11669	11384		
2004	12471					12471	12452	12429	12403	12373	12339	12301	12256	12204	12141	12066	11974	11858	11708	11507	11225	10807		
2003	12295				12295	12276	12253	12228	12198	12165	12127	12083	12031	11970	11896	11805	11691	11543	11344	11067	10655	10000		
2002	12119			12119	12101	12078	12052	12024	11991	11954	11910	11859	11799	11726	11636	11523	11377	11182	10908	10502	9857	8758		
2001	11943		11943	11925	11903	11877	11849	11817	11780	11737	11687	11627	11555	11467	11356	11212	11020	10750	10350	9713	8631	6840		
2000	11725	11725	11707	11685	11661	11633	11601	11565	11523	11474	11415	11344	11258	11149	11007	10818	10554	10161	9538	8473	6718	4598		
1999	10236	10221	10201	10180	10156	10128	10096	10060	10017	9965	9904	9828	9733	9610	9445	9213	8871	8325	7397	5863	4012	2639		
1998	11511	11472	11448	11421	11389	11354	11313	11264	11207	11137	11052	10945	10807	10621	10361	9976	9362	8319	6593	4512	2968	2059		
1997	12759	12689	12659	12624	12585	12539	12485	12422	12345	12250	12132	11978	11772	11484	11057	10377	9221	7308	5001	3290	2282	1682		
1996	13567	13460	13424	13382	13333	13276	13208	13127	13026	12900	12737	12518	12212	11757	11034	9804	7771	5318	3488	2427	1788	1380		
1995	11803	11678	11642	11600	11550	11491	11420	11333	11223	11081	10890	10624	10229	9600	8530	6760	4626	3043	2111	1556	1200	957		
1994	9000	8877	8845	8807	8762	8708	8641	8558	8449	8304	8101	7799	7320	6504	5155	3528	2321	1610	1186	915	729	595		
1993	7869	7733	7700	7661	7614	7555	7482	7387	7261	7083	6819	6400	5687	4507	3084	2029	1408	1037	800	638	520	432		
1992	8691	8505	8461	8409	8345	8264	8159	8019	7823	7532	7069	6281	4978	3407	2241	1555	1146	884	704	575	477	401		
1991	8934	9671	9612	9538	9446	9326	9166	8942	8609	8080	7179	5690	3894	2561	1777	1310	1010	805	657	545	458	389		

1990	12655	12244	12151	12033	11881	11677	11391	10967	10293	9145	7248	4960	3263	2264	1668	1287	1026	837	695	584	495	422
1989	13944	13388	13258	13091	12866	12551	12084	11341	10077	7987	5466	3595	2494	1838	1418	1130	922	765	643	545	465	
1988	15187	14440	14258	14013	13670	13161	12352	10975	8699	5953	3916	2717	2002	1544	1231	1004	834	700	594	507		
1987	11548	10841	10655	10394	10008	9392	8345	6614	4526	2978	2066	1522	1174	936	764	634	533	452	385			
1986	11269	10398	10143	9766	9165	8144	6454	4417	2906	2016	1486	1146	913	745	619	520	441	376				
1985	15710	14141	13614	12777	11353	8998	6158	4051	2810	2071	1598	1273	1039	862	725	614	524					
1984	19569	16959	15916	14142	11208	7670	5046	3501	2580	1990	1586	1294	1074	903	765	653						
1983	17498	14231	12645	10022	6859	4512	3130	2307	1779	1418	1157	960	807	684	584							
1982	23348	16873	13373	9152	6020	4177	3078	2374	1892	1544	1281	1077	913	779								
1981	30510	17475	11959	7867	5458	4022	3103	2473	2018	1675	1407	1193	1018									
1980	22499	8819	5801	4025	2966	2288	1824	1488	1235	1038	880	751										
1979	14697	3790	2629	1937	1495	1191	972	807	678	575	491											
1978	13606	2434	1794	1384	1103	900	747	628	532	454												
1977	13184	1738	1341	1069	872	724	608	516	440													
1976	18940	1926	1535	1253	1040	874	741	632														
1975	23625	1915	1562	1297	1090	924	789															
1974	19461	1287	1068	898	761	650																
1973	18240	1001	841	713	609																	
1972	19256	888	753	643																		
1971	18677	730	623																			
1970	15459	516																				
TOTAL: 2000 Scrap Rate		272065	263561	255827	249564	244831	241646	239717	238727	238391	238705	239916	241906	244452	247599	250805	253596	256290	259234	262464	265804	269243
TOTAL: Sustained Growth rate		272065	277211	282358	287504	292651	297797	302944	308090	313237	318383	323530	328676	333823	338969	344116	349262	354409	359555	364702	369848	374995
<b>MARKET PENETRATION OF NEW HEAVY VEHICLE ENGINE TECHNOLOGY: GROWTH BY INCREASED SALES SCEANARIO</b>																						
100% New Sales		4.79%	13.58%	21.84%	29.38%	36.19%	42.33%	47.90%	53.04%	57.86%	62.36%	66.48%	70.28%	73.83%	77.12%	80.30%	83.49%	86.58%	89.46%	92.06%	94.31%	96.05%
75% New Sales		4.79%	11.27%	17.37%	22.92%	27.95%	32.47%	36.58%	40.37%	43.92%	47.24%	50.28%	53.09%	55.70%	58.13%	60.47%	62.82%	65.11%	67.23%	69.14%	70.80%	72.09%
<b>MARKET PENETRATION OF NEW HEAVY VEHICLE ENGINE TECHNOLOGY: GROWTH BY INCREASED VEHICLE AGE SCENARIO</b>																						
100% New Sales		4.79%	8.89%	12.90%	16.81%	20.63%	24.37%	28.03%	31.61%	35.11%	38.53%	41.88%	45.15%	48.34%	51.45%	54.48%	57.41%	60.22%	62.90%	65.37%	67.52%	69.20%
75% New Sales		4.79%	7.81%	10.77%	13.65%	16.47%	19.23%	21.93%	24.57%	27.15%	29.67%	32.14%	34.55%	36.91%	39.20%	41.43%	43.59%	45.67%	47.64%	49.46%	51.05%	52.29%

\*Note: Sales data in italics is linear extrapolation of sales 1990 - 2000

APPENDIX Q GRAPHICAL REPRESENTATION OF THE VEP RESULTS

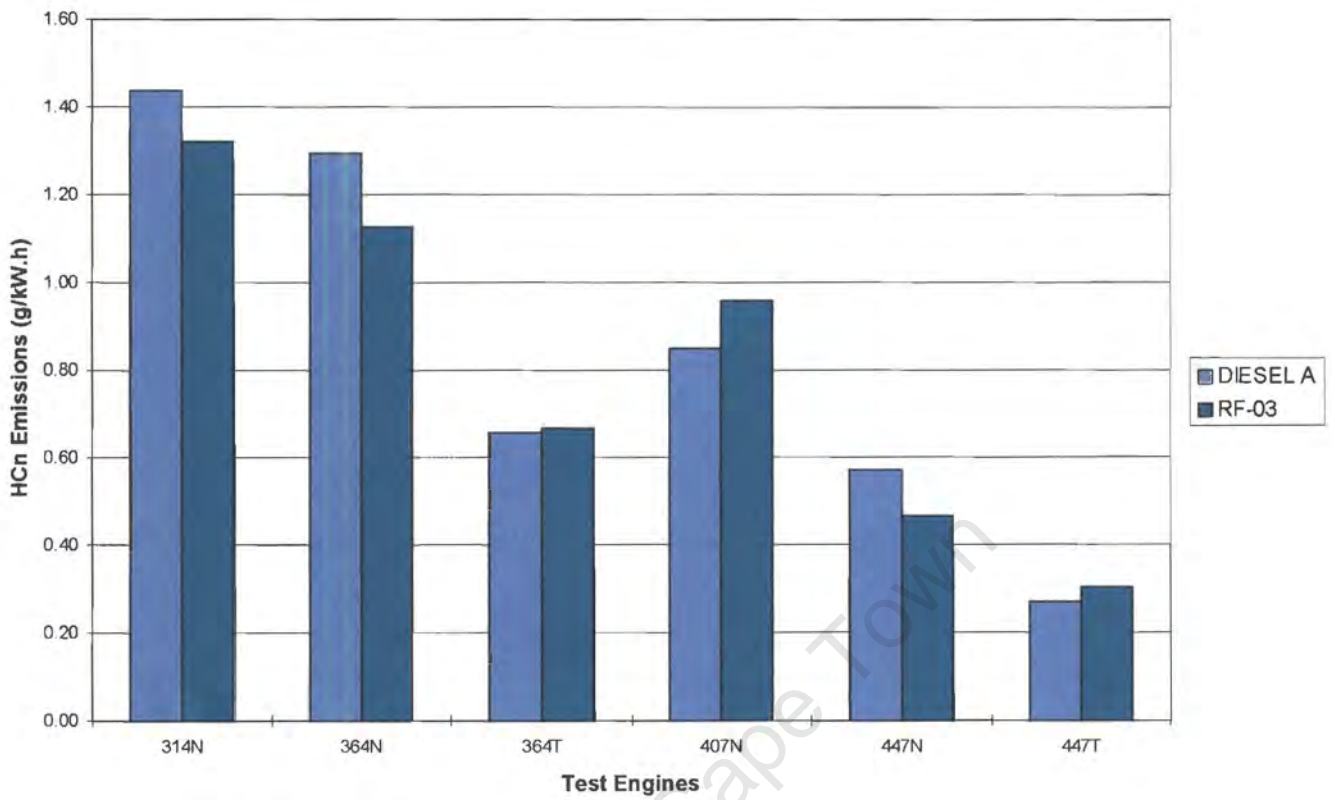


Figure Q - 1: Total Hydrocarbon Emissions (HC<sub>n</sub>): Diesel Sea-Level Results

