An investigation into the climate change mitigation potential of road transport emissions in eThekwini Municipality.

By

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ABSTRACT

The South African transport sector as a whole is the second largest source of green house gas (GHG) emissions, with South Africa's road transport sector contributing 80-90% of the total transport emissions. As such there is a need to estimate and assess the contribution and implications of emissions from the road transport sector for both ambient air quality and climate change. This justifies the need for a coherent a holistic vehicle emission modelling framework and scenario analysis for the management of co-emitted emissions in urban areas.

The eThekwini Municipality has been progressive in terms of addressing climate change. However, ambient air quality data indicates that road transport is an increasing source of emissions in the municipality. Previous studies of road transport in the municipality have failed to account for off-road transport and therefore over-estimate emissions from on-road vehicles. Furthermore, little work, to date, has been carried out in terms of understanding the mitigation potential of different interventions that could be implemented in the road transport sector. As such the main aim of this study was to compile a baseline emission inventory for the road transport sector for the municipality that could be used to assess the local applicability of potential mitigation measures that have been previously investigated at a national level. These interventions were then prioritised in terms of ability to contribute towards reducing air pollution.

The Computer Programme to Calculate Emissions from Road Transport (COPERT) IV model was used to compile an inventory for the municipality based on the on and off road eNATIS vehicle database. The analysis revealed that passenger vehicles and HCV's produced the greatest quantities of emissions, with diesel engine vehicles responsible for more of the emissions. This baseline was then used to investigate interventions that would simultaneously reduce emissions in the road transport sector. This study found that the most suitable measures include the use of improved efficiency petrol and diesel internal combustion engines, biofuels, shifting freight from road to rail and shifting passengers from cars to public transport (reduced vehicle kilometres and modal shift). By employing these proposed mitigation measures, simultaneous reductions of air quality and climate change emissions can be achieved.

PREFACE

This study was carried out in the School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Westville campus under the supervision of Doctor Tirusha Thambiran between February 2014 and December 2016. This study represents original work by the author, except where otherwise indicated. Where the work of other authors has been utilised, it has been duly acknowledged. This thesis has not been submitted in any form for any degree to any University.

Signed: ___________

Kaveesh Roopcharan Date: 12 December 2016

Signed: ________________

Dr Tirusha Thambiran Date: 12 December 2016

DECLARATION

I ***Kaveesh Roopcharan*** declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
   a. Their words have been re-written but the general information attributed to them has been referenced
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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Kaveesh Roopcharan Date: 12 December 2016

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LIST OF ABBREVIATIONS

The following are definitions of abbreviations used in this study:

APPA	Atmospheric Pollution Prevention Act (Act 45 of 1965)
AQA	Air Quality Act (see NEMAQA)
AQM	Air Quality Management
AQMP	Air Quality Management Plan
H_2S	Hydrogen sulphide
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CNG	Compressed natural gas
DEAT	Department of Environmental Affairs and Tourism
DoE	Department of Energy
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GHG	Green house gases
GWP	Global warming potential
HEV	Hybrid electric vehicle
IPCC	Intergovernmental Panel on Climate Change
ICE	Internal combustion engine
LPG	Liquefied petroleum gas
MPP	Multi Point Plan
NEMAQA	National Environmental Management Air Quality Act
NF_3	Nitrogen trifluoride
NH_3	Ammonia
NMVOC’s	Non-methane volatile organic compounds

NO_x	Oxides of nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
N_r	Reactive nitrogen
O_3	Ozone
OH	Hydroxyl free radical
Pb	Lead
PHEV	Plug-in hybrid electric vehicle
PM_{10}	Particulate matter with an aerodynamic diameter of < 10 microns
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of < 2.5 microns
ppb	Parts per billion
ppm	Parts per million
SAAQIS	South African Air Quality Inventory System
SANS	South African National Standards
SAPIA	South African Petroleum Industries Association
SEPA	Swedish Environmental Protection Agency
SF_5CF_3	Trifuoromethyl sulphur pentafluoride
SO_2	Sulphur Dioxide
TRS	Total reduced sulphur
TSP	Total suspended particulate
UKZN	University of KwaZulu-Natal
VKT	Vehicle kilometres travelled
VOC's	Volatile organic compounds
$\mu g/m^3$	Micrograms per cubic meter

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CHAPTER 1: INTRODUCTION

1.1) Background

The Earth is a dynamic planet consisting of a range of processes and interactions which are in a constant state of change. In recent times humans have begun to alter the dynamics of these processes and the manner in which living organisms interact with each other and the planet. Population growth and migration towards urban areas has resulted in the rate of urbanisation increasing across the globe, with projections indicating that the world's urban population will grow by 66 % by the year 2055 (United Nations, 2001; United Nations, 2014). Urbanisation places tremendous pressure on infrastructure, natural resources and the capabilities of management (Ahmed, 2010).

Socio-economic processes act as drivers for the consumption of vast quantities of fuels and natural resources in urbanised areas. Consequently a variety of wastes and emissions are produced, which results in multiple contemporary environmental issues such as air quality degradation, water pollution, excess waste and resource depletion (Hao and Wang, 2005). Adding to these contemporary issues are the concerns over anthropogenic climate change attributed to the release of GHG and its associated complexities (Ahmed, 2010).

Air pollution and poor air quality in urban areas has become one of the major environmental issues that is prevalent across the world in many major cities (Hao and Wang, 2005). Air pollution refers to gases or aerosol particles which are emitted anthropogenically and build up to concentrations sufficiently high to cause direct or indirect damage to plants, animals, other life forms, ecosystems, structures, or works of art (Jacobson, 2002; Amann *et al*., 2011; Cui *et al*., 2014). The state of air pollution is expressed as air quality which is defined as the measure of the concentrations of gaseous pollutants, size or abundance of particulate matter (Monks *et al*., 2009). The state of air quality is of concern due to its far reaching effects on health, ecosystems, heritage and climate.

The fundamentally shared chemical origin of air pollutants from point and non-point sources, across various spatial and temporal scales makes air quality both a local and global problem (Monks *et al*., 2009). Despite these close linkages, climate change and air pollution has been regarded as separate concepts from a scientific and especially a political view point. Such linkages which have been identified include the acceptance that various greenhouse gases (GHG) and common air pollutants are co-emitted from industrial and transport sectors (Swart *et al.*, 2004). Climate may alter concentrations of GHG, acidic pollutants and precursor gases via variations in atmospheric circulation, meteorology and dispersion which in turn has an effect on ambient air quality (Jacob and Winner, 2009; Thambiran and Diab, 2010). Thus it can be concluded that air quality is affected by meteorology, which is in turn sensitive to climate change. It is thus pertinent that policy and management initiatives adopt a holistic and integrated stance which adapts to climate change and pro-actively encourages climate change mitigation.

Within an urbanised area the transport sector which is inclusive of road, rail and air networks, is a consistent source of numerous atmospheric pollutants (Kousouslidou *et al.*, 2010; Nzitachristos and Smit, 2014). Resitoglu and Altinisik (2015) have reviewed the works of different international organisations in attempt to quantify this sector's role in emission production. The review included research conducted by the United States Environmental Protection Agency (USEPA), Organisation for Economic Co-operation and Development (OECD), Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA) and European Economic Area (EEA). The review collectively concluded that between 20-30% of emissions originated from the transport sector as a whole which impacted negatively upon global warming and climate change. Further evidence supporting this review lies in the findings by Takeshita (2012), who indicated that globally the entire transportation sector is the second largest producer of emissions. This equates to an estimated 22-30% of carbon dioxide (CO_2) emissions with approximately three quarters of this figure being emitted specifically from road vehicles (Takeshita, 2012). Based on such findings and combined with limited use of emission control technologies, the consensus seems to be that the road transport sector has emerged as the largest source of urban air pollution (Resitoglu and Altinisik, 2015).

The South African transport sector as a whole is the second largest source of GHG emissions, producing approximately one third of South Africa's GHG emissions accounted for within the national emissions inventory (CSIR, 2013; Merven *et al.*, 2012). Of this value South Africa's road transport produces 80-90% of the total transport emissions (CSIR, 2013; DEAT, 2013). In South Africa values for road transport emissions was estimated at 29.6

million tonnes of CO_2 equivalent ($MtCO_2$-eq) in 1990, 29.8 $MtCO_2$-eq in 1994, 36.6 $MtCO_2$-eq in 2000 and 43.4 $MtCO_2$-eq in 2010 displaying an upward trend (DEAT, 2009; DEAT, 2013). This is expected to worsen in the future as the consensus is that vehicle ownership is expected to rise (Moriarty and Honnery, 2008). Subsequently the impacts of traffic emissions on human health and urban environmental health become a concern, which justifies the need for a coherent regulatory framework for the management of both traffic emissions and air quality in urban areas (Costabile and Allegrini, 2005).

Emissions of GHG, acidic pollutants and precursor gases from vehicles which are considered important climate forcing agents and air pollutants are affected by a changing climate. Some compounds when in a gaseous state are water soluble and can be effectively be removed by precipitation from the troposphere which results in acid formation (Speidel *et al.*, 2007). Such complexities thus pertain to the over-arching chemistry-climate linkages. One specific manifestation of the chemistry-climate linkages for the road transport sector pertaining to water quality within the coastal zone is that of ocean acidification which is caused by rising concentrations of atmospheric CO_2 from vehicular emissions (NRC, 2010; IPCC, 2013). Although this phenomenon may be highly attributed to CO_2 against the backdrop of global climate change, indirect drivers of ocean acidification such as sulphur dioxide (SO_2), reactive nitrogen (N_r), otherwise known as acidifying pollutants from the road transport sector, have emerged to be just as influential in coastal zones that are densely populated (Doney *et al.*, 2007). Excess GHG and acidifying pollutants from vehicles have the ability to induce several adverse effects on biotic and abiotic components within an ecosystem (NRC, 2010; IPCC, 2013). In most instances the effects of these emissions are related to the characteristics of the precursor's gases and its ability to react and give rise to secondary pollutants, with the most direct and focused effects of such pollutants being the acidification of terrestrial and aquatic ecosystems (Menz and Seip, 2004).

Given that interactions between the ocean and atmosphere occurs slowly over a few decades, it may take many years for the oceans to adjust to vehicular emissions emitted thus far. Thus a considerable time has to pass before the full negative effect of increased vehicular emissions is witnessed. Therefore the most severe effects may be expected in the decade to come, thus the need for pro-active approaches to mitigate against emissions from the road transport sector at present (Kelly and Caldwell, 2013).

1.2) Motivation

1.2.1) Reduction of co-emitted emissions

Relatively little attention has been given to the benefits of reducing N_r and SO_2, particularly from the road transport sector in forms such as ammonia (NH_3) and hydrogen sulphide (H_2S) which are precursors to other criteria pollutants and short lived climate forcers such as tropospheric ozone (O_3) (Aneja *et al*., 2009). This may also be applied to CO_2 whose role in acidification has largely been over looked. Given the global warming potential of GHG and acidic properties of some of N_r and sulphur dioxide (SO_2), quantification at a local scale is necessary to assess, control and mitigate these multiple impacts (NRC, 2010; Abiodun *et al*., 2013). A reduction of impacts locally will have an amplified effect and contribute to improved resilience at a regional scale and thus would further support climate change adaptation efforts (Zunckel *et al.*, 2000; Huang *et al*., 2013). Under these circumstances emissions of particular pollutants such as GHG, acidifying and precursor gases make the road transport sector an appropriate option for solving air quality management (AQM) and climate change issues. Numerous benefits can be derived from climate change mitigation policies and implementation of the co-benefits approach when reducing co-emitted emissions from the road transport sector (Geng *et al*., 2013).

Reductions need to occur through a more fortified and holistic response to emission controls, in order to achieve sustained maintenance of a long term air pollution and climate policy. Simulations have shown that if current regulations and issues pertaining to air quality and climate change are not properly dealt with in a co-operative manner, any future benefits from emission reductions will be partly offset through a continuously changing climate (Jacob and Winner, 2009; Takeshita, 2012).

1.2.2) Co-benefits of reducing GHG, acidifying and precursor gases

Continuous research into these and other emerging linkages should be a high priority to enhance scientific understanding and to satisfy economic and political objectives (Swart *et al*., 2004). Transport mitigation offers several co-benefits which include a reduction in accidents, improved urban air quality, increased productivity through reduction of time between trips and a reduction of GHG (National Climate Change Response Green Paper, 2010). This presents a key opportunity to apply the co-benefit approach in order to fulfill national responsibilities and update city management plans such as the air quality management plan (AQMP) (Dong *et al*., 2015; Smit *et al*., 2015). Research into co-benefits and trade-offs will enhance co-ordination across policy areas and cut costs, while the dissemination of these benefits, coupled with better anticipation of trade-offs could boost public support for climate action (Dong *et al.*, 2015; Smith *et al.*, 2015).The co-control of atmospheric emissions in conjunction with the benefits for climate change and air quality lies at the centre of this approach (Geng *et al.*, 2013). Benefits include air quality and human health improvements, improved energy supply, security, technological innovation, industrial and economic development and job creation (Jacob and Winner, 2009; Thambiran and Diab, 2011a; Takeshita, 2012). Local impacts are simpler to mitigate against, given that external stressors to climate change and acidification are derived from identifiable sources. Such activities are additive and showcases local commitment to a global reduction of GHG. Such a process can co-occur whilst the process of globally reducing CO_2 continues (Thambiran and Diab, 2011b).

Thus the complex nature of the issue at hand provides various challenges and opportunities with regards to managing the effects of poor air quality in urban areas in order to derive co-benefits under the context of climate change (Kelly and Caldwell, 2013; Cui *et al.*, 2014). By better understanding such synergies management can become more capable of achieving national and international emission reduction targets while simultaneously making it economically viable (Swart *et al.*, 2004).

1.2.3) The state of the knowledge base in South Africa

Historically, much of South Africa’s GHG, dust, SO_2 and N_r emissions have been attributed to industrial infrastructure located over the highly industrialised region of Mpumalanga (Held and Mphepya, 2000; DEAT, 2009; Miroslav, 2011). While several studies have monitored and simulated such emissions primarily on the Highveld and surrounding areas of South Africa in the past, gaps in the current knowledge are still prevalent when trying to determine the magnitude and potential impacts of GHG, acidifying and precursor gases from sources along coastal parts of the country, particularly from the road transport sector (Held and Mphepya, 2000; Mphepya, 2006; Scorgie and Kornelius, 2009; Miroslav, 2011). The emergence of the road transport sector as a considerable source of emissions exacerbates this situation particularly in the South African coastal zones (Liu *et al.*, 2011). Such studies are thus deemed to be vital given that it can definitively attribute emissions to the road transport sector.

Specific characteristics of the South African coastal zone are condusive to the development of infrastructure, industry, transport networks and housing. Such areas promote economic development and urban growth as is the case of eThekwini Municipality (Richard *et al.*, 2001; Curran *et al.*, 2002; Akegbejo-Samsons, 2009). Contemporary studies are limited by the lack of complete inventories when trying to determine and model deposition rates, and so this study therefore focused on the compilation of an emissions inventory by means of an emissions model for the road transport sector, using the eThekwini Municipality as a case study.

eThekwini Municipality is located on the east coast of South Africa and covers approximately 2297 km^2. The coastal city of Durban covers approximately 225.91 km^2 and is located within the eThekwini Municipality. eThekwini Municipality possesses 98 km of coastline, 18 major catchments, 16 estuaries and 4000 km of rivers (uMoya-NILU, 2015). Durban is considered to be the economic hub of KwaZulu-Natal (DEAT, 2007). eThekwini Municipality now houses key infrastructure such as the Port of Durban, various industries and an extensive transportation network which acts as sources of emissions, making it a suitable area to consider the energy use and environmental impacts of road transportation within urban areas.

Located within eThekwini Municipality lies industrial hotspots such as south Durban which has till present remained largely unquantified in terms of its acid production and effects from the road transport sector (Miroslav, 2011; eThekwini, 2013; eThekwini, 2014).South Durban is of particular importance given that it has grown to be the second largest industrial centre in South Africa (Matooane and Diab, 2001; eThekwini, 2009). The combined influence of climate change, a growing population, increased emission sources and concerns over air quality act as driving forces that increases the city’s vulnerability to a changing climate. Given the industrial context and lack of data which describes GHG, acidifying pollutants and precursor gases within eThekwini Municipality, it is imperative that estimates of emissions from the road transport sector be compiled by means of an emissions inventory. Such estimates may be used to identify pollutants which are emitted from this sector in large quantities and areas which are prone to elevated concentrations which are detrimental to environmental health. Such information may then be used to inform decision making and institute appropriate mitigation measures within the road transport sector to develop resilience to a changing climate within the eThekwini Municipality.

1.3) Aim and objectives

Given the context of this research space, the aim of this study is to quantify GHG, acidifying pollutants and precursor gas emissions from on and off road vehicles within the road transport sector of eThekwini Municipality for the year 2010 using the Computer Programme to Calculate Emissions from Road Transport IV (COPERT IV) model and to discuss the benefits for reducing these impacts from a climate change perspective.

The objectives are to:

- To compile a disaggregated road transport emission inventory of GHG and acidifying pollutants in tonnes/year in the priority area identified for the year 2010.
- To identify trends of high concentrations and exceedences of air pollutants using existing air quality monitoring data in the priority area identified.
- To model and simulate the impact of nationally appropriate road transport mitigation measures on the emissions in eThekwini Municipality.
- To make recommendations towards managing atmospheric emissions from the road transport sector within eThekwini Municipality based on the simulated impact of nationally appropriate road transport mitigation measures

1.4) Structure of thesis

Chapter 2 provides an overview of GHG, acidifying pollutants and precursor gas emissions and their potential impacts on the environment from a climate change. This is followed by Chapter 3 which discusses the meteorological controls on pollution dispersal, air quality management in South Africa thus far and literature that supports concepts for reducing GHG and air pollutants for the benefit of off-setting some of these impacts. Subsequent to this an analysis of mitigation potential and mitigation measures for South Africa and eThekwini Municipality is presented. This provides the theoretical context for the study as well as places this work within the broader context of climate change in South Africa. Chapter 4 describes how data were obtained and transformed for model input, in order to develop the road transportation emissions inventory for this study. The results and implications for air quality management in eThekwini Municipality are discussed in Chapter 5. Chapter 6 consists of the concluding remarks and key recommendations for implementing a more integrative approach to managing atmospheric emissions within the road transport sector of eThekwini Municipality.

CHAPTER 2: LITERATURE REVIEW

2.1) Introduction

Air pollution which consists of natural and anthropogenic emissions results from the combination of a higher rate of emissions and adverse weather conditions (Preston-Whyte, 1980). Natural emissions include biogenic volatile organic compounds, dust emissions and lightning emissions. Anthropogenic emissions include emissions related to fuel production, industrial and domestic combustion, transportation (road, rail, air and ships), waste disposal, industrial processes, solvent production and agriculture (Monks *et al*., 2009).

Atmospheric GHG, precursor gases and acidifying pollutants have been greatly exacerbated through industrial scale practices. Industrial point sources and road transport networks are the greatest consumers of fossil fuels especially in rapidly industrialising and developing countries. This has led to an increase in the concentrations and occurrence of gaseous and particulate pollutants in the atmosphere which contributes to air pollution events (Lu and Tian, 2007 and Huang *et al*., 2008). CO_2 and the emission of N_r and S through natural pathways have a regulating and positive effect on the environment, however various reviews and studies conducted in Europe, Eastern North America, and Southern China have shown that these compounds have been linked to air and water quality issues when present in high enough concentrations (Menz and Seip, 2004; Dentener *et al*., 2006; Monks *et al*., 2009; IPCC, 2013; Lajtha and Jones, 2013). Major sources of anthropogenic emissions have been attributed to the industrial sector, with a growing proportion of emissions attributed to the road transport sector.

The global transport sector was responsible for the production of 7.0 $GtCO_2eq$ of direct GHG emissions (inclusive of non-CO_2 gases) in 2010. This made the global transport sector responsible for approximately 23% of total energy related CO_2 emissions (IEA, 2012). Approximately 80% of these emissions had been emitted from road vehicles. It has been shown by the IPCC (2014) that growth in GHG emissions has been ongoing since the Fourth Assessment Report (AR4) despite the use of more efficient road vehicles. The demand for road transportation in developing economies such as South Africa is thus predicted to accelerate in the forth coming decades (DEAT, 2013). The ramifications of such growth for GHG, precursor gases and acidifying pollutant has prompted research to reveal evidence about the transformation pathways, effects, and benefits of reducing acidic deposition within ecosystems (Menz and Seip, 2004). This has great ecological significance given that such compounds are precursors to various secondary pollutants and conditions which form the foundation for contemporary air and water quality issues (Fang *et al.*, 2013; Huang *et al.*, 2013).

