

**ASSESSMENT OF EXHAUST EMISSIONS FROM IMPORTED USED MOTOR  
VEHICLES**

**(A case for Zambia)**

**By**

**Joseph Nkamba**

**The University of Zambia**

**Lusaka**

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## DECLARATION

I Joseph Nkamba hereby declare that the work performed and the contents of this dissertation submitted for the Master degree in Thermofluids Engineering to the University of Zambia, apart from the help and guidance from my Supervisor Professor F. D Yamba, is my own work and has not previously been submitted to another University or Institution of Higher Education for a Degree.

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## CERTIFICATE OF APPROVAL

This thesis authored by Joseph Nkamba has been approved as partial fulfilment of the requirement for the award of Master of Engineering in Mechanical Engineering (Thermal Fluids Engineering) of the University of Zambia.

- |                             |               |             |
|-----------------------------|---------------|-------------|
| 1. Dr. Zwelibanzi B. Dlodlo | Signed: ..... | Date: ..... |
| 2. Dr. Lennox Siwale        | Signed: ..... | Date: ..... |
| 3. Dr. Edwin Luwaya         | Signed: ..... | Date: ..... |
| 4. Dean Post Graduation     | Signed: ..... | Date: ..... |

## ABSTRACT

Zambia is tipped to be an emerging economy with current GDP (purchasing power parity) at US \$ 61.79 billion (CIA World Fact Book 2015). Recorded real growth rate was at 6.5% in 2014, 6.7% in 2013 while 2012 recorded 6.8% growth rate making the country one of the fastest growing economies in sub Saharan Africa thanks to the estimated 6.33 million (2014) people that constitute Zambia's workforce.

The Transport Sector was cited to be a major source of this economic growth and specifically associated with the upgrading of 9,403 km out of a total of 40,454 km from gravel to bituminous standards and more kilometers expected to be upgraded with the various road rehabilitation projects underway.

This economic growth complemented by increased access to financing (financial inclusion) has resulted in more people being able to afford at the minimum, the purchase of a used motor vehicle aged on average 8 years old. Given the 'used' condition coupled by old age of these motor vehicles entering Zambia's borders in increasing numbers, citizens across the country have raised concerns on the potential environmental and safety impacts that these vehicles may have, with some advocating for a total ban of such imports.

To investigate the allegations raised, a study was commissioned as part of the partial fulfillment of the award of Masters of Engineering Degree by the University of Zambia.

An MGT 5 gas analyzer was used to conduct tail pipe emission testing from vehicles imported and presented for registration at Mimosa Motor Vehicle Inspection Centre in Lusaka.

A total of 200 out of 116,007 imported used motor vehicles were assessed using an MGT 5 gas analyzer. All but 6 out of the 200 motor vehicles subjected to the study were passenger cars with engines ranging from 998cc to 4500 cc. with ages ranging from 1998 to 2009.

From the tailpipe emission tests conducted, the exhaust contents were CO, CO<sub>2</sub>, NO<sub>x</sub>, and HC. Lambda and O<sub>2</sub> contents were also measured to establish whether the engines in the motor vehicles presented were operating at stoichiometry or sub-stoichiometry ratios. The average emission levels found from the study of the two hundred motor vehicles were CO<sub>2</sub> 13.33 (% vol), CO (0.62 % vol), HC 204.93 ppm, O<sub>2</sub> (1.06 % vol), λ (1.02) and NO<sub>x</sub> (25.94 ppm).

The results were compared with the ZABS 560:2004 standard for imported used motor vehicles and Euro 4 (in the case of Hydrocarbons and NO<sub>x</sub>).

The study concluded that these imported used motor vehicles meet both the Zambian Standard for imported used motor vehicle set by the Zambia Bureau of Standards and the Euro 4 emission standard for gasoline engine motor vehicles.

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**Keywords:** Emissions, concentrations, volumes, MGT 5 gas analyzer, standards, CO, CO<sub>2</sub>, NO<sub>x</sub>, HC, lambda, O<sub>2</sub>, stoichiometry, ZABS, ZS 560:2004, % Vol, ppm, Euro 4, environment.

## **DEDICATION**

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Finally, I am grateful to my wife Thelma for her support without which I couldn't have reached this far. I dedicate this work to all my children and urge them to remain superior academic and professional individual's which will be key to their future.

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## **CHAPTER 1: BACKGROUND**

### ***1.1 Introduction***

Urban air pollution generates alarming levels of mortality through widespread chronic diseases in the World ([www.worldbank.org](http://www.worldbank.org)). The Bank cited the deteriorating urban air quality in China as a result of power plants and increasing vehicle fleet which the Bank has estimated to contribute to the equivalent of 3 to 6 million life years lost annually.

In Europe, the European Commission admitted that clean air was essential to health and to the environment and that since the industrial revolution, the quality of the air has deteriorated considerably – mainly as a result of human activities. The Commission observed rising industrial and energy production, the burning of fossil fuels and the dramatic rise in traffic on the roads as major contributions to air pollution in towns and cities which, in turn, has led to serious problems for both health and the environment. The Commission further observed that human toll for poor air quality is worse than for road traffic accidents, making it the number one environmental cause of premature death in the EU (European Commission, 2013).

Japan has been singled out as a unique example of a country in the World that has overcome the severe air pollution of nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) through the mandatory retirement of old, high emission vehicles in metropolitan areas. It is not clear however which policy instruments have been effective in mitigating the air pollution from automobiles (Kazuyuki Iwata, 2014) because of the use of several policy instruments and measures in her efforts to minimize emissions.

Dr. Brauer reported in a World Bank study that Air pollution from motor vehicles is a contributing risk factor to the top 5 diseases in the world: ischemic heart disease, stroke, chronic obstructive pulmonary disease (chronic bronchitis and emphysema), lung cancer, and acute lower respiratory infections (e.g. pneumonia) in children.

Schwela, 2012, wrote that urban air pollution in sub-Saharan Africa is on the rise, due to rapid economic and population growth and an increase in motorization. It is now estimated to cause roughly 49,000 deaths per year in the region. One main cause of this pollution is the use of fossil fuels in transport, combined with a lack of emission

controls on vehicles, and poor monitoring and enforcement systems. Along with harming human health, pollution from vehicles has a wide range of direct and indirect effects on ecosystems, agriculture and materials. Thus, there is an urgent need to better monitor and manage urban air quality and identify the most effective measures to reduce pollution.

According to a [www.unep.org](http://www.unep.org),2016, report on clean fuels and Vehicles (PCFV) on Africa, a total of 49 African countries have taken significant steps phasing out leaded petrol and introduction of low sulphur content diesel. Sudan and Nigeria were the first to phase out leaded petrol in 2002 where as Zambia managed to implement the measure in 2006 despite setting a target phasing out date of 2009. The report revealed that only 12 out of 49 countries have motor vehicle import restrictions based on the age while the rest have either no restriction or impose heavier import tax penalties for vehicles beyond specified ages.

Further, Zambia was cited in the report has specified the diesel sulphur content of 500 parts per million for imported diesel and 5000 parts per million for diesel produced at local refineries.

In terms of the environmental safety, Zambia through the Zambia Bureau of Standards (ZABS) formulated ZS 560:2004 a standard for used imported motor vehicles and set limits for carbon monoxide and hydrocarbons to be produced by these motor vehicles. Despite the lack of vehicle import restriction on the basis of age, Zambia through the Zambia Revenue Authority (ZRA) and Road Transport and Safety Agency (RTSA) have imposed specific import duty fines for motor vehicles aged beyond 5 years from the year of manufacture and carbon tax (surcharge) as licensing fines based on motor vehicle engine capacities regardless of age.

Given the vehicle emissions research and control measures discussed which aim to control pollutants, most countries around the world are now exploring a gradual shift to cleaner fuels. Further, to counter this increasing harm on the environment which has been blamed for global increase in temperature, acid rain, and rise in cancer cases, blamed on pollutants, there has been a drastic shift towards increased research in renewable energy technologies which are sustainable.

## **1.2 Status quo and policies on vehicle pollutant emissions**

In terms of policy framework to control emissions, (Dieter and Gary, 2012) in their study showed that most of the 27 sub-Saharan African countries investigated in the region have adopted Environment Protection Acts, and often they specify vehicle fuel parameters, emission standards and air quality.

Their study further concluded with the following findings:

- i. Urban air pollution is on the rise in sub-Saharan Africa, and a major cause is the use of fossil fuels in transport.
- ii. Vehicle emission standards are inadequate and poorly enforced, and only eight countries in the region have operational routine air quality monitoring systems.
- iii. Deaths and injuries from road crashes are taking a serious toll, especially on pedestrians and cyclists.
- iv. Africa has less than 3% of the world's population of motor vehicles, but more than 11% of global road fatalities and that there is a need to increase awareness of this problem amongst politicians, planners, engineers and the public.
- v. Traffic congestion is of growing concern in many cities. The causes include ineffective public transport, lack of transport demand measures; poor quality of cycling and walking infrastructure; lack of integrated land-use policies, and poor road discipline. However, the extent of the congestion problem and the resulting economic, social and environmental impacts are rarely quantified or assessed.
- vi. Transport policies in sub-Saharan African tend to favour automobiles, which short-changes poor and vulnerable populations. There is a need for policies that ensure a more equitable appropriation of space, from the standpoint of accessibility, safety and environmental protection.
- vii. Africa has the lowest historical greenhouse gas (GHG) emissions of any continent, but its emissions are also now growing rapidly, driven by a sharp increase in fossil-fuel use. An integrated approach that incorporates climate considerations in transport planning could reduce transport related GHG

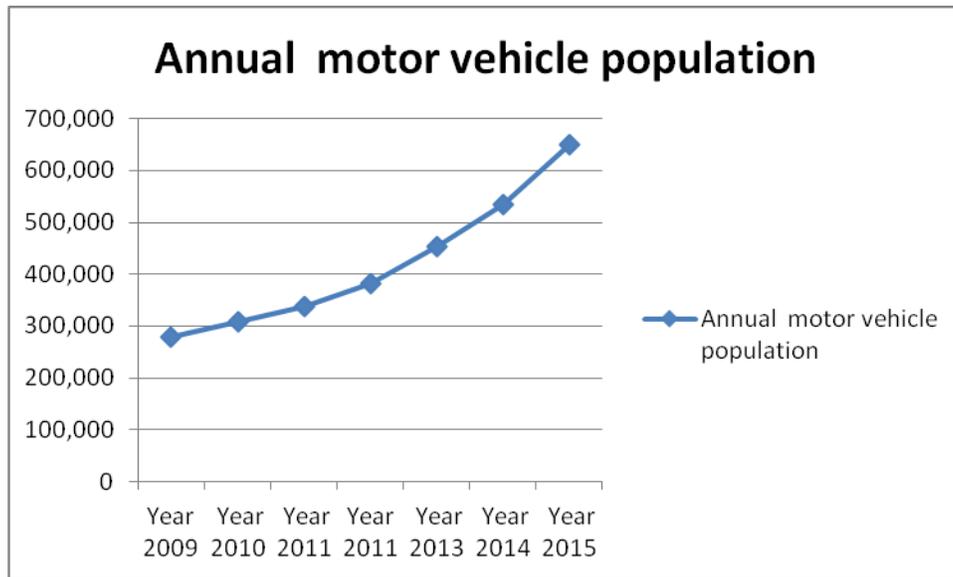
emissions and also increase the resilience of transport infrastructure and systems.

In terms of setting legal and regulatory vehicle emissions standards, sixteen countries in the sub Saharan Africa have set fuel specifications for gasoline and fourteen for diesel. No country in the region has diesel Sulphur content under 50 parts per million, and several have Sulphur content between 2,000 and 5,000 ppm, or even above 5,000 ppm. Only five countries have promulgated emission standards for vehicles, and only eight have set air quality standards (another two have proposed them). A substantial improvement has been the phasing-out of leaded fuel, which started in 2003 and has now been essentially completed across the region.

### ***1.3 Problem Statement***

Zambia has a motor vehicle population of approximately 650,539 excluding security and other classified motor vehicles not requiring registration on its national database. This figure is clearly an underestimation, and though less than most SADC countries, Zambia's motor vehicle population is on the increase as can be seen from the trend shown in figure 1.3.

**Figure 1.1 Annual motor vehicle population increase**



**(Source : RTSA, 2016)**

Despite this rising trend in the motor vehicle population, the country faces limited road infrastructure, lack of sufficient vehicle emission standards and uncoordinated traffic flow management program. The responsibility to control traffic is vested in both the Zambia Police and the Road Transport and Safety Agency, while the responsibility of formulating vehicle safety standards lies with the Zambia Bureau of standards which is a body under the Ministry of Commerce, Trade and Industry.

The uncoordinated management of road vehicle traffic in Zambia has resulted in increased traffic congestion mostly in urban cities and this increases vehicle pollutant emissions and expected increase in the emission of greenhouse CO<sub>2</sub>. The Zambia Bureau of Standards (ZABS), standard for imported used motor vehicles stipulates pollutant emission limits for carbon monoxide(4.5% volume), and hydrocarbons(1,200 parts per million) and clearly omits life cycle based environmental impacts of these imported motor vehicles since most of the motor vehicles imported arrive in the country with less than five years remaining before final cannibalization or complete disposal or destruction.

Zambia like other sub-Saharan Africa countries is alleged to be home to many old vehicles believed by all citizens to be without emissions controls, has poor vehicle maintenance culture, and lack of cleaner fuels. Some members of the public perceive that the country's national regulatory framework specific to vehicle pollutant emissions is inadequate, lacks appropriate monitoring equipment, and existing laws and regulations are poorly enforced due to disjointedness in policies.