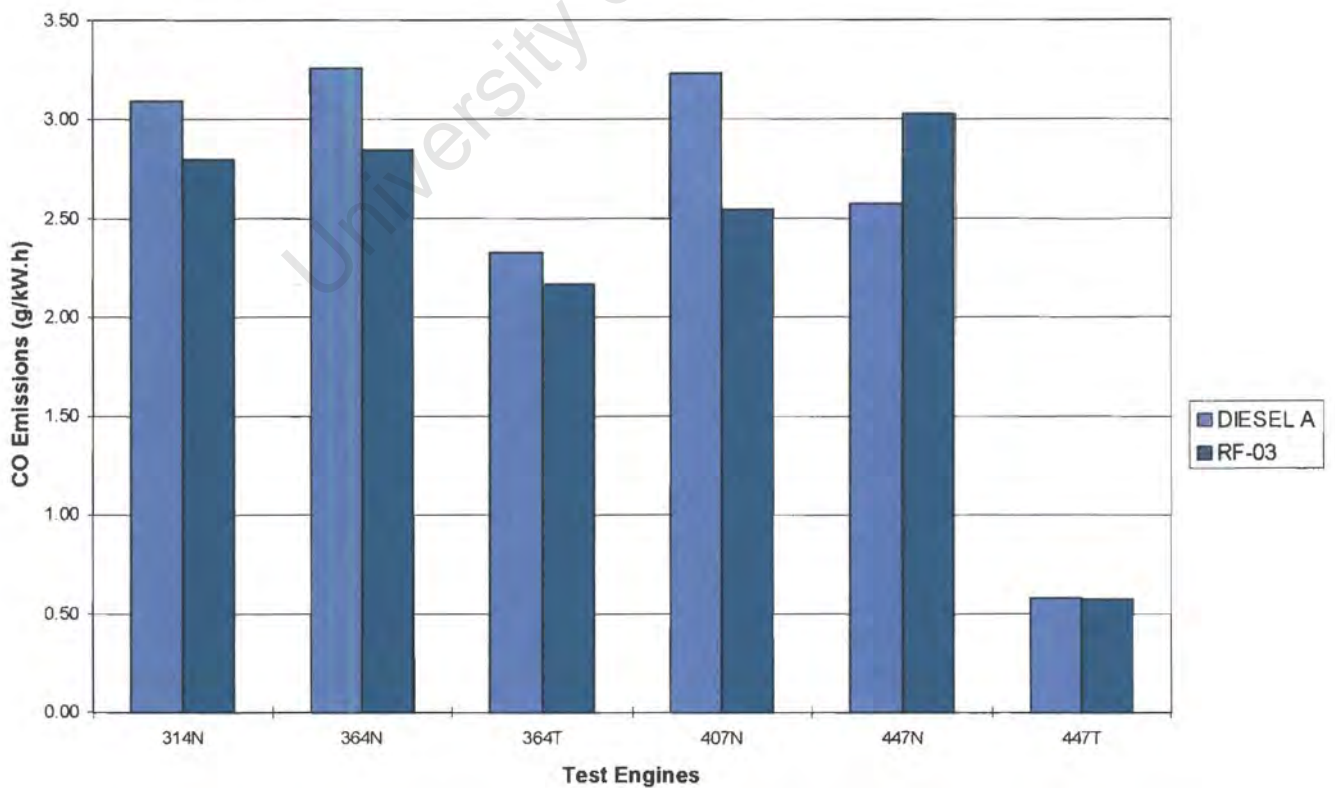


Figure Q - 2: Carbon Monoxide Emissions (CO): Diesel Sea-Level Results

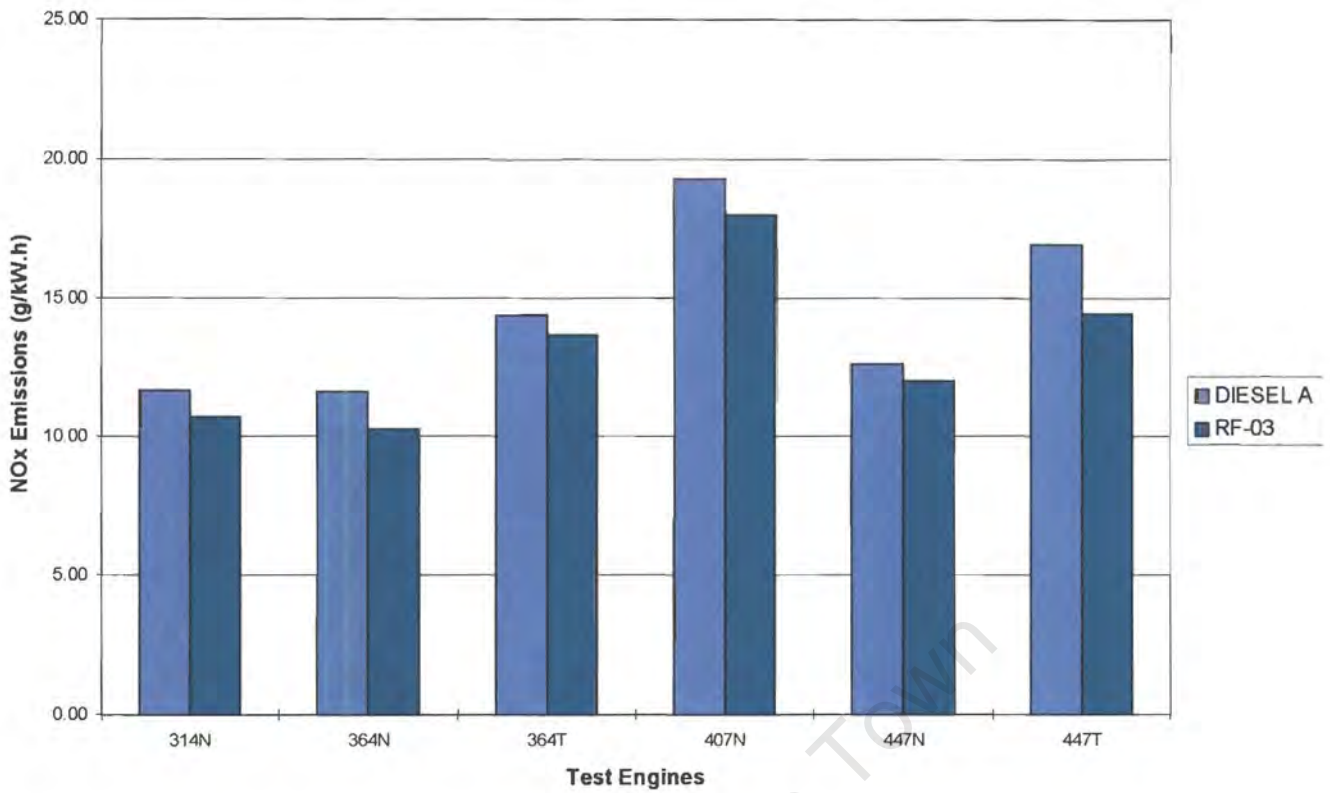


Figure Q - 3: Oxides of Nitrogen Emissions (NO<sub>x</sub>): Diesel Sea-Level Results