In light of this, a review of literature relevant to GHG, precursor gases and acidifying pollutants and their associated sources and sinks is provided in this chapter. This is further supplemented by relevant literature explaining the migration pathways which transport and influence emission concentrations prior to being received by the receptor. The potential critical loads, emerging impacts under climate change and effects of deposition within coastal ecosystems are then discussed. Finally potential management actions, mitigation measures, research and regulatory strategies to curb atmospheric GHG and acidifying pollutant in light of climate change is presented.

2.2) Characteristics and chemical reactivity of GHG, precursor gases and acidifying pollutants

Qualitatively it is known that industrial nodes and transport networks are a source of GHG, precursor gases and acidifying pollutants (Seinfeld and Pandis, 2006). Due to the roles such sources play in the urban landscape, research has become focused on gaining a quantitative understanding of these sources and the assimilation capacity of the respective sinks (Lajtha and Jones, 2013).

CO_2 and nitrogen oxide (N_2O) are well affirmed climate forcers whilst sulphur dioxide (SO_2), nitrogen oxides (NO_x) ammonia (NH_3) and PM are seen as the major acidifying pollutants and precursor gases (Dentener *et al*., 2006; Camargo and Alonso, 2006; Lu and Tian, 2007). Once emitted into the atmosphere, these primary gaseous pollutants have the potential to undergo complex chemical reactions which result in the formation of strong acids (Camargo and Alonso, 2006). The volume and extent of such emissions when deposited are usually dependent on the type and quantity of fuel used, chemical processes and the abatement technologies in place to control emissions; this makes the source type a critical consideration when quantifying acidifying pollutants (Lajtha and Jones, 2013).

2.2.1) GHG emissions

2.2.1.1) Carbon dioxide (CO_2)

CO_2 is emitted through the burning of fossil fuels from industry and the road transport sector, solid waste, wood products and chemical reactions. While CO_2 emissions come from a variety of natural sources, anthropogenic emissions are responsible for the increase that has occurred in the atmosphere since the industrial revolution with emission production expected to worsen in future (IPCC, 2007; IPCC, 2013; Ntziachristos and Samaras, 2014). CO_2 is sequestered from the atmosphere when it is absorbed by vegetation or the ocean as part of the biological carbon cycle. Anthropogenic activities are altering the carbon cycle both by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks, such as forests, to remove CO_2 from the atmosphere. It is known that the world's oceans currently sequests approximately 25% of CO_2 emissions each per year (NCA, 2014; Tompkins and Deconcini, 2015).

In addition to its influence on climate change, CO_2 also has severe implications for coastal ocean chemistry. (Krishnamurthy *et al.*, 2009, IPCC, 2013). The current shift in chemistry is termed ocean acidification and is primarily attributed to the uptake of anthropogenic CO_2. The rate of change in ocean acidity is now 50 times faster than any known historical change with the acidity of ocean surface waters having increased by 30% over the past 250 years as a result of absorbing 560 billion tonnes of CO_2 (Doney, 2010; NCA, 2014)

Carbon species, weak acids and bases that exchange hydrogen ions within the ocean help to maintain the pH of the ocean (NRC, 2010). Dissolved inorganic carbon within the ocean maintains pH through the following balanced chemical equilibrium. CO_2 reacts with ocean water to form carbonic acid (H_2CO_3) in equation 1. This contributes to the acidification of ocean water by shifting the equilibrium in equation 2 in favour of bicarbonate ions (HCO_3^-) and thus reduces carbonate ion (CO_3^{2-}) concentration (Doney, 2010; Beman *et al.*, 2011).

$$CO_{2(aq)} + H_2O = H_2CO_3 \qquad [1]$$

Most of the H_2CO_3 then dissociates into hydrogen ion (H^+) and HCO_3^- in equation 2. HCO_3^- from equation 2 further dissociates providing H^+ and CO_3^{2-} in equation 3 (Doney, 2010; Doney *et al.*, 2007).

$$H_2CO_3 = H^+ + HCO_3^- \qquad [2]$$

$$HCO_3^- = H^+ + CO_3^{2-} \qquad [3]$$

H^+ in equation 4 is then able to react with HCO_3^{2-} present within the ocean to again form H^+ and CO_3^{2-}. Thus it can be said that ocean acidification is directly proportional to CO_2, HCO_3^- and H^+ and inversely proportional to CO_3^{2-} and pH (pH= 2log [H^+]) (Borges and Gypens, 2010).

$$H^+ + HCO_3^- = 2H^+ + CO_3^{2-} \qquad [4]$$

Research has indicated that CO_2 concentrations are increasing by 0.5% per year from 380 ppmv, with little doubt that such increases are responsible for ocean acidification during this time (Doney *et al.*, 2007; Turley and Findlay, 2009, IPCC, 2013). Under the IPCC IS92a business-as-usual emission scenario, there is now a higher confidence that CO_2 uptake has reduced average surface ocean pH by 0.1 pH units from approximately 8.21 to 8.10 below preindustrial levels and may further reduce pH by up to 0.5 units by 2100 (Caldeira and Wickett, 2005; Orr *et al.* 2005; Doney *et al.*, 2009; IPCC, 2013). Even under the optimistic SRES scenario b1, mean ocean pH will be below 7.9 pH units. At such rates atmospheric CO_2 concentration will certainly be expected to be twice that of pre-industrial concentrations exceeding 500 ppmv accompanied by climate change and global temperature increases of 2°C by 2050 to 2100 (Hall Spencer *et al.*, 2008; Hoegh-Guldberg *et al.*, 2009; Beman *et al.*, 2011).

Complicating this matter is the simultaneous occurrence of anthropogenic climate change and ocean acidification in the near future. Even though the absorption of CO_2 by the oceanic sink reduces atmospheric GHG, ocean warming will dampen CO_2's ability to dissolve in ocean water by reducing the ocean's capacity to absorb CO_2 from the atmosphere. For instance given the scenario of a 2°C temperature increase under 2x pre-industrial CO_2 concentrations, ocean water absorbs about 10% less CO_2 than it would under current conditions, with pH remaining unchanged. Therefore a warmer ocean has less capacity to extract CO_2 from the atmosphere, yet still undergoes the same rate of ocean acidification. This is because HCO_3^- is converted to CO_3^- in a warmer ocean, releasing H^+ ions which stabilises the pH. This sets up a positive feedback mechanism which exacerbates both issues (IPCC, 2013). Thus CO_2 is such a concern under a changing climate given its dual role and opportunities to remedy such concerns.

2.2.1.2) Nitrous oxide (N_2O)

N_2O is relatively unreactive and predominantly emitted by biological, agricultural and industrial nitric acid production, as well as during combustion of fossil fuels. Natural emissions of N_2O are mainly produced through microbial processes in soils and the oceans in a process known as nitrification which can be accelerated by several agricultural practices and activities (Aneja *et al.*, 2009; Fang *et al.*, 2011). N_2O acts as the main precursor of nitric oxide (NO) and nitrogen dioxide (NO_2). N_2O is removed from the atmosphere when it is assimilated by certain types of bacteria or destroyed by ultraviolet radiation or chemical reaction. N_2O exerts considerable forcing on the atmosphere because of its long residence time of 114 years and global warming potential GWP of 265 (IPCC, 2007; and IPCC, 2013). The IPCC (2013) has reported that the concentration of N_2O has risen from 270 ppb in 1750 to 324.2 ppb in 2011 with an increase of 5 ppb since 2005.

2.2.2 Non-CO_2 GHG emissions, precursor gases and acidifying pollutants

The road transport sector is also responsible for the emission of non-CO_2 pollutants which act as climate forcers. Some of these emissions which are covered in this review include oxides of nitrogen (NO_x), nitrogen dioxide (NO_2), ammonia (NH_3), sulphur dioxide (SO_2) and particulate matter (PM) (IPCC, 2014).

2.2.2.1) Oxides of nitrogen (NO_x)

NO_x refers to the sum of NO and NO_2. NO_x are among the most important components of the atmosphere, producing an array of oxidised products. NO_x are created from lightning, microbial activity, biomass burning, fuel combustion, and from the destruction of N_2O stated above. The dominant producer of NO_x is the road traffic sector and industrial sources which is attributed to the oxidation of non-combustible species present in the combustion chamber combustion of fuels (Menz and Seip, 2004; Sharma *et al.*, 2010; Buthelezi and Davies, 2015). NO_x are indirect GHG and influence climate through the formation of ozone (O_3) in the troposphere where it has positive radiative forcing effects (Thambiran and Diab, 2010).

NO_x are particularly important vehicular emission given its role in O_3 formation and effect on acidification (uMoya-NILU, 2015). NO_x emissions are related to the air to fuel ratio and combustion temperatures (Gkatzoflias *et al.*, 2012). Emissions of NO_x in diesel vehicles are generally lower than those for petrol vehicles (Thambiran and Diab, 2011). Reactions from NO_x to any of the oxidised products take a mere 4 to 20 hours to occur. The mean tropospheric residence time has been given at 12-24 hours for both gas phase NO_x and its products, while particulate nitrate has a range of 3-9 days. Because of these short atmospheric life times, the spatial distribution of the effects of NO_x is expected to be local or regional (IPCC, 2013).

2.2.2.2) Nitrogen dioxide (NO_2)

NO_2 is a recognised as a criteria pollutant and major precursor of acidic deposition. It also contributes to the formation of tropospheric ozone (or smog) by photochemical reactions with non-methane hydrocarbons which has implications for health (Liu *et al.*, 2011; Buthelezi and Davies, 2015). The ultimate receptor and site of deposition is the human lung and the severity of inhalation depends on the concentration of NO_2.The nitrite ion (NO_2^-) and unionized nitrous acid (HNO_2) are interrelated through the chemical equilibrium $NO_2^- + H^+ \leftrightarrow HNO_2$. The relative concentrations of NO_2^- and HNO_2 depend on the pH of the water. NO_2^- concentration is directly proportional to pH while the concentration of HNO_2 is inversely proportional. Both NO_2^- and HNO_2 may contribute to the total toxicity of nitrite in water. Furthermore HNO_2 can inhibit the nitrification process which results in increased accumulation of NO_2^- (and HNO_2) in the aquatic environment, enhancing toxicity. Given that NO_2^- concentration is often greater in aquatic ecosystems than the HNO_2 concentration, NO_2^- is considered a major agent responsible for nitrite toxicity to aquatic organisms (Camargo and Alonso, 2006).

2.2.2.3) Nitric acid (HNO_3)

NO_x is relatively insoluble in water hence it is often vented into the troposphere where they ultimately form HNO_3. HNO_3 is the most important oxidation product of NO_x and is extremely water soluble, rapidly depositing to surfaces as water droplets. HNO_3 may further form corrosive ammonium nitrate aerosols (NH_4NO_3) upon reacting with NH_3. HNO_3 is removed by dry and wet deposition in about 1 week. However HNO_3 can be transformed back into NO_x via photolysis (Seinfeld and Pandis, 2006).

2.2.2.3.1.) Reactivity in the atmosphere

The troposphere is an oxidative medium which tends to shift species towards an oxidised state. This corresponds with NO which is oxidised to NO_2 and lastly HNO_3 (Bhatia, 2002; Seinfeld and Pandis, 2006). Nitrogen’s complex pathways and involvement of various species in the transformation, transportation and deposition phases greatly affects one’s ability to quantify N_r deposition patterns (Migliavacca *et al.*, 2005; Lu and Tian, 2007; Monks *et al.*, 2009). Given its importance the multiple formation pathways taken by N_r in the atmosphere are illustrated once emitted.

Tropospheric NO_x is commonly emitted as NO. NO photo chemically reacts with and reduces O_3 during the daytime to produce NO_2 within a few minutes as illustrated in equation 5 (Seinfeld and Pandis, 2006).

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad [5]$$

During the day the photolytic production of hydroxyl (OH) radical results in the oxidation of NO_2 to HNO_3 via the OH radical in equation 6. This pathway is abundant in summer when the concentrations of photo chemically produced OH radicals are at its peak (Seinfeld and Pandis, 2006; Fang 2011).

$$NO_2 + OH \rightarrow HNO_3 \qquad [6]$$

At night NO_2 is oxidised by O_3 to produce NO_3 radical in equation 7 (Seinfeld and Pandis, 2006; Fang 2011).

$$NO_2 + O_3 \rightarrow NO_3 + O_2 \qquad [7]$$

In equation 8 NO_3 rapidly reacts with NO_2 to form dinitrogen-pentoxide (N_2O_5) with a noon lifetime of 5 seconds. This pathway is abundant in winter as N_2O_5 is thermally unstable (Seinfeld and Pandis, 2006; Fang 2011).

$$NO_3 + NO_2 \rightarrow N_2O_5 \qquad [8]$$

The hydrolysis of N_2O_5 yields $HNO_{3(g)}$ as illustrated by equation 9 (Abiodun *et al.*, 2011).

$$N_2O_5 + H_2O_{(surface)} \rightarrow 2HNO_3 \qquad [9]$$

It has been found that equation 9 occurs rapidly upon contact with background H_2SO_4 aerosols present. The effect of such reaction is the removal of N_2O_5 into a relatively stable species which further removes NO_2 from the NO_x system which reduces the rate of O_3 destruction (Seinfeld and Pandis, 2006). When gas phase HNO_3 dissolves in precipitation, it forms aqueous $HNO_{3(aq)}$ which dissociates by means of equation 10 (Abiodun *et al.*, 2011). The oxidation reactions depend upon temperature, humidity, solar radiation, and the availability of reactive aerosol surfaces (Seinfeld and Pandis, 2006).

$$HNO_{3(g)} = HNO_{3(aq)} = H^+ + NO_3^- \qquad [10]$$

2.2.2.4) Ammonia (NH_3)

NH_3 is the third most abundant N-containing gas in the atmosphere and is alkaline in nature (Seinfeld and Pandis, 2006). The majority of NH_3 emissions are produced from chemical fertilisers, livestock farming, sewage treatment, biomass burning and biological processes in soils, while the minority is produced by the road transport and industrial sector. Emission of NH_3 from petrol vehicles equipped with three-way catalysts is a particularly relevant source in urban areas (Asman 1998; Kean *et al.*, 2000; Sharma *et al.*, 2010; Ntziachristos and Samaras, 2014). The increasing role that the road transport sector plays in NH_3 production in recent years has been attributed to the three-way catalytic chemistry of petrol vehicles which unintentionally increased production of NH_3 (Kean *et al.*, 2000; Liu *et al.*, 2014). Therefore the road traffic sector is considered a significant source of NH_3 in the urban environment.

As the primary alkaline gas in the atmospheric, NH_3 is capable of neutralising nitric acid (HNO_3), sulphuric acid (H_2SO_4) and hydrochloric acid (HCl) to form inorganic aerosols like ammonium nitrate (NH_4NO_3) and ammonium sulphate $(NH_4)_2SO_4$, and ammonium chloride (NH_4Cl) that are subsequently deposited (Aneja *et al.*, 2001, Sharma *et al.*, 2010; Liu *et al.*, 2011). Ammonium (NH_4^+) ions are a pivotal component with regards to the formation of tropospheric aerosols (Seinfeld, Pandis 2006). These compounds contribute significantly to $PM_{2.5}$ which affects global radiative forcing (Liu *et al.*, 2014). NH_3 has a high affinity to water and its residence time in the lower atmosphere is approximately 10 days. In addition, it is an important component of the N cycle, with an excess causing eutrophication of ecosystems and acidic deposition since ammonium nitrification produces H^+ ions (Erisman *et al.*, 2001; Camargo and Alonso, 2006).

2.2.2.4.1) Reactivity in the atmosphere

Hydrogen can react with NO in the presence of carbon monoxide (CO) in the atmosphere to generate NH_3 as a secondary pollutant as illustrated in equation 11 (Gandhi and Shelef, 1991).

$$2NO + CO + 4H_2 \rightarrow 2NH_3 + CO_2 + H_2O \qquad [11]$$

Apart from this, NH_3 can also act as a precursor to NO and N_2O in equations 12 and 13 below. Atmospheric NH_3 can be oxidised to NO and N_2O in two separate reactions (Gandhi and Shelef, 1991).

$$2NH_3 + 2\frac{1}{2}O_2 \rightarrow 3NO + 2H_2O \qquad [12]$$

$$6NH_3 + 8NO_2 \rightarrow 7N_2O + 9H_2O \qquad [13]$$

2.2.2.2.2) Reactivity in water

Aqueous atmospheric particles play an important role in atmospheric chemistry prior to removal as illustrated by equation 14 (Camargo and Alonso, 2006).

$$NH_3 + H_2O = NH_4^+ + OH^- \qquad [14]$$

Once deposited NH_4^+ can be oxidised in water to nitrate in two steps ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) via aerobic chemoautotrophic bacteria. In anaerobic waters anaerobic bacteria can utilize nitrite and nitrate as terminal acceptors of electrons which produce N_2O and N_2 (Camargo and Alonso, 2006). The relative concentrations of NH_4^+ and NH_3 depend on the pH and temperature of water. NH_3 concentration is directly proportional to pH and temperatures while the concentration of NH_4^+ is inversely proportional. NH_3 is extremely toxic to aquatic organisms. Moreover, NH_3 can inhibit the nitrification process which results in increased accumulation of NH_4^+ (and NH_3) in the aquatic environment, enhancing toxicity (Camargo and Alonso, 2006).

2.2.2.5) Sulphur dioxide (SO_2)

SO_2 and its derivatives are well recognised air pollutants and climate forcing agents, primarily associated with the combustion of sulphur containing fossil fuel and industrial refining processes. Other sources include volcanic emissions, ships and diesel vehicles (Zunckel *et al.*, 2000; Lajtha and Jones, 2013). SO_2 is a criteria pollutant which has been identified as a precursor of H_2SO_4 and sulphate aerosols which has negative implications on health (Bhatia, 2002; Fang *et al.*, 2013). The overall effect of SO_2 derived aerosols on radiative forcing is believed to be negative thus having a cooling effect on climate (IPCC, 2013). Other than its effect on radiative forcing SO_2 is integral in the formation of urban smog and acid rain.

Chemical reactivity of atmospheric S is inversely proportional to the oxidation state, thus S compounds with the oxidation state -2 or -1 are rapidly transformed by hydroxyl radicals relative to other species. This results in a residence time of a few days. Therefore H_2S and SO_2 can have rapid implications for ecosystem health, since both are efficiently removed by dry deposition at a rate of 1cm s^{-1}, with an atmospheric lifetime of about 70 hours and 1 day respectively (Seinfeld and Pandis, 2006; Fowler *et al.*, 2005). With respect to the aqueous state, solubility of S compounds is directly proportional to the oxidation state. As such S compounds with oxidation state +6 (H_2SO_4) tend to occur both as a liquid and gas (hence H_2SO_4 affinity to form liquid acid). The following are the average S atom's residence time (Seinfeld and Pandis, 2006): T^d_S =120 hours, T^w_S = 90 hours, T_S = 50 hours, where T equals the average residence time, d = dry deposited and w = wet deposited.

2.2.2.5.1) Reactivity in the atmosphere

The oxidative nature of the atmosphere allows S containing species to move through a chain of oxidation states, starting from reduced H_2S which is eventually oxidised to SO_2 and lastly H_2SO_4 (Seinfeld and Pandis, 2006). Possible reaction sites for SO_2 in the atmosphere include the surface of airborne solid particles, moisture droplets and ammonia present in the atmosphere where it is oxidised to form H_2SO_4, which contributes to the acidification (IPCC, 2007, IPCC, 2013). Given its importance the formation pathways taken by S in the atmosphere is illustrated.

In equation 15 S emissions react with atmospheric oxygen to produce SO_2 which further reacts with atmospheric H_2O to produce sulphurous acid (H_2SO_3) which is present in acid rain (Seinfeld and Pandis, 2006).

$$SO_2 + H_2O(l) = H_2SO_{3(aq)} \qquad [15]$$

SO_2 is then oxidised to form sulphur trioxide (SO_3) in equation 16 (Seinfeld and Pandis, 2006).

$$2SO_2 + O_2 = 2SO_{3(g)} \qquad [16]$$

SO_3 reacts with H_2O to produce sulphuric acid (H_2SO_4) in equation 17 (Seinfeld and Pandis, 2006).

$$SO_3 + H_2O(l) = H_2SO_{4(aq)} \qquad [17]$$

H_2SO_4 has a very high affinity to water even at low relative humidity (Seinfeld and Pandis, 2006). When gas phase H_2SO_4 dissolves in precipitation, it forms aqueous H_2SO_4 or acid rain (Liu *et al.*, 2011). H_2SO_4 further dissociates by means of equation 18.

$$H_2SO_{4(aq)} = 2H^+ + SO_4^{2-} \qquad [18]$$

2.2.2.6) Particulate Matter (PM)

PM is a collective term pertaining to a multitude of atmospheric particles which are broadly composed of soil, smoke, pollen, smoke, moisture droplets and aerosols emitted from a variety of natural and anthropogenic sources (Ntziachristos and Samaras, 2014). Anthropogenic sources of PM include diesel vehicles, factory and utility smokestacks, construction sites, tilled fields, unpaved roads, stone crushing, and burning of wood. Natural sources of PM include sea spray, wind blown dust and volcanic emissions (IPCC, 2013). PM typically has a lifetime of one day to two weeks in the troposphere and approximately a year in the stratosphere but can have significant direct and indirect radiative forcing effects and large regional impacts (Boucher *et al.*, 2013; IPCC, 2013).