Resulting from these perceived inadequate environmental policies and resulting emission standards some citizens in Zambia with concerns for road safety and the environment impact of imported motor vehicles allege that used motor vehicles entering the country are unroadworthy and pollutant emissions produced by these vehicles are excessive and do not meet Zambian standards, hence the need for the Zambian Government to either ban the importation or review existing pollutant emission standards to reduce on the environmental impact of these motor vehicles.

The current Zambia Bureau of Standards ZS 560-2004, a safety standard for used imported motor vehicles, stipulates vehicle pollutants as follows:

- i. carbon monoxide 4.5% volume
- ii. hydrocarbon 1,200 parts per million

and excludes guidelines for limits for other pollutants such as NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub>.

This study is conducted to confirm or otherwise the perception that imported used motor vehicles are environmentally hazardous compared to new motor vehicles bought from the showrooms. The study employs the use of appropriate tools and equipment to assess pollutant emissions produced by the used motor vehicles to establish the emissions levels and their contents and compare them against local, regional and international standards.

#### ***1.4 Objective of the study***

In general the objective this study is aimed at assessing the levels of vehicle emissions from a sample of imported used motor vehicles and compare with both the ZABS 560-2004 standard and international standards. The results of the study are used to establish whether used imported motor vehicles meet local and international standards

which information will aid in instituting vehicle emission control policy guidelines and achieve an improved standards guideline which will ensure reduced emission levels from imported motor vehicles.

The specific objectives of the study are to:

- i. Conduct tailpipe emission testing to obtain results of actual vehicle emissions from imported motor vehicles of CO, CO<sub>2</sub>, HC, NO<sub>x</sub>.
- ii. Compare the emission levels with the local vehicle emission standards
- iii. To take advantage of the capabilities of the emissions analyzer to measure carbon dioxide and lambda (excess air coefficient) to assess the combustion efficiency of the engines of the motor vehicles under study.

### ***1.5 Research Question to be answered***

Do imported used motor vehicles entering Zambia meet both the local and international emission standards?

### ***1.6 Significance of the study***

This study is an applied research as it employed the use of technology to measure motor vehicle emissions from imported used motor vehicles. The results from this work will therefore provide an essential insight into conditions of imported motor vehicles entering Zambia. This insight may be a basis for future efforts by policy makers to establish the national position regarding pollutant emission levels from imported used motor vehicles.

## CHAPTER 2: LITERATURE REVIEW

### ***2.1 Pollutant Emissions and controls in selected countries***

Emissions of many air pollutants have been shown by many researchers to have a variety of negative effects on public health and the natural environment. (Takizad, 2012) Takizad explained that Emissions that are principal pollutants of concern include: Hydrocarbons, carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), Particulate Matter (PM), sulphur oxide (SO<sub>x</sub>) and Volatile Organic Compounds (VOCs). He further pointed out that hydrocarbons are a major contributor to smog, which in turn is a major problem in urban areas and that carbon monoxide poisoning is a killer.

To investigate the widely held belief that older models of motor vehicles emit more, Takizad, conducted a study on vehicle emissions of three vehicle models (Pride, Peugeot 206 and Samand) made in 2004, 2006 and 2008 and observed the amount of HC and CO emissions using an MGT5 gas analyzer. His study revealed that those cars manufactured in 2008 had emission levels close to Euro IV Standard and vehicles manufactured in 2004 had emission levels close to Euro II Standard. He concluded that an increase in vehicle age gave a corresponding emissions increase.

Sameer Akbar & Kojima in 2002 observed in their paper, titled 'Making Vehicle Emissions Inspection Effective-Learning from Experience in India,' that governments in Asia relied on various types of inspection programs for controlling vehicle emissions and recorded varying successes. Further, the paper revealed that in South Asia, Bangladesh and Sri Lanka were just developing a vehicle emissions inspection program and Pakistan had test centers on a trial basis. Nepal had been operating centralized emissions inspection test centers for three- and four-wheels in the Kathmandu Valley since 1996, supplemented by roadside inspections. Bhutan planned to start emissions testing program in January 2003 to complement its vehicle safety and roadworthiness inspection program. India had a nation-wide inspection program since the 1980s, called Pollution Under Control (PUC).

The paper concluded with several recommendations but key among them were:

- i. To minimize false emission passes, a test protocol that is difficult to cheat on or bypass, and strong and rigorous audit and supervision schemes need to be established from the outset. The protocols should be capable of preventing temporary tuning that enables dirty vehicles to pass.
- ii. In designing test protocols, substantially reducing measurement differences among test centers, and improving reproducibility and accuracy should be given a high priority.
- iii. Dilution of gas during measurements should be tightly controlled to avoid entraining clean air into the exhaust gas, thereby lowering readings and making it more difficult to identify high emitters.
- iv. International experience with spark-ignition vehicles has amply demonstrated that dynamometers are essential to minimize false passes. The dynamometer tests should set limits on NO as well as CO and HC.
- v. Readings should be taken after a pre-established time by a computer rather than at arbitrary moments convenient to the tester, as is currently the case. It is also recommended that the test results not be made available to the test technician until the computer has entered the results in the database, lest the tester intervenes to modify the results.

Some cities were also using a technology developed by Stedman of the University of Denver, which used lasers to detect emissions while vehicles passed by on public roads, thus eliminating the need for owners to go to a test center. Stedman's laser detection of exhaust gases is commonly used in metropolitan areas. (Wikipedia, Vehicle Emission Control, 2012).

Boulter et al, observed in 2007 that emission levels were dependent upon many parameters including vehicle-related factors such as model, size, fuel type, technology level and mileage, and operation factors such as speed, acceleration, gear selection, road gradient and ambient temperature. They further stated that the power to move a car comes from burning fuel in an engine and that pollution from cars came from by-products of this combustion process (exhaust) and from evaporation of the fuel itself.

Samuel *et al*, in 2002 during the proceedings of the Institute of Mechanical Engineers noted that vehicle emission levels depended on mode of operation and vehicle engine design. He expressed concern at the failure by the automotive test drive cycles for emission measurements used by the United States of America and Europe to represent these real world driving patterns. He concluded though that the amount of pollutant levels from vehicles were mostly likely being underestimated because of the characteristics of the existing drive cycles and recommended that both USA and European Union revise their drive test cycles to achieve real world driving patterns which will produce accurate pollutant levels from vehicles.

On the effects of engine capacity or displacement on the levels of pollutant emissions, the [www.wikipedia.engine](http://www.wikipedia.engine) displacement defines it as the volume swept by all the pistons inside the cylinders of a reciprocating engine in a single movement from top dead centre (TDC) to bottom dead centre (BDC). It specified it in cubic centimetres (cc or cm<sup>3</sup>), litres (l), and does not include the total volume of the combustion chamber. In sizing an internal combustion engine, the scholars established the following general formula:

$$\text{displacement} = \frac{\pi}{4} \times \text{bore}^2 \times \text{stroke} \times \text{number of cylinders}$$

The scholars concluded that bigger displacement caused by increase in either the number of cylinders, stroke size or bore diameter contributes significantly to fuel consumption and hence increases exhaust emissions containing pollutants and GHGs.

Pilusa,2012, in published paper on reduction of vehicle emissions from diesel engines using a whale filter stated that when petroleum based fuels such as petrol or diesel burn in an engine, the main toxic substances present in the exhaust gases are incomplete combustion oxides hydrocarbons containing CO, NO<sub>x</sub>, HC and particulates. He further stated that CO was the most toxic substances found in exhaust gases and is odourless, tasteless and colourless. Pilusa stated further that HC and CO emissions are primary products of incomplete combustion. On diesel engines, the paper stated that the combustion in these engines produce particulates which are so fine and invisible though

in certain operating conditions, diesel engines may produce visible particles appearing as smoke.

Wasser, 1996 noted that countries around the globe are implementing various emission standards to curtail pollution from automobiles which have been widely found as a major source of pollution.

### **2.1.1 India**

Taking the example of India, emission standards were published on October 6, 2003, through the National Auto Fuel Policy. This envisaged a phased program for introducing Euro 2-4 program for introducing Euro 2-4 emission and fuel regulations by 2010. The implementation schedule of EU emission standards in India is summarized in Table 2.1

**Table 2.1 India vehicle emission standards implementation schedule**

<b>Standard</b>	<b>Reference</b>	<b>Date</b>
India 2000	Euro 1	2000
Bharat Stage II	Euro 2	2001
		2003.04
		2005.04
Bharat Stage III	Euro 3	2005.04
		2010.04
Bharat Stage V	Euro 4	2010.04

**(source [www.wikipedia.com](http://www.wikipedia.com))**

The above standards apply to all new 4-wheel vehicles registered in some selected respective regions.

#### **i. Trucks and Buses Emission**

Emission standards for new heavy-duty diesel engines-applicable to vehicles of gross vehicle weight (GVW>3,500kg) are listed in Table 2.2. Emissions are tested over the ECE R49 13-mode test (through the Euro II stage)

**Table 2.2 Emission Standards for diesel trucks and bus engines, g/kWh)**

Year	Reference	CO	HC	NO	PM
1992	-	17.3-32.6	2.7-3.7	-	-
1996	-	11.2	2.4	14.4	-
2000	Euro I	4.5	1.1	8	0.36
2005	Euro II	4	1.1	7	0.15
2010	Euro III	2.1	0.66	5	0.1

(source [www.wikipedia.com](http://www.wikipedia.com))

The table in figure 2.2 shows how India as a country has made efforts in complying with European emission standards from 1992-2010.

**ii. Light duty gasoline vehicles**

Emissions standards for gasoline vehicles (GVW < 3,500 kg) are summarized in Table 2.3 Ranges of emission limits refer to different classes of light commercial vehicles (compare the EU light-duty vehicle emission standards page). The lowest limit in each range applies to passenger cars (GVW < 2,500 kg; up to 6 seats).

**Table 2.3 India emission standards for gasoline automobiles g/kWh**

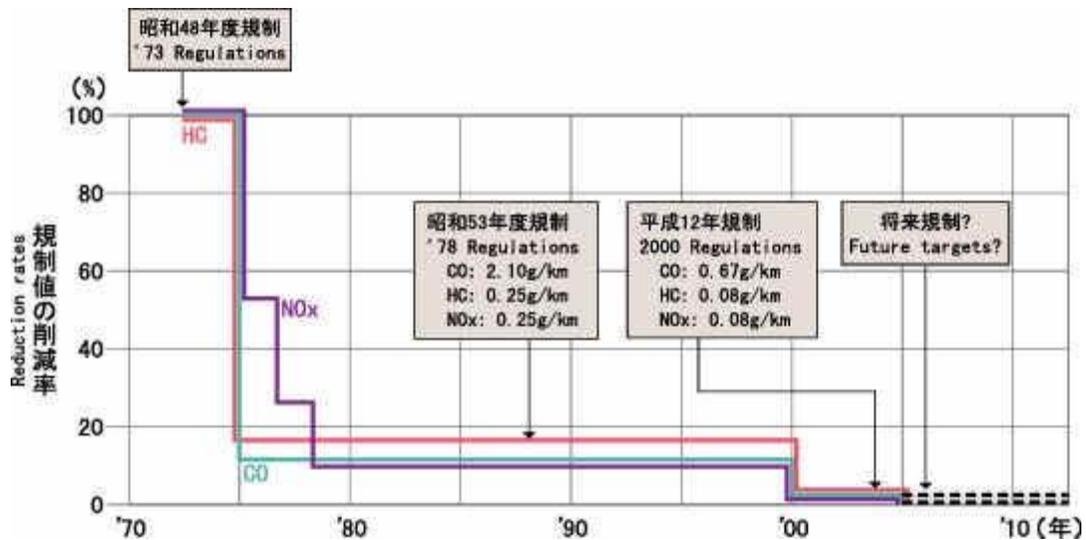
Year	Reference	CO	HC	HC + NO <sub>x</sub>	PM
1992	-	17.3-32.6	2.7-3.7	-	-
1996	-	5.0-9.0	-	2.0-9.0	-
2000	Euro I	2.72-6.90	-	0.9-1.70	0.14- 0.25
2005+	Euro II	1.0-1.5	-	0.7-1.2	0.08- 0.17

(source [www.wikiapedia.com](http://www.wikiapedia.com))

### 2.1.2 Japan

Further, vehicle pollutant emission controls became more stringent in the middle seventies and further reductions in all emissions targeted to much lower levels by 2010.

**Figure 2.1 Graduated Emissions Controls for Japan**



Source: [Transportpolicy.net](http://Transportpolicy.net)

Figure 2.1 depicts the four stroke gasoline engine emissions regulations achieved results from the seventies up to the year 2010.

From this figure the 1978 Japan emission regulations stipulated the following targets to be achieved by 1990:

i	CO:2.10g/Km
ii	HC:0.25g/Km
iii	NO: 0.25g/Km

Having achieved these targets for new motor vehicles, Japan 2000 regulations were revised downwards and limits set out as indicated below:

i	CO:0.67g/Km
ii	HC:0.08g/Km
iii	NO: 0.08g/Km

These emission limits were to be achieved by year 2005 and while at the same time, emission targets for year 2010 and beyond are yet to be introduced.

Starting June 10, 1968, the Japanese Government passed the (Japanese: Air Pollution Control Act) which regulated all sources of air pollutants. As a result of the 1968 law, dispute resolutions were passed under the 1970 (Japanese: Air Pollution Dispute Resolution Act).