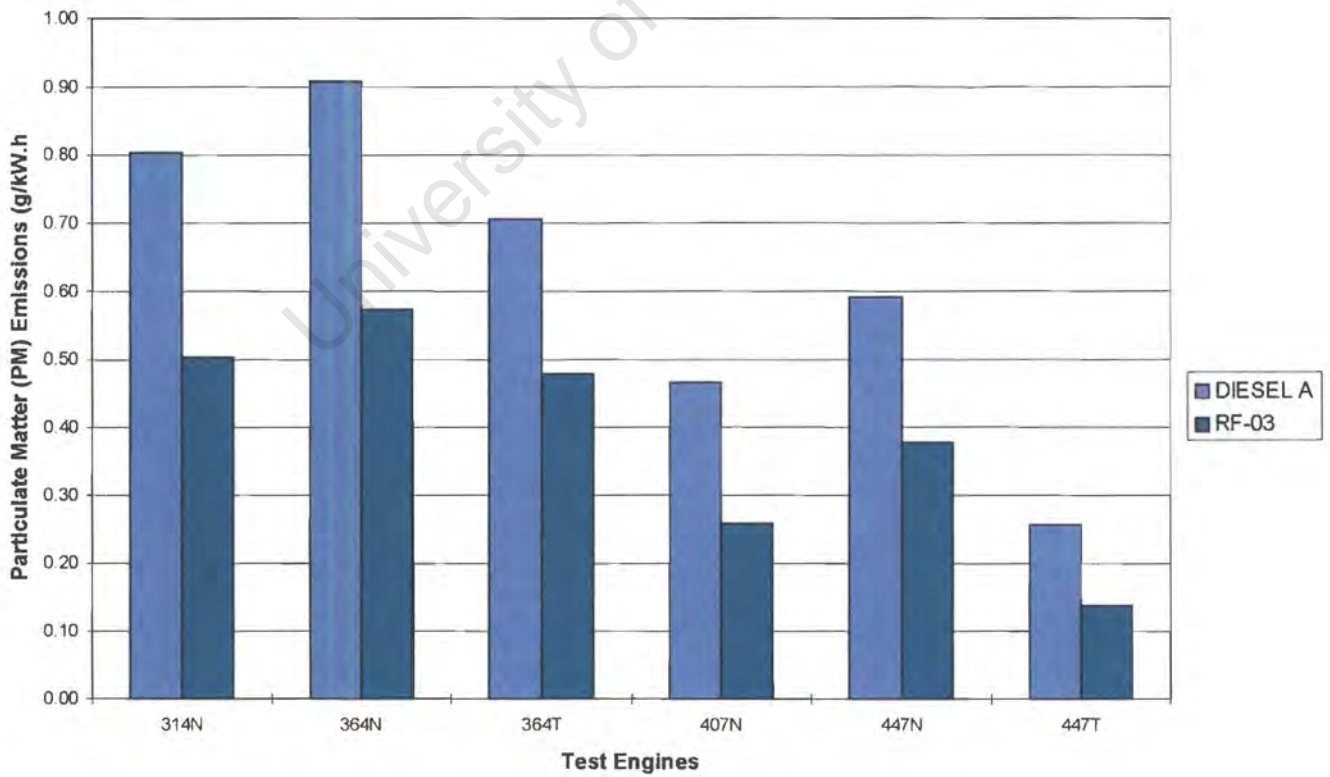


Figure Q - 4: Particulate Matter (PM) Emissions: Diesel Sea-Level Results

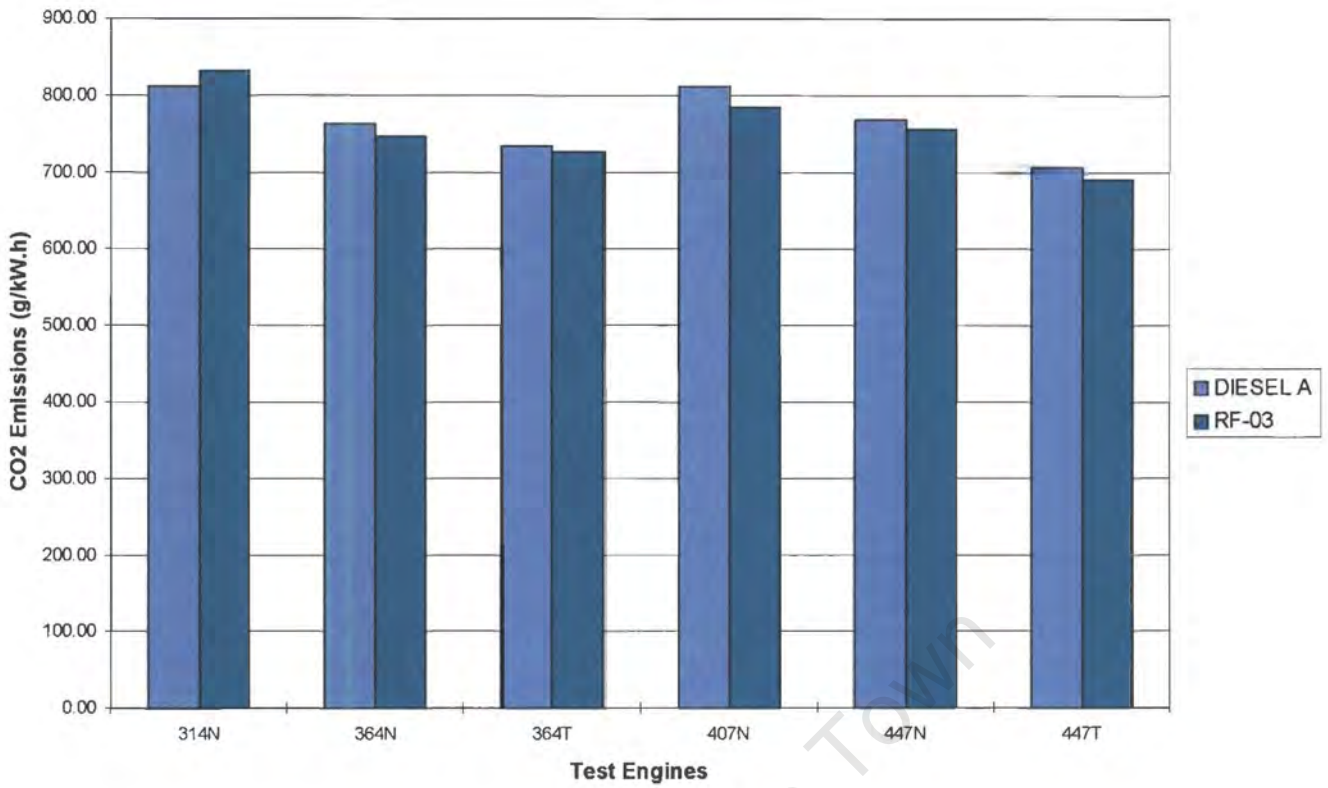


Figure Q - 5: Carbon Dioxide (CO<sub>2</sub>) Emissions: Diesel Sea-Level Results

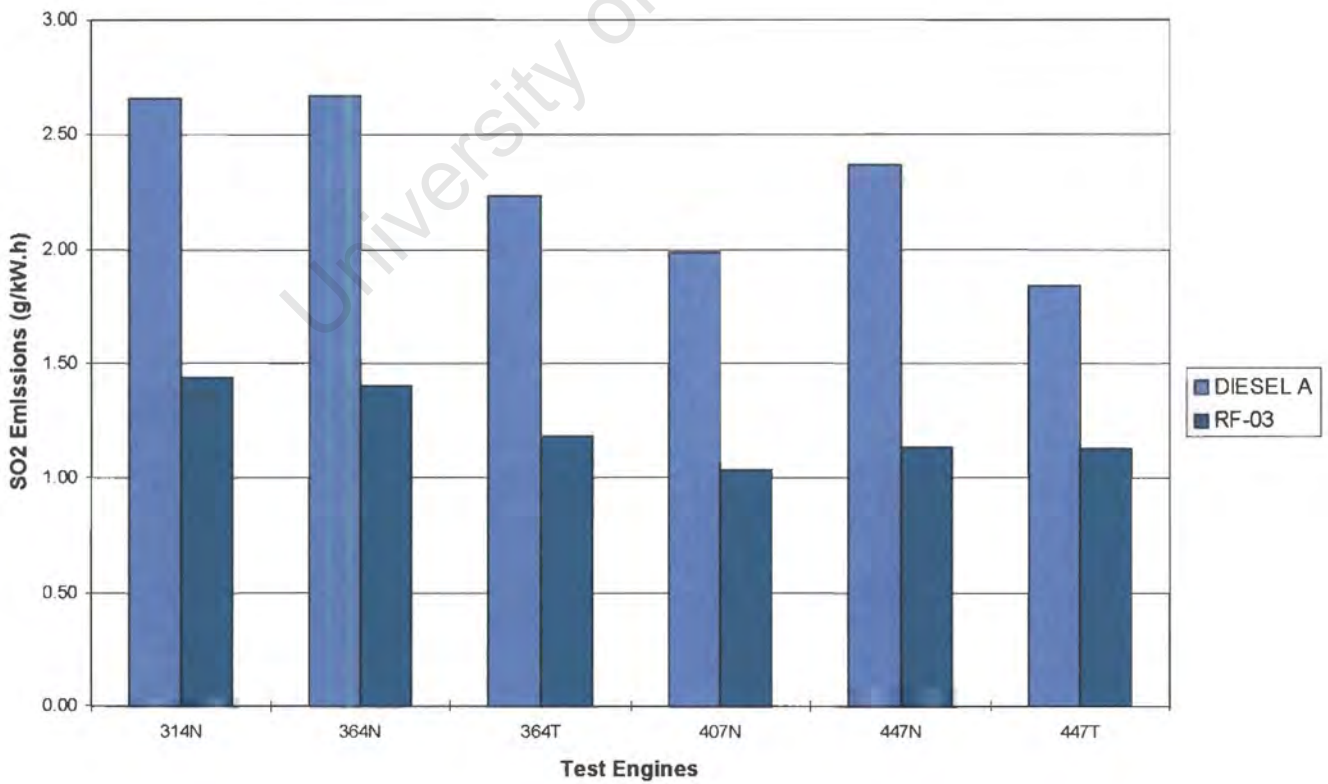


Figure Q - 6: Sulphur Dioxide Emissions (SO<sub>2</sub>): Diesel Sea-Level Results

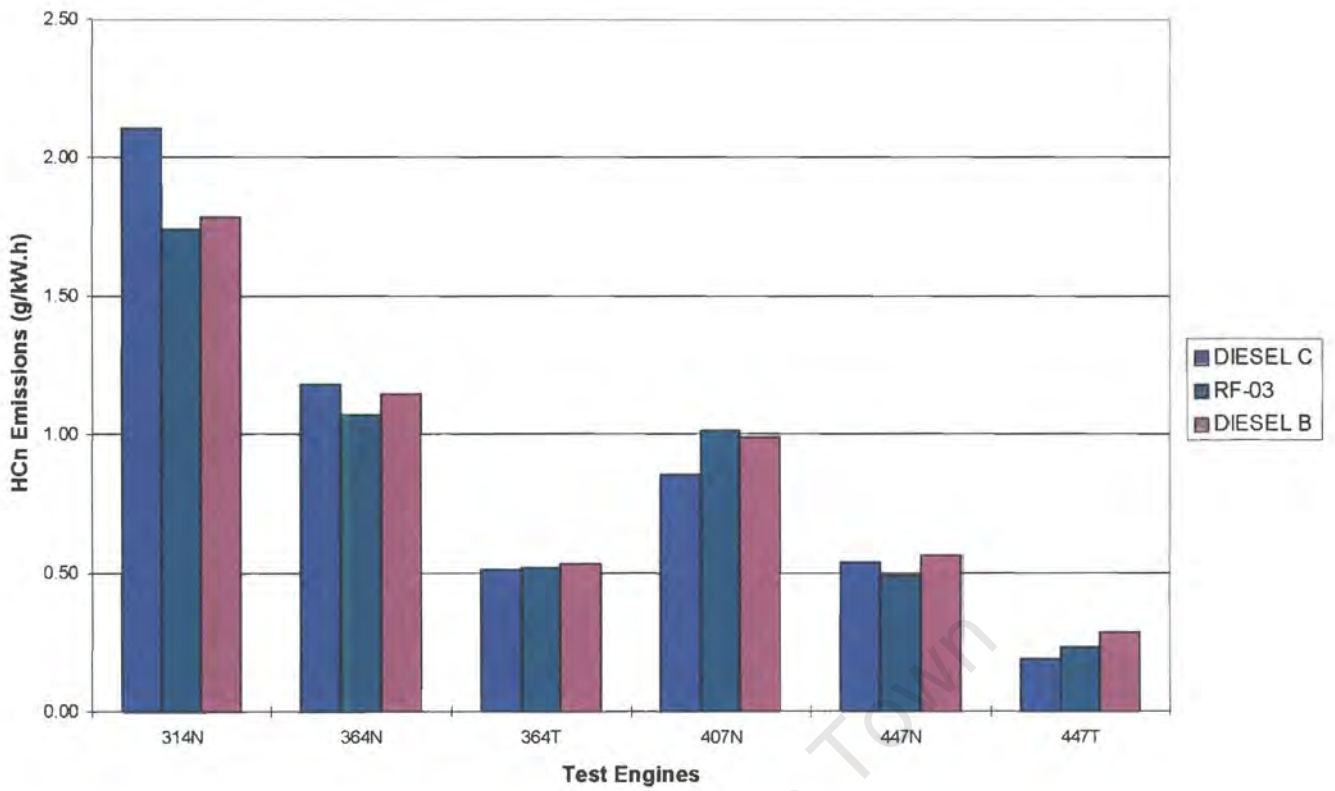


Figure Q - 7: Total Hydrocarbon Emissions (HC<sub>n</sub>): Diesel High Altitude Results