PM_{10} and $PM_{2.5}$ specifically refer to atmospheric particulate matter that possess a diameter of <10 µm and 2.5 µm respectively (Amato *et al*., 2014). $PM_{2.5}$ is mainly related to combustion processes (motor vehicles, smelting, incinerators), rather than mechanical processes as is the case with PM_{10}. $PM_{2.5}$ formation results from three processes in the atmosphere namely change of phase from the gas to solid phase, gas molecule aggregation to form a new particle or from reactions of gases to form vapours that nucleate to form particles (uMoya-NILU, 2015). PM is also a criteria pollutant which is detrimental to human health and is a function of particulate chemical composition (source dependent) and particle size.

Black carbon and sulphate aerosols have the ability to influence climate through interactions with radiation and clouds. Black carbon has the ability to absorb solar radiation. Black carbon is primarily produced from the combustion of fossil fuels and biomass and is considered a component of $PM_{10.}$ Sulphate aerosols make up the $PM_{2.5}$ component and are formed as a result of the oxidation of SO_2. Sulphate aerosols contribute to global cooling by reflecting sunlight back into space (Thambiran and Diab, 2010). Sulphate aerosols also indirectly affects climate by inducing changes in clouds. Currently research indicates that anthropogenic aerosols have exerted a cooling influence on the Earth via scattering, offsetting global warming and thus cooling the planet. This effect is projected to be minimised in future in response to air quality policies would eventually unmask this warming (IPCC, 2013).

With regards to vehicular traffic as a primary source, diesel vehicles act as a significant source of PM of varying diameters (Thambiran and Diab, 2011). Emissions may be divided into exhaust and non-exhaust emissions. Exhaust PM originates from the incomplete combustion of fuel and its additives. Non-exhaust contributions can further be distinguished into road dust, brake, tyres and road wear (Amato *et al.*, 2014). Non-exhaust sources are particularly relevant given the high concentrations of additives such as heavy metals, sulphides and carbonaceous aerosols derived from wearing of brake, tyres and lubricants. Overall the extent to which particulates are considered harmful depends on their chemical composition and size, e.g. particulates emitted from diesel vehicle exhausts mainly contain unburned fuel oil and hydrocarbons that are known to be carcinogenic (Amato *et al.*, 2009).

2.3) Air pollution and meteorological drivers

The effect of emissions on air quality is strongly dependent on weather, which is in turn dependent upon climate. This can deteriorate or enhance air quality (Jacob and winner, 2009). Once pollutants are emitted, prevailing weather conditions will determine how efficiently it disperses. On warmer days the air masses near the surface of the earth can be much warmer than the air masses above. This results in turbulence which mixes pollutants into the surrounding air. Sometimes large volumes of this warm air will rise to great heights resulting in atmospheric instability, rapid mixing and dispersal of pollutants. Conversely when the condition of the atmosphere is very stable there is very little mixing. This occurs when air masses near the surface of the earth are cooler than the air above (a temperature inversion). This cooler air is denser and will not rise up, trapping any pollutants released near the surface. These are known as temperature inversions which are common in winter, often forming during calm clear nights with light winds under stable atmospheres (Preston-Whyte, 1970).

Wind speed also contributes to the speed at which pollutants are dispersed from their source. However, strong winds don't always disperse the pollutants but instead can transport pollutants to a larger more densely populated area (Tyson and Preston-Whyte, 2000). On the other hand lower wind speeds can allow pollutants to accumulate around the source of the release. Changes in climate affect these meteorological processes by perturbing ventilation rates (wind speed, mixing depth, convection, frontal systems), precipitation scavenging, dry deposition, chemical production and loss rates, natural emissions, and background concentrations (Jacob and winner, 2009).

Most often than not meteorological factors have a significant effect on the concentration of air pollution that accumulates over a location. Weather fluctuates naturally with these changes altering measured pollution concentrations. As such meteorological data is needed to study the source of pollution release, it’s transportation pathways and vertical mixing over any given location.

2.4) Deposition and generalised effects of GHG, precursor gases and acidifying pollutants

GHG, precursor gases and acidifying pollutants are ultimately removed by dry or wet depositional processes at the end of respective residence times after being transformed and transported by air circulations (Figure 1). It is then sequestered, assimilated, transformed, stored or destroyed. Concerns are raised when pollutants are not assimilated or effectively dispersed by the atmosphere and biotic and abiotic receptors experience negative changes once a particular boundary or threshold is passed. Depending on the concentration of these emissions and length of exposure time, biotic and abiotic receptors may be affected in numerous ways.

It known that in the past 200 years the inorganic carbon system of the ocean has been the primary sink, buffering the effects of all anthropogenic CO_2 produced (Sabine *et al.*, 2004; Beman *et al.*, 2011). It is estimated that approximately 35% of N_r and S in the atmosphere are deposited on earth (Menz and Seip, 2004; Doney *et al.*, 2007). About 40-80% of S in the atmosphere may be converted and wet deposited as H_2SO_4, while the remaining S is dry-deposited as SO_2. Depending on the particular chemical form, N_r in the atmosphere may either cause basic or acidic conditions, with wet deposition of NO_3 being acidic, while the dry deposition of NH_3 is alkaline. The fate of atmospheric NH_4 and NH_3 input to ocean alkalinity shall be dependent on the rate to which NH_4 is converted to NO_3 by nitrification, since nitrification reduces alkalinity by two equivalents for every one mole of NH_4 (IPCC, 2013). Figure 5 below depicts some of the variables that influence the process of atmospheric transportation and deposition, from the source to the receptor.

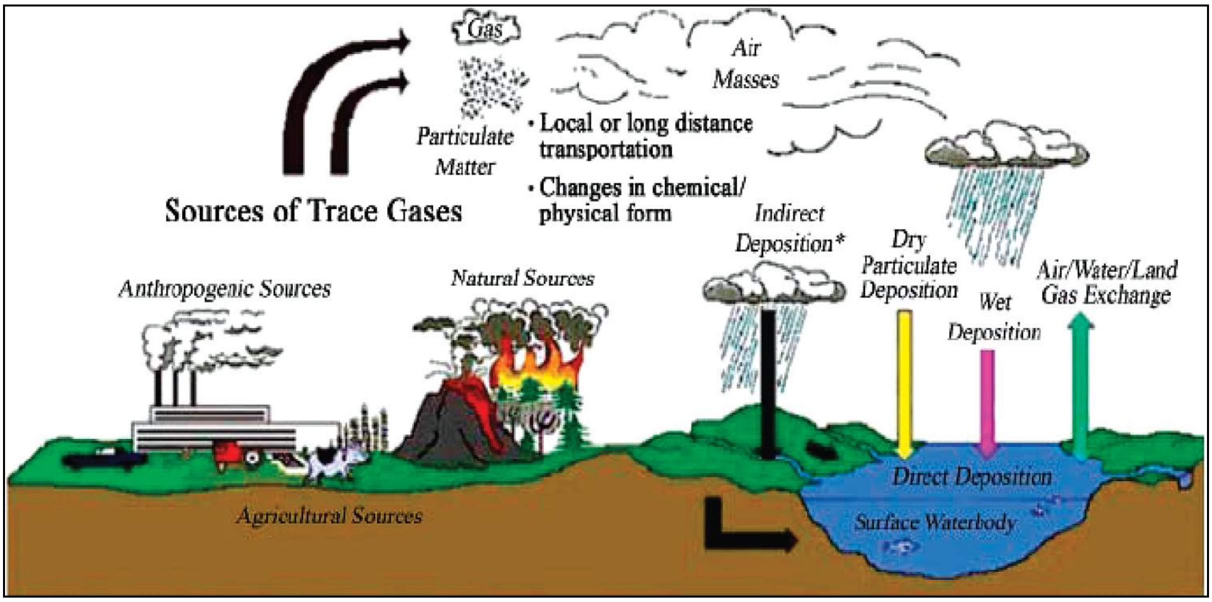

Figure 1: Transportation, transformation, and deposition of gaseous emissions (Aneja et al., 2009)

According to Rockström *et al*., (2009) anthropogenic activity should not occur unrestrained at a global scale. Instead it should occur and operate within a safe space known as a global boundary. This ensures the prevention of any major self inflicted harm upon the human race (Rockström and Karlberg, 2010). Prior to initiation of intense anthropogenic activities, Earth's systems were regulated naturally and stayed within a relatively narrow range but this is no longer the case (Rockström *et al*., 2009). It has been determined that at present, some of these planetary boundaries have already been surpassed.

In most cases boundaries are defined by a critical value for one or more control variables, such as CO_2 or NO_x concentration (Rockström *et al*., 2009). Once deposited anthropogenic emissions become a concern once the concentration exceeds the environmental threshold. Such a concentration is termed the critical load of a pollutant (Monks *et al*., 2009). A critical load is a quantitative estimation of an exposure to one or several pollutants, below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge (Nilsson and Grennfelt, 1988; Hettelingh *et al*., 2013).

For the nitrogen cycle the control variable is the rate at which N_2 is removed from the atmosphere and converted to N_r. For climate change it is the atmospheric concentration of CO_2 and for ocean acidification it is the mean saturation state of aragonite. Analysis has suggested that the climate change and nitrogen thresholds have already been crossed, with the threshold for ocean acidification likely to be crossed in the near future. This most often results in abrupt environmental change thus hindering human development. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable (Figure 2). This situation is made worse by the fact that if one boundary is transgressed, then the probability of crossing the other boundaries increases due to the close linkages present between the systems (Schlesinger, 2009). Current rates for global activities cannot continue without significantly eroding the resilience of major components of the Earth's system. In order to mitigate against further transgressions it is suggested the thresholds be constrained to the values in Table 1 (Rockström *et al.*, 2009). At a regional to local scale specific values exist to describe the threshold of environmental mediums such as air and water (Table 2) (Huang *et al.*, 2013; Cui *et al.*, 2014). If deposition within the environment reaches the critical load, then the area represented is said to be at risk of degradation.

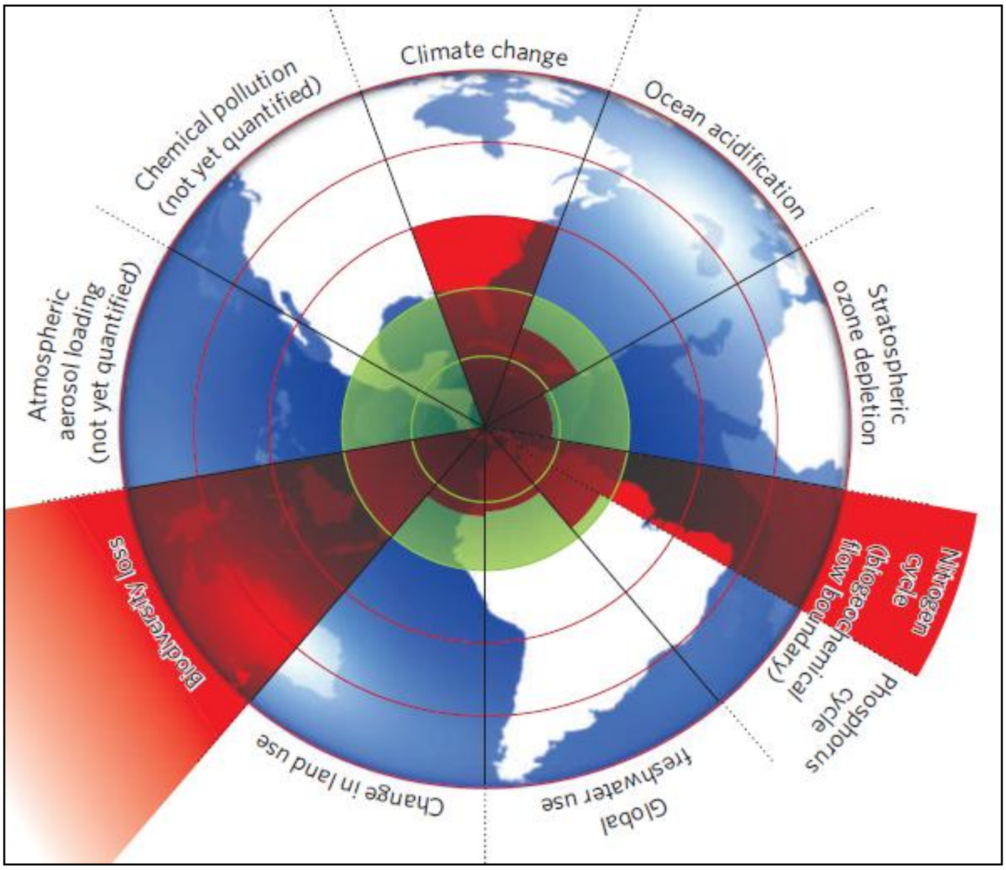

Figure 2: The exceeded boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle) (Rockström et al., 2009)

Table 1: Planetary boundary threshold values (Rockström *et al*., 2009).

Earth system process	**Parameter**	**Proposed boundary**	**Current status**	**Pre-industrial value**
Climate change	Atmospheric CO_2 concentration	350	387	280
Nitrogen	Atmospheric assimilation of N_2	35	121	0
Ocean acidification	mean saturation state of aragonite	2.75	2.90	3.44

Table 2: Threshold values to prevent degradation.

Criteria/ Compound	**Threshold value**	**Impact on ecosystem**	**Reference**
Total N	1000 mg $Nm^{-2}a^{-}$	Terrestrial vegetation degradation via deposition	Dentener *et al* ., 2006; Im *et al*., 2013.
pH	0.2units	Coral degradation	Doney *et al*., 2009; Turley and Findlay, 2009; Borges and Gypens, 2010; Doney, 2010.
Aqueous CO_2	550ppmv	Coral degradation	
Hypoxia (O_2)	~60mmol/kg	Various aquatic organisms	Doney, 2010
Eutrophication	440 µg TN/L	Coastal marine ecosystems	Swedish Environmental Protection Agency (SEPA), 2000
Eutrophication	0.2mg/L	Oligotrophic waters and most natural or semi-natural ecosystems	Cui *et al*., 2014
Ambient SO_2	20 µg/m^3 or 10.63 ppb per annum	Vegetation degradation via ambient SO_2	European Topic Centre on Air pollution and Climate change Mitigation (ETCACM), 2011
Ambient NO_2	30 µg/m^3 or 11.45 ppb per annum	Vegetation degradation via ambient NO_2	ETCACM, 2011

2.4.1) Adverse effects of acid deposition

The anthropogenic acidification of an ecosystem often has the ability to induce several adverse effects on primary and secondary producers. Given the short atmospheric lifetimes (days to about a week) of some GHG, acidifying and precursor gases, deposition occurs primarily along the coast downwind of the primary emission source. Fluvial action then transports these nutrients across land and discharges it into the ocean. This increases the probability of acidifying and precursor gases causing a change in coastal ecosystems by 10-50% relative to anthropogenic CO_2 (Doney *et al.*, 2007; Doney *et al.*, 2009).

2.4.2) Effects of acidic deposition on vegetation

Air pollution and climate change can interact chemically and physically to impact upon ecosystems through changes in exposure and sensitivity which causes adverse effects on plant biodiversity (Posch, 2002; Swart *et al.*, 2004). Increased inputs of N in soil, allows nitrophilic plant species such as exotics, sedges and grasses to increase productivity. In the long term the increased plant productivity makes it possible for characteristic/indigenous species to be competitively excluded by the relatively fast growing nitrophilic plant species (Menz and Seip, 2004; Bobbink *et al.*, 2010). In general terms, expected impacts will depend on individual plant species physiological make up, resilience and biomass allocation pattern. While this may be the case it can be deduced that acid-resistant plant species will be the most abundant and dominate species that are characteristic of intermediate pH conditions (Bobbink *et al.*, 2010). The European Topic centre on Air Pollution and Climate Change Mitigation (ETCACM) defines critical levels for NO_2 and SO_2 for the protection of vegetation. This critical level for NO_2 is 30 $\mu g/m^3$ or 11.45 ppb per annum and 20 $\mu g/m^3$ or 10.63 ppb per annum for SO_2 and presented in Table 2.

2.4.3) Effects of acidic deposition on soils

Anthropogenically induced acidification of precipitation typically has a pH value of 3.5–5.0 (Menz and Seip, 2004). The effect that acids will have on a particular type of soil depends largely on the fate of sulphate and nitrate anions. If these anions are leached out of soil then it will be accompanied by cations (Bobbink *et al.*, 2010). This translates into a substantial amount of an acidic soils leachate been composed of aluminium (Al^+) ions and H^+ ions. A soil which is basic in nature will produce leachate composed of more calcium (Ca^{2+}) and magnesium (Mg^{2+}) which is base cations. This will promote an increase in the concentration of trace metals in soil water through both leaching processes (Camargo and Alonso, 2006).

2.4.4) Effects of acidic deposition on water bodies

Eutrophication is a process which occurs through excessive wastewater effluents, atmospheric deposition, agricultural and urban runoff (Water Research Commission, South Africa, 2008). Anthropogenic eutrophication can initiate the development of primary producers which can cause aquatic ecosystems to undergo ecological and toxicological changes (Camargo and Alonso, 2006; Glasow *et al*., 2013). In addition to P and N, increased concentrations of harmful substances like Al, Pb, Hg, NH_4^+, NO_2^- and NO_3^- may be leached from the soil and enter into neighbouring water resources, thus contributing to acidification along the coast (Monks *et al*., 2009).

Although evidence has shown that CO_2 is primarily responsible for ocean acidification, it has also revealed the need to also consider the effects of atmospheric N_r and S deposition particularly in the coastal waters (Dentener *et al*., 2006; Bates and Peters, 2007; Fabry *et al*., 2008). The acidification effects from S and N_r have been shown to have a localised effect within the coastal zones relative to anthropogenic CO_2 and are thus worth quantifying for climate adaption purposes within coastal cities at a local scale (Fabry *et al*., 2008; Kelly and Caldwell, 2013).

Enhanced microbial decomposition ensures hypoxic conditions also favour the formation of reduced compounds, such as hydrogen sulphide H_2S which devastates aquatic species. The toxicity of H_2S means that even at low concentrations it can act on the nervous system to cause acute mortalities in aquatic species (Table 3) (Camargo and Alonso, 2006;Bhargava and Bhargava, 2013). A study by Wallace *et al*., (2014) sought to quantify linkages between acidification, hypoxia, and eutrophication, with the assumption that acidification of coastal systems is a function of the intensity of nutrient loading rates. Impacts on ocean biogeochemistry either through direct fluxes of material into the ocean (coloured arrows) or indirectly via climate change and altered ocean circulation (black arrows). The grey arrows denote the interconnections among ocean biogeochemical dynamics in Figure 3 (Doney, 2010). An overlooked affect of this process is localised acidification by CO_2 produced through microbial action. Results showed the spatial and temporal correspondence between reduced concentrations of dissolved oxygen and pH and the occurrence of extremes of these variables in areas with the highest intensity of nutrient loading. Such observations provided evidence and indicated that eutrophication and acidification were primarily driven by microbial respiration in coastal systems. These variables reinforce linkages between eutrophication and acidification (Wallace *et al.*, 2014).