### **2.1.3 United States of America**

In the United States of America, the six common air pollutants of primary concern are *particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead.*

These pollutants are detrimental to health, the environment, and a person's home and other belongings. The worst two of the six pollutants are particle pollution and ground-level ozone, which have to be regulated by the Environmental Protection Agency (EPA). Particle pollution, or particulate matter, consists of soot, smoke, and chemically formed "droplets". These particles are very small and can bury themselves deep inside the lungs. Ground-level ozone is found in smog and can also negatively affect the lungs. Smog contains volatile organic compounds (VOCs) and nitrogen oxides (NO<sub>x</sub>). VOCs come from motor vehicles burning gasoline, petroleum refineries, chemical manufacturing plants, etc, while NO<sub>x</sub> results from burning gasoline, coal, or oil.

As a result of the 1970 law, in 1973 the first installment of four sets of new emissions standards was introduced. Interim standards were introduced on January 1, 1975 and again for 1976. The final set of standards was introduced for 1978. While the standards were introduced they were not made immediately mandatory, instead tax breaks were offered for cars which passed them. The standards were based on those adopted by the original US Clean Air Act of 1970, but the test cycle included more slow city driving to correctly reflect the Japanese situation (*Bertelsen,2001*).

Further, Bertelsen stated that the 1978 limits for mean emissions during a "Hot Start Test" of CO, hydrocarbons, and NO<sub>x</sub> were 2.1 grams per kilometer (3.38 g/mi) of CO, 0.25 grams per kilometer (0.40 g/mi) of HC, and 0.25 grams per kilometer (0.40 g/mi) of

NO<sub>x</sub> respectively. Maximum limits are 2.7 grams per kilometer (4.35 g/mi) of CO, 0.39 grams per kilometer (0.63g/mi) of HC and 0.48 grams per kilometer (0.77g/mi) of NO<sub>x</sub>. The 10-15 mode hot cycle test used to determine individual fuel economy ratings and emissions observed from the vehicle being tested using a specific testing regime.

The NO<sub>x</sub> and PM law introduced emission standards for specific categories of in-use highway vehicles including commercial goods vehicles such as trucks, vans and buses irrespective of the fuel type. The regulation also applies to diesel powered passenger cars (but not gasoline cars). In-use vehicles in the specified categories must meet 1997/98 emission standards for the respective new vehicle type (in the case of heavy duty engines NO<sub>x</sub> = 4.5g/kWh, PM = 0.25g/kWh). In other words, the 1997/8 new vehicle standards are retroactively applied to older vehicles already on the road. Vehicle owners have two methods to comply:

- i. Replace old vehicles with newer, cleaner models
- ii. Retrofit old vehicles with approved NO<sub>x</sub> and PM control devices.

Vehicles have a grace period, between 9 and 12 years from the initial registration to comply.

Furthermore, the regulation allows fulfillment of its requirements to be postponed by an additional 0.5 – 2.5 years, depending on the age of the vehicle. This delay was introduced in part to harmonize the NO<sub>x</sub> and PM Law with the Tokyo diesel retrofit program. The NO<sub>x</sub> and PM Law is enforced in connection with Japanese vehicle inspection program, where non-complying vehicles cannot undergo the inspection in the designated areas. This in turn, may trigger an injunction on the vehicle operation under the road transport vehicle law.

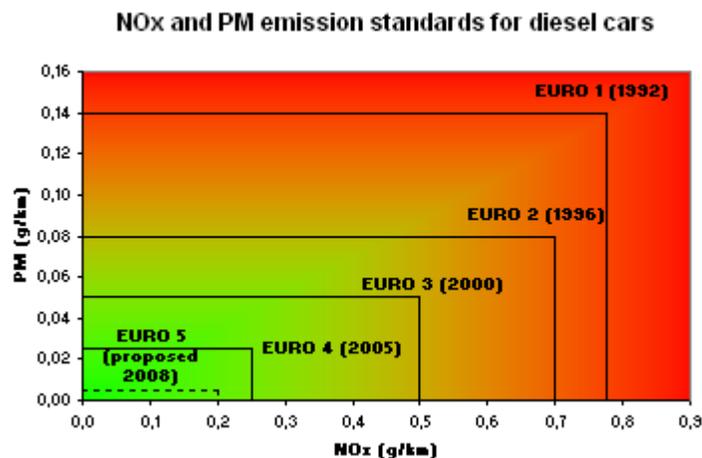
As regards efforts in reducing greenhouse gas (GHG) emissions in Japan which is estimated at 20% as coming from the transportation sector, a 70% reduction in GHG emission reductions by 2050 are projected as a feasible goal (Nishimura, 2011). He further stated that even though substantial GHG emission reductions by 2050 are projected, coordinated policy measures would make the most optimistic sales mix scenario more feasible, and help realize further GHG emission reductions.

### 2.1.4 European Union

Before a new vehicle can be approved for sale the European Union (EU) it must meet certain standards for exhaust emissions as specified by EU directives. These standards are vehicle type specific and for petrol fuelled vehicles are sub-divided into passenger cars and light – duty vehicles.

The passenger cars are further sub-divided according to their laden weight (below or above 2.5. tones) and the number of seats they have, whilst the light duty vehicles are subdivided into three different categories by vehicle mass. For all petrol vehicles the regulatory test cycle involves starting the engine when cold followed by driving a cycle simulating urban and sub-urban driving (EC 15 + EUDC). The emissions are monitored for the whole cycle and, after dividing by the cycle's length (11.007km), the emission standards are expressed in grams of pollutant per kilometer.

**Figure 2.2 NOx and PM emission standards for EU**



**(Source. [www.transportnet.com](http://www.transportnet.com))**

From the figure, both nitrogen oxides and particulate matter standards have been set at stringent levels, reflecting the seriousness with which the European Union intends to address emissions from automobiles.

### 2.1.5 South Africa

South Africa's first clean fuels program was implemented in 2006 with the banning of lead from petrol and reduction of Sulphur levels in diesel from 3, 000 parts per million (ppm) to 500ppm, along with a niche grade of 50ppm. The clean fuel 2 standard,

expected to begin in 2017, includes the reduction of Sulphur to 10ppm; the lowering of benzene from 5percent to 1 per cent of volume; the reduction of aromatics from 50 percent to 35 percent of volume; and the specification of olefins at 18 percent of volume. All these were considered as significant efforts in steps to crucial effects of rising pollutant emissions from motor vehicles.

Further, South Africa has since banned the driving of used imported motor vehicles on its roads due to excessive emissions and reduced mechanical safety among other reasons.

## ***2.2 Motor Vehicle Emissions Testing Methods in the selected countries or regions***

To achieve accurate emission measurement results, methods and procedures for emissions collections and analysis have evolved with the development and improvement of vehicle fuel systems and technologies. The following emission test procedures have been used over the years and newer methods have been developed to replace the earlier procedures. Different countries are using one or more of the methods under listed either partly or in full. Some countries have engaged the use of different methods for testing vehicle pollutant emissions for use in research, and enforcement of emission standards. The methods in current use are:

- i. On-board data link interrogation first generation OBD and OBDII.
- ii. Remote OBD X interrogation
- iii. Remote emissions sensing combined with other tests.
- iv. Loaded chassis dynamometer based smoke emission test.
- v. Loaded chasses dynamometer based mass emission test.
- vi. Non dynamometer smoke measurement test for diesel.
- vii. Non dynamometer non diesel engine idle emission tests.

## ***2.3 Critique Summary of Motor Vehicle Emission Testing Methods***

On board mobile emission tests and all those methods based on data link have the weakness of testing engine emissions before treatment from the catalytic converters. On –board, data link and remote on board diagnosis interrogation emission testing procedures despite their reliable source of data suffer from the deficiency to get

emission tests based on actual driving conditions which vary considerably from one test to another. Remote sensing procedures on the other hand is a cost effective way of measuring air pollution from mobile sources and has wider applications than traditional board diagnostic systems or tailpipe emission measurement procedure.

However, remote sensing engine testing lacks credibility in accountability especially if used in heavy traffic conditions. It is difficult to attribute the test results to a particular vehicle and this makes the method susceptible to arguments in cases where emission test programs are used in traffic law enforcement.

Loaded chassis dynamometer though possessing potential for producing accurate results is diminishing in use due to motor vehicle driving configurations (from rear positioned final drives to front position final drives) changes over the years. This makes the experiment of loaded chassis dynamometer a rare sight.

Further, since the mid 19<sup>th</sup> century, dynamometers have been used to measure torque and rotational speed (measured in rpm) from which power produced by an engine, motor or other rotating prime mover can then be calculated.

A chassis dynamometer measures power from the engine through the wheels. Because of frictional and mechanical losses in the various drive train components, the measured horsepower is generally 15 – 20 percent less than the brake horsepower measured at the crankshaft or flywheel on an engine dynamometer.

Dynamometer emission tests are very expressive, and have usually involved removing fleet vehicles from service for a long period of time. The data derived from such testing is not representative of “real world” driving conditions, and cannot be deemed as quantifiable, especially due to the relatively low amount of repeatable tests at such a facility. Due to these reasons, the chassis dynamometer could not be used to assess emission in this study.

#### ***2.4 Motor Vehicle Emission Testing in Zambia***

The improvements in the design of emission analyzers have led to their wider cost effective application in the testing of vehicular engine emissions. The versatility in

testing various gases simultaneously have earned vehicle emission analyzers a first choice ranking by researchers in emissions testing.

Portable emission testing systems were developed in the late 1990s in order to better identify actual in-use performance of vehicles. These emissions systems were designed to measure emissions during the actual use of an internal-combustion engine vehicle or equipment in its regular daily operation, in a manner similar in operation to a chassis dynamometer. Simply put, more testing can be done more quickly, by less operators, dramatically increasing the amount of testing done in a time period. This in turn, significantly reduces the 'cost per test', yet at the same time increases the overall accuracy required in a 'real – world' environment.

Because the law of large numbers will create a convergence of results, it means that repeatability, predictability, and accuracy are enhanced, while simultaneously reducing the overall cost of the testing.

In Zambia, the Zambia Bureau of Standards (ZABS) in collaboration with various stakeholders developed the ZS 560:2004 to standardize imported used motor vehicle safety and environmental aspects. Key among areas to be inspected on these motor vehicles was the engine emissions.

To achieve reasonable accuracy in emission testing, the Standard proposed general 4 or 5 gas analyzer for gasoline and smoke testers for diesel engines.

Given the lower acquisition and operating and maintenance costs of these portable emission testing equipment, the country saw the importation of 5 gas engine emission analyzers by the Road Transport and Safety Agency (RTSA) which is the institution mandated to enforce automobile emissions.

For these reasons, data collection in this study employed the use of an MGT 5 produced by a Germany Company called MAHA Maschinebau GBMH with the capability to test CO, CO<sub>2</sub>, HC, NO<sub>x</sub> and Oxygen. This type of gas analyzer also produces readings for lambda and oil temperature.

## **CHAPTER 3: INTERNAL COMBUSTION PRINCIPLES**

### ***3.1 Pollutant Emissions from Internal Combustion Engines***

Fuels and oxidizers are the two essential ingredients of a combustion process. Fuels can be classified as substances that liberate heat when reacted chemically with an oxidizer. Use of these fossil fuels contributes to pollution and global warming effects because of the net positive amount of various pollutants and GHG emissions inherent to their utilization. Fuels derived from biomass or from other renewable means represent potentially attractive alternatives to fossil fuels and are currently the subject of intensive research and development. (McAllister, 2011).

The combustion of hydrocarbon fuel uses  $O_2$  from the atmosphere and releases equivalent amount of  $H_2O$  and  $CO_2$  always with trace elements of numerous other compounds including hydrocarbons ( $CH_4$ ,  $C_2H_2$ ,  $C_2H_8$ ,  $C_6H_6$ ...etc), carbon monoxide (CO), nitrogen oxides (NO,  $N_2O$ ) and reduced nitrogen ( $NH_3$  and HC), Sulphur gases, hydro carbons, and particles. A review of the atmospheric budgets of these gases shows that burning of fossil fuels and recent biomass has led to global alternations in the composition of our atmosphere (Prather and Logan, 2004).

### ***3.2. Pollutant Formation***

Spark ignition and compression ignition engines are a major source of urban air pollution. The spark ignition engine exhaust contains oxides of nitrogen (nitric oxide, NO, and small amounts of nitrogen dioxide,  $NO_2$  collectively known as  $NO_x$ , carbon monoxide (CO), and organic compounds which are unburned or partially burned hydrocarbons (HC). The relative amounts depend on engine design and operating conditions but are of order:  $NO_x$ , 500 to 1000 ppm or 20g/kg fuel; CO, 1 to 2 percent or 200g/kg; and HC, 3000 ppm or 25g/kg. Piston blow-by gases, and fuel evaporation and release to the atmosphere through vents in the fuel tank and carburetor after engine shut-down, are also sources of unburned hydrocarbons. While there is a working solution for evaporative vehicular emissions, several strategies have been used in curtailing pollutant formation in the exhaust.

One of the most important variables in determining spark ignition engine emissions is the fuel/air equivalence. The spark ignition engine is operated close to stoichiometric or slightly fuel rich, to ensure smooth and reliable operation.

***i. Carbon Monoxide***

Carbon monoxide, a colorless, odorless, poisonous gas, is generated in an engine when it is operated with a fuel rich equivalent ratio. When there is not enough oxygen to convert all carbon to CO<sub>2</sub>, some fuel does not get burned and some carbon ends up as CO. The exhaust emissions of a spark ignition engine contains typically 0.2-5% carbon monoxide. Carbon monoxide is not only undesirable emission, but it also represents lost chemical energy that was not fully utilized in the engine. Carbon monoxide (CO) emissions from internal combustion engines are controlled primarily by the fuel/air equivalence ratio. Spark ignition engines often operate close to stoichiometric at part load and fuel rich at full load and therefore CO emissions are significant and must be controlled. Carbon monoxide forms due to incomplete oxidation of carbon contained in the fuel. Diesels always operate on the lean side of stoichiometric and therefore CO from diesel engines are too low or insignificant to be considered in this research.