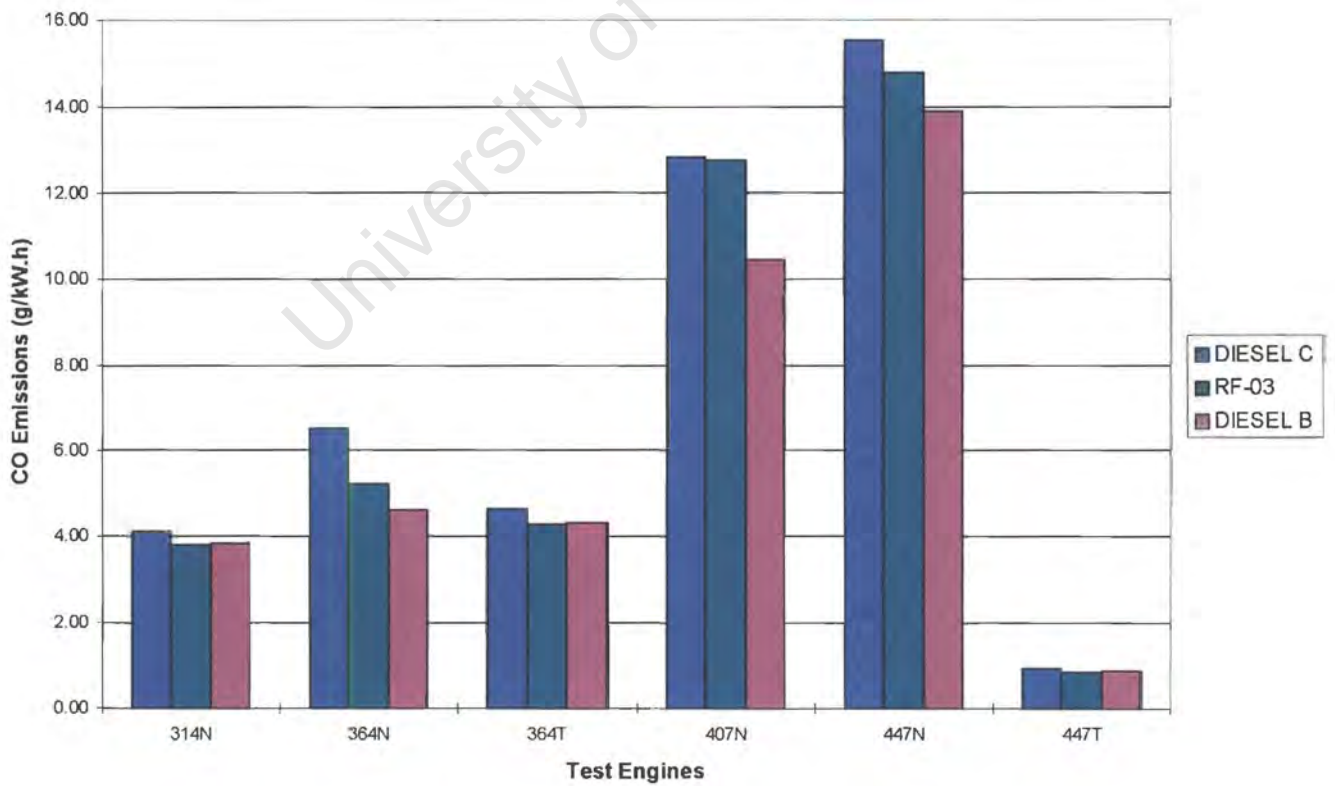


Figure Q - 8: Carbon Monoxide Emissions (CO): Diesel High Altitude Results

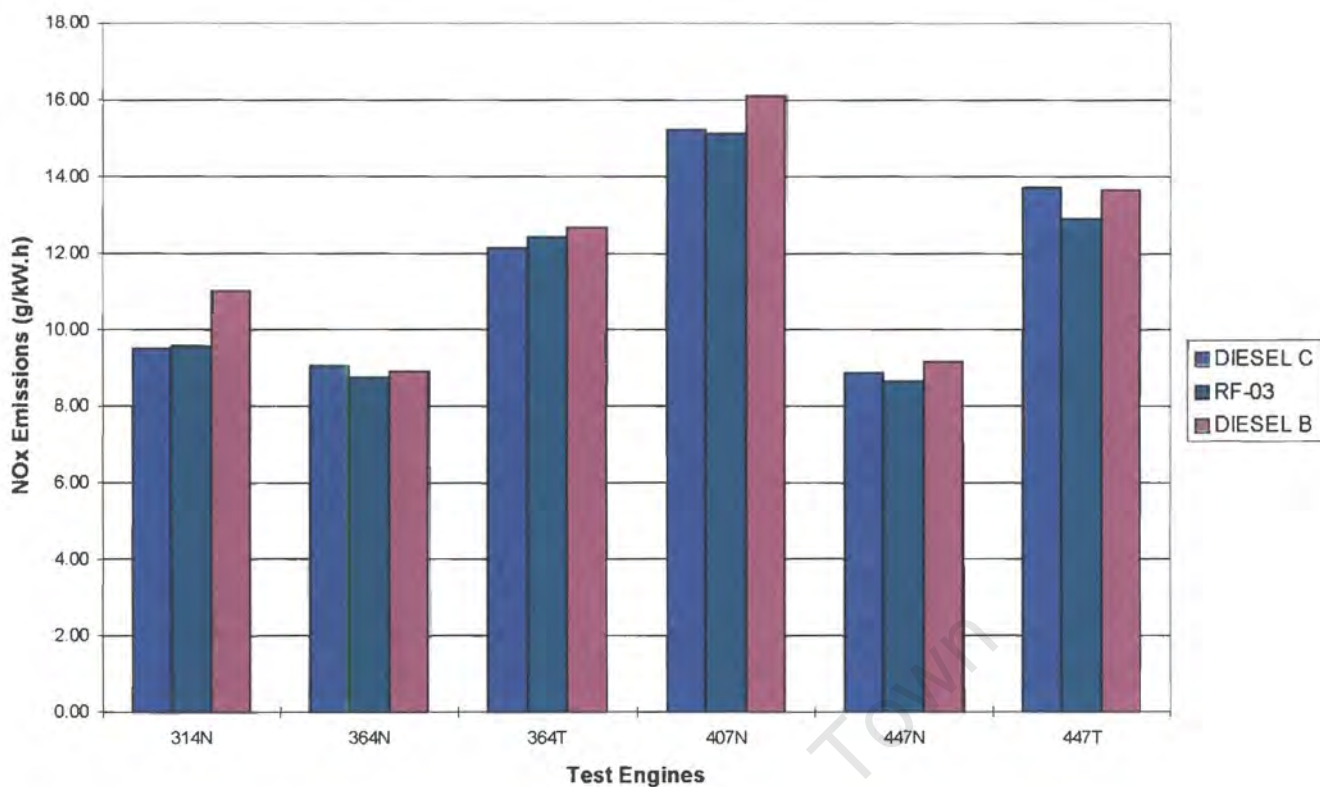


Figure Q - 9: Oxides of Nitrogen Emissions (NO<sub>x</sub>): Diesel High Altitude Results