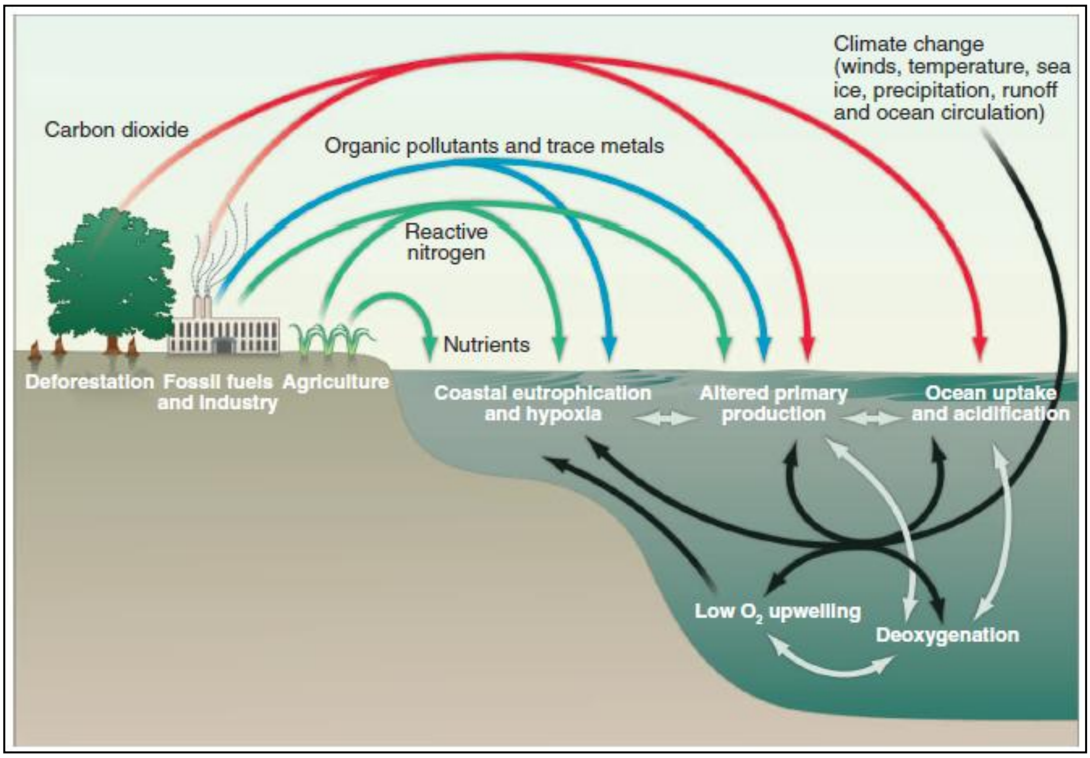

Figure 3: Schematic of anthropogenic impacts on ocean biogeochemistry either through direct fluxes of material into the ocean) or indirectly via climate change (Doney, 2010)

Table 3: Recommended limit for nitrogen species in aquatic ecosystems.

Criteria/ Compound	**Recommended limits**	**Reason**	**Reference**
Total N	0.2–1.0 mg/L	Protection of aquatic organisms	Cui *et al.*, 2014
NH_3	0.01-0.02 mg/L		Camargo and Alonso, 2006
NO_2	0.08-0.35 mg N/L		
NO_3	2.9–3.6 mg N/L		

2.4.5) Implications of climate change on environmental effects

The assessment undertaken of currently available literature for various areas indicates that excessive atmospheric emissions of acidifying pollutants can give rise to numerous environmental problems. Acidification can negatively impact upon ecosystems with limited acid neutralizing capacity (Camargo and Alonso, 2006). Excessive warming and reduced precipitation in some regions may elevate concentrations of these compounds through a reduction in diluting processes which allows toxicity processes to become more common (IPCC, 2013). Additionally, increases in water temperature under a warming climate might stimulate or enhance the development, maintenance and proliferation of primary producers, resulting in a higher occurrence of eutrophication processes and toxic algal blooms (Camargo and Alonso, 2006).

2.5) Near-term climate change and ambient air quality

The IPCC (2013) has concluded with high confidence that emission reductions strategies which target and reduce local air pollution could have a near-term impact on climate. Short-lived air pollutants having opposing effects on climate, hence overall improvements in air quality will affect climate but this depends largely on which pollutants mitigation strategies target, since pollutants can either cool or warm the climate. For instance reducing (SO_2 or PM) emissions reduces its cooling effect on climate, whereas NO_x emission control has both a cooling (through reducing of tropospheric ozone) and a warming effect (due to its impact on methane lifetime and aerosol production) patterns (Figure 4) (IPCC, 2013). This supplements the conclusion that the road transport sector should not only be reducing GHG emissions but also non-CO_2 emissions, acidifying and precursor gases because it has been recognised as a prime candidate from which to derive co-benefits. Thus in the right configuration a given plan can target several emissions at once. Given this theoretical insight, it is important to not exclude the health implications when devising a particular mitigation plan for real world application. Figure 4 below sums up the possible effect of targeting a particular pollutant (IPCC, 2013). Some linkages are yet to be fully analysed or even identified, making it complicated to fully quantify their impact. Hence the task at hand is to assess, understand and quantify these processes through climate modelling in order to make clear the overall interaction between air pollutants and climate.

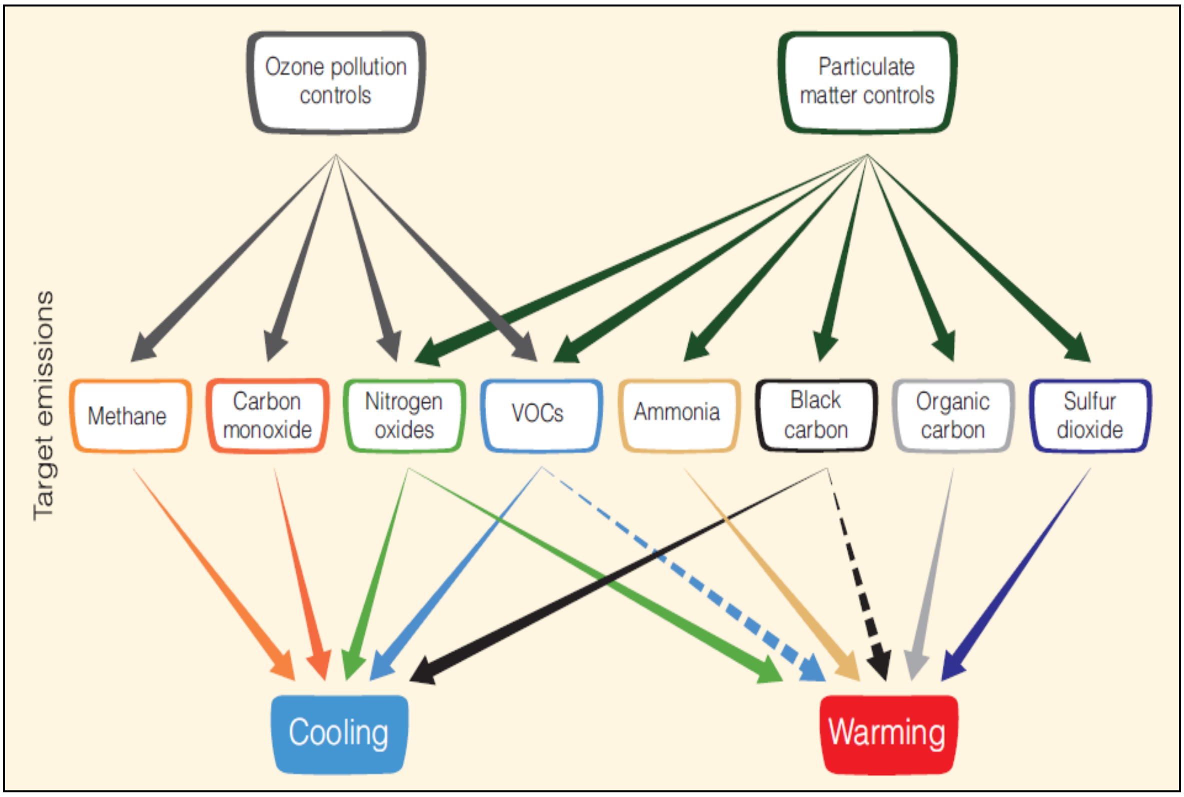

Figure 4: The impact of mitigation measures on specific emissions and climate. Solid black line indicates known impact and dashed line indicates uncertain impact (IPCC, 2013)

CHAPTER 3: AIR QUALITY AND CLIMATE CHANGE IN SOUTH AFRICA: A REVIEW

3.1) Introduction

In order to prevent the degradation of biotic and abiotic receptors and it is vital that one understands the meteorological controls on transportation and atmospheric dispersion of emissions in the area of interest. Furthermore, key to reducing potential impacts of air pollution is the implementation of legislation. In South Africa significant research has been undertaken to understand the key determinants of atmospheric emissions and air quality. In addition to this, various forms of legislation have been promulgated which need to be understood to ensure that boundaries are not exceeded. Such legislation ultimately forms the foundation upon which local municipalities currently manage air quality standards. Finally, an identification of interventions and an analysis of mitigation potential from the road transport sector for South Africa are presented.

3.2) Meteorological controls on transportation and atmospheric dispersion of air pollution

Having gained insight into the characteristics and responsiveness of GHG, precursor gases and acidifying pollutants emitted by the road transport sector, it is vital that decision makers be mindful of local meteorological controls on transportation and atmospheric dispersion of emissions. This is a relevant exercise given that such controls ultimately influence the extent to which human and environmental receptors are exposed to such emissions. Prediction of atmospheric transportation pathways often depends on area specific knowledge of both regional and local scale climate and weather (Diab and Preston-Whyte, 1980). Across varying temporal (days or hours) and spatial scales the concentration of pollution in the atmosphere fluxes in accordance to the stability state of the atmosphere and associated changes in mixing depth and meteorology (Diab and Preston-Whyte, 1980). Given the overall complexity and influence of these variables over transportation and dispersion characteristics, a description of local controls on atmospheric ventilation by vertical mixing and horizontal transport of air masses will be given for eThekwini Municipality.

3.2.1) Transportation

The wind field of eThekwini Municipality throughout the year reflects a dominant north east and southwest component parallel to the coastline (Tyson *et al.*, 1979; Diab and Preston-Whyte, 1980; Higdon, 2007). Such air flow is dependent on a number of local winds. Thus the importance of the examination of the nature of the following reviewed winds is to gain insight into their influence on the transportation mechanism of atmospheric pollution in Durban (Preston-Whyte, 1970).

3.2.1.1) General meso scale circulation: The sea breeze and the effect of gradient winds

Differential heating of land and sea masses in summer is more intense as compared to winter. This allows land temperatures to easily exceed those over the sea. This sets up an offshore gradient flow which advects heated land air towards a distinctly cooler sea so as to setup a steep temperature gradient. Relatively cool marine air is then advected over the land which has a moderating effect over the coast. (Preston-Whyte, 1970; Tyson and Preston-Whyte, 2000).

The main components of the gradient wind along the coast of Durban blow in the north easterly and south westerly directions. An approaching high pressure system often results in a weakened pressure gradient which allows north-east gradient winds to prevail. The arrival of a low pressure system from the south-west allows pressure gradients to steepen and north easterly gradient winds to strengthen. In addition to being super imposed upon topographically induced winds, the sea breeze and its nature becomes substantially influenced by the velocity and wind field of the gradient wind altering the strength of the sea breeze in day time conditions so as to form an angle with the coastline (Preston-Whyte, 1970).

Given the cyclical manner of the sea breeze it is important to note its influence especially during the summer months when the strengthened sea breeze increases atmospheric ventilation and lowers air pollution episodes. On the other hand it may also serve to return land derived pollution that has been transported offshore, back to the land during winter when it is weakened (Preston-Whyte, 1970; Scott and Diab, 2000; Tyson and Preston-Whyte, 2000).

3.2.1.2) The land breeze and effect of gradient winds

Land breezes are cool, nocturnal offshore winds. General formation and functioning off the land breeze mechanism is similar to that of the sea breeze, with the exception being the substitution of land surface heating by surface cooling to set up a pressure gradient. This is common in the Umbilo, Umhlatuzana and Mgeni River valleys of south Durban (Preston-Whyte, 1970; Preston-Whyte, 1980; Tyson and Preston-Whyte, 2000).

The normally turbulent post frontal south-westerly winds can inhibit the development of a strong land breeze circulation which transports pollution into the ocean. As the pollutant laden land air attempts to penetrate into the ocean it becomes entrained in the stronger north-north-east to north easterly gradient wind which then transports pollutant laden land air southwards back over the city (Figure 5). This air layer is usually stable and non-turbulent thus an increase in gradient wind speeds in this direction may partially or totally suppress the land breezes ability to transport pollutants away and increase pollution over the city (Preston-Whyte, 1970; Tyson and Preston-Whyte, 2000).

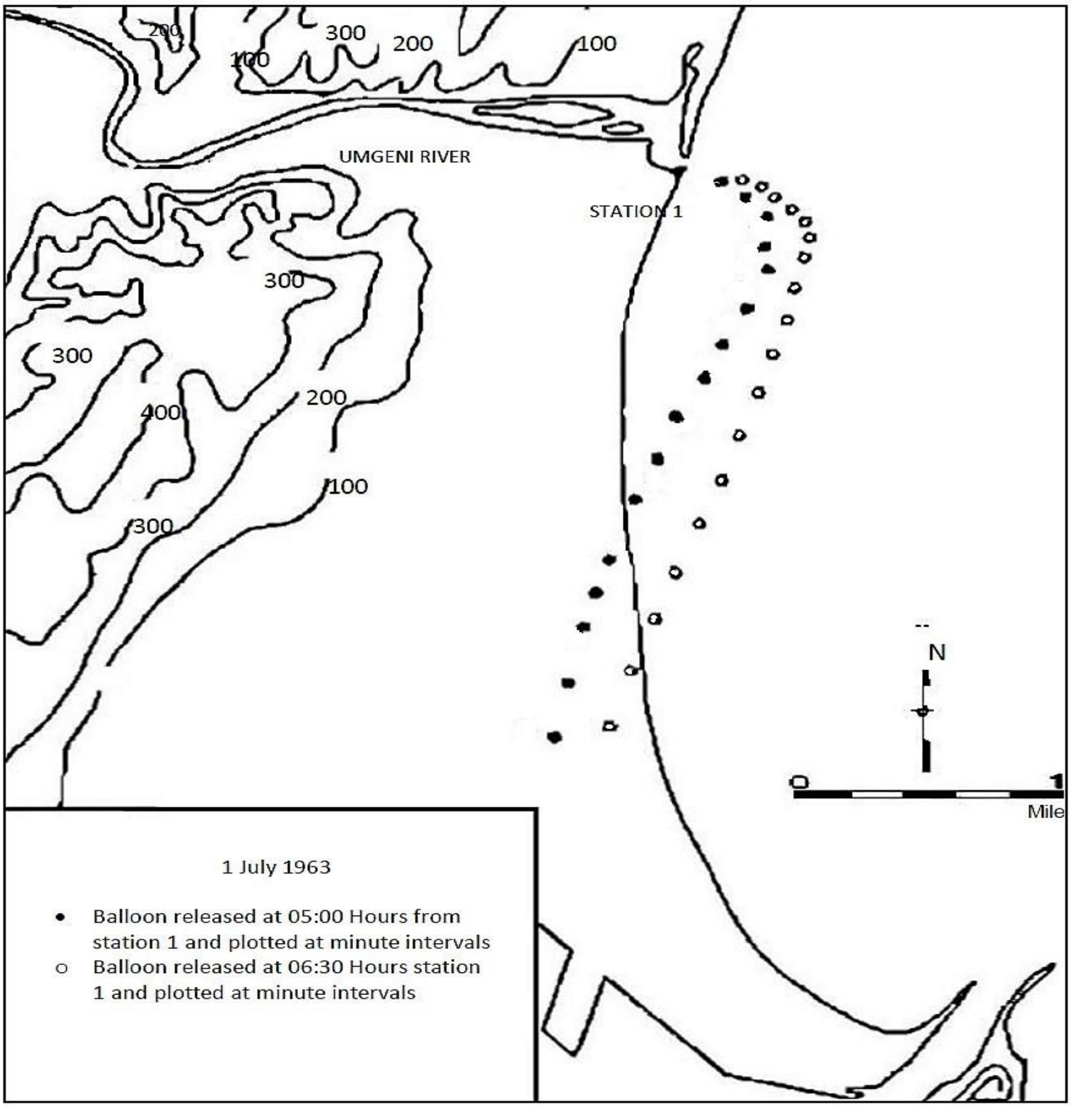

Figure 5: Interaction between drainage wind and relatively stronger north easterly gradient wind at sea, 1/07/63 (Preston-Whyte, 1970)

3.2.1.3) Concluding remarks on transportation

Offshore movement of a deep layer of land-cooled air provides a mechanism for the dispersion of atmospheric pollution away from the coast. Due to the superimposition of the land breeze, mountain-plain and drainage winds large volumes of air are capable of being transported to the coast which increases the risk of an extensive pollution episode (Figure 6). Given the area that these circulations operate over complexity increases as local and regional emission sources have to be considered (Preston-Whyte, 1970).

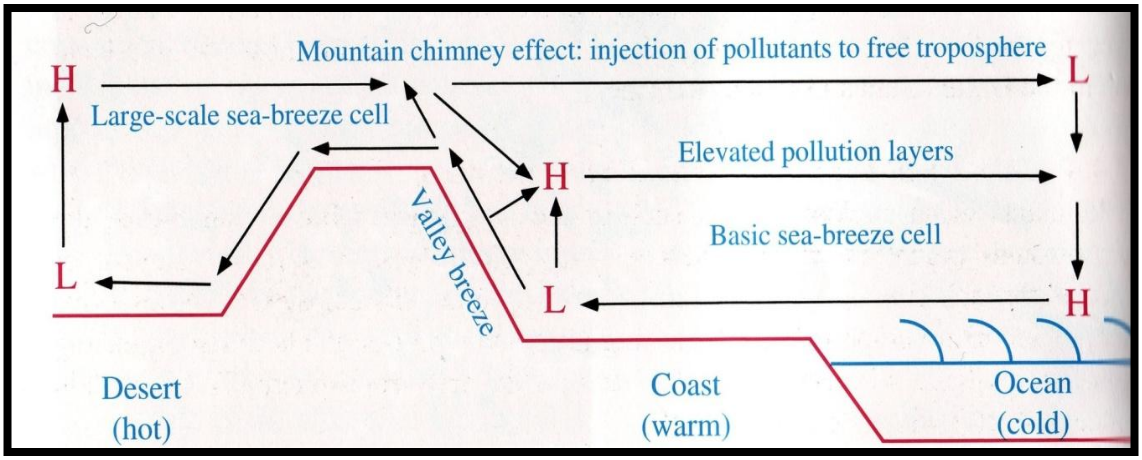

Figure 6: Illustration of local winds along the east coast of South Africa (Tyson and Preston-Whyte, 1974)

3.2.2) Atmospheric dispersion: Implications for vertical mixing and horizontal transport

Average frequency and occurrence of winds over Durban have been shown to be influenced by numerous factors (Diab and Preston-Whyte, 1980). Consequently poor vertical and horizontal dispersion of pollutants result in south Durban particularly in winter (DEAT, 2007). As such integration of meso scale systems and local circulation over complex terrain in south Durban needs to occur in order to quantify the vertical and horizontal components of dispersion (Diab and Preston-Whyte, 1980).

3.2.2.1) Vertical mixing in winter and summer

Subsiding air masses and calm clear conditions that prevail during winter particularly in the morning hours provide the conditions necessary for temperature inversions and meso scale winds to develop. Consequently the frequency and strength of surface inversions are highest in the southern-hemisphere's winter months of June and July (Diab and Preston-Whyte, 1980). A temperature inversion can be defined as "a rise in temperature which exceeds 0.5 ºC over an interval of 50 mbs in an upward direction" (Taljaard, , 1961). During periods of stability, near surface cooling of air masses takes place at night and allows for the development of steep near-surface temperature inversions (Preston-Whyte, 1970). The inversion acts as a "lid", trapping the pollutants close to the ground, preventing upward movement of air. Meso scale winds then subsequently become the transport mechanism (as opposed to dispersal), of atmospheric pollutants which are trapped beneath the subsidence or radiation inversions (Preston-Whyte, 1970). Dispersion conditions deteriorate when there is a temperature inversion. Combined with low wind speeds, the potential for increased pollution concentrations is greatly increased (Scott and Diab, 2000; DEAT, 2007).

Generally weather in Durban is synonymous with the migration of low pressure systems along its coast. As opposed to inversions, non-surface inversion conditions develop before the onset of a low pressure system (Figure 7) (Diab and Preston-Whyte, 1980). Increased instability, wind velocity, rainfall, changes in air temperature and maximum mixing-depth prevail during summer and provide the conditions necessary for ventilation and mixing of pollution to an acceptable level in order for dispersion to occur (DEAT, 2007).. As the low pressure systems approaches Durban the subsidence inversion reaches its lowest level just before the wind field reverses and strengthens. The low pressure system then removes and weakens the inversion and allows for a maximum mixing depth (Diab and Preston-Whyte, 1980; Scott and Diab, 2000). Cloud formation and strong winds thus prevents meso scale circulations from transporting pollutants. This combined with rainfall allows the frontal system to properly ventilate the atmosphere and lower pollution concentrations (Scott and Diab, 2000).