***ii. Oxides of nitrogen (NO<sub>x</sub>)***

Exhaust gases of an engine can have up to 2000 ppm of oxides of nitrogen. Most of this will be nitrogen oxide (NO), with a small amount of nitrogen dioxide (NO<sub>2</sub>), and traces of other nitrogen – oxygen combinations. These are all grouped together as NO<sub>x</sub>, with *x* representing some suitable number. NO<sub>x</sub> is a very undesirable emission, and regulations that restrict the allowable amount continue to become more stringent. Released NO<sub>x</sub> reacts in the atmosphere to form ozone and is one of the major causes of photochemical smog. NO<sub>x</sub> is created mostly from nitrogen in the air.

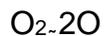
Nitrogen can also be found in fuel blends, which may contain trace amounts of NH<sub>3</sub>, NC, and HC, but this would contribute only to a minor degree. There are a number of possible reactions that form NO, all of which are probably occurring during the combustion process and immediately after.

These include but are not limited to:

Atmospheric nitrogen which exists as a stable diatomic molecule at low temperatures, and only very small trace amounts of oxides of nitrogen are found.

However, at the very high temperatures that occurs in the combustion chamber of an engine, some diatomic nitrogen ( $N_2$ ) breaks down to monatomic nitrogen (N) which is reactive:  $N_2 \rightarrow 2N$ . The chemical equilibrium constant for NO<sub>x</sub> formation is highly dependent on temperature, with a much more significant amount of N generated in the 2500-3000 K temperature range that can exist in an engine.

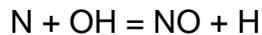
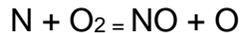
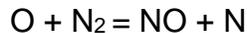
Other gases that are stable at low temperatures but become reactive and contribute to the formation of NO<sub>x</sub> at high temperatures include oxygen and water vapor, which break down as follows:



The higher the combustion reaction temperature, the more diatomic nitrogen,  $N_2$ , will dissociate to monatomic nitrogen, N, and the more NO<sub>x</sub> will be formed. At low temperatures very little NO<sub>x</sub> is created. Although maximum flame temperature will occur at a stoichiometric air-fuel ratio (cfJ=1), but the maximum NO<sub>x</sub> is formed at a slightly lean equivalence ratio of about cfJ=0.95.

At this condition, flame temperature is still very high, and in addition, there is an excess of oxygen that can combine with the nitrogen to form various oxides. In addition to temperature, the formation of NO<sub>x</sub> depends on pressure air-fuel ratio, and combustion time within the cylinder, chemical reactions not being instantaneous. The highest concentration is formed around the spark plug, where the highest temperatures occur. Because they generally have higher compression ratios and higher temperatures and pressure, CI engines with divided combustion chambers and indirect injection (IDI) tend to generate higher levels of NO<sub>x</sub>. Even though nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are usually grouped together as NO<sub>x</sub> emissions, nitric oxide is the predominant oxide of nitrogen produced inside the engine cylinder. The principal source of NO is the

oxidation of atmospheric nitrogen. The mechanism of NO formation from atmospheric nitrogen has been studied extensively and generally accepted that in near stoichiometric fuel-air mixtures, the principal reactions governing the formation of NO from molecular nitrogen (and its destruction) are:



Chemical equilibrium considerations indicate that for burned gases at typical flame temperatures, NO<sub>2</sub>/NO ratios should be negligibly small. A plausible mechanism for the persistence of NO is the following:

$\text{NO} + \text{H}_2\text{O} \longrightarrow \text{NO}_2 + \text{OH}$  subsequently, conversion of this NO<sub>2</sub> to NO occurs via

$\text{NO}_2 + \text{O} \longrightarrow \text{NO} + \text{O}_2$  unless the NO<sub>2</sub> formed in the flame is quenched by mixing with cooler fluid.

In the formation of NO<sub>x</sub> in compression ignition engines, the kinetic mechanisms for NO and NO<sub>2</sub> formation described under the spark ignition engine kinetics also applies to diesel engines. The difference however is that injection of fuel into the cylinder occurs just before combustion starts, and that non-uniform burned gas temperature and composition result. NO<sub>x</sub> is one of the primary causes of photochemical smog, which has become a major problem in many large cities of the world. Smog is formed by the photochemical reaction of automobile exhaust and atmospheric air in the presence of sunlight. NO<sub>2</sub> decomposes into NO and monatomic oxygen:



In order to achieve NO<sub>x</sub> emission reduction, Mahallaway, 2013 identified three main different NO formations;

- i. Thermal NO in which NO is formed by the reaction of the molecular nitrogen from the combustion air with atomic oxygen, and the subsequent reactions.

- ii. Low NOX burners in which he proposed to slow and control the rate of fuel and air mixing, therefore reducing oxygen availability in the ignition and main combustion zones.
- iii. Staged combustion in which low excess air levels in the primary combustion zone with the remaining air are added at higher levels in the furnace to complete the combustion.
- iv. Flue gas recirculation in which oxygen concentrations and combustion temperatures are reduced by recirculating some of the flue gases to the furnace without increasing total net gas mass flow.

Re-burning in which 75 to 80 percent of the furnace fuel input is burned in the cyclone furnace with minimum excess air. This secondary combustion zone is operated sub-stoichiometrically to generate hydrocarbon radicals which reduce NO formation.

**iii. Hydrocarbons (HC)**

Hydro carbons are more appropriately organic emissions and result from incomplete combustion of hydrocarbon fuel. The level of hydrocarbon in exhaust is generally expressed in terms of the total hydrocarbon concentration expressed in parts per million carbon atoms. Engine exhaust gas contains a wide variety of hydrocarbon compounds as shown in the table 3.3. The table further shows the average breakdown by class of the hydrocarbons in spark ignition engine exhaust gases both with and without catalytic converter, with gasoline fuel.

**Figure 3.1 Carbon percent of total HC with and without catalytic converters**

Carbon percentage of total HC				
	Paraffins	Olefins	Acetylene	Aromatics
Without catalyst	57	27	8	32
With a catalyst	33	15	2	26

**(Source: [www.dieselNet.com](http://www.dieselNet.com))**

Some of these gases are inert and therefore unreactive in terms of contributing to photochemical smog. Others are highly reactive in the photochemical smog production while others are carcinogens.

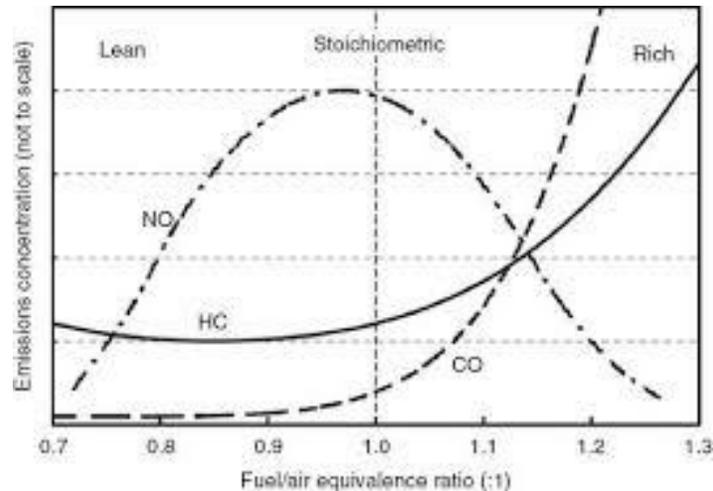
Exhaust gases leaving the combustion chamber of a spark ignition (SI) engine up to 6000 ppm of hydrocarbon components, the equivalent of 1-1.5% of the fuel. About 40% of this is unburned gasoline fuel components. The other 60% consists of partially reacted components that were not present in the original fuel. These consist of small non-equilibrium molecules which are formed when large fuel molecules break up (thermal cracking) during the combustion reaction. It is often convenient to treat these molecules as if they contained one carbon atom, as CH<sub>1</sub>. The makeup of HC emissions will be different for each gasoline blend, depending on the original fuel components. Combustion chamber geometry and engine operating parameters also influence the HC component spectrum. When hydrocarbon emissions get into the atmosphere, they act as irritants and odorants; some are carcinogenic. All components except CH<sub>4</sub> react with atmospheric gases to form photochemical smog. Some of the identified causes of hydrocarbons are:

- i. Air fuel ratio ( $\lambda$ )
- ii. Non-Stoichiometric Combustion
- iii. Incomplete combustion
- iv. Crevice volumes
- v. Leak past the exhaust valve
- vi. Valve overlap
- vii. Deposits on combustion chamber walls
- viii. Oil on combustion chamber walls

Each of the above factors are discussed in the following paragraphs.

### ***Air fuel ratio ( $\lambda$ )***

**Figure 3.2 Effects of air/fuel on NO,CO and HC formation**



**Source ([www.dieselNet.com](http://www.dieselNet.com))**

**Figure 3.2** shows that HC emission levels are a strong function of air fuel equivalence ratio (AF). With a fuel-rich mixture there is not enough oxygen to react with all the carbon, resulting in high levels of HC and CO in the exhaust products. This is particularly true in engine startup, when the air-fuel mixture is purposely made very rich. It is also true to a lesser extent during rapid acceleration under load. If air fuel ratio (A/F) is too lean poorer combustion occurs, again resulting in HC emissions. The extreme of poor combustion for a cycle is total misfire. This occurs more often as A/F is made leaner.

According to [www.DieselNet.com](http://www.DieselNet.com), NO<sub>x</sub> peaks at about 10% weak of stoichiometric where the charge temperature and oxygen availability are still relatively high. CO is low at weaker than about 10% lean of stoichiometric but increases rapidly for rich mixtures. HC reduces rapidly as the mixture is weakened but rises sharply at excessively lean conditions due to partial burns.

### ***Incomplete Combustion***

Even when the fuel and air entering an engine are at the ideal stoichiometric mixture, perfect combustion does not occur and some HC ends up in the exhaust. There are several causes of this. Incomplete mixing of the air and fuel results in some fuel particles not finding oxygen to reach with. Flame quenching at the walls leaves a small volume of unreacted air-and-fuel mixture. The thickness of this unburned layer is on the order of tenths of a mm. Some of this mixture, near the wall that does not originally get burned as the flame front passes, will burn later in the combustion process as additional mixing occurs due to swirl and turbulence.

Another cause of flame quenching is the expansion which occurs during combustion and power stroke. As the piston moves away from TDC, expansion of the gases lowers both temperature and pressure within the cylinder. This slows combustion and finally quenches the flame somewhere late in the power stroke. This leaves some fuel particles unreacted. High exhaust residual causes poor combustion and a greater likelihood of expansion quenching. This is experienced at low load and idle conditions. High levels of exhaust gas recirculation (EGR) will also cause this. It has been found that HC emissions can be reduced if a second spark plug is added to an engine combustion chamber. By starting combustion at two points, the flame travel distance and total reaction time are both reduced and less expansion quenching results.

### ***Crevice Volumes***

During the compression stroke and early part of the combustion process, air and fuel are compressed into the crevice volume of the combustion chamber at high pressure. As much as 3% of the fuel in the chamber can be forced into this crevice volume. Later in the cycle during the expansion stroke, pressure in the cylinder is reduced below crevice volume pressure, and reverse blowby occurs. Fuel and air flow back into the combustion chamber, where most of the mixture is consumed in the flame reaction. However, by the time the last elements of reverse blowby flow occur, flame reaction has been quenched and unreacted fuel particles remain in the exhaust.

Location of the spark plug relative to the top compression ring gap will affect the amount of HC in engine exhaust, the ring gap being a large percent of crevice volume. The farther the spark plug is from the ring gap, the greater is the HC in the exhaust. This is because more fuel will be forced into the gap before the flame front passes. Crevice volume around the piston rings is greatest when the engine is cold, due to the differences in thermal expansion of the various materials. Up to 80% of all HC emissions can come from this source.

### ***Leak Past the Exhaust Valve.***

As pressure increases during compression and combustion, some air-fuel is forced into the crevice volume around the edges of the exhaust valve and between the valve and valve seat. A small amount even leaks past the valve into the exhaust manifold. When the exhaust valve opens, the air-fuel mixture which is still in this crevice volume gets carried into the exhaust manifold, and there is a momentary peak in HC concentration at the start of blow down.

### ***Valve Overlap.***

During valve overlap, both the exhaust and intake valves are open, creating a path where air-fuel intake can flow directly into the exhaust. A well-designed engine minimizes this flow, but a small amount can occur. The worst condition for this is at idle and low speed, when real time of overlap is greatest.

### ***Deposits on Combustion Chamber Walls.***

Gas particles, including those of fuel vapor, are absorbed by the deposits on the walls of the combustion chamber. The amount of absorption is a function of gas pressure, so the maximum occurs during compression and combustion. Later in the cycle, when the exhaust valve opens and cylinder pressure is reduced, absorption capacity of the deposit material is lowered and gas particles are desorbed back into the cylinder. These particles, including some HC, are then expelled from the cylinder during the exhaust stroke. This problem is greater in engines with higher compression ratios due to the higher pressure these engines generate. More gas absorption occurs as pressure goes up. Clean combustion chamber walls with minimum deposits will reduce HC emissions

in the exhaust. Most gasoline blends include additives to reduce deposit buildup in engines.