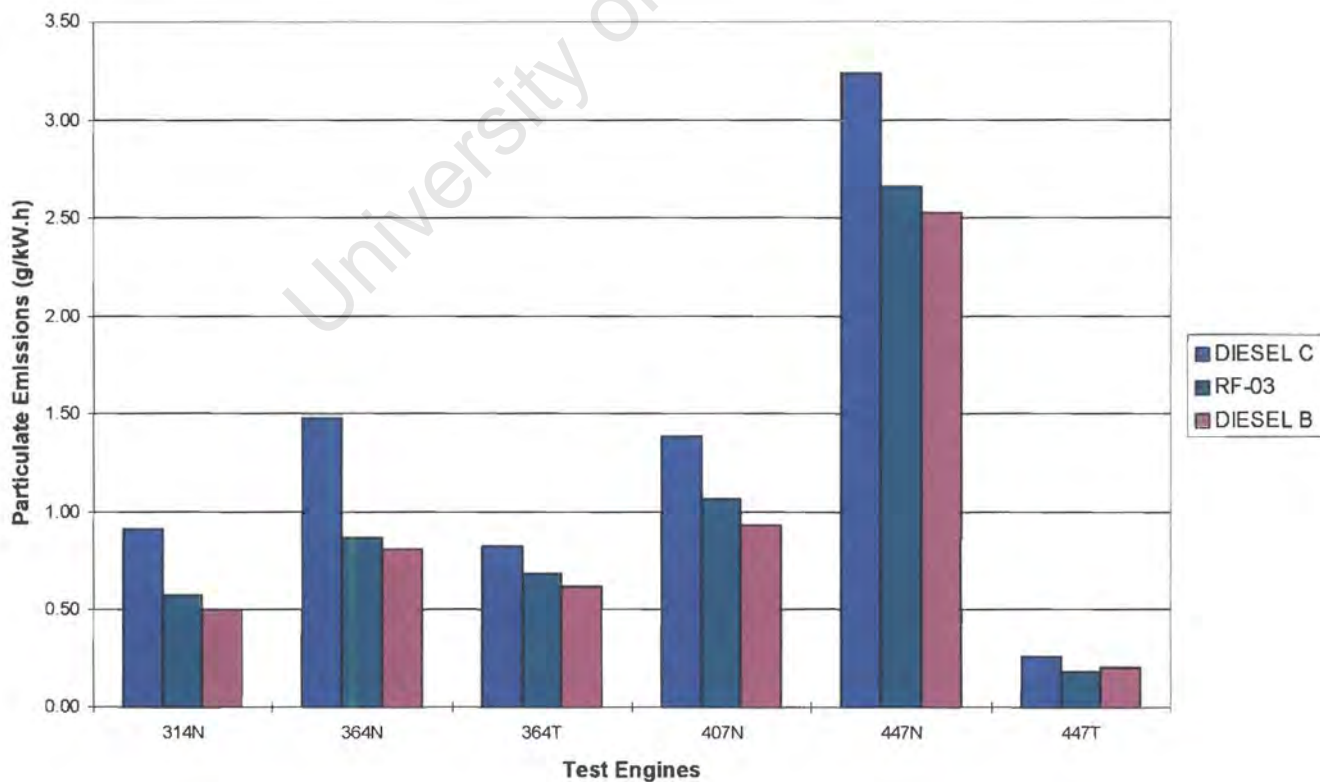


Figure Q - 10: Particulate Emissions (PM): Diesel High Altitude Results

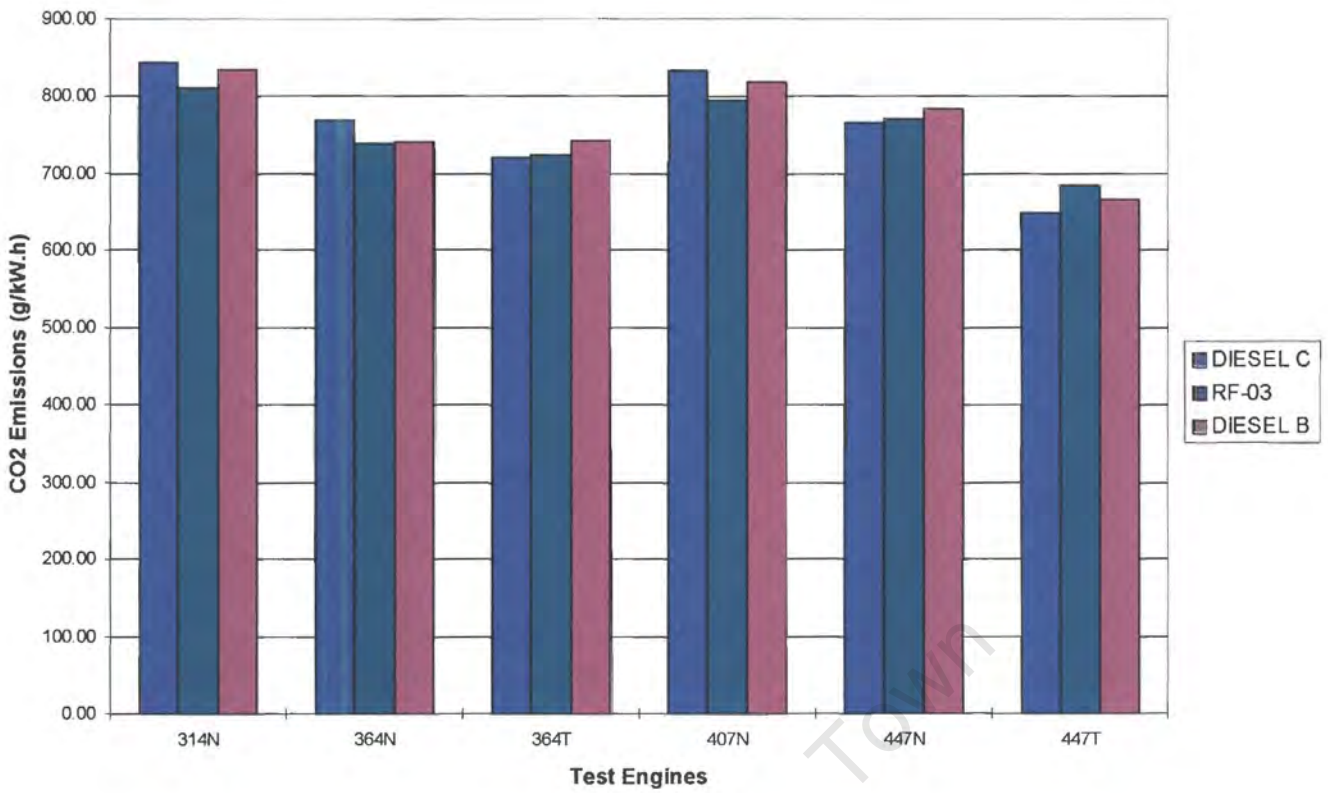


Figure Q - 11: Carbon Dioxide Emissions (CO<sub>2</sub>): Diesel High Altitude Results

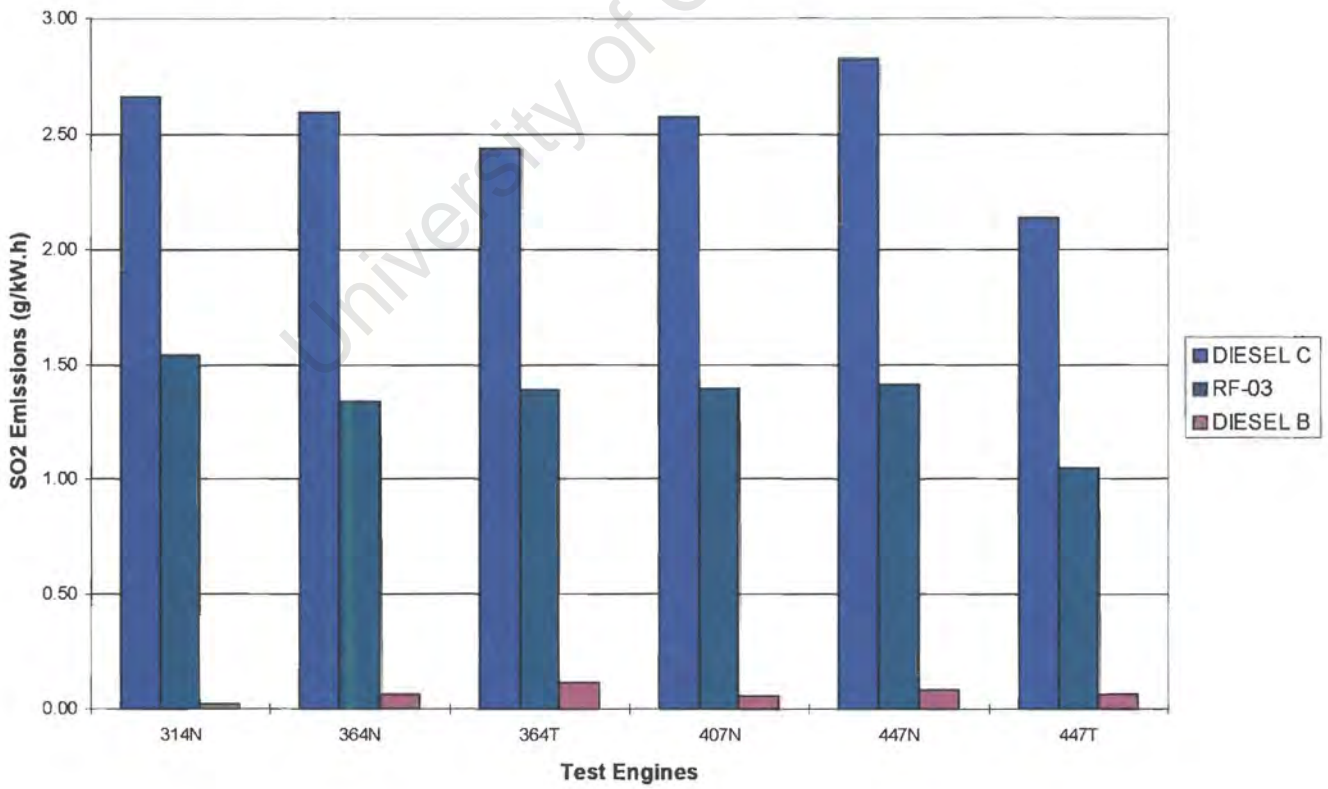


Figure Q - 12: Sulphur Dioxide Emissions (SO<sub>2</sub>): Diesel High Altitude Results