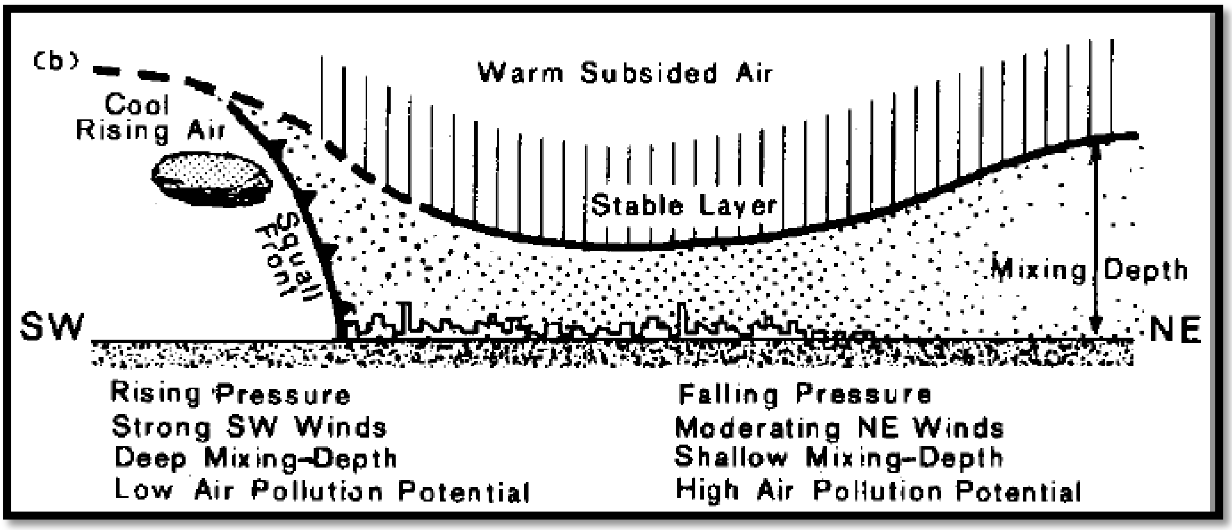

Figure 7: Variation of potential air pollutant episodes with time with the passage of a low pressure system past Durban (Diab and Preston-Whyte, 1980)

3.2.2.2) Horizontal transport

An elevated level of air pollutants generally forms as a result of reduced wind velocity, reduced vertical mixing and low horizontal transport in winter nights and early mornings (DEAT, 2007). The pressure gradient between the mountainous inland areas and coast serves as a mechanism to horizontally transport inland pollution to Durban during winter nights (DEAT, 2007). Once polluted air masses have reached the coast, the relatively cold air drains out from the Umhlatuzana and Umbilo river valleys in south Durban and travels horizontally over the alluvial flats where it is confined and dammed on the western side of the Bluff ridge. This does not last long since the drainage winds are transported north east between the Bluff and Berea ridges. The flat topography of this area means it is capable of steering the cold air between the Bluff and Berea ridges in the south westerly direction. This is also due to drainage winds that rapidly cool the alluvial flats to and sets up a pressure gradient (parallel to the ridges) between itself and the relatively warmer bay area. A north westerly land breeze north of the alluvial flats may form prior to damming of the air under these conditions. As such the gradient needs to be steep enough to initiate air movement large enough to overcome the land breeze (Preston-Whyte, 1970, (Scott and Diab, 2000). The air and pollution subsequently ends up over the CBD of Durban which acts as a receptor for inland pollutants (Scott and Diab, 2000).

A similar phenomenon occurs in the Mgeni river valley, to the north of the CBD. As a low pressure system approaches, the north easterly gradient winds strengthen to suppress offshore air flow and sea penetration. The scale of the movement of cool nocturnal offshore air then becomes localised and drains mainly from river valley mouths. Upon exiting the mouth the cold air penetration seawards will depends upon the direction and relative velocity of the drainage winds (Figure 8). Cold air from the Mgeni River valley may become entrained into the prevailing north easterly gradient wind if it is dominant over the sea (Figure 5) (Preston-Whyte, 1970; Scott and Diab, 2000). The dominant gradient wind will therefore transport cold land air over the CBD of Durban (Diab and Preston-Whyte, 1980).

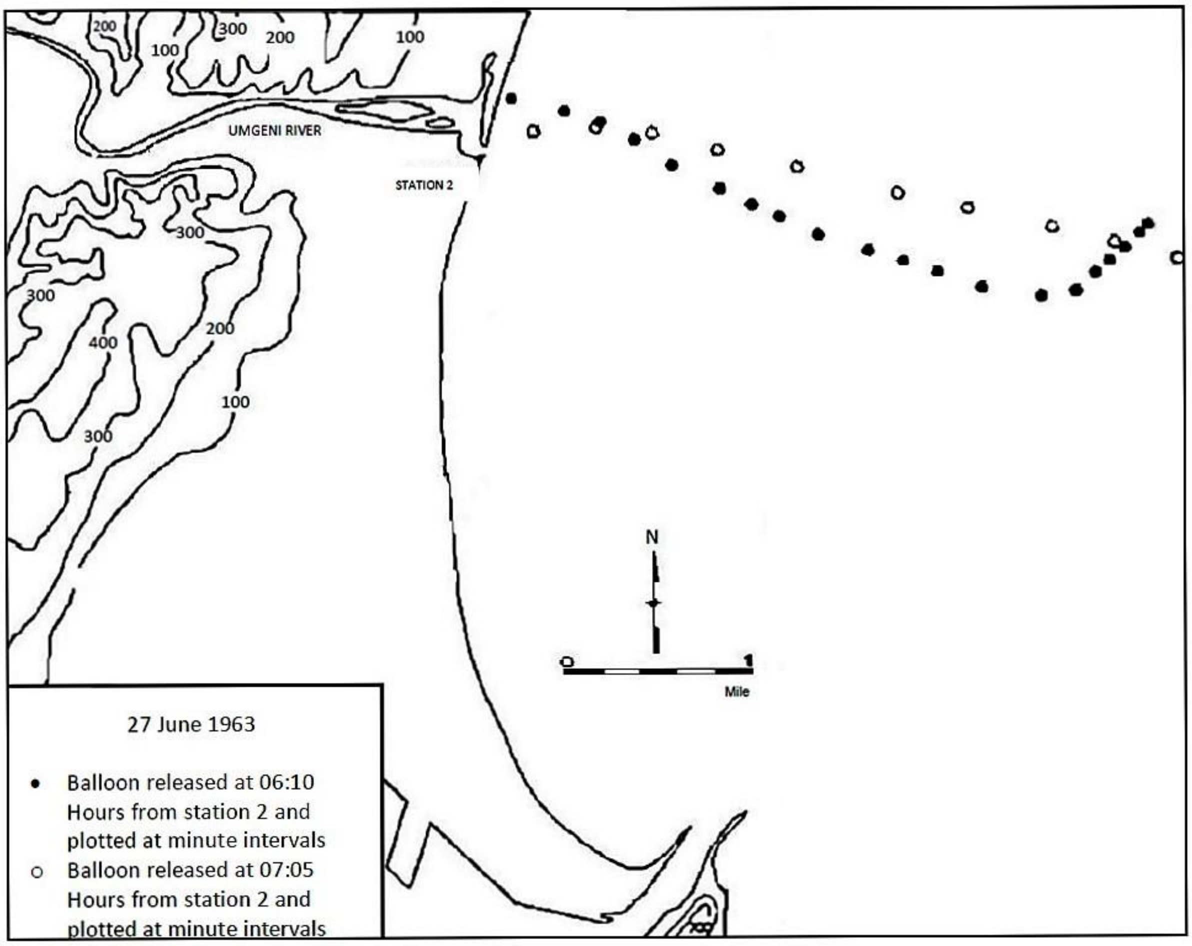

Figure 8: Seaward penetration and pollution dispersion by drainage wind under fine conditions with weakened gradient winds, 27/06/63 (Preston-Whyte, 1970)

The culmination of the various winds discussed allows atmospheric pollutants to accumulate over Durban and occasionally may be supplemented by sources from outside the city. The movement of air at night between the Berea and Bluff ridges poses a potential problem to the city. Decreased velocities, stability and depth of the air mass could serve as a transportation mechanism for pollutants to the city from the south west. Similarly cool drained air masses from the Mgeni River valley may be entrained and transported from the north-east gradient winds (Preston-Whyte, 1970; Preston-Whyte, 1980). Given the occurrence of dominant wind directions and associated pressure systems air flow is often reversible which may result in recirculation of pollutants over Durban (DEAT, 2007). Pollutants are not merely dispersed, often, influencing ambient air quality which is reflected in recorded ambient air quality data. Pollution episodes are therefore likely to occur if and when emissions from the industrial or transportation sectors are not properly controlled which may have severe implications for human and coastal ecosystem health and functioning.

3.3) Air quality management in South Africa

3.3.1) Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965)

The Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965) was the key air quality legislation from the mid 1960's, when South Africa was first declared a controlled area in 1968. The control of an array of gases, smoke, dust and vehicular emissions fell within the scope of the APPA. The APPA did not include targets or standards which were based on emission guidelines. During 1996, the South African Constitution (Act No. 108 of 1996) was promulgated and consisted of the Bill of Rights (Lazarus *et al.*, 1997). This prompted the acknowledgement that in order for this legislation to be effective in the context of air quality, it was vital that air pollution concentrations be conducive to a healthy environment and community (DEAT, 1965).

3.3.2) National Environmental Management Act (NEMA) (Act No. 107 of 1998)

The National Environmental Management Act (NEMA) (Act No. 107 of 1998) was developed as a framework under which numerous environmental legislations fell each of which targeted a specific environmental sector. NEMA provides the legislative framework under which environmental management is carried out. NEMA's main purpose is the provision of co-operative environmental governance and guidance for decision making on matters concerning the environment and society (DEAT, 2007). NEMA places its interests on the principles which underpin sustainable management and its repercussions on society and the receiving environment. The principles act as a general framework under which environmental management and its implementation plans are devised. It further places responsibility on the state to fulfill all the basic needs of South African citizens. NEMA's principles include the implementation of alternatives and best practicable options such as minimisation, reduction and recycling of waste; the promotion of interested and affected parties; the duty of care and remediation of environmental damage; the polluter pays principle and lastly environmental justice for all. Overall NEMA is designed to ensure that no conflict occurs between the sustainable development of society, the environment and economy. Co-operative governance, conflict resolution, integrated environmental management, international agreements, compliance and enforcement are covered within the NEMA (DEAT, 2007).

3.3.3) National Environmental Management: Air Quality Act (AQA) (No. 39 of 2004)

The most common international approach employed throughout various countries for the control of air pollution for human health and sustainability is the management of ambient air quality. Air Quality Management (AQM) firstly involves the management and identification of all components whose radiative properties influence the climate and those which impact on the lifetime and concentrations of other GHG's that subsequently reduce ambient air quality and secondly mitigation techniques which act to bring about reduced concentrations that are conducive to the human health and the sustainability of ecosystems (Thambiran and Diab, 2010).

South Africa's existing approach to manage ambient air quality mimics the international methodology and is based on the AQM approach which is underlain by the National Environmental Management: Air Quality Act (Act No. 39 of 2004) (AQA). The promulgation of the AQA in the year 2004 saw a momentous alteration to the manner in which air quality in South Africa was managed. The key alteration came in the form of a shift from source-based management to that of ambient air quality management. The AQA scope consists of a considerably more detailed range of air quality components relative to the APPA which consisted of simple pollution prevention.

The scope of the AQA is to reform the law regulating air quality so as to protect the environment by providing appropriate measures to prevent pollution and ecological degradation. This sets the path for firstly securing ecologically sustainable development while promoting justifiable economic and social development, secondly providing national standards for regulating air quality and lastly providing management structures and control for all spheres of government (DEAT 2004). Such objectives found within the scope not only caters for the protection of the environment but further gives effect to section 24(b) of the Constitution by securing an environment which is not detrimental to the wellbeing of individuals.

The AQA serves as a benchmark for the correct management of air quality in South Africa. The AQM approach and AQA comprises of numerous principles or tools which aim to improve ambient air quality. These include an air quality and meteorological monitoring network, the licensing of specific activities emission inventories, predictive models, reporting and the accountability of non-compliance regulatory implements and various mitigation strategies which reduce emissions from sources to guarantee compliance with ambient standards (Elsom and Longhurst, 2004). This approach also requires the assignment of ambient air quality standards to assess AQM performance and simultaneously sets emission standards to measure and monitor the concentration of pollution (DEAT, 2007).

The threshold or tolerance of the environment (through scientific evaluation) will determine what pollutant concentrations may constitute poor or clean air for biotic and abiotic components. This has resulted in industries being more cautious which was not the case with the APPA which failed to address air quality management by over emphasising source based control without a clear plan for ambient air quality management (eThekwini Municipality, 2007). The public and industry will thus have a role in the management of emissions by law, in order to reach the ambient air quality goals (DEAT, 2007).

3.4) The air quality management plan for eThekwini Municipality for 2007 and 2015

In terms of section 15 (2) of the National Environmental Management: Air Quality Act (AQA) (No. 39 0f 2004), municipalities are required to prepare an air quality management plan (AQMP). This plan sets out objectives, strategies and procedures for the respective levels of government to meet the requirements of the NEMA with regards to AQM and reporting. In 2005 eThekwini Municipality commenced with early preparations which resulted in an AQMP framework. A sub-section of eThekwini Municipality’s health unit subsequently compiled and implemented an AQMP in 2007 (eThekwini Municipality, 2014).

The AQMP document serves to correctly direct decision makers, with its master plan serving as a guide of action that should be carried out in order to shift the air quality status to that of a positive one (eThekwini Municipality, 2007). The AQMP enables the municipality to plan, coordinate and achieve AQM goals in a logical, structured and measured approach. Its primary task is to improve and maintain the status of air quality, mitigate the ill effects of air pollution on human and environmental health, addressing the effects of emissions from point and non-point sources and instituting best practise methods. As part of this ongoing process of evaluating and improving air quality, the municipality has published the draft AQMP for 2014 in March 2015 (eThekwini Municipality, 2014; uMoya-NILU, 2015).

Since 2007 key additions to the knowledge base has been made by the latest AQMP in 2015. Findings in the 2007 AQMP suggests that activities in the south Durban account for majority of SO_2 emissions, other sources of emissions were yet to be quantified at the time and NO_x, and PM_{10} were under represented (eThekwini Municipality, 2007). Emissions of pollutants have now been accounted for by the various sources, particularly that of traffic emissions (Thambiran and Diab, 2011; uMoya-NILU, 2015).

The 2015 AQMP report states that the air quality of the urban areas largely conforms to the standards set out in AQA. Most sources of emissions have been identified quantified and prioritised. Emissions of SO_2 have been updated for the whole of the eThekwini Municipality, with industry accounting for most SO_2 emissions from Durban and south Durban. The latest report implicates the road transport sector in the growing role it plays in the emission of GHG, acidifying pollutants and precursor gases as it is now the second biggest source of emissions (uMoya-NILU, 2015). There is general compliance for SO_2 concentrations relative to the NAAQS since 2006. Emissions of NO_x and PM_{10} have been updated and primarily stem from traffic emissions. Overall NO_2 and PM_{10} concentrations are in general compliance with the NAAQS except in areas of high traffic such as Pinetown and Durban where exceedances occur. Residential fossil fuel contribution to indoor air pollution in informal settlements is only a small source of pollutants (uMoya-NILU, 2015).

3.5) Municipal and community sector contributions to GHG emissions across all sectors in eThekwini Municipality

3.5.1) Municipal GHG contributions

Apart from the AQMP which focuses on air pollutants, other documents are published by the municipality to supplement the knowledge base. Such documents include values of GHG throughout the municipality which are listed within the eThekwini Municipality’s GHG inventory technical reports for the year 2011 and 2012 (eThekwini Municipality, 2013; eThekwini Municipality, 2014). These values have been quantified as municipal and community sector emissions for all sectors (other than industry and transport) and are listed below in Table 4 and 5. Data from these documents provide insight into the sectors responsible for the greatest and least amount of emissions within the eThekwini Municipality in descending order and more importantly indicates how much the road transport sector contributes relative to other sectors (eThekwini Municipality, 2013; eThekwini Municipality, 2014).

The eThekwini Municipality GHG Inventory includes all important sources of GHG emissions occurring within the Municipality's geopolitical and organisational boundaries. Direct and indirect emissions are accounted for separately within each sector through the categorisation of emissions as either scope one, two or three emissions. Differentiating between emission scopes helps to avoid the possibility of double counting emissions and misrepresenting emissions when reporting. Municipal operations emissions included in the inventory were categorised into the following scopes:

1. Scope 1 – Direct emission sources owned or operated by eThekwini Municipality.
2. Scope 2 – Indirect emission sources.
3. Scope 3 –Indirect and embodied emissions over which eThekwini Municipality exerts significant control or influence.

The principal municipal emission source contributing 44.5% and 46.4% to the municipality's total 2011 and 2012 GHG emission inventory was power generation facilities which contributed the greatest percentage of emissions. Table 4 and 5 then illustrate the sectors which comprised the remainder of the emissions. The transit and vehicle fleet ranked relatively lower on the table given that much of the fleet located within eThekwini Municipality' is privately owned. Employee air travel ranked last.

Table 4: Municipal sector emissions in descending order for 2011 (eThekwini Municipality, 2013).

Municipal Sector	**Emissions Scope**	**Emissions (tCO_2e)**	**% total**
Power Generation Facilities	Scope 2	690 311	44.5
Solid Waste Facilities	Scope 1	150 483	24.9
	Scope 1	234 507	
	Scope 2	17 310	
Buildings & Other Facilities	Scope 1	156 351	11.2
	Scope 2	1747	

Streetlights & Traffic Signals	Scope 2	119 798	7.8
	Scope 3	1333	
Water Delivery Facilities	Scope 2	67 405	4.3
Wastewater Facilities	Scope 1	29 675	3.9
	Scope 2	31 037	
Transit Fleet	Scope 3	31 951	2.1
Vehicle Fleet	Scope 1	18 581	1.2
Employee Air Travel	Scope 3	932	0.1

Table 5: Municipal sector emissions in descending order for 2012 (eThekwini Municipality, 2014).

Municipal Sector	**Emissions Scope**	**Emissions (tCO_2e)**	**% total**
Power Generation Facilities	Scope 1	3552	46.4%
	Scope 2	705364	
Certified Emission Reduction	Scope 1	219173	14.4%
Streetlights and Traffic Signals	Scope 2	108101	12.4%
	Scope 3	1079	
	Scope 3	31951	
	Scope 1	46654	
Buildings and Other Facilities	Scope 1	15082	11.8%
	Scope 2	164935	
Wastewater Facilities	Scope 1	35979	6.1%
	Scope 2	57100	
Sanitation and Solid Waste Facilities	Scope 1	71370	4.8%
	Scope 2	1850	
Water Delivery Facilities	Scope 2	64048	4.2%
Additional Scope 3 Emissions	Scope 3	286	0.0%

Emission estimates from the AQMP are further supplemented by and compared to a study of a similar nature which sought to quantify vehicle air pollutant emissions for certain vehicle sectors for the year 2008 (uMoya-NILU, 2015). This provides some insight into the distribution of emissions across different vehicle sectors (Table 6) (Thambiran and Diab, 2011).

Table 6: Comparison of NO_x, SO_2 and PM_{10}, estimates (tonnes) across two studies (Thambiran and Diab, 2011; uMoya-NILU, 2015).

	NO_x		**SO_2**		**PM_{10}**	
Year of study	2008	2014	2008	2014	2008	2014
Sector	Thambiran and Diab, 2011	uMoya-NILU, 2015	Thambiran and Diab, 2011	uMoya-NILU, 2015	Thambiran and Diab, 2011	uMoya-NILU, 2015
Passenger vehicles	25940		670		260	
LCV's	12884		417		610	
HCV's	33641		834		1626	
Total emission	72465	68292	1921	1585	2496	2439

3.5.2) Community GHG contributions

Community-scale emissions included within the 2011 inventory were categorised into the following scopes:

1. Scope 1 – All direct emission sources located within the geopolitical boundary of eThekwini Municipality.
2. Scope 2 – Indirect emissions that result as a consequence of activity within eThekwini Municipality’s geopolitical boundary.
3. Scope 3 – Indirect and embodied emissions that occur as a result of activity within the geopolitical boundary.

The principal community sector emission source within the eThekwini Municipality in 2011 and 2012 was the industrial sector, contributing 34.07% and 33.59% to total community emissions (Table 7 and 8). The second major contributor was the on and off-road (ground) transport sector contributing 21.72% and 22.21% to overall community emissions. This was to be expected as majority of the fleet is privately owned. These two sectors accounted for the bulk of emissions in 2011 and 2012 with a steady upward trend in the overall quantity emitted. The remainder of emissions where accounted for by the air and water transport systems, residential and commercial sectors. Smaller contributions were made by the agriculture, land use and forestry and solid waste sectors as illustrated in Table 7 and 8.