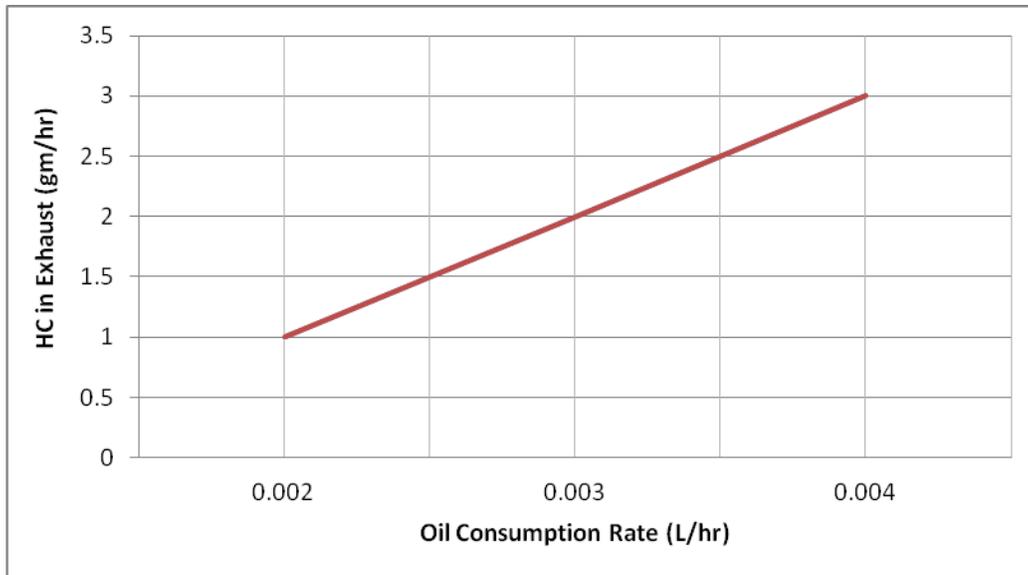
Older engines will typically have a greater amount of wall deposit buildup and a corresponding increase of HC emissions. This is due both to age and to less swirl that was generally found in earlier engine design. High swirl helps to keep wall deposits to a minimum. When lead was eliminated as a gasoline additive, HC emissions from wall deposits became more severe. When leaded gasoline is burned the lead treats the metal wall surfaces, making them harder and less porous to gas absorption.

### ***Oil on Combustion Chamber Walls.***

A very thin layer of oil is deposited on the cylinder walls of an engine to provide lubrication between them and the moving piston. During the intake and compression strokes, the incoming air and fuel comes in contact with this old film. In much the same way as wall deposits, this old film absorbs gas particles, depending on gas pressure. During compression and combustion, when cylinder pressure is high, gas particles, including fuel vapor, are absorbed into the old film. When pressure is later reduced during expansion and blowdown, the absorption capability of the old is reduced and fuel particles are desorbed back into the cylinder. Some of this fuel ends up in the exhaust. Propane is not soluble in oil, so in propane-fueled engines the absorption-desorption mechanism adds very little to HC emissions.

As an engine ages, the clearance between piston rings and cylinder walls becomes greater, and a thicker film of oil is left on the walls. Some of this oil film is scraped off the walls during the compression stroke and ends up being burned during combustion. Oil is a high-molecular-weight hydrocarbon compound that does not burn as readily as gasoline. Some of it ends up as HC emissions. This happens at a very slow rate with a new engine but increases with engine age and wear.

**Figure 3-3 HC exhaust emissions as a function of engine oil consumption.**



**Source ([www.dieselnet.com](http://www.dieselnet.com))**

Further, as an engine ages, clearance between the pistons and cylinder walls increases due to wear ([www.dieselnet.com](http://www.dieselnet.com)). Figure 3.5 shows that this increases oil consumption and contributes to an increase in HC emissions in three ways:

- i. There is added crevice volume,
- ii. There is also added absorption-desorption of fuel in the thicker oil film on cylinder walls, and there is
- iii. More oil burned in the combustion process. Oil consumption also increases as the piston rings and cylinder walls wear. In older engines, oil being burned in the combustion chamber is a major source of HC emissions. The increase in HC emissions is therefore both from combustion of oil and from the added crevice volume flow.

Mahallawy,2002 observed in general that an effective method of reducing NO<sub>x</sub> emissions will require a more complete understanding of nitrogen chemistry in combustion. He further stated that the main parameters relevant to the formation reactions of NO<sub>x</sub> are combustion temperature, oxidant concentration or its partial pressure, and the length of time spent in the high temperature region, and any reduction

of these parameters leads to reduction of NO<sub>x</sub> formation. Bowman 2003, reviewed existing and emerging technologies for reducing NO<sub>x</sub> emissions and identified two forms:

The first was that modification of the combustion process to control fuel and air mixing and reduce flame temperatures and the second as post combustion treatment of the fuel/exhaust gas to remove NO<sub>x</sub> in fluidized bed combustion.

Regarding reduction of sulphur compounds pollutants, Bowman 2003, identified the following techniques;

- i. Pre-combustion techniques
- ii. Combustion techniques
- iii. Sorbent injection technologies
- iv. Wet and dry scrubbing technologies

Temperature and residence time,  $T_{res}$ , are two important parameters influencing the formation of combustion pollutants. Temperature affects the onset of certain chemical reactions and consequently, the formation of certain chemical species. Residence time, which is the length of time that reactants reside inside a combustor for them to complete combustion (McAllister 2011). Carbon monoxide CO is the major intermediate species before CO<sub>2</sub> is formed.



McAllister 2011 wrote that nitrogen oxides (NO<sub>x</sub>) consists of nitric oxide and nitrogen dioxide and is formed in the combustion process through four major routes namely thermo NO, prompt NO (fernimore), N<sub>2</sub>O route, and fuel bound Nitrogen.

To control NO formation, Chen, 2011 suggested a reduction in peak temperature and predicted that a reduction of 30-70K in peak temperature could decrease NO formation by half. For automobiles, McAllister suggested the use of re-introduction into the intake of inert gasses to reduce peak temperature in a method called the exhaust gas recirculation (EGR).

Oxides of Sulphur ( $\text{SO}_x$ ) are produced from combustion processes and may contain  $\text{SO}$ ,  $\text{SO}_2$  and  $\text{SO}_3$ . Among these species,  $\text{SO}_3$  is known to have great affinity for water and at low temperature, it creates sulphuric acid via –



To quantify the emissions, McAllister revealed that a genetic way was the emission index. She stated that for certain chemical species, the ratio of the mass of pollutant species  $i$ , to mass of fuel burned is the emissions index.

$$\text{EI}_i = \frac{m_{i,\text{emitted}}}{m_{f,\text{burned}}}$$

Since EI is a dimensionless quantity, the units are conventionally expressed as g/kg. These emissions pollute the environment and the resulting carbon dioxide contributes to global warming. The major causes of these emissions are non-stoichiometric combustion, dissociation of nitrogen, and impurities in the fuel and air. The emissions of concern are hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen ( $\text{NO}_x$ ), Sulphur, solid carbon particulates and carbon dioxide which is a greenhouse gas (GHG). Ideally, engines and fuels could be developed such that very few harmful emissions are generated, and these could be exhausted to the surroundings without a major impact on the environment. With present technology this is not possible, and after-treatment of the exhaust gases to reduce emissions is very important. This consists mainly of the use of thermal or catalytic converters and particulate traps (in diesel engines).

### **3.3 Factors affecting Combustion Emission Levels**

The mixture being delivered to the engine, as defined by excess air factor exercises a decisive influence on the composition of the exhaust gas. The engine produces its maximum torque at approximately  $\lambda=0.9$ ; thus this ratio is generally programmed for full load operation.

Other major engine design and operation factors with significant influence on engine emissions are:

***i. Mixture Formation***

Mixture preparation embraces both the air-fuel ratio and quality of the air fuel mixture entering the combustion chamber. The fuels homogeneity, its stratification patterns and its temperature at ignition are all essential factors in determining combustibility and combustion sequence (Brugen and Bazlen 1996)

***ii. Exhaust gas recirculation***

Exhaust gas can be conducted back to the combustion chamber to reduce peak combustion temperatures. Higher combustion temperatures induce an over proportional increase in the formation of NOX emissions (Brugen and Bazlen 1996).

***iii. Valve timing***

A large degree of valve overlap is imperative for high volumetric efficiencies, and this leads to an increase internal EGR, a measure which at idle leads in particular to a rough running and higher HC emissions. Variable valve timing is therefore desirable for optimum adaptation (Brugen and Bazlen 1996).

***iv. Combustion Chamber design***

Low HC emissions are best achieved with a compact combustion chamber featuring a minimal surface area and no recesses. A centrally located spark plug with short flame travel produces rapid and relatively complete combustion of the mixture, resulting in low HC emissions and reduced fuel consumption (Brugen and Bazlen 1996).

***v. Ignition system***

The design of the spark plug, its position in the combustion chamber, together with the spark energy and spark duration all exercise a major influence on the ignition, the mixtures combustion sequence, and therefore on emissions levels.

#### ***vi. Crankcase ventilation (blow-by)***

The concentration of HC in the crankcase can be many times that found in the engines exhaust gasses. Control systems conduct these gases to a suitable point in the engines intake tract, from where they are drawn into the combustion chamber.

### **3.4 Pollutant Emissions Control Measures**

#### ***3.4.1 Exhaust Gas Treatment***

Though the above discussion focused on engine emission control, further reductions in emissions can be obtained by removing pollutants from exhaust gases in the engine exhaust system. Devices developed to achieve this result include catalytic converters (oxidizing catalysts for HC and CO, reducing catalysts for NOX, and three way catalytic converters for all three pollutants), thermal reactions (for HC and CO), and traps or filters for particulates.

The catalytic converters used in spark ignition engines consist of an active catalytic material in a specially designed metal casing which directs the exhaust gas flow through the catalyst bed. The active material for CO and HC oxidation or NO reduction must be distributed over a large surface area so that the mass transfer characteristics between the gas phase and the active catalyst surface are sufficient to allow close to 100 percent conversion with high catalytic activity.

#### ***i. Oxidation catalyst***

The function of an oxidation catalyst is to oxidize CO and hydrocarbons to CO<sub>2</sub> and water in an exhaust gas treatment stream which typically contains about 12 percent CO<sub>2</sub> and H<sub>2</sub>O, 100 to 200 parts per million NO about 20 ppm, SO<sub>2</sub> 1 to 5 percent, O<sub>2</sub> 0.0 to 5 percent CO and 1000 to 6000 ppm, C1 HC, often with small amounts of lead and phosphorous.

### ***ii. NO catalyst***

NO is removed by reduction using the CO, hydrocarbons and H<sub>2</sub> in the exhaust.

### ***iii. Three way catalyst***

Chemically, if an engine is operated at all times with an air/fuel ratio at or close to stoichiometry, then both NO reduction and CO and HC oxidation can be done in a single catalyst bed. The catalyst effectively brings the exhaust gas composition to near equilibrium state at these exhaust conditions i.e. a composition of CO<sub>2</sub>, H<sub>2</sub>O and N<sub>2</sub>.

### ***iv. Thermal reactors***

Oxidation after passage through the exhaust port can be enhanced with a thermal reactor-and enlarged exhaust manifold that bolts directly onto the cylinder head. Its function is to promote rapid mixing of the hot exhaust gases with any secondary air injected into the exhaust port, to remove non uniformities in temperature and composition in the exhaust gases, and to retain the gases at a high enough temperature for sufficient time to oxidize much of the HC and CO which exists the cylinder. Mahallawy 2002 stated that reducing emissions from vehicle engines may be achieved by:

- i. Keeping compression ratio below the usual 10:1 for petrol engines
- ii. Enriching the mixture of fuel to bring the post combustion level of NO as low as possible
- iii. Removing NO and unburned fuel from exhaust using a catalytic converter

The methods used to alter the composition of the exhaust gases from the spark ignition engines are divided into basic categories: engine-design measures and exhaust gas treatment. The selection of procedures to be employed in any given country is determined by its specific legal requirements.

### ***Fuel metering***

This method employed a specific residence time at high temperatures for burning the exhaust gas components which failed to burn during normal combustion in the engine cylinders. In the rich range ( $\lambda=0.7—1.0$ ), the process must be supported with supplementary air injection. In a lean running engine ( $\lambda =1.05—1.2$ ), the residual oxygen in the exhaust gas is sufficient for afterburning. ( Brugen and Bazlen 1996)

### ***Catalytic afterburning***

The catalytic converter is composed of a carrier substrate, which serves as a base for the catalytic material, mounted within the housing vibration proof, heat-insulated supports. Granulate or ceramic or metallic monolith structures are employed as substrate materials. The active catalytic layer consists of small quantities of noble metals (Pt, Rh, Pd), and is sensitive to lead. For this reason, it is essential that engines with catalytic converters be run on unleaded fuel exclusively as lead destroys the effectiveness of the active layer. The units conversion rate is largely a function of operating temperature; no meaningful treatment of pollutants takes place until the converter has reached an operating temperature of approximately 250 degrees. Operating temperatures of approximately 400...800 degrees provide ideal conditions for maximum efficiency and extend service life. ( Brugen 1996)

Emission controls from automobiles can be grouped into three basic types; engine, evaporative and diagnostics. Each of these can be further divided as follows;

- a. Engine adjustments (1968 to 1974)
- b. Oxidizing Catalysts (1975 to 1980)
- c. Closed Loop three-way catalytic converter (1981 to current)

Engine efficiency has been steadily improved with improved engine design, more precise ignition timing and electronic ignition, more precise fuel metering, and computerized engine management. Advances in engine and vehicle technology continually reduce the toxicity of exhaust leaving the engine, but these alone have generally been proved insufficient to meet emissions goals. Therefore, technologies to detoxify the exhaust are an essential part of emissions control.