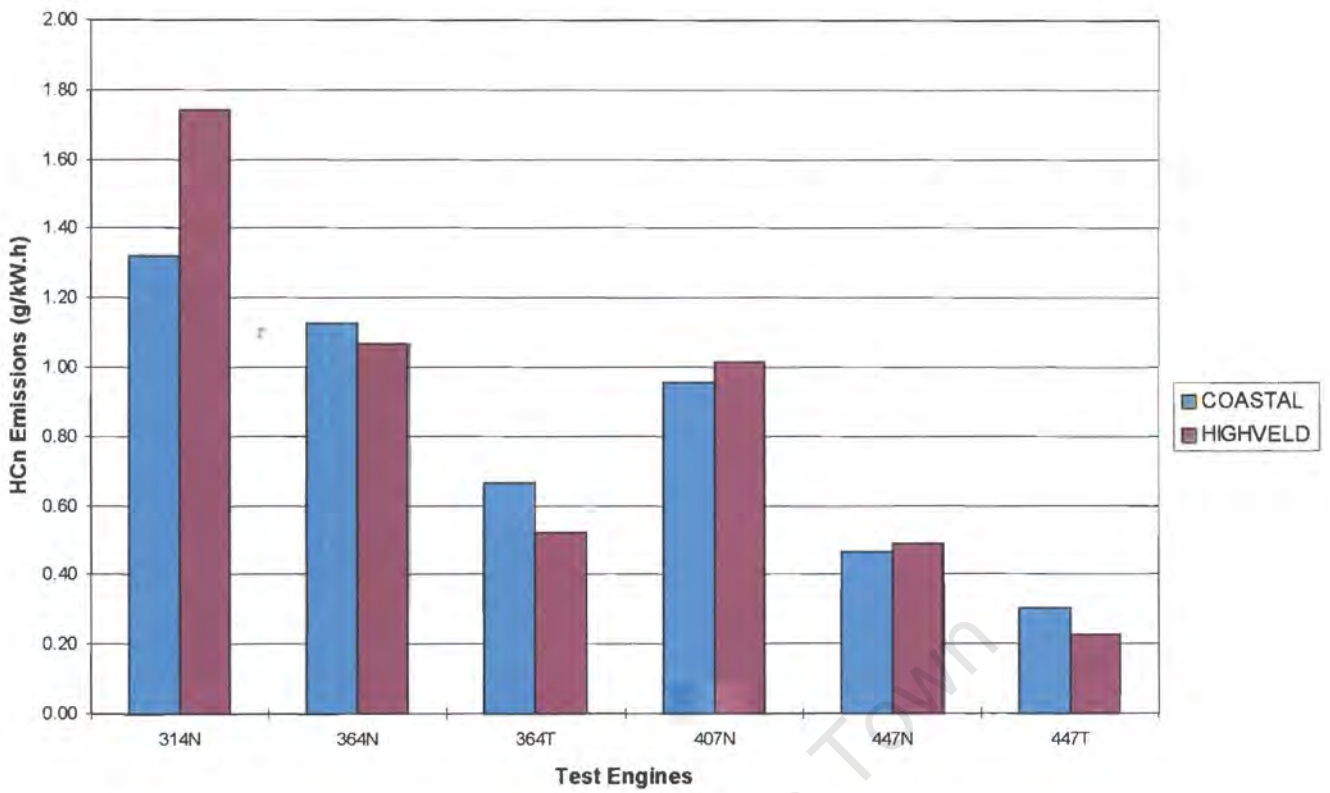


Figure Q - 13: Coastal and Highveld Comparison: Total Hydrocarbon Emissions (HC<sub>n</sub>)

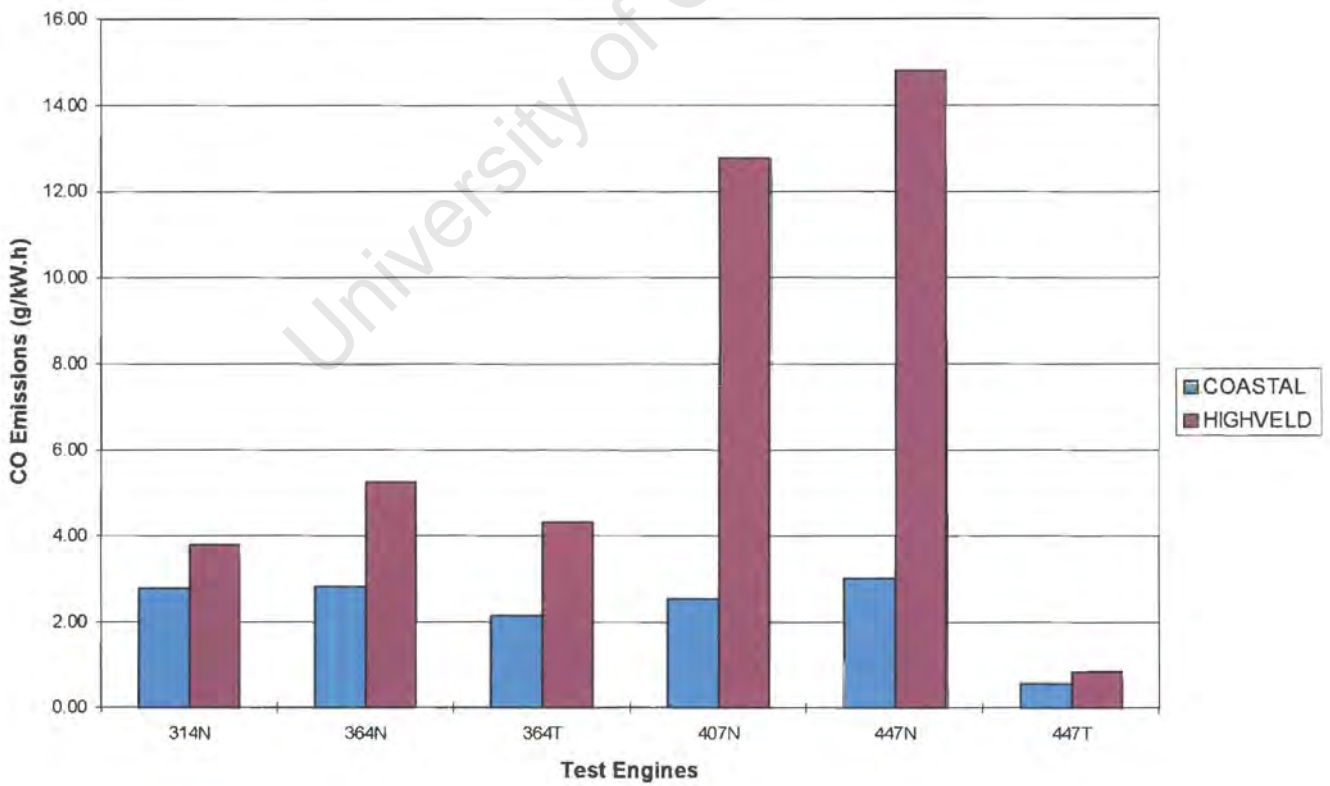


Figure Q - 14: Coastal and Highveld Comparison: Carbon Monoxide Emissions (CO)

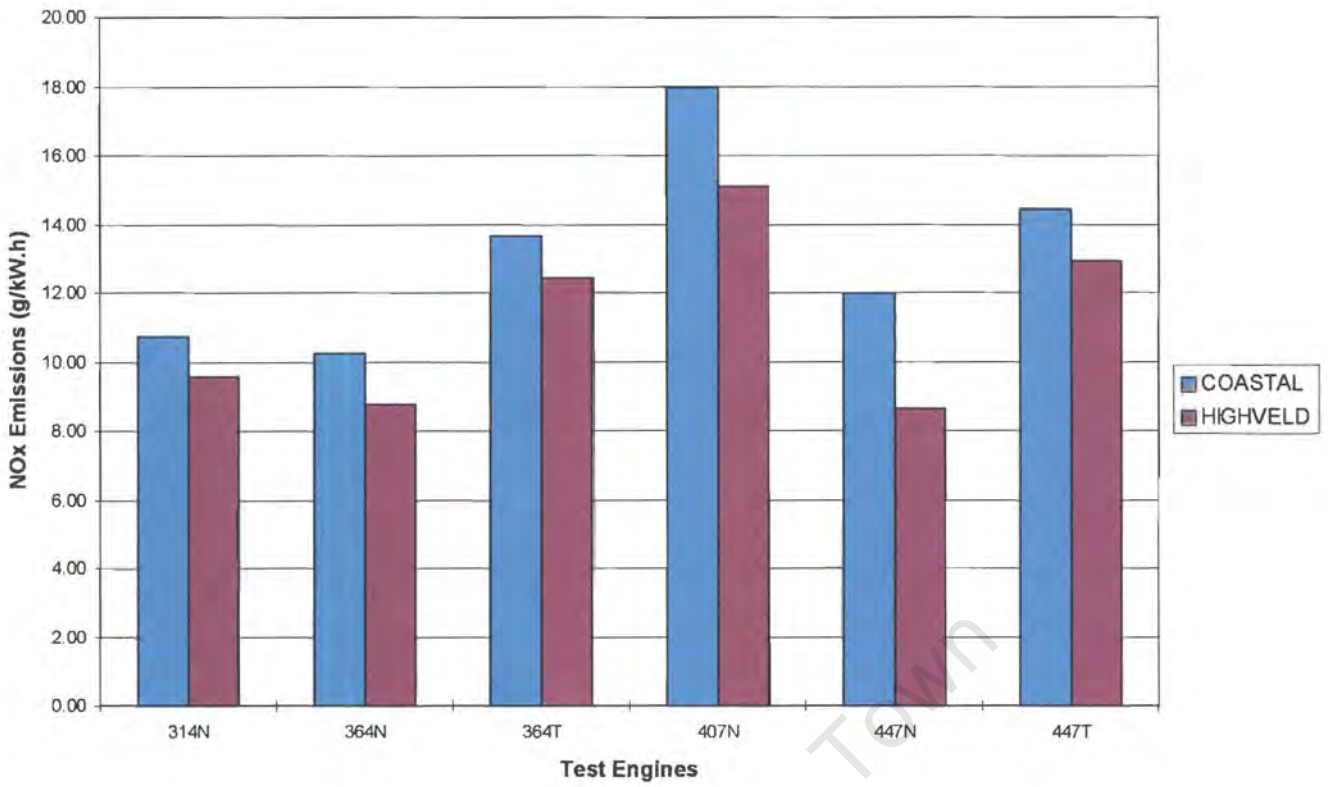


Figure Q - 15: Coastal and Highveld Comparison: Oxides of Nitrogen (NO<sub>x</sub>) Emissions