Table 7: Community sector emissions in descending order for 2011 (eThekwini Municipality, 2013).

Community Sector	**Emissions Scope**	**Emissions (tCO_2e)**	**% total**
Industrial	Scope 1	4 147 892	34.07
	Scope 2	4 742 415	
On-road and off-road Vehicles	Scope 1	5 668 964	21.72
Air and Water Transport Systems	Scope 3	4 599 854	17.63
Residential	Scope 1	179 841	13.78
	Scope 2	3 417 110	
Commercial	Scope 2	3 067 300	11.75
Agriculture, Land Use and Forestry	Scope 1	65 322	0.25
Solid Waste	Scope 1	209 280	0.80

Table 8: Community sector emissions in descending order for 2012 (eThekwini Municipality, 2014).

Community Sector	**Emissions Scope**	**Emissions (tCO_2e)**	**% total**
Industrial	Scope 1	4505089	33.59%
	Scope 2	4843557	
On-road and Off-road Vehicles	Scope 1	6183253	22.21%

Rail, Air and Water Transport Systems	Scope 3	4679690	16.81%
Residential	Scope 1	214097	13.66%
	Scope 2	3587450	
Commercial	Scope 2	3142391	11.29%
Industrial process & Product Use	Scope 1	375850	1.35%
Solid Waste	Scope 1	212230	0.76%
Agriculture, Land Use and Forestry	Scope 1	90264	0.32%

These values are further supplemented by and compared to a study of a similar nature which sought to quantify vehicular GHG emissions for certain vehicle sectors for the year 2008. This provides insight into the distribution of emissions across different vehicle sectors which were not provided by the inventories obtained from the municipality (Table 9). These values do not include CO as the above tables had done, thus accounting for the small difference in the total values of the 2011 and 2012 studies (Thambiran and Diab, 2011).

Table 9: Comparison of CO_2 and N_2O estimates (tonnes) across various studies.

	CO_2			**N_2O**		
Year of study	2008	2011	2012	2008	2011	2012
Sector	Thambiran and Diab, 2011	eThekwini Municipality, 2013	eThekwini Municipality, 2014	Thambiran and Diab, 2011	eThekwini Municipality, 2013	eThekwini Municipality, 2014
Passenger vehicle	2140251			115		
LCV's	1252630			52		
HCV's	2642054			71		
Total emission	6034935	5610687	6119854	238	51605	56040

3.5.3) Growth of CO_2 emissions from the road transport sector

Total emissions show an increase of 6.2% from year 2011 to 2012, which is equivalent to an additional 1 710 996.0 tCO_2e emitted. In terms of mobile fuel combustion from on-road and off-road vehicles, emissions show an increase from 5 267 209 tCO_2e in 2010 to 5 668 964 tCO_2e in 2011 to 6,183,253 tCO_2e in 2012. This translates to an 8% increase between years 2010 and 2011 and a 9% increase in emissions from on-road and off-road vehicles between 2011 and 2012, indicating an upward emission trend (Table 7 and 8). This places the road transport sector emissions within eThekwini Municipality in a position which could pose a risk to environmental and human health if not controlled or abated in future.

3.6) Identification of interventions and analysis of mitigation potential for the road transport sector

Apart from the industrial sector within eThekwini Municipality on-road and off-road vehicle emissions for 2011 and 2012 are highly ranked as indicated by Table 7 and 8. Having characterised the role that the road transport sector plays in contributing to the total amount of emissions in eThekwini Municipality, it has been determined that without the implementation of rigorous and sustainable mitigation policies, the road transport sector could surpass other energy end-use sectors in terms of it’s rate of emission production in future. Research and development is thus constantly undertaken by transportation service providers to reduce transport emissions and become inherently more carbon efficient, however this is partially offset by the increasing demand for and turnover of stock and infrastructure (CSIR, 2013). Claims made by the IPCC (2014) iterate that a higher emission reduction potential in the transport sector is now possible at lower costs as compared to AR4 in the past which provides potential climate mitigation solutions from the road transport sector.

Although emission reduction is possible within South Africa, political and socio-economic conditions may act as severe constraints to the implementation of an effective air quality management plan (Ntziachristos and Samaras, 2014). While there has been significant reduction of industrial emissions in the country, emissions from the road transport sector continues to be a potential hazard. Effective assessment of possible emission reduction strategies must entail the most economically viable solutions which consider the area, topography, institutional capacity and source characteristics of pollutants (Buthelezi and

Davies, 2015). This has prompted the identification of the best suited interventions for mitigation based on a review of current literature, promulgated by different organisations and author's research endeavours.

3.6.1) Efficient technologies, energy and fuel carbon intensity reduction

The reduction in energy and fuel carbon intensity deals with the reduction of traditional liquid fuels (petrol and diesel) within the road transport sector by substituting oil based products with natural gas, bio methane, or bio fuels, electricity or hydrogen produced from low GHG sources (IPCC, 2014). This approach to climate change mitigation can be applied to all vehicles which utilise the traditional combustion engines. This is achieved through firstly utilising a modern fleet of vehicles capable of supporting such fuel use in addition to being equipped with technologies such as catalytic converters, fuel injection devices and turbo charged engines. This increases the efficiency of vehicles particularly freight vehicles by means of technological improvements (Buthelezi and Davies, 2015).

The addition of electric driven vehicles and hybridised concepts fuelled by batteries or fuel cells (when using low carbon electricity generation), offer significant potential reductions in GHG. Before realising this potential, such vehicles will require considerable time to penetrate the market, turnover of the current vehicle fleet and lastly the fuel utilised and it's associated emission factor. After which it will have to overcome a limited driving range, long recharge times and high battery costs that lead to relatively high vehicle retail prices (Greene and Plotkin, 2011; Ntziachristos and Samaras, 2014).

Costs associated with this approach include maintenance costs and investment into alternative power trains. Innovation and time is assumed to reduce cost of these technologies in future making it more economically attractive relative to conventional engine vehicles (DEAT, 2014; IPCC 2014). Such retail prices could discourage customer's willingness to pay and thus affect market penetration despite being off-set by fuel savings in future. Presently such vehicles require large investments and should be coupled with incentives and regulatory policies which reward such purchases. It is important to note that measures such as electric vehicles, compressed natural gas (CNG) and hydrogen will need supplementary infrastructure investment (DEAT, 2014). Overall the uptake of low-carbon fuels and it's immediate cut in CO_2 emission benefits could enable transport systems to operate with lower carbon intensities however this will be highly dependent on supply and distribution of low carbon fuels (IPCC, 2014).

3.6.2) Reducing vehicle kilometres travelled (VKT) and carbon consumption by means of a shift in modal intensity

Altering human behaviour, driver profiles, beliefs and attitudes towards road use can also significantly limit emissions in conjunction with appropriate vehicle technologies listed above in section 3.6.1. The success of emission reductions and reduced vehicle kilometres travelled via modal shifts is determined by the rate at which passengers and freight are shifted from cars and freight vehicles to public transport and freight rail services (DEA, 2014). This may occur via increased investment in public transport, incentivising growth in low energy intensity sectors, walking and cycling infrastructure, modifying roads, airports, and railways to become more attractive for users and reduce travel time and distance (IPCC, 2014). Further to this, efforts are needed to eliminate inefficiencies in operational handling, excess emissions, behaviour and speed control within the current road freight transport system. Efficiency results in fewer kilometres travelled and less emissions (Schoeman, 2010; CSIR, 2013). A reduction in vehicle kilometres travelled and fuel consumed by HCV’s can reduce air pollution and GHG emissions by 20-24% (Thambiran and Diab, 2011).

Costs associated with this approach include investment from road infrastructure to passenger transport infrastructure. This highlights the role which government and the private sector will have to play when providing the initial investments needed to promote modal shifts (Buthelezi and Davies, 2015). It is important to note that estimated cost and effectiveness of a modal shift is highly site specific and thus may not always be the best solution. Another drawback of this approach is that total potential of this measure is based on simple scaling of potential from a single local area to national level (DEA, 2014; Tongwane *et al.*, 2015). For measures aimed at advancements in vehicle technologies (energy and fuel intensity reduction), the likely costs are known and are relatively similar to international benchmarks. This can not be said for modal shifts, as it is rather difficult to quantify since it depends highly on the area in which it is implemented.

3.6.3) Eco-driving

Eco-driving is an efficient driving concept that has now been applied to modern vehicles, which aims to limits vehicular emissions and save energy through fuel efficiency. The premise of this concept involves altering the driver profiles based on general advice to drivers such as anticipating road conditions, limiting harsh acceleration, braking slowly and driving smoothly in order to keep vehicles moving at a constant speed for as long as possible (Lárusdóttir and Ulfarsson, 2015). Benefits include fuel savings, less maintenance, fewer accidents, less operational costs and emission reductions (Li *et al.*, 2015). Given that eco-driving is a concept it can not simply be purchased as an upgrade to reduce vehicular emissions. Through initiatives championed by the Department of Transport, eco-driving awareness needs to be promoted to the public and to private companies. This can be done by firstly providing training and knowledge via the national learner’s examination at all testing grounds. This will provide all future generations with adequate knowledge and equip them with techniques to drive more efficiently while enforcing good driving habits from the onset. Those who already have obtained licences can be educated on the benefits of eco-driving through compulsory and pre-existing initiatives set up by car insurance agencies, advanced driver training courses, logistic companies in the private sector and the Department of Transport.

3.6.4) Adaptive design for fuel efficiency

Adaptive designs for energy conservation and emission reduction can be applied within the motor manufacturing industry. While the motor manufacturing industry continuously produces efficient engines which reduce fuel consumption through newer technologies as cited in section 3.6.1, it can also rapidly develop and apply non-mechanical aesthetic components which can obtain eco-driving efficiencies. The motor manufacturing industry should consider applying pre-existing aerodynamics research from high performance vehicles which have proven successful, to specific standard vehicles to compliment other efficient technologies as well. Such components act to reduce vehicle mass, tyre resistance and aerodynamic drag in order to lower vehicle fuel consumption and to comply with latest Euro standards (Bauer *et al.*, 2015). Such changes to standard vehicles will have limited maintenance as it merely forms part of the non-metal body work of a vehicle such as bumpers. Examples of such components include air intakes, ducts, splitters, rear diffusers and spoilers. These components are proven to effectively reduce the vehicles drag coefficient by

0.5% per year, while reducing the net weight of the vehicle hence aiding eco-driving by saving fuel and reducing emissions. If applied at present, this will equate to a total reduction of approximately 10% by the year 2030 (Bauer *et al.*, 2015).

With regards to mechanical components, the engine needs to operate at optimum efficiency which requires precise gear shifting to further reduce fuel consumption. To overcome poor driving behaviour and to achieve precise gear shifting and fuel saving, gears shifts need to be carried out or indicated by on board intelligent system or optimisation algorithms which are dependent on engine torque and driving situation. Thus it is suggested that the motor manufacturing industry make such technologies more widely available on standard or low to middle income vehicles (Eckert *et al.*, 2015).

3.6.5) Implementing smart traffic signal control

To further aid in applying the concept of eco-driving in urban areas, one would require specific traffic conditions free of congestion which promotes shorter travel times, higher average speeds; fewer gear shifts and reduced emissions (Bigazzi and Clifton, 2015). Currently the traffic signals (robots) are controlled by a fixed-cycle in the urban transport system. The disadvantages of such a system are that it can not dynamically adjust its timing to ensure the efficient and intelligent handling of vehicles during various scenarios of traffic congestion. With the development of a variety of smart inexpensive sensors and communication technologies, many advanced methods have been developed and implemented in cities such as London to adjust signal timings according to real-time traffic data. Not only does this technology relieve traffic congestion, it also reduces excess vehicular emissions while saving time and fuel. Such savings could even increase if coupled with newer vehicle technologies which are lacking in eThekwini Municipality (Boubaker *et al.*, 2015).

3.6.6) Autonomous driving

Advances in autonomous vehicles and smart transportation systems which include the eco driving concept indicate a rapidly approaching future in which intelligent vehicles shall automatically control the entire driving process (Li *et al*, 2015; Prata *et al.*, 2015). The benefits of such driving include the elimination of human error and variations in driving profiles whilst making travelling a smoother process by refining pre-existing technologies such as cruise control, so that the fuel economy and emissions are able to be reduced.

3.6.7) Analysis of current mitigation potential for South Africa

An analysis of cost and mitigation potential was conducted by the DEA (2014) for the key socio-economic sectors. This included the energy sector, industrial sector, waste sector and agricultural and other land use sectors. In particular the Technical Appendix E provides an overview of the emissions trends, existing policies and potential future abatement opportunities for the transport sector (DEA, 2014). This includes emissions from road transport, rail transport and aviation sectors. These sectors are associated with the IPCC emissions categories.

A study by the Energy Research Centre published in 2012 provided the assumed growth in activity levels and the assumed survival rates for the road transport sector when developing the reference case projections. This along with other data inputs were entered into the Ricardo-AEA’s Sustainable Transport (SULTAN) tool and the fuel use and direct baseline emissions from the fleet in 2010 were calculated. As a result of this analysis currently recommended mitigation opportunities with the most potential include efficient technology options which translate into energy and carbon fuel intensity reduction; behavioural aspects relating to the acceptance and utilisation of new technologies; and modal shift options as a means to reduce GHG and non-GHG emission for climate change mitigation in South Africa (IPCC, 2014). Table 10 provides a description of mitigation strategies derived from the DEA (2014) with regards to total mitigation potential for the transport sector, assuming all measures are implemented.

Table 10: Total mitigation potential for the transport sector, for 2020, 2030 and 2050 (in $ktCO_2e$) (DEA, 2014).

Sub-Sector	**Mitigation measure**	**2020**	**2030**	**2050**
Road transport	Road - biofuels	1959	8286	30374
	Road - improved efficiency - diesel internal combustion engine (ICE)	1875	8122	28448
	Road - improved efficiency - petrol ICE	4349	12538	25241
	Road - shifting passengers to public transport	820	3087	9396
	Road -alternate fuels - petrol HEV	450	1872	7522
	Road - alternative fuels - diesel HEV	176	933	5041
	Road - shifting freight from road to rail	1840	2729	2997
	Road - alternative fuels - petrol PHEV	64	467	1951
	Road - alternate fuels - diesel PHEV	22	202	1152
	Road - alternative fuels - EV	-	57	750
	Road - alternative fuels - FCEV	-	4	616
Total		11575	38545	115068

If all technically available mitigation potential measures within the road transport sector were to be implemented, GHG emissions could be reduced by 11575 $ktCO_2$ by 2020 or 97.52% of all transport emissions, 38545 $ktCO_2$ by 2030 or 97.52% of all transport emissions and 115068 $ktCO_2$ or 98.22% of all transport emissions by 2050 (Table 10). These figures are inclusive of direct combustion of fuel and indirect emissions from these fuels. Thus the road transport sector should intuitively be the primary target for local municipality's emission reduction initiatives (Thambiran and Diab, 2011; Buthelezi and Davies, 2015).

3.7) Conclusion

The implications of local air quality regulations have thus far controlled non-CO_2 emissions from road transportation. Such regulations target near surface pollution and ultimately aim to ensure the protection of human health and ambient air quality. The recognition of the significance of regional climate change within the context of mitigation has encouraged an increasing awareness of the climate impact of non-CO_2 emissions (IPCC, 2014). Although emissions from road transportation are being reduced due in part to efforts made to protect human health from poor ambient air quality, the operation of these controls could potentially be expanded upon so as to act as an agent to mitigate against climate change (Oxley *et al.*, 2012).

The strategies described above for reducing CO_2 emissions encompass a variety of methods which may not necessarily be additive. The combined use of such strategies and the overall mitigation potential can only be achieved and assessed if integrated into a single optimised system. This should be inclusive of non-CO_2 emissions, acidifying and precursor gases, vehicle load and occupancy factors and indirect GHG emissions from vehicle manufacture and infrastructure (Hawkins *et al.*, 2012; Borken-Kleefeld *et al.*, 2013).

CHAPTER 4: METHODOLOGY

4.1) Introduction

In this chapter the state of ambient air quality is determined from monitored ambient air quality data and the methodologies outlined below. Methodologies which outline the development of an emissions inventory for GHG, precursor gases and acidifying pollutants from the road transport sector within eThekwini Municipality are then described as set out in the objectives in Chapter 1. Given the diversity of vehicle technologies and propulsion systems, the calculation of emissions from road vehicles is a complex and challenging task which requires good quality activity data and emission factors. Thus this chapter presents the overall research design, model and data inputs used in a systematic manner in order to allow for the compilation of a high quality emission inventory (Ntziachristos and Samaras, 2014). Specifically, each step of the method is presented. The chapter further goes on to describe any assumptions made and how data were transformed and analysed.

4.2) Ambient air quality data

Basic air quality monitoring in the municipality commenced in 1985 by means of the bubbler method and soil index. In 2005 this progressed to the use of 14 fully automated monitoring stations, with the addition of 4 more in 2013 (uMoya-NILU, 2015). This provides eThekwini Municipality with a good record of criteria pollutants and meteorology at various locations. The South African Air Quality Information System (SAAQIS) provided data upon request, which were used to construct trend lines of pollutants, using monthly averages for south Durban for the period 2004-2014 (SAAQIS, 2015). The data were then screened and checked to ensure there were no missing data. This step ensured that there was good coverage of over 70% of the data. Data were then processed and analysed to indicate hourly exceedences of the pollutants selected for this study for the entire data set by means of data filtering in Excel. This helped identify morning and afternoon trends with regards to the expected peak traffic volumes and areas which exceeded annual vegetation thresholds of NO_2 and SO_2. The Tongaat, New Germany, Amanzimtoti, Cato Ridge and Alverstone stations are also presented but were omitted from discussion since they were recently added to the network and did not reveal any relevant trends for this study. Information and locations of monitoring sites are listed in Table 11 and Figure 9 below.

Table 11: eThekwini Municipality's continuous monitoring stations (SAAQIS, 2015).