### ***Air Injection***

One of the first-developed exhaust emission control systems is secondary air injection. Originally, this system was used to inject air into the engine's exhaust ports to provide oxygen so unburned and partially burned hydrocarbons in the exhaust would finish burning. Air injection is now used to support the catalytic converter's oxidation reaction, and to reduce emissions when an engine is started from cold. After a cold start, an engine needs a fuel-air mixture richer than what it needs at operating temperature, and the catalytic converter does not function efficiently until it has reached its own operating temperature. The air injected upstream of the converter supports combustion in the exhaust head-pipe, which speeds catalyst warm-up and reduces the amount of unburned hydrocarbon emitted from the tailpipe.

### ***Exhaust gas recirculation***

In the United States and Canada, many engines in 1973 and newer vehicles (1972 and newer in California) have a system that routes a metered amount of exhaust into the intake tract under particular operating conditions. Exhaust neither burns nor supports combustion, so it dilutes the air/fuel charge to reduce peak combustion chamber temperatures. This, in turn, reduces the formation of NOX.

### ***Catalytic converter***

The catalytic converter is a device placed in the exhaust pipe, which converts hydrocarbons, carbon monoxide, and NOX into less harmful gases by using a combination of platinum, palladium and rhodium as catalysts.

There are two types of catalytic converter, a two-way and a three-way converter. Two-way converters were common until the 1980s, when three-way converters replaced them on most automobile engines.

### ***Evaporative emissions control***

Evaporative emissions are the result of gasoline vapors escaping from the vehicle's fuel system. Since 1971, all U.S. vehicles have had fully sealed fuel systems that do

not vent directly to the atmosphere; mandates for systems of this type appeared contemporaneously in other jurisdictions. In a typical system, vapors from the fuel tank and carburetor bowl vent (on carbureted vehicles) are ducted to canisters containing active carbon. The vapors are adsorbed within the canister, and during certain engine operational modes fresh air is drawn through the canister, pulling the vapor into the engine, where it burns. The effects of high Sulphur gasoline leads to higher NO<sub>x</sub>, CO and HC emissions because Sulphur impacts the three way catalytic converter in the following ways;

Fuel Sulphur reduces conversion efficiency for CO, HC and NO<sub>x</sub> because Sulphur competes with these gaseous pollutants for catalyst reaction space and interferes with the management of oxygen on the catalyst surface. Research showed that emissions of HC and CO dropped by 9-55% and NO<sub>x</sub> emissions reduced by 8-77% when Sulphur in fuel is reduced from 200-600ppm to 18-50ppm. High temperatures are required to completely reverse Sulphur inhibition which could thermally damage the catalysts and reduce its efficiency.

## CHAPTER 4: METHOD AND DATA COLLECTION

### 4.1. Methodology and procedure for data collection

#### 4.1.1 Data requirements for the study

The data requirements included various passenger vehicles being presented at RTSA Mimosa for pre-registration inspection. A one month sample of the imported motor vehicles entering the country and being present for pre-registration inspection was taken. Given the measurement equipment available, the study focused on gasoline engine motor vehicles only.

#### 4.1.2 Equipment and Tools

In this study, the equipment used to conduct the study is included in table 4.1 below.

**Table 4.1 Table of equipment used in tailpipe exhaust measurements**

	Equipment Type
i.	Computer processor
ii.	Computer monitor
iii.	Printer
iv.	MGT 5 Gas analyzer
v.	Exhaust test pipe probe with a 30cm probe
vi.	Engine oil temperature probe with a 30 cm probe

The personal computer included was a normal PC with a normal monitor running on Windows 8.1 with capability to transfer the readings to excel format and enable printing with an HP color printer. The MGT 5 gas analyzer shown in figure 4.2 had a 20 meters long poly pipe with an exhaust probe attached. The analyzer also had a 20 meters electric cable with a engine temperature probe at its designed similar to engine oil dip stick. This was to enable the measurements for engine oil temperatures in degrees Celsius which represent the approximate engine temperature which has an effect on engine emissions.

was used to test vehicle tailpipe emissions from imported motor vehicles presented to MIMOSA vehicle testing centre of the Road Transport and Safety Agency (RTSA).

**Figure 4.1 Picture of the MGT 5 Gas Analyzer**



Exhaust collection pipe

Engine temperature cable

The schematic diagram of the pneumatic functional design of the gas analyzer is shown in appendix A.

The MGT5 gas analyzer has a 30 cm gas tight probe which is used to collect exhaust fumes approximately 30 cm into the spout. During measurements, the gas is sucked through the measurement probe into the main filter/water separator. Any exhaust gas containing water is diverted into the bottom protective filter and water is removed by the internal water pump out through the drain valve. Once cleaned of water, the exhaust gas passes the second protective filter into the measurement chamber containing two gas test valves, an active charcoal canister and measurement gas pump for CO, HC, NO<sub>x</sub>, O<sub>2</sub> and lambda.

The functional parameters and measurement accuracy are summarized in the table 4.3.

**Table 4.2 Functional Capabilities of the MGT 5 gas analyzer**

Mains	240 V, 50Hz
Warm up time	480s
Measurement range HC	0-400ppm
Measurements range CO	0-15% <i>volume</i>
Measurement range CO <sub>2</sub>	0-20% <i>volume</i>
Measurement range NOx	0-5000 ppm
Measuring accuracy	HC 0.1ppm CO 0.001% <i>vol</i> CO <sub>2</sub> 0.01% <i>vol</i> O <sub>2</sub> 0.01% <i>vol</i> NOx 1ppm
Working pressure	0.75 <i>min</i> -1.1 <i>max bar</i>
Total flow rate	3.2 <i>l/min</i>
Lambda	0.5-9.99/0.01

#### **4.1.3 Equipment Calibration**

This 5-gas unit uses electrochemical sensors for the O<sub>2</sub> and NO<sub>x</sub> measurements. Life of these sensors varies with use, but in general they last ~ 1-2 years. The other measurements for HC, CO, and CO<sub>2</sub> are done with a NDIR cell. Re-calibrating of the unit is done using a Bar 97 gas mixture every once a year. All sensors are calibrated at once. Calibrations last up to a year, but periodic checking was done every morning.

The unit is connected to a Computer monitor and printer and results can be printed showing all gas concentrations on a single page.

To perform any tailpipe emission test, the analyzer must be connected to 240 volts 50 Hz power outlet and after a short warm up period of about 60 seconds, the analyzer will display current exhaust concentrations. The analyzer will turn off after it senses CO

levels below 3% for more than 15 minutes. It will also perform an “auto zero” periodically when exhaust gases aren’t present. The gas analyzer also had three self-checking capabilities and conducted daily self checks for the following:

- i. Air leaks
- ii. Contamination
- iii. Calibration

Prior to its use on any given day, the leakage test, contamination test and calibration settings had to be checked. To check the three analyzer statuses, the MGT 5 would be connected to power and through the USB data cable to the PC, Monitor and printer.

Using the attached probe poly front seal, the entire 30 cm probe length is covered. The computer screen once ready, will prompt a question asking whether the test is a calibration, leakage or contamination test. Select YES and the gas pump will immediately be activated. The gas pump will fill the entire pneumatic system with oxygen under pressure of approximately 3 bar and hold it for over 30 seconds.

If the no lost calibration settings, no leakage or contamination is detected, the the MGT 5 will prompt via the PC screen a command to proceed with gasoline exhaust measurements.

No periodic calibration was done during the 30 days of exhaust measurements as the settings were to last for 12 months.

#### ***4.2 Data Collection Procedure***

A total sample of 200 petrol powered motor vehicles were selected over a period of 30 days. The sample included any make and type of motor vehicle but with a focus on passenger vehicles of varying weights. The sample ranged from the smallest hatchback such as Daihatsu boon to minibuses such as Toyota Regius, Toyota Hiace or Toyota Noah of varying engine capacities and years of make but all running on gasoline.

Motor vehicles were presented to an examiner at the test centre entrance located 40 meters before the testing station. One after another they were allowed entrance to the testing station where the test was setup.

At the test station and under ambient temperature conditions, the following steps were followed strictly to ensure uniformity and integrity of measurement results. At the entrance of the Mimosa inspection workshop with part of the motor vehicle body stationed inside of the workshop drivers were asked to leave the engine on idling. As the engine was running the test required the following steps:

- i. Open the engine compartment
- ii. Removing the engine dip stick and inserting in its place the MGT 5 temperature probe.
- iii. Entering the chassis number (VIN), make/model of the vehicle.
- iv. Noting and entering engine capacity
- v. Reading off the year of make from the original seat belt and entering the year of make appearing on it.
- vi. Inserting the exhaust probe 30 cm into the exhaust pipe and fastening it.
- vii. From the PC screen selecting exhaust inspection
- viii. The screen will prompt two options for diesel and OTTO Measurement (meaning gasoline). Otto measurements must be chosen.
- ix. After 30 seconds, the screen will zero all values and this is followed by measurement values including engine oil temperature with an option for printing or saving. Printing was chosen
- x. The measurement values would appear as shown in appendix 4.
- xi. The probe is removed from the tailpipe and measurement results printed.
- xii. If results appear in green it implied that engine emissions where within the set limits for selected gases.
- xiii. If the emissions appears in amber it meant that emissions were almost meeting or surpassing the upper set limits which were in accordance with the ZS 560:2004.
- xiv. Engine emissions measured results appearing in red it implied that the engine was producing emissions beyond the set upper limits for ZS 560:2004.

- xv. The limits for selected gases are; CO  $\leq$  4.5% gas by volume, HC  $\leq$  1200 parts per million (ppm).

A typical computer screen at showing results is shown as appendix C

### **4.3 Sample Categorization**

A total of 200 gasoline motor vehicles were subjected to the study out of a total of 116,007 motor vehicles imported in the year 2014. None of the sampled motor vehicle engines were turbo charged though majority of them had variable valve timing technologies. All but 4 nos. motor vehicles from the sample had in-line engine design configurations. The two tables 4.5.1 and 4.5.2 show in summarized form the number of motor vehicles subjected to the emission tests by age and engine capacity respectively.

**Table 4.3 Summary of vehicles tested categorized according to age**

Year	1988-1990	1991-1993	1994-1996	1997-1999	2000-2002	2003-2005	2006-2008	2009-2010
No. of motor vehicles	2	2	5	70	72	46	2	1

**Table 4.4 Summary of motor vehicles tested categorized according to engine capacity**

Engine CC	0.98-1.5cc	1.6-2.1cc	2.2-2.7cc	2.8-3.3cc	3.4-3.9cc	4.0-4.5cc
No. of motor vehicles	99	68	16	11	4	2

The average sample detailed results of the emission test results are shown in the appendices D.

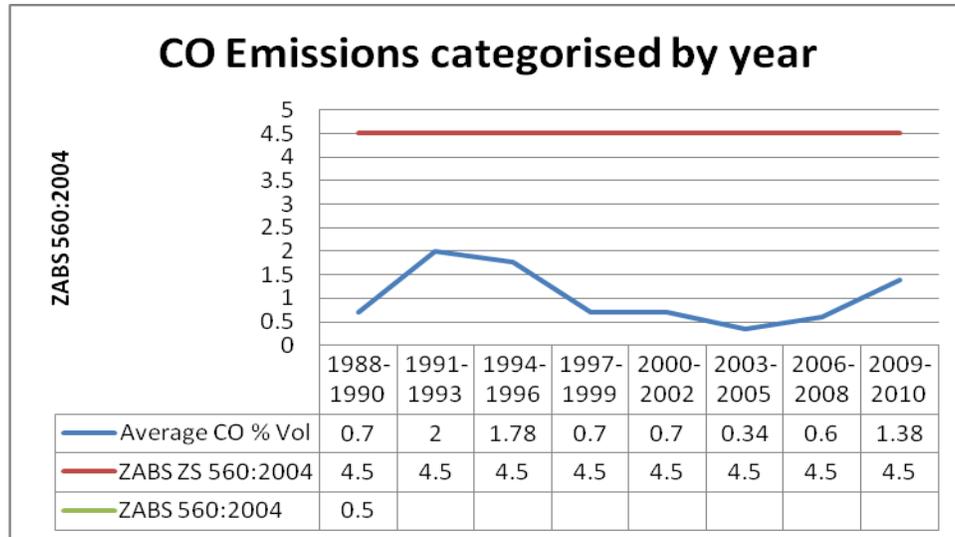
## CHAPTER 5: RESULTS, DATA ANALYSIS AND DISCUSSIONS

### 5.1 Data analysis by age and engine capacity of the sampled motor vehicles

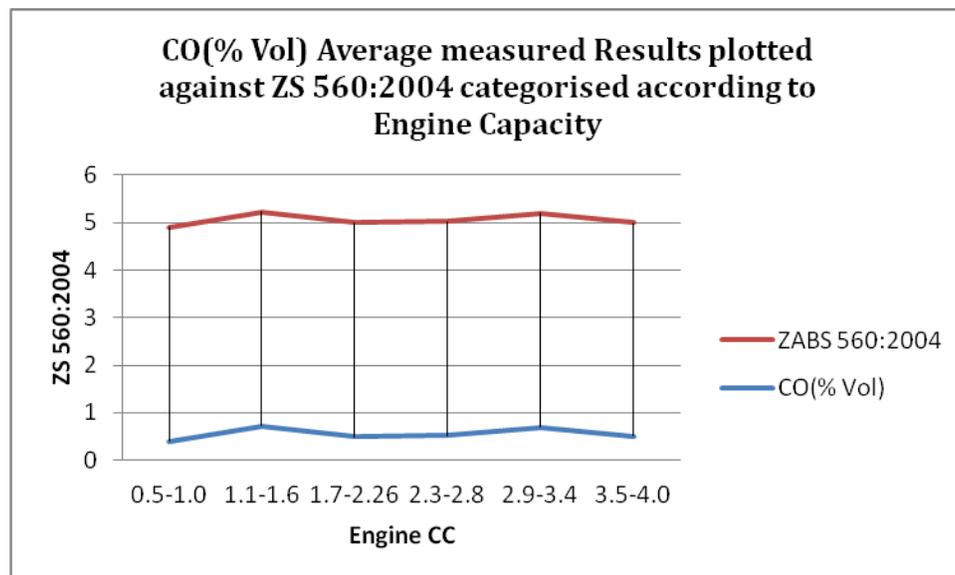
#### 5.1.1. Carbon Monoxide

The figure 5.1a and 5.1b shows the carbon monoxide emission test results compared to the age.