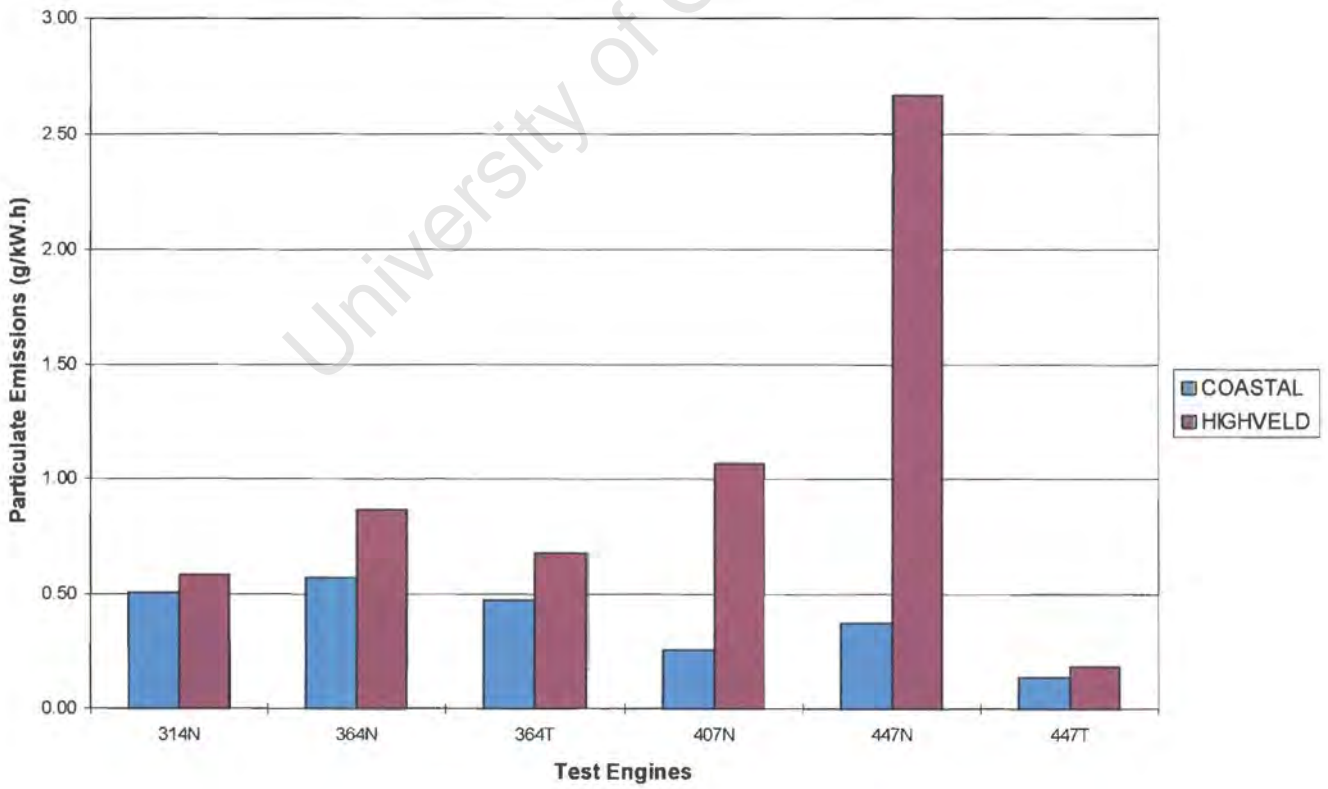


Figure Q - 16: Coastal and Highveld Comparison: Particulate Matter (PM) Emissions

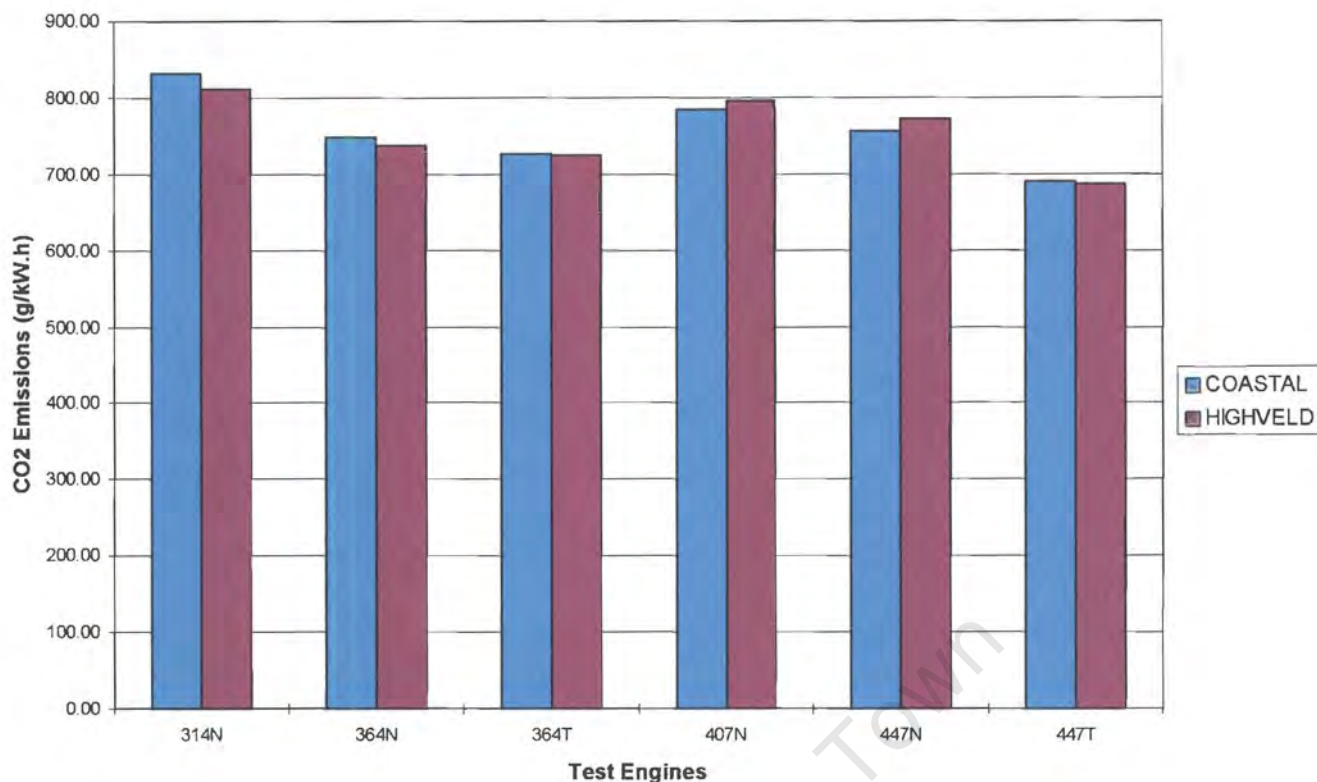


Figure Q - 17: Coastal and Highveld Comparison: Carbon Dioxide (CO<sub>2</sub>) Emissions

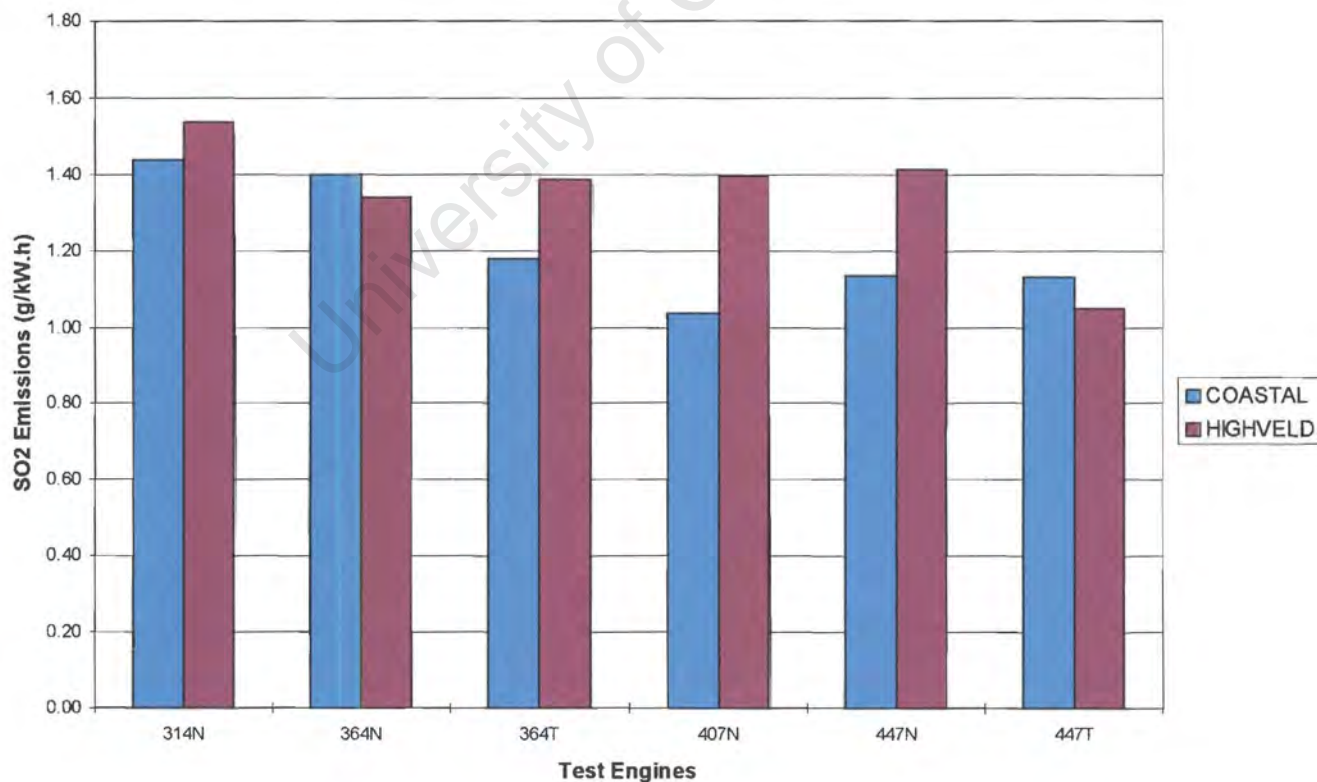


Figure Q - 18: Coastal and Highveld Comparison: Sulphur Dioxide (SO<sub>2</sub>) Emissions