Station name	**Monitoring period**	**Siting rationale**	**Parameters measured**
Prospection	2004-ongoing	Industrial	SO_2
Southern Works	2004- ongoing	Urban industrial	SO_2, PM_{10}, NO_x, TRS, Met
Settlers School	2004- ongoing	Residential	SO_2, TRS
Ganges	2004- ongoing	Suburban traffic	SO_2, NO_x, PM_{10}
Grosvenor	2004- ongoing	Residential	SO_2, Met
Nizam School	2004- ongoing	Urban	SO_2, Met
King Edward	2004-2006	Urban	NO_x, PM_{10}
Warwick	2004- ongoing	Traffic	NO_x, CO
Wentworth	2004- ongoing	Industrial	SO_2, PM_{10}, $PM_{2.5}$, NO_x, Met
City Hall	2004- ongoing	CBD traffic	NO_x, PM_{10}
Alverstone	2004- ongoing	Urban	O_3
Ferndale	2005-2013	Urban	SO_2, PM_{10}, $PM_{2.5}$, NO_x
Jacobs	2004- ongoing	Industrial	SO_2, NO_x, Met
Sapref	2004-2008	Meteorological data	Temperature, Relative Humidity, Pressure
Harbour	2004-2009	Meteorological data	Temperature, Relative Humidity, Pressure
Edgewood	2004- ongoing	Meteorological data	Temperature, Relative Humidity, Pressure
Tongaat	2004- ongoing	Meteorological data	Temperature, Relative Humidity, Pressure
	2014- ongoing	Network	SO_2, NO_x, PM_{10},O_3, Met

		expansion	
Amanzimtoti	2014- ongoing	Network expansion	SO_2, NO_x, PM_{10},O_3, Met
New Germany	2014- ongoing	Network expansion	SO_2, NO_x, PM_{10},O_3, Met
Cato Ridge	2014- ongoing	Network expansion	SO_2, NO_x, PM_{10},O_3, Met

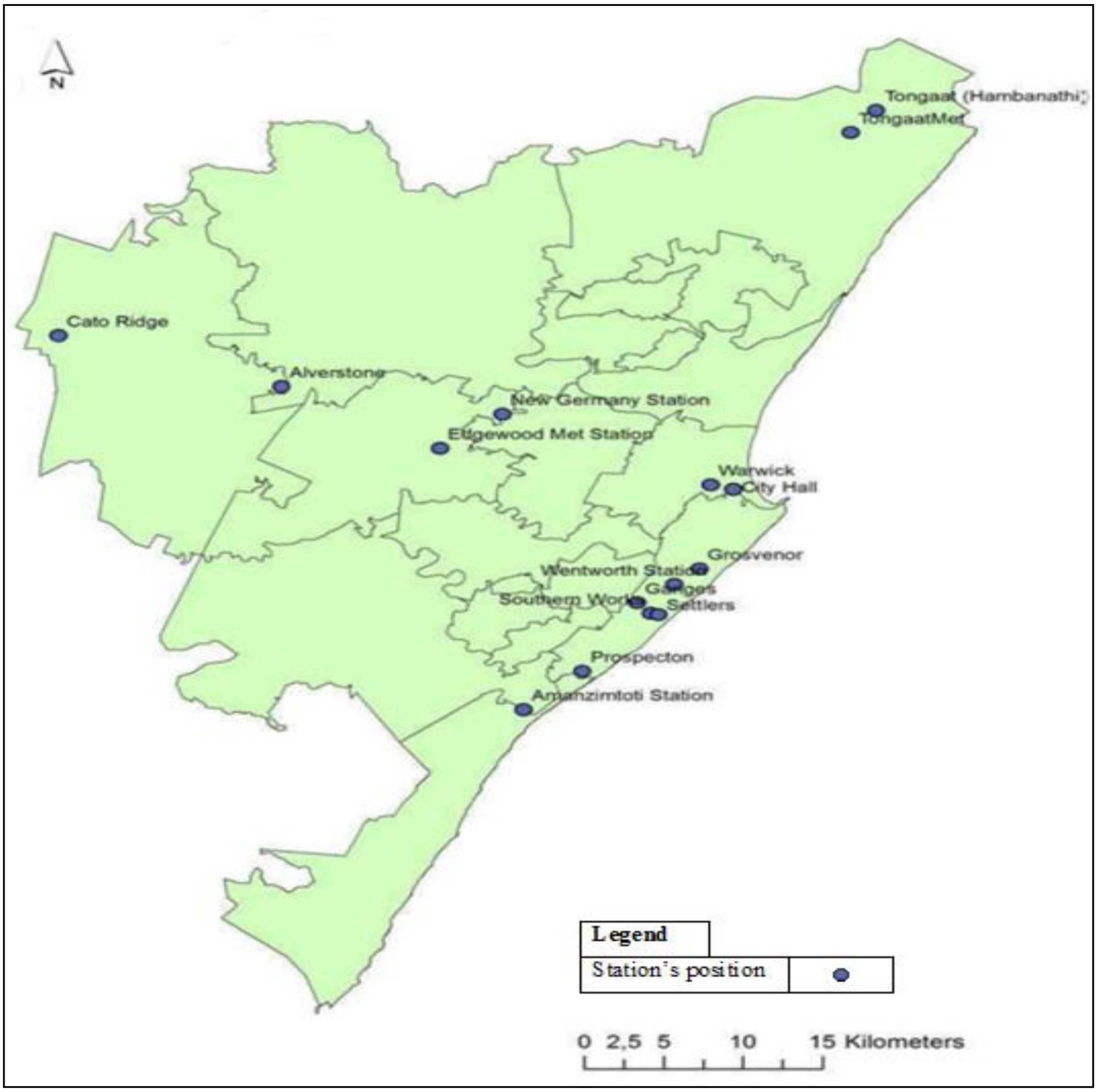

Figure 9: Location of monitoring stations throughout eThekwini Municipality

4.3) GHG emission inventory

A GHG emissions inventory quantifies anthropogenic GHG emissions for a given process, system or country for a specific time (Hillmer-Pegram *et al.*, 2012). The primary focus of GHG inventory is to collect and process emission data timeous so as to inform policy and decision making (Chavez and Ramaswami, 2011). The generic approach for compiling a GHG emissions inventory entails compiling data on activities that emit or remove GHG emissions (Hillmer-Pegram *et al.*, 2012). This is an iterative and exhaustive process which requires the collection of a variety of data measured directly or indirectly. Extensive data collection, justification, tedious assessment of uncertainties, completeness, consistency in methodology and accuracy needs to occur to the highest degree (IPCC, 2006). The choice of GHG sources and activities will depend upon the study location and its boundaries (Bader and Bleischwitz, 2009; Hillmer-Pegram *et al.*, 2012). This often provides the initial steps towards drafting a climate change response strategy, by acting as an indicator of emissions intensive sectors and providing a baseline measurements against which climate targets are set (Ibrahim *et al*, 2012). Fundamentally the general equation for the direct measurement of GHG emissions involves direct monitoring and stoichiometry. This is given as:

$$\text{GHG emissions} = \text{Emissions Data} \times \text{GWP} \times (12/44) \quad \ldots.[19]$$

Where GHG emissions are given in metric tonnes of CO_2 equivalent (tCO_2eq) and emissions data refers to the actual weight of the gases calculated in teragrammes (TG).

However, the equation most often employed for estimating GHG emissions is based upon emission factors as illustrated in equation 20 (IPCC, 2006):

$$\text{GHG emissions} = \text{Activity data (AD)} \times \text{emission factors (EF)} \times \text{GWP} \quad \ldots.[20]$$

Where:

Activity data refers to the intensity of human activity, which varies according to each of the inventory components. Emission factors refer to the emission per unit of activity and GHG emissions are expressed as tCO_2eq per unit activity (Ibrahim *et al.*, 2012).

4.4) Methods for estimating GHG, precursor gases and acidifying pollutants from the road transport sector

4.4.1) GHG emission inventory method: Inter-governmental Panel on Climate Change (IPCC)

The IPCC (2006) emissions inventory guidelines are intended for the compilation of national inventories. Despite this it is possible to use these guidelines at the local level. The IPCC (2006) inventory methods are production based which implies that GHG emissions data calculations are based on emission factors from national scenarios and estimates (Bastianoni *et al.*, 2004). Inventory guidelines exist in particular for CO_2, N_2O and CH_4. Also included are nitrogen trifluoride (NF_3), trifluoromethyl sulphur pentafluoride (SF_5CF_3), halogenated ethers, and other halocarbons (IPCC, 2006). These emissions should be reported in tonnes of CO_2 equivalent (tCO_2eq) using the most recent IPCC global warming potentials. Also included are precursors gases such as NO_x, NH_3, NMVOC, CO and SO_2 (IPCC, 2006). It is further recommended that the IPCC (2006) standard be utilised by cities or local municipalities which possess a population of more than one million people.

The overall accuracy of the IPCC (2006) methodology depends on the particular tier utilised. Tiers are described as the level of complexity within a methodology, which eventually influences the data collection process. Tier 1 is a simplistic method. Tier 2 is an intermediate level of complexity and Tier 3 has the most complex methodology in terms of data collection. Tier 1 utilises the default emission factors combined with unspecific activity data making it feasible for all countries to use, even those without proper data records. However this means that Tier 1 is not considered to be the most accurate and context specific choice. Tier 2 and Tier 3 are the higher tier methods and regarded as being more accurate since these tiers employ detailed country specific disaggregated activity data and emission factors (IPCC, 2006).

The IPCC (2006) guidelines provide an affluent and diverse data base with default emission factors which are recognised internationally even when national emissions data are lacking. Decision trees and detailed equations for each tier provide guidance with regards to collecting information and activity data at each step to estimate emission factors when these are lacking. The IPCC methodology considers both anthropogenic GHG emissions and anthropogenic GHG emissions removals in its main sectors such as energy, transport, industrial processes and product use, agriculture, forestry, waste and other indirect emissions. Identifying vital sectors that have a major influence on GHG emissions which are country or city specific is often the first step in this methodology. These sectors are further divided into sub-sectors, with inventories having to be compiled for each sub-sector by adding the emissions and removals for each gas. The sum of the emission inventories for these sub-sectors makes up the total inventory (IPCC, 2006).

Consistent guidelines are thus developed for countries to estimate their overall GHG emissions however cities differ in terms of scale, processes, service and production flows (IPCC, 2006). Thus when utilising the IPCC (2006) guidelines at city-scale, not all reporting rules need to be followed. Major emission sectors such as aviation and marine are excluded. The IPCC (2006) guidelines only accounts for emissions from local production, in accordance to the territorial principle, thus emissions from imported products linked to final consumption are not included. This has major implications on cities whose major economic activity is domestic, because these cities will report high emissions, even though the product is not necessarily consumed within its borders. Cities who are major importers of products, will report low emissions due to low production, even though they are major consumers and this is therefore not representative of their contribution to global GHG emissions flows (IPCC, 2006).

4.4.2) Choice of calculation methods for road transport

Identifying a fitting methodology for estimating road transport emissions requires a decision tree which is specific to the road transport sector. This will also depend upon the local context (data availability etc). Given the importance of the road transport sector, it is fitting to utilise a decision tree when applying a tier methodology. The emission estimation methodology must also cover exhaust emissions of NO_x, CO_2, N_2O, NH_3, SO_x, exhaust PM. The listed emissions can be categorised into the following groups:

- Group 1: pollutants for which a detailed methodology exists. This is based on specific emission factors for engine conditions and urban, rural and highway traffic. The pollutants found within this group are NO_x, N_2O, NH_3 and PM.
- Group 2: pollutants are estimated based on fuel consumption and the results are of the same quality as those for the pollutants in group 1. These pollutants are CO_2 and SO_2.

4.4.2.1) Tier 1 methodology

Figure 10 below illustrates the procedure to select a method for estimating exhaust emissions from the road transport sector within any nation. The Tier 1 methodology uses fuel as the activity indicator along with average fuel specific emission factors with appropriately wide upper and lower values. This is based on the Tier 1 methodology described in the IPCC (2006) guidelines above. This yields an inventory that is disaggregated according to the four vehicle sectors. Road transport is almost certainly a major sector in all countries. Thus the Tier 1 method should only be used if there is a lack of more detailed information other than fuel statistics. Despite this all efforts need to be made to collect the detailed statistics required for use with the higher tier methods, preferably Tier 3 (Ntziachristos and Samaras, 2014).

4.4.2.1.1) Equation

The Tier 1 approach for exhaust emissions uses the following general equation (Ntziachristos and Samaras, 2014):

$$E_i = \sum_j \left(\sum_m (FC_{j,m} \times EF_{i,j,m})\right) \quad ....[21]$$

Where:

E_i = emission of pollutant i [g],

$FC_{j,m}$ = fuel consumption of vehicle sector j using fuel m [kg],

$EF_{i,j,m}$ = fuel consumption-specific emission factor of pollutant i for vehicle sector j and fuel m [g/kg]. The Tier 1 emission factors ($EF_{i,j,m}$) have been calculated based on the Tier 3 method.

4.4.2.1.2) Activity data

Tier 1 requires relevant fuel statistics for each type of fuel sold for road transport. The fuels to be considered include gasoline, diesel, LPG and compressed natural gas (CNG). For the majority of fuels these statistics are usually available at a national level. CNG for most countries has a negligible contribution to emissions at present. The Tier 1 methodology also requires that the fuel sales are disaggregated according to the four vehicle sectors (Ntziachristos and Samaras, 2014). The vehicle sectors to be considered are passenger vehicles, light commercial vehicles, heavy commercial vehicles and motorcycles. Equation 21 requires the fuel consumption statistics to be split by vehicle sector, as South African national statistics do not provide such vehicle sector details this tier was not chosen for this study.

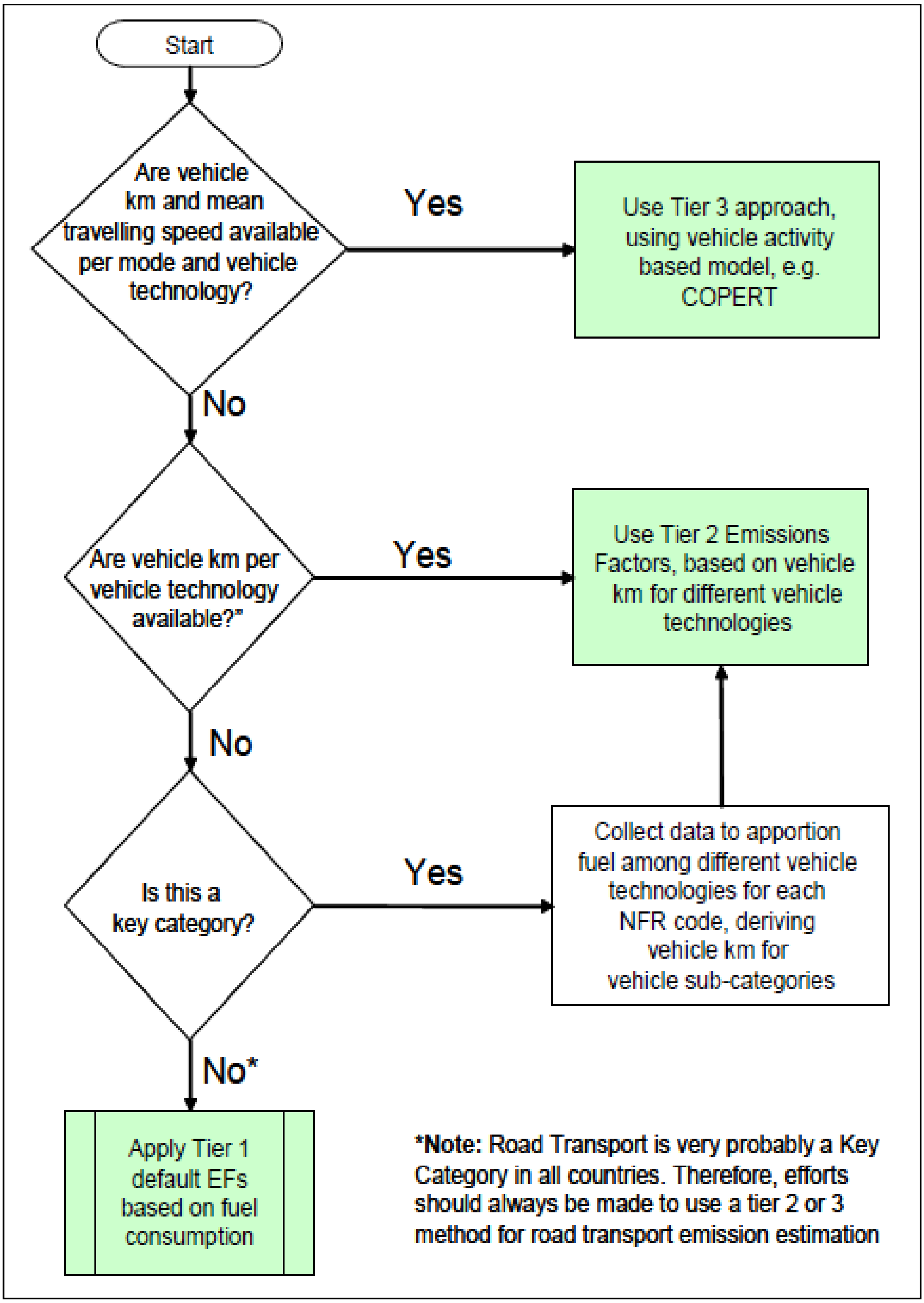

Figure 10: Decision tree for road transport exhaust emissions (Ntziachristos and Samaras, 2014)

4.4.2.2) Tier 2 methodology

4.4.2.2.1) Equation

Tier 2 method considers the fuel type utilised by vehicle sectors and their emission standards in this case. Thus the four broad vehicle sectors used in the Tier 1 approach have to be sub-divided into different technologies, (k) according to relevant emission control legislation, along with the number of vehicles and the annual mileage per technology. These vehicle km data are multiplied by the Tier 2 emission factors. Hence equation 22 or 23 used is (Ntziachristos and Samaras, 2014):

$$E_{i,j} = \sum_k (\langle M_{j,k} \rangle \sum EF_{i,j,k}) \ldots . [22]$$

or

$$E_{i,j} = \sum_k (N_{j,k} \sum M_{j,k} \sum EF_{i,j,k}) \ldots . [23]$$

where,

$\langle M_{j,k} \rangle$ = total annual distance driven by all vehicles of sector j and technology k [veh-km],

$EF_{i,j,k}$ = technology-specific emission factor of pollutant i for vehicle sector j and technology k [g/veh-km]. The units for Tier 2 emission factors are given in grammes per vehicle-kilometre (g/km). These average European emission factors were determined using the Tier 3 methodology which follows in using typical values for driving speeds, ambient temperatures, highway, rural, urban mode mix and fuel composition,

$M_{j,k}$ = average annual distance driven per vehicle of sector j and technology k [km/veh],

$N_{j,k}$ = number of vehicles in nation's fleet of sector j and technology k.

4.4.2.2.2) Activity data

Tier 2 approach requires relevant fleet composition and fuel statistics for each type of fuel sold for road transport available from the national government. For the majority of fuels these statistics are usually available at a national level. CNG for most countries has a negligible contribution to emissions at present. Data on the annual distance driven per vehicle technology can be calculated on the basis of appropriate assumptions for annual mileage or scientific literature. Then by applying a trial and error approach, it is possible to reach a good match between the calculated and the statistical fuel consumption per fuel (Ntziachristos and Samaras, 2014).

4.4.2.3) Tier 3 methodology

4.4.2.3.1) Exhaust emissions

The Tier 3 method calculates exhaust emissions based on a combination of reliable, verified data (e.g. emission factors) and activity data. In the Tier 3 approach, total exhaust emissions from road transport are calculated by the addition of three different sources namely: hot emissions, cold start emissions and evaporative emissions, during engine warm up and cool down (Ayemang *et al.*, 2010). The difference between emissions during the hot stabilised phase and the warming up phase is vital because of the large difference in vehicle emissions emitted during these two periods. Emissions of some pollutants during the warming-up period are many times higher than during hot operation and a different methodological approach is required to estimate the additional emissions during this period (Ntziachristos and Samaras, 2014). These exhaust emissions are the major component of emissions from road vehicles. It further consists of vehicle start-up and running emissions, which are emitted when the engine is running at optimum temperature. Start-up emissions may either be from a cold start or a warm start which will depend on the temperature of the engine when started (Gkatzoflias *et al.*, 2012). Figure 11 illustrates the concept of vehicle emission stages as a function of engine temperature.

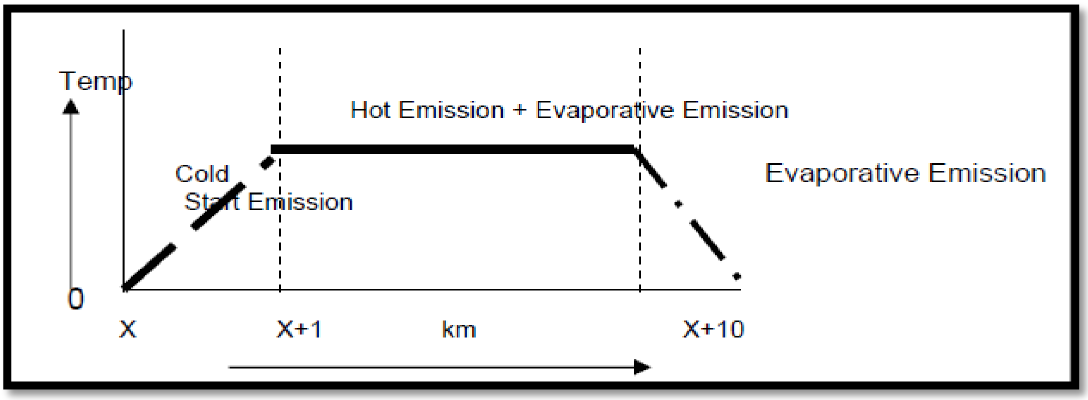

Figure 11: Concept of vehicle emission stages (Nzitachristos and Smit, 2014)

4.4.2.3.2) Evaporative emissions

Emissions from vehicles can be separated into two categories: exhaust and evaporative emissions (Agyemang-Bonsu *et al.*, 2010). The minor component, evaporative or vapour emissions, is composed almost entirely of volatile organic compounds (VOC’s). These are emitted through running losses which are incurred when a vehicle is operated at optimum temperature. “Hot soaks” emissions are a consequence of fuel evaporation from a hot engine at the end of a journey; “diurnal” emissions are due to the evaporation of fuel from the gasoline tank which results in emission of non-methane volatile organic compounds (NMVOCs) whether the engine is engaged or not (Ayemang *et al*., 2010; Gkatzoflias *et al*., 2012; Nzitachristos and Smit, 2014).

Having gained insight into the requirements needed to apply either Tier 1, Tier 2 or Tier 3 methodologies, from the discussion it is evident that only a Tier 2 or Tier 3 methodology should be applied when estimating emissions from the road transport sector (Ntziachristos and Samaras, 2014). Based on a lack of reliable verified emission factors and other required data inputs cited in section 4.4.2.3.1 a Tier 2 methodology was employed to calculate emissions from the road transport sector within this study.