**Figure 5.1a CO Carbon Monoxide Emission Test Results categorized by Engine Age**



**Figure 5.1b Average Carbon Monoxide Results categorized by engine capacity**



From figures 5.1a and 5.1b it was observed that both motor vehicles with older engines and those categorized according to engine capacity were within the ZS 560:2004 standard. Figure 5.1a however despite showing that the sampled motor vehicles met the ZABS standards showed higher CO emissions in older engines than in engines produced after 1994.

Further, the comparison of the average carbon monoxide emissions on the basis of engine capacity revealed that the entire sample of the used imported motor vehicles were within the ZABS 560:2004 regardless of the engine capacity. Beyond 1994, CO emission levels measured were lower regardless of engine capacities.

Given that these used motor vehicle emissions met the national standard, it follows that the public assertions of negative environmental impact regarding CO emissions from older engines of high cubic capacities were found inconsistent.

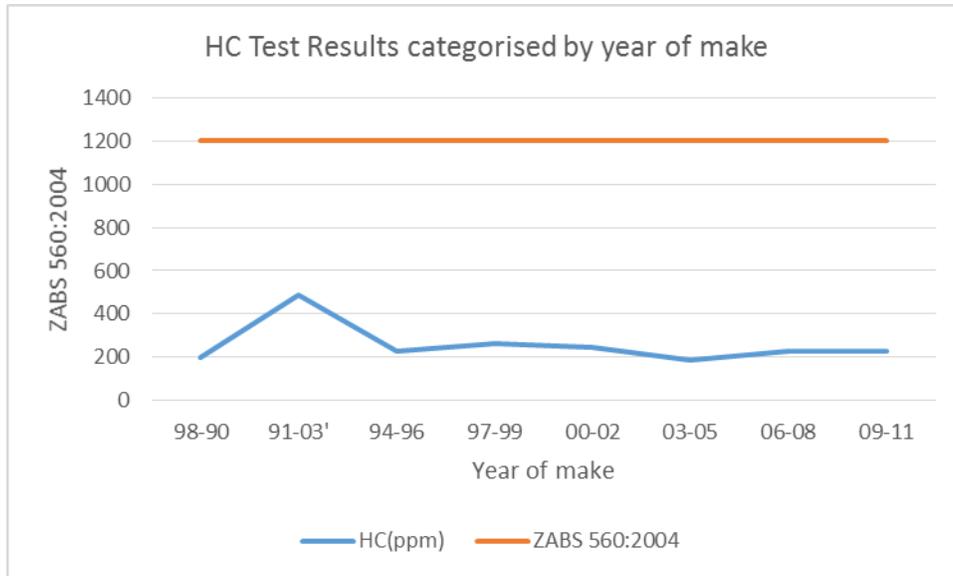
#### ***5.1.2 Hydrocarbon (HC) concentrations***

The Zambia Bureau of standards (ZABS) standards ZS 560:2004 stipulated the following limits for hydrocarbon emission concentrations:

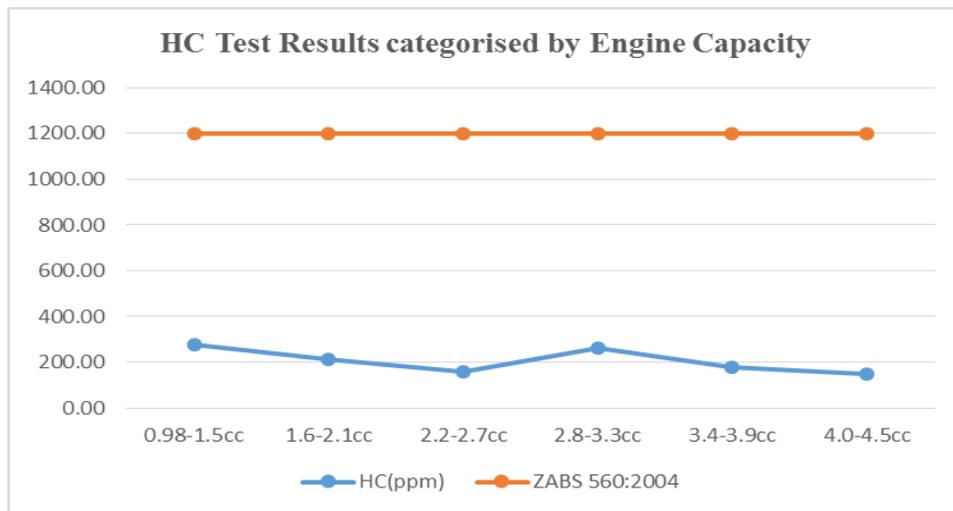
- 4 – cycle engine: 1, 200ppm
- 2 – cycle engine: 7, 800ppm
- special engine: 3300ppm

From the emission tests conducted during the study, the results of the hydrocarbon concentration levels are shown in the figures 5.2 a and 5.2b below:-

**Figure 5.2a Emission Test Results categorized by year of engine make for HC**



**Figure 5.2b Emission Test Results for HC categorized by Engine CC**



Observing from figures 5.1.2 a and b above, average hydrocarbon test results from the two hundred petrol powered motor vehicles of varying age and engine capacities were found to be emitting below the ZABS standards ZS560:2004 which sets the limit of 1,200 parts per million. Figure 5.2a also showed a rise in hydrocarbon levels for engines produced between 1991 and 1993 followed by a drop in HC levels in the subsequent years regardless of engine cubic capacity.

Though these levels were within the standard, it was prudent to investigate other factors that could have contributed to this phenomenon in class falling within the years 1991-1993.

After thoroughly checking the data set in the years 1991-1993, it was established that there were only two motor vehicles whose individual HC emission concentrations were 724 ppm and 249 ppms respectively with engine temperatures of 30 degrees and 47 degrees. It could be concluded that the two engines were operating at sub optimal temperatures.

### **5.1.3 Carbon Dioxide Test Results**

The ZABS Standard ZS 560:2004 contains no mention of carbon dioxide and its effects on the environment. This study however took advantage of the measurement capabilities of the MGT 5 gas analyzer and included results from the tailpipe emission tests for carbon dioxide. Figure 5.3 below shows carbon dioxide emissions levels compared to the age of the motor vehicle.

**Figure 5.3 Emission Test Results for CO<sub>2</sub> Categorized according to the Age of the Engine**

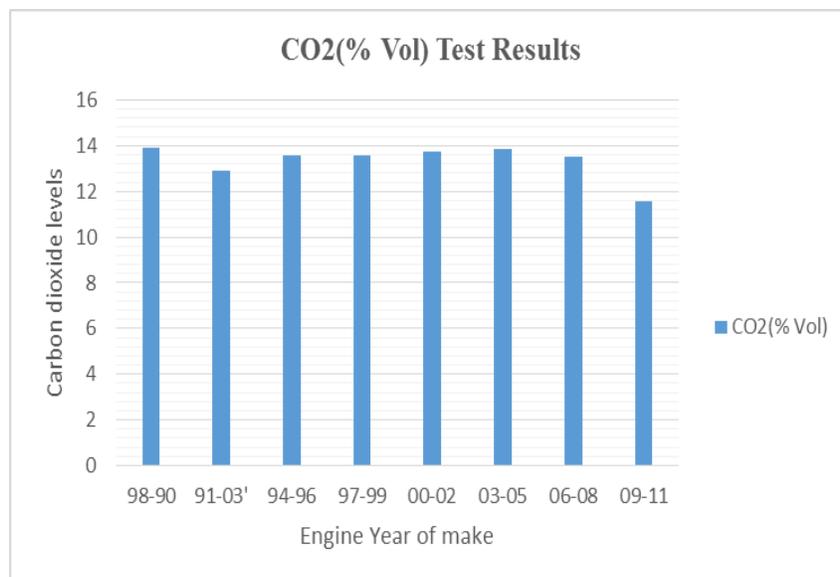


Figure 5.3 shows that the carbon dioxide levels were generally below 14% volume. The trend showed in the chart was similar to the one plotted against engine capacity.

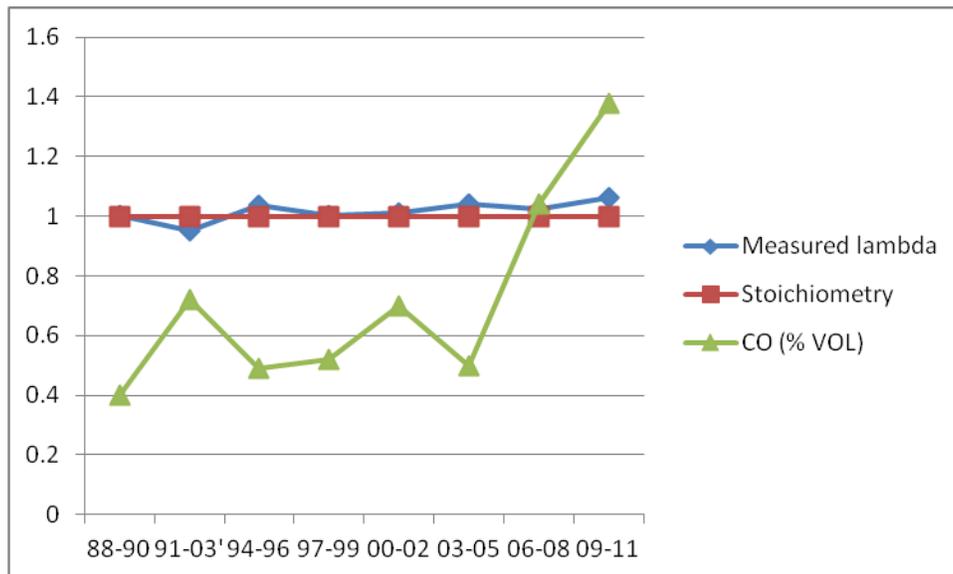
No comparisons could be made particularly with Japan which is the main origin of the motor vehicles exported to Zambia and included in the sample. This was due to the measurement units employed by Japanese Authorities.

## 5.2 Other Tail Pipe Emission Results

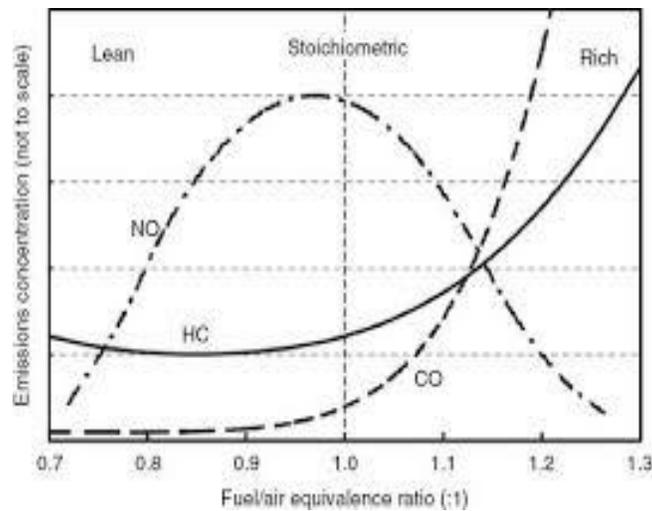
### 5.2.1 Lambda analysis

Due to importance of the air fuel ratio and its effects on the engine emissions in general, the study included results for lambda. The term lambda is defined as "actual air/fuel ratio divided by 14.7", therefore stoichiometry, the point at which the most energy can be obtained from a given amount of fuel is  $14.7/14.7 = 1$ . Richer mixtures are lambda more than one; leaner mixtures are lambda less than one. Measured results for lambda, CO and stoichiometry are shown in 5.4.

**Figure 5.4 Lambda analysis**



**Figure 5.5 Equivalence ratio comparative chart**



From the graph plotted in figure 5.2.1, the relationship among the three engine combustion factors are consistent with engine thermodynamics and therefore warrants accuracy in the results.

The graph above shows that there is a strong relationship between carbon monoxide and oxygen.

## CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

### 6.1 Conclusion

Based on the results obtained, the following conclusions were drawn on the levels of vehicle emissions from automobiles imported into the republic of Zambia.

**i. Carbon monoxide**

All the two hundred motor vehicles subjected to the tailpipe carbon monoxide (CO) emissions at MIMOSA met the ZS 560:2004 standard. The Zambia Bureau of standards ZS560:2004 prescribes a compulsory limit of carbon monoxide to 4.5% volume.

**ii. Hydrocarbon**

All the two hundred motor vehicles subjected to hydrocarbon emission testing at Mimosa vehicle testing centre met the ZS 560:2004 National standard. The national cut-off limit for used motor vehicles is 1, 200 parts per million while the European Union cut off limit is 1000ppm.