**APPENDIX R TABULATED RESULTS OF THE INVENTORY MODELLING STUDY**

**Table R - 1: Baseline Model Results**

<b>TOTAL ANNUAL EMISSIONS (kt/annum)</b>					
<b>LCV</b>	<b>MCV</b>	<b>HCV</b>	<b>MCV &amp; HCV</b>	<b>All CV</b>	<b>Pollutant</b>
1.17	1.82	10.59	12.41	13.58	<b>HC<sub>n</sub></b>
12.92	5.13	44.86	49.99	62.91	<b>CO</b>
16.61	13.13	167.14	180.26	196.88	<b>NO<sub>x</sub></b>
5.81	2.17	19.87	22.03	27.84	<b>SO<sub>2</sub></b>
2690.73	998.69	9777.92	10776.61	13467.34	<b>CO<sub>2</sub></b>
2.84	1.00	7.71	8.72	11.56	<b>PM</b>

**Table R - 2: Baseline Model Results: Altitude / Sea-Level Distribution**

<b>TOTAL ANNUAL EMISSIONS</b>					
<b>Altitude</b>	<b>Sea-Level</b>	<b>Altitude</b>	<b>Sea-Level</b>	<b>Total</b>	<b>Pollutant</b>
<b>(kt/annum)</b>	<b>(kt/annum)</b>	<b>(%)</b>	<b>(%)</b>	<b>(kt/annum)</b>	
9.49	4.09	70%	30%	13.58	<b>HC<sub>n</sub></b>
51.13	11.77	81%	19%	62.91	<b>CO</b>
126.18	70.70	64%	36%	196.88	<b>NO<sub>x</sub></b>
17.19	10.65	62%	38%	27.84	<b>SO<sub>2</sub></b>
9115.69	4351.65	68%	32%	13467.34	<b>CO<sub>2</sub></b>
8.57	2.99	74%	26%	11.56	<b>PM</b>

**Table R - 3: Scenario Modelling Results for Hydrocarbon Emissions (HC<sub>n</sub>)**

<b>TOTAL ANNUAL EMISSIONS (kt/annum)</b>					<b>Change From Baseline</b>	<b>Scenario</b>
<b>LCV</b>	<b>MCV</b>	<b>HCV</b>	<b>MCV &amp; HCV</b>	<b>All CV</b>		
1.17	1.82	10.59	12.41	13.58	0.00%	<b>Baseline Model Emissions</b>
1.17	1.90	10.70	12.59	13.76	1.37%	<b>Model with no Synthetic Fuel</b>
1.17	0.93	6.67	7.59	8.76	-35.45%	<b>All MCVs &amp; HCVs are TI</b>
1.17	0.85	4.79	5.65	6.82	-49.80%	<b>All NA MCVs &amp; HCVs are turbo</b>
1.17	0.00	5.77	5.77	6.94	-48.90%	<b>Park of 20 000+ kg GVM only</b>
1.17	1.67	9.93	11.60	12.77	-5.94%	<b>Park Euro 1 Compliance</b>
0.97	1.51	9.33	10.85	11.82	-12.94%	<b>Park Euro 2 Compliance</b>
0.68	1.00	7.05	8.05	8.73	-35.69%	<b>Park Euro 3 Compliance</b>
1.17	1.78	10.45	12.22	13.40	-1.33%	<b>10% of CVs are CNG-fuelled</b>
1.22	1.37	9.19	10.56	11.78	-13.26%	<b>100% of CVs are CNG-fuelled</b>

**Table R - 4:** Scenario Modelling Results for Carbon Monoxide Emissions (CO)

TOTAL ANNUAL EMISSIONS (kt/annum)						
LCV	MCV	HCV	MCV & HCV	All CV	Change From Baseline	Scenario
12.92	5.13	44.86	49.99	62.91	0.00%	Baseline Model Emissions
14.30	5.52	47.73	53.24	67.54	7.37%	Model with no Synthetic Fuel
12.92	5.85	34.06	39.90	52.82	-16.03%	All MCVs & HCVs are TI
12.92	5.70	25.86	31.56	44.48	-29.30%	All NA MCVs & HCVs are turbo
12.92	0.00	41.39	41.39	54.32	-13.66%	Park of 20 000+ kg GVM only
12.92	5.12	44.83	49.95	62.87	-0.05%	Park Euro 1 Compliance
11.77	5.12	44.83	49.95	61.72	-1.88%	Park Euro 2 Compliance
10.63	4.33	39.53	43.87	54.50	-13.37%	Park Euro 3 Compliance
12.29	4.87	44.16	49.03	61.32	-2.52%	10% of CVs are CNG-fuelled
6.66	2.60	37.82	40.42	47.07	-25.17%	100% of CVs are CNG-fuelled

**Table R - 5:** Scenario Modelling Results for Oxides of Nitrogen Emissions (NO<sub>x</sub>)

TOTAL ANNUAL EMISSIONS (kt/annum)						
LCV	MCV	HCV	MCV & HCV	All CV	Change From Baseline	Scenario
16.61	13.13	167.14	180.26	196.88	0.00%	Baseline Model Emissions
17.74	12.89	166.66	179.56	197.30	0.21%	Model with no Synthetic Fuel
16.61	10.46	124.34	134.79	151.41	-23.10%	All MCVs & HCVs are TI
16.61	19.44	176.52	195.96	212.57	7.97%	All NA MCVs & HCVs are turbo
16.61	0.00	197.83	197.83	214.44	8.92%	Park of 20 000+ kg GVM only
14.67	9.91	101.65	111.56	126.22	-35.89%	Park Euro 1 Compliance
5.75	7.72	79.06	86.78	92.53	-53.00%	Park Euro 2 Compliance
5.13	5.51	56.47	61.98	67.12	-65.91%	Park Euro 3 Compliance
15.07	11.90	151.44	163.34	178.41	-9.38%	10% of CVs are CNG-fuelled
1.14	0.85	10.17	11.02	12.16	-93.82%	100% of CVs are CNG-fuelled

**Table R - 6:** Scenario Modelling Results for Particulate Matter Emissions (PM)

TOTAL ANNUAL EMISSIONS (kt/annum)						
LCV	MCV	HCV	MCV & HCV	All CV	Change From Baseline	Scenario
2.84	1.00	7.71	8.72	11.56	0.00%	Baseline Model Emissions
3.48	1.20	8.91	10.12	13.60	17.65%	Model with no Synthetic Fuel
2.84	0.77	5.11	5.88	8.73	-24.49%	All MCVs & HCVs are TI
2.84	1.07	5.54	6.61	9.45	-18.24%	All NA MCVs & HCVs are turbo
2.84	0.00	6.44	6.44	9.28	-19.68%	Park of 20 000+ kg GVM only
2.42	0.92	7.04	7.96	10.38	-10.16%	0.3% Fuel Sulphur Limit
2.23	0.87	6.70	7.56	9.80	-15.25%	0.2% Fuel Sulphur Limit
2.04	0.82	6.35	7.17	9.21	-20.34%	0.1% Fuel Sulphur Limit
1.94	0.80	6.17	6.97	8.91	-22.88%	0.05% Fuel Sulphur Limit
1.86	0.77	6.02	6.79	8.65	-25.18%	0.005% Fuel Sulphur Limit
2.65	0.86	6.89	7.75	10.40	-10.06%	Park Euro 1 Compliance
1.22	0.35	3.14	3.49	4.71	-59.24%	Park Euro 2 Compliance
0.76	0.15	1.73	1.88	2.64	-77.15%	Park Euro 3 Compliance
2.57	0.91	7.01	7.92	10.49	-9.24%	10% of CVs are CNG-fuelled
0.15	0.06	0.68	0.73	0.88	-92.35%	100% of CVs are CNG-fuelled

**Table R - 7:** Scenario Modelling Results for Sulphur Dioxide Emissions (SO<sub>2</sub>)

TOTAL ANNUAL EMISSIONS (kt/annum)						
LCV	MCV	HCV	MCV & HCV	All CV	Change From Baseline	Scenario
5.81	2.17	19.87	22.03	27.84	0.00%	Baseline Model Emissions
8.79	3.31	30.42	33.72	42.52	52.70%	Model with no Synthetic Fuel
3.49	1.35	12.38	13.73	17.22	-38.15%	0.3% Fuel Sulphur Limit
2.36	0.91	8.34	9.25	11.61	-58.31%	0.2% Fuel Sulphur Limit
1.23	0.46	4.31	4.77	6.00	-78.46%	0.1% Fuel Sulphur Limit
0.66	0.24	2.29	2.53	3.19	-88.54%	0.05% Fuel Sulphur Limit
0.15	0.04	0.47	0.52	0.66	-97.61%	0.005% Fuel Sulphur Limit
5.23	1.95	17.88	19.83	25.06	-10.00%	10% of CV's are CNG fuelled
0.00	0.00	0.00	0.00	0.00	-100.00%	100% of CV's are CNG fuelled

**Table R - 8:** Scenario Modelling Results for Carbon Dioxide Emissions (CO<sub>2</sub>)

TOTAL ANNUAL EMISSIONS (kt/annum)						
LCV	MCV	HCV	MCV & HCV	All CV	Change From Baseline	Scenario
2690.73	998.69	9777.92	10776.61	13467.34	0.00%	Baseline Model Emissions
2690.73	816.76	8640.31	9457.07	12147.80	-9.80%	All MCVs & HCVs are TI
2690.73	1106.95	9101.04	10207.99	12898.72	-4.22%	All NA MCVs & HCVs are turbo
2690.73	0.00	10219.20	10219.20	12909.93	-4.14%	Park of 20 000+ kg GVM only
2696.91	1001.19	9800.26	10801.44	13498.36	0.23%	10% of CVs are CNG-fuelled
2752.53	1023.64	10001.32	11024.96	13777.48	2.30%	100% of CVs are CNG-fuelled

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