4.5) Emissions inventory model choice

The estimation of GHG, air pollutants and precursor gas emissions from on and off road vehicles are required to effectively carry out planning within the road transport sector. Emission inventory models are vital tools which are required to inform decision making and complete such planning. Emissions inventory models permits one to alter the fleet structure, technology, vehicle activity and proportions of driving conditions in order to estimate the total fuel consumption and emissions for a particular area or fleet. Such models consist of fuel consumption, emission factors from emissions measurement programmes and estimates from fuel consumption and emissions simulation models. Various emissions inventory models exist with some being more popular than others. This section briefly presents key European and American vehicle emission models which includes COPERT, HBEFA (Handbook of Emission Factors for Road Transport), ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems), MOVES (Motor Vehicle Emission Simulator) and MOBILE. Their databases, advantages, disadvantages, modelling approaches are discussed below.

4.5.1) Types of emission inventory models

Models used to estimate the emissions produced from transportation system can be classified into static models and dynamic models. Static models are classified to average speed models and aggregated emission factor models which are easier to use. This approach tends to model emissions and fuel consumption factors based on macroscopic activity type and quantity of fossil-fuel consumed, transport productivity and mileage. Dynamic models are classified to traffic situation models which are often more complex. This approach tends to model emissions at street level and then calculate urban scale inventories by an integration process. Such approaches are characteristic of finer resolution, better accuracy, instantaneous speed capability of evaluating emission through dynamic traffic control, detailed specifications of the transport fleet and also the road class (Elkafoury *et al*., 2013).

4.5.1.1) Static models

4.5.1.1.1) MOBILE 6

MOBILE 6 vehicle emission factor model is a software tool for predicting gram per mile emissions of hydrocarbon, CO, NO_x, CO_2, PM and emissions for mobile sources under various driving conditions. The purpose of this model is to determine regional mobile emissions inventories and to inform air quality management and planning (EPA, 2003). MOBILE 6 is classified as an aggregated emission factor model which means that it operates at a simplistic level with a single emission factor being used to represent a particularly broad category of vehicle and a general driving (Wang and Mcglinchy, 2009).

MOBILE 6 consists of a database of emission factors developed from the federal test procedure which is inclusive of a range of vehicle types, capacity classes, technologies, age and average speeds (EPA, 2003). MOBILE 6 also allows the users to adjust the database of emission factors for many of these parameters. The MOBILE 6 modelling process is advantageous given that it is straightforward. On the other hand MOBILE 6 models group all passenger cars in one class without considering vehicle technologies used (Elkafoury *et al*., 2013). This combined with the fact that MOBILE 6 is unable to account for road gradient means that it only provides a qualitative description of emissions. The database of emission factors are derived from federal test procedure emission data rather than “real-world” driving cycles making it unsuitable for countries other than the USA proving to be a further disadvantage (EPA, 2003; Wang and McGlinchy, 2009).

4.5.1.1.2) MOVES

Released in 2014, the EPA has now replaced MOBILE with MOVES as the official emissions model, which estimates CO_2, N_2O, CH_4, CO, NO_x, SO_2, PM, NH_3 and hydrocarbon emissions from mobile sources at the national, county and project level (Koupal *et al*., 2003; EPA, 2015). The purpose of MOVES is to create emission factors or emission inventories and provide an accurate estimate of both on and off road mobile emissions (Wang and

McGlinchy, 2009). MOVES differs from the previous MOBILE model in that it is clearly designed to use the same set of emission rates at a large scale (national-level inventories) and at a small scale (street level inventories) whilst generating emissions from both on and off road vehicles (Koupal *et al.*, 2003). MOVES also incorporates new technology vehicles such as hybrid and hydrogen vehicles making it capable of incorporating modern fleets (Elkafoury *et al.*, 2013).

The MOVES model includes a default database that summarises emission relevant information specifically for the United States of America. With this design new data that may become available can be easily be added to the database which easily updates the model. In addition MOVES may be customised as per the user's wishes, which allows and facilitates for the import of data specific to a user or a local area (EPA, 2015). This is advantageous since coupling MOVES emission rates with different sources of high-resolution vehicle activity data can further enhance and inform research efforts designed to assess the environmental impacts of the transportation sector. However the MOVES interface is complicated and the structure of input variables and algorithms involved in running MOVES is time consuming. This makes it difficult to assess more complicated transportation networks and to undertake analyses of larger more transportation systems without proper training and data acquisition (Elkafoury *et al.*, 2013; Guensler *et al.*, 2016).

4.5.1.1.3) Fuel based emissions inventories

Fuel based emissions inventories are primarily utilised to estimate total emissions when there is a lack of vehicle activity data and detailed emission factors. Such emissions inventories use fuel consumption as a proxy to estimate vehicle emissions (Schifter *et al.*, 2005; Singer and Harley, 2000). Fuel based emissions inventories are calibrated for typical emission factors per unit fuel consumed and overall driving conditions using remote roadside emissions measurements which measure the ratio of different gases in exhaust fumes.

4.5.1.2) Dynamic models

4.5.1.2.1) HBEFA 3.2

The HBEFA is a database of emission factors and set of predefined fleet structures for Germany, Austria, Netherlands, Sweden and Switzerland. Emission factors are provided for CO, NO_x, CO_2, NH_3, N_2O, NO_2, hydrocarbon, fuel consumption and non-regulated air pollutants. The HBEFA in its most recent version 3.2 was updated in 2014 and has been designed for the development of emission factors for Germany, Austria, Netherlands, Sweden and Switzerland. Version 3.2 is classified as a traffic situation model (Rexeis, 2013). This modelling approach incorporates speed, road gradients, cold start situations, air conditioner use, and traffic situations into emission estimation (Elkafoury *et al.*, 2013). Such traffic situations are defined qualitatively in accordance with specific road types, average speeds and traffic conditions (e.g. urban free flow, urban congested, stop-and-go) which can be applied equally to all vehicle categories in Germany, Austria, Netherlands, Sweden and Switzerland. Traffic situations are linked to specific driving patterns for each vehicle category which may be expressed as a speed-time curve (Franco *et al.*, 2012).

Emission factors for these underlying driving patterns originate from emission test results and extensive analyses of driving behaviour. The emission factors for each traffic situation are then calculated by combining and weighting the emission factors of these driving patterns. This is based on analyses of statistical base data obtained through transport surveys and vehicle registration data. This has been achieved in HBEFA by using a computer program called "Art.combino" through linear combinations (Wang and McGlinchy, 2009; Rexeis, 2013).

The driving patterns and traffic situations in HBEFA have been specifically based on the driving characteristics in Germany, Austria, Netherlands, Sweden and Switzerland and the resultant emission factors are intended for use in those countries only. As such caution should be taken when applying the emission factors of individual traffic situations in HBEFA to other countries (Wang and McGlinchy, 2009). Unlike MOBILE 6 or MOVES, HBEFA does not allow the user to change mileage, fleet structure and vehicle emissions regulations. As such the user has to compile their own scenarios of fleet structure, travel demand and technologies external to the model which is often labour intensive and time consuming. Because of this, emission factors from the HBEFA database are often extracted and implanted in other models such as COPERT. This provides facilities to consider possible scenarios and policy options within the European context (Franco *et al.*, 2012; Rexeis, 2013). Similar to MOVES, HBEFA requires a large and diverse data set which can be hardly found and be reconciled for an entire country (Elkafoury *et al.*, 2013).

4.5.1.2.2) ARTEMIS

ARTEMIS aims to compile an improved emission model for road transport through a synchronised methodology for national and regional inventories. To achieve this ARTEMIS integrates and combines the emission data from other models (COPERT and HBEFA). Because of this ARTEMIS has emerged as one of the most comprehensive road vehicle emission models in the world which may be applied at both the macro and the micro level (Wang and McGlinchy, 2009).

ARTEMIS consists of five sub-models for calculating hot exhaust emissions. This includes the traffic situation model, the average speed model, the kinematic regression model and two instantaneous models, with the last three being for passenger cars and light commercial vehicles only. Although the instantaneous and kinematic models are the best way to take account of driving dynamics, they need complex kinematic data and are generally difficult to use. In contrast, the traffic situation approach is capable of taking into consideration the kinematics in a more reliable but relatively simple way (Sjödin and Jerksjö, 2008; Wang and McGlinchy, 2009).

The approach followed by ARTEMIS is similar to that of traffic situations used in the HBEFA, although the methodology has been refined (Sjödin and Jerksjö, 2008; Elkafoury *et al.*, 2013). Parameters such as the area (urban, rural), the road type, the speed limit and the level of traffic congestion have been used to define over 200 typical traffic situations in Europe. ARTEMIS is at an advantage given that it can simulate driving dynamics in a more reliable yet simpler way. However as discussed in the HBEFA section, caution must be taken when applying the emission factors of individual traffic situations in ARTEMIS to other countries outside the Europe since these traffic situations were developed based on European driving characteristics. Traffic situation models also require a large and diverse data set about speed and the corresponding traffic situation (Elkafoury *et al.*, 2013).

4.5.1.2.3) COPERT IV

COPERT is classified as a static average speed model. Such models are the most commonly used and are based on the premise that average emissions over a trip differs according to the average speed of the trip (Elkafoury *et al.*, 2013). Average speed models are advantageous for a number of reasons (Sjödin and Jerksjö, 2008). Firstly the models are user friendly easy to operate and model inputs and the data available to users correspond relatively well.

However the most important concern is that the same average speed may be achieved through very different driving patterns, which does not describe the instantaneous situation of the vehicle. This results in varied emission levels, particularly at lower average speeds. In addition, average speed has been found to be a less reliable indicator for the emissions from vehicles of new generations (Wang and McGlinchy, 2009; Elkafoury *et al.*, 2013).

Despite being classified as a static model, it has been shown that the speed used for calculating emission in the latest versions of COPERT IV is sub classified so that different vehicle technologies in every speed range has its own unique emission factor for hot emissions and cold start emissions. In this case, COPERT IV can be classified as both a static and dynamic model, making it appropriate for use in both micro and macro scale applications (Elkafoury *et al.*, 2013). Given this insight and its ease of use COPERT IV was chosen to model traffic emissions in this study.

COPERT IV is a computer based tool consisting of a collection of equations and emission factors recommended for the calculation of emissions from road networks (Ayemang *et al.*, 2010; Nzitachristos and Smit, 2014). COPERT IV may be applied in an air quality and impact assessment; compilation of urban/regional inventories; projections of energy, CO_2 and pollutants across various vehicle categories and fleets based on fuel consumption (Gkatzoflias *et al.*, 2012). COPERT IV is utilised by several European member states in their official reporting of national emission inventories for road transport (Kousouslidou *et al.*, 2010). The COPERT IV model has the ability to estimate various vehicular emissions that include CO_2, N_2O, CO, CH_4, SO_2 and NO_x on the basis of fuel consumption per vehicle sector (Stroe *et al.*, 2014; van Hulsel *et al.*, 2014). COPERT has a similar limitation as MOBILE in that it uses average speeds, but it is able to compensate for road gradient using correction factors (developed from additional emissions tests), and for congestion by altering the fractions of urban and inner city travel.

Emission factors are expressed in terms of emissions per kilometres or emissions per consumed unit of fuel within COPERT IV (Gkatzoflias *et al.*, 2012). With regards to emissions other than $CO_{2,}$ the emission factors are reasonably defined within the model as a function of parameters based on a large number of measurements and field experiments conducted. The calculation of emission factors depended on the COPERT IV program, which required the compilation of reliable data (Cai and Xie, 2007; Ayemang *et al.*, 2010).

Thus equation 24 uses an appropriate model, namely COPERT IV to estimate emissions based on Tier 3 methodology (Ntziachristos and Samaras, 2014):

$$E_{TOTAL} = E_{HOT} + E_{COLD} \ldots.[24]$$

where,

E_{TOTAL} = total emissions (g) of any pollutant for the spatial and temporal resolution of the application,

E_{HOT} = emissions (g) during stabilised (hot) engine operation,

E_{COLD} = emissions (g) during transient thermal engine operation (cold start).

The variation of emissions within these three phases must also be considered due to the significant difference in vehicle emission when performing under varying driving conditions (Cai and Xie, 2007; Ayemang *et al.*, 2010). Different activity data and emission factors are specific to each driving situation. Cold-start emissions are attributed mainly to urban and rural driving, as it is expected that a limited number of journeys start at highways. Thus for driving conditions, total emissions can further be calculated by means of the equation 25 within the model (Ntziachristos and Samaras, 2014):

$$E_{TOTAL} = E_{URBAN} + E_{RURAL} + E_{HIGHWAY} \ldots.[25]$$

where:

E_{URBAN} = total emissions (g) of any pollutant for the urban driving situations.

E_{RURAL}= total emissions (g) of any pollutant for the rural driving situations.

$E_{HIGHWAY}$ = total emissions (g) of any pollutant for the highway driving situations.

Overall this method entails that total emissions are calculated using activity data for each vehicle sector with suitable emission factors. The emission factors differ with regards to the input data per nation (driving situations, climatic conditions), making it suitable for the South African context (Ntziachristos and Samaras, 2014). A summary of the variables and data required by COPERT IV and the intermediate calculated values is illustrated in Figure 12.

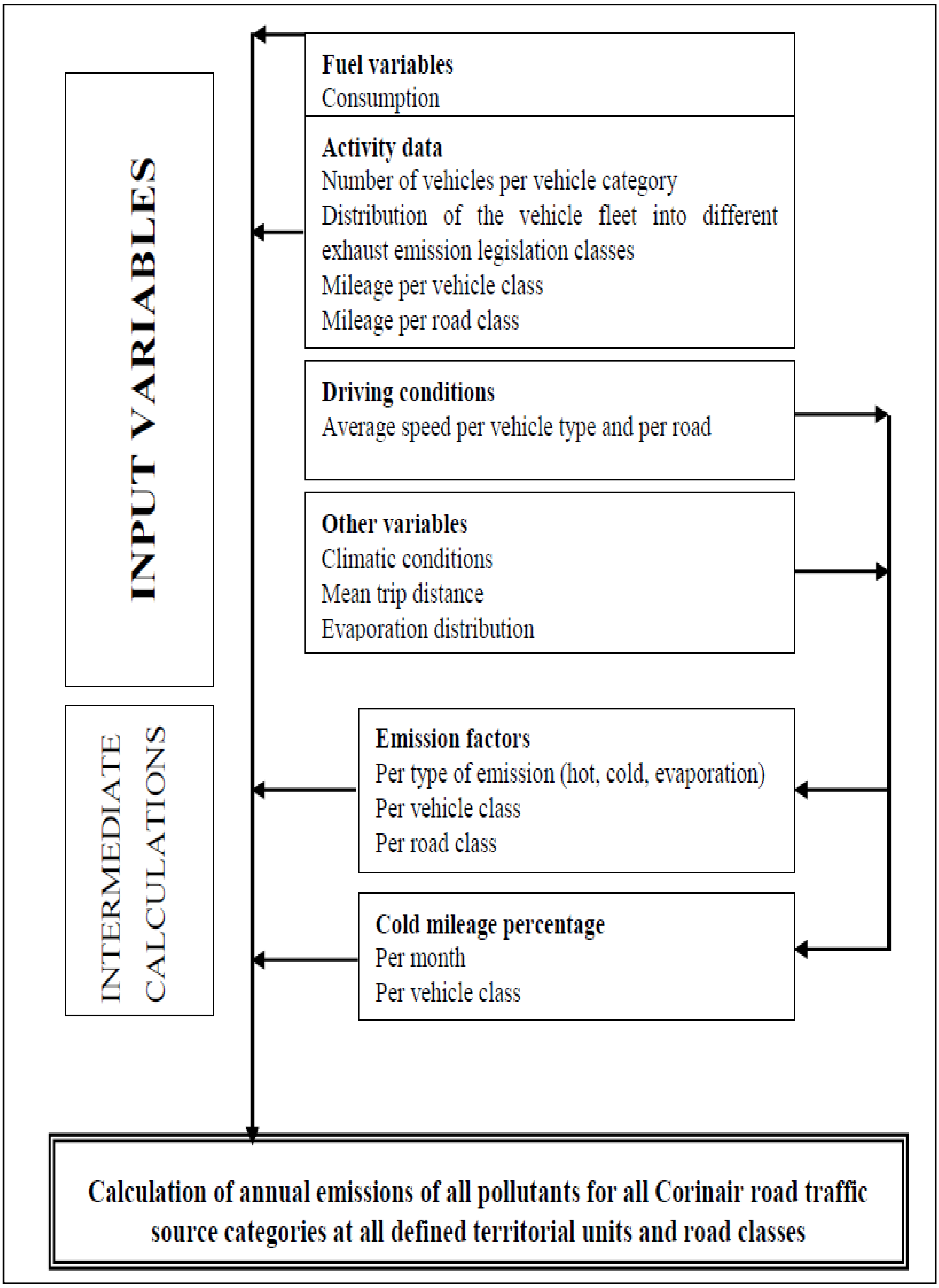

Figure 12: Flow chart for the use of Tier 2 methodology within COPERT IV (Ntziachristos and Samaras, 2014)

4.6) Data compilation and emission estimates for eThekwini Municipality

The following discussion outlines the decisions taken and method selected to achieve the study's aims and objectives. Consideration was also given to the cost and the detail required for the academic level at which the study was to be conducted at. Based on the Tier 2 methodologies (section 4.4.2.2) and having adhered to its guidelines, total emissions in this study were calculated by means of COPERT IV emissions inventory model for the year 2010. In addition, a review of literature in relation to the South African fleet was conducted and concluded that COPERT IV is suitable for South Africa. This is based on key findings which included the identification of similarities between European and South African vehicle fleets (Wong, 1999; Merven *et al.*, 2012). Reviews indicate that the emission factors produced for South Africa by Wong and Dutkiewicz (1998) and Stone (2000) are generally coherent with the emission factors employed by the COPERT IV model when available. This allows for the use of European transport emission models particularly COPERT IV for this investigation (Stroe *et al.*, 2014). By considering all of these variables COPERT IV was employed to calculate and quantify vehicular emissions for eThekwini Municipality. The following describes the data utilised and assumptions made when applying this methodology to obtain emission estimates.

COPERT IV was tasked with generating total emissions and emission factors of 8 vehicular pollutants for eThekwini Municipality. The estimation of emissions relied on the identification of the variables and data required in Figure 12. Data were sourced and acquired primarily by means of data requests to the respective organisations and through publicly available data from the respective government websites. In most cases the data compiled spanned a period from 2004 to 2014, however only data up to the year 2010 was entered into the model as this was the upper limit of the information recorded within the registered on and off road vehicle database provided by electronic National Administration Traffic Information System (eNATIS) (Table 12). As such this study analysed data and produced emissions for the year 2010. Data collection and processing are outlined in the steps below and assumptions and procedures needed to identify and obtain these required parameters are described for eThekwini Municipality.

Table 12: Data sources and their respective range.

Data type	**Data source**	**Period**	**Reference**
Registered vehicle database	eNATIS	1900-2010	eNATIS, 2011
Fuel consumption	Department of Energy	2005-2013	Department of Energy, 2015
Technology/emission standard	eNATIS	1900-2010	Automobile Association, 2014;Diesel net, 2015
Distinction of vehicle class to engine capacity	eNATIS	1900-2010	eNATIS, 2011
Telematics/circulation	Published literature		SA, 1996;Merven *et al.*, 2012
Reid vapour pressure (RVP)	South African National Standards (SANS) and Petroleum Products Act		SANS, 2006a,b; South African Petroleum Industry Association (SAPIA), 2008;Petroleum Products Act, 2011
Ambient air quality data	SAAQIS	2004-2014	SAAQIS, 2015
Meteorological data	South African Weather Service (SAWS)	2009-2014	SAWS, 2015

4.6.1) Population of each vehicle sector and class

Data concerning on and off road vehicle population for eThekwini Municipality up until 2010 were obtained from the eNATIS vehicle registration database. The eNATIS (2011) vehicle database had to be appropriately filtered to assemble input data for COPERT IV. This entailed the classification of vehicles into appropriate categories. This was carried out by using the vehicle registration details which enabled one to filter out excess vehicles by first selecting the appropriate province (KZN) and licensing office (Amanzimtoti, Durban Windsor Park, Pinetown, Umbumbulu and Umhlanga). Information on all of the vehicles sectors (passenger, light commercial vehicle (LCV), heavy commercial vehicle (HCV) and motorcycles) registered to the eThekwini Municipality were tallied and overall totals for each type was recorded.

4.6.2) Technology and emission standard

Given the lack of detail in terms of exact age distributions of the vehicles within eNATIS, the year in which registration occurred was used to allocate vehicles to European emission standards by applying the appropriate filters to different time periods (Automobile Association, 2014).

4.6.3) Distinction of vehicle sector according to age, fuel type and engine capacity

The model required that vehicles be classified in accordance to the designated COPERT IV sub-classes; hence each of the 4 vehicle sectors had to be disaggregated into separate sub-classes by filtering for vehicles type, age, fuels consumed and