**iii. Carbon dioxide**

Even though carbon dioxide is a known GHG and appears on the five gases tested in the experiment, the ZS 560:2004 does not prescribe the national standard for used motor vehicles. The European Union however has set 130g/km as the cut off limit for carbon dioxide emissions.

Due to the difference in the procedures used for testing and reporting carbon dioxide levels from the study compared with drive test cycles used in testing and reporting carbon dioxide used in the euro standards, it was difficult to make a direct comparison of the test results. The average of 14 percentage volume recorded from most vehicles could not be compared directly with the European standards unless substantial conversion calculations could be performed.

#### **iv. Nitrogen oxide (NO<sub>x</sub>)**

Out of the of 200 motor vehicles subjected to this study over 32 motor vehicle were found emitting varying levels nitrogen oxides. The levels of nitrogen oxides increased with increase in engine oil temperatures. Further, the nitrogen oxide test calibration was in parts per million whereas the European limits are in grams per kilometer. This required conversion computations to make the results comparable.

The overall conclusion is that used imported motor vehicles coming to Zambia meet the international and local standards and therefore should not be stereotyped as environmentally unacceptable in terms of pollutant emissions serve for other safety related factors.

### **6.2 Recommendations**

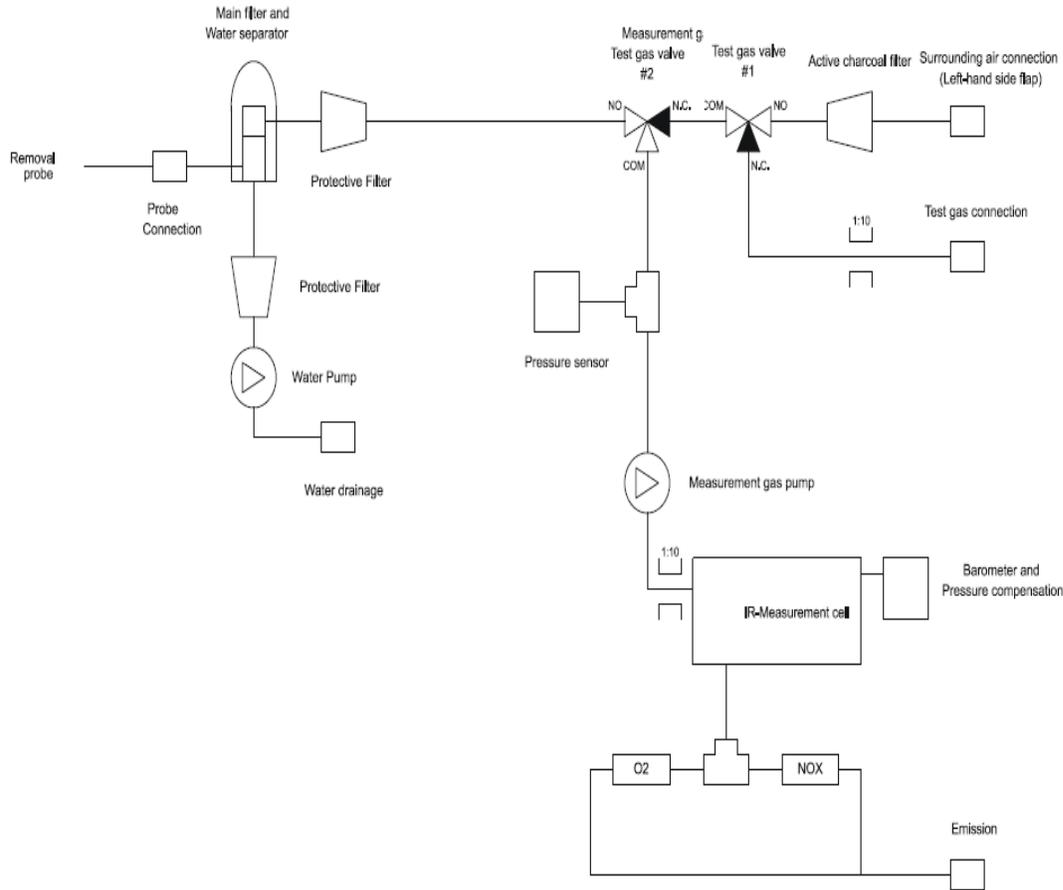
Following the conclusions made under section 6.1, the following recommendations were made:-

- i. Zambia through the Zambia Bureau of Standards(ZABS), Zambia Environmental Agency(ZEMA), Road Transport and Safety Agency (RTSA) and Zambia Revenue Authority(ZRA) in consultation with all environmental stakeholders must immediately engage in consultation to revise the ZS 560:2004 and bring it in line with any of the worlds comparable fuel efficiency and GHG standards. Majority of the motor vehicles subjected to the emission testing study originated from Japan with a small proportion coming from United Kingdom. The standards for the two world regions differ not only in reporting units but also in driving cycles which are the bases for the standard. A single standard on emissions must be adopted which bear features of both world regions.
- ii. The reporting units specified in the ZABS 560:2004 are in parts per million for hydrocarbons and percent volume for carbon monoxide and carbon dioxide. These units must be aligned as per either the Japanese fuel efficiency standards and related emissions or the UK reporting format. This will enable easy of comparison. The units must clearly show that the standard is for used motor vehicles.

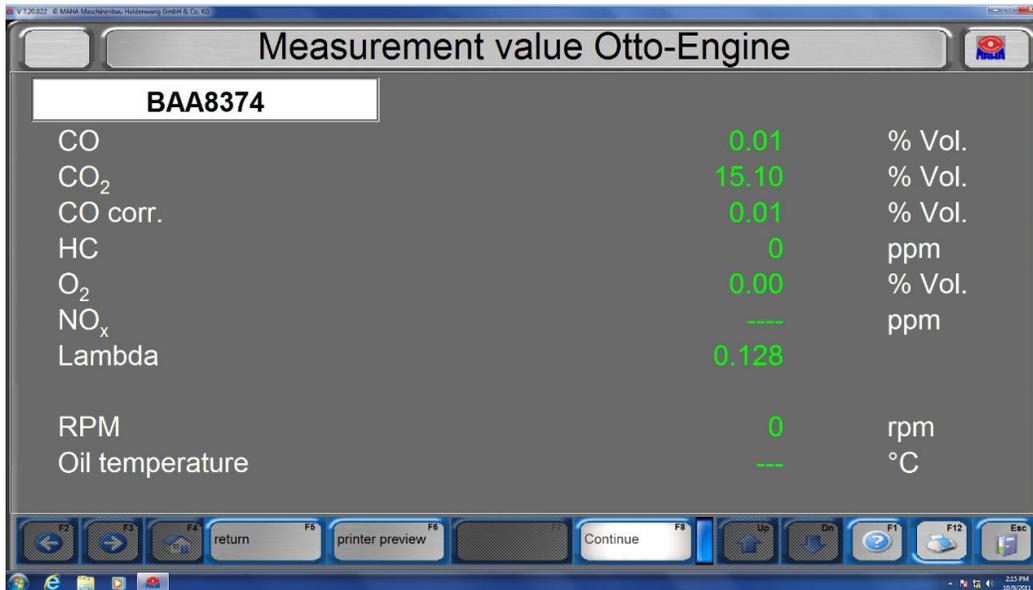
- iii. Until the emission policy is finalized and agreed by all major stakeholders, both the carbon surtax import carbon taxes imposed on used motor vehicle importers must be formally withdrawn until a more objective method of vehicle emission pollution controls are established
- iv. The pre-export motor vehicle inspection programme currently being administered by ZABS through JEVIC be revised to give prominence to exhaust emission levels.
- v. Zambia Revenue Authority which currently penalizes motor vehicles over five years must review its tax policy and align it with not just current emission levels but also whole life cycle environmental impacts such as tyre disposal, air-conditioning gas disposal, used oil disposal and any other environmental harmful aspects over the full life of the used motor vehicles.

# APPENDICES

## Appendix A Pneumatic Layout of the MGT 5 Gas Analyzer



## Appendix B Measurement screen for MGT 5 GAS Analyzer



**APPENDIX C Sample of data categorization according to year of make**

	Year of Make	CC	CO <sub>2</sub> (% Vol)	HC(ppm)	O <sub>2</sub> (% Vol)	Nox	λ
Toyota Hilux	1988	2.44	13.7	162	0.51	217	1
Toyota Hilux	1988	2.44	14.16	235	0.81	0	1.006
Toyota corona	1992	1.8	12.18	724	0.18	150	0.924
Toyota corona	1992	1.8	13.67	249	0.43	121	0.982
Mazda Demio	1996	1.32	13.39	301	1.74		1.069
Toyota corola	1996	1.49	12.77	236	2.34	0	1.109
Toyota Corrola	1996	1.49	13.65	237	0.94	0	1.022
Toyota Corrola	1996	1.49	13.58	305	0.58	0	0.984
Toyota Gaia	1996	1.99	14.5	74	0.11	0	0.999
Daihatsu Boon	1997	0.99	13.7	295	0.88	0	1.017
Toyota Corola	1997	1.49	13.74	334	0.54	147	0.986
Toyota Corola	1997	1.49	13.67	221	0.49	117	0.99
Toyota corola	1997	1.49	13.91	227	0.82	0	1.028
Toyota corola	1997	1.49	12.83	348	2.41	0	1.106
Toyota Corrola	1997	1.49	13.75	226	0.58	0	0.988
Toyota Ipsum	1997	1.99	14.98	118	0.29	0	0.992
BMW	1998	1.9	13.95	114	0.63	0	1.017
BMW 318	1998	1.9	14.29	168	1.02	0	1.034
BMW 318	1998	1.9	14.29	168	1.02	0	1.034
Honda Fit	1998	1.33	13.56	361	1.15	0	1.023
Honda Marron	1998	1.49	12.97	372	0.65	0	0.964
Nissan Xtrail	1998	1.99	14.05	218	0.53	0	1.004
Peugot 1007	1998	1.58	12.38	317	0.63	0	0.924
Peugot 1007	1998	1.58	14.79	37	0.05	0	1.000
Toyota Corola	1998	1.49	13.32	402	1.45	175	1.048
Toyota Corola	1998	1.49	14.56	215	1.23	0	1.042
Toyota corola	1998	1.49	11.89	1125	4.28	0	1.171
Toyota Corola	1998	1.49	13.18	247	1.62	0	1.060
Toyota Corola	1998	1.49	13.67	267	0.77	0	1.004
Toyota Corola	1998	1.49	14.27	128	0.33	0	1.004
toyota corona	1998	1.8	13.1	573	1.91	0	1.062
Toyota Corrola	1998	1.49	14.29	67	0.59	52	1.025
Toyota Corrola	1998	1.49	13.4	229	1.49	0	1.052
Toyota corrola	1998	1.49	14.39	227	0.84	0	1.015
Toyota Hiace	1998	2.43	13.31	217	0.37	0	0.570
Toyota Hiace	1998	2.43	13.14	201	0.96	159	0.992

**APPENDIX D Sample of data categorization according to engine capacity**

	Year of Make	CC	CO <sub>2</sub> (% Vol)	HC(ppm)	O <sub>2</sub> (% Vol)	Nox	λ
Daihatsu Boon	1997	0.99	13.7	295	0.88	0	1.017
Mazda Demio	1996	1.32	13.39	301	1.74		1.069
Honda Fit	1998	1.33	13.56	361	1.15	0	1.023
Toyota corola	1996	1.49	12.77	236	2.34	0	1.109
Toyota Corrola	1996	1.49	13.65	237	0.94	0	1.022
Toyota Corrola	1996	1.49	13.58	305	0.58	0	0.984
Toyota Corola	1997	1.49	13.74	334	0.54	147	0.986
Toyota Corola	1997	1.49	13.67	221	0.49	117	0.99
Toyota corola	1997	1.49	13.91	227	0.82	0	1.028
Toyota corola	1997	1.49	12.83	348	2.41	0	1.106
Toyota Corrola	1997	1.49	13.75	226	0.58	0	0.988
Honda Marron	1998	1.49	12.97	372	0.65	0	0.964
Toyota Corola	1998	1.49	13.32	402	1.45	175	1.048
Toyota Corola	1998	1.49	14.56	215	1.23	0	1.042
Toyota corola	1998	1.49	11.89	1125	4.28	0	1.171
Toyota Corola	1998	1.49	13.18	247	1.62	0	1.06
Toyota Corola	1998	1.49	13.67	267	0.77	0	1.004
Toyota Corola	1998	1.49	14.27	128	0.33	0	1.004
Toyota Corrola	1998	1.49	14.29	67	0.59	52	1.025
Toyota Corrola	1998	1.49	13.4	229	1.49	0	1.052
Toyota corrola	1998	1.49	14.39	227	0.84	0	1.015
Toyota Raum	1998	1.49	13.86	228	0.9	0	1.019
Toyota Sprinter	1998	1.49	12.93	353	0.33	0	0.908
Peugot 1007	1998	1.58	12.38	317	0.63	0	0.924
Peugot 1007	1998	1.58	14.79	37	0.05	0	1
Toyota corona	1992	1.8	12.18	724	0.18	150	0.924
Toyota corona	1992	1.8	13.67	249	0.43	121	0.982
toyota corona	1998	1.8	13.1	573	1.91	0	1.062
BMW	1998	1.9	13.95	114	0.63	0	1.017
BMW 318	1998	1.9	14.29	168	1.02	0	1.034
BMW 318	1998	1.9	14.29	168	1.02	0	1.034
Toyota Gaia	1996	1.99	14.5	74	0.11	0	0.999
Toyota Ipsum	1997	1.99	14.98	118	0.29	0	0.992
Nissan Xtrail	1998	1.99	14.05	218	0.53	0	1.004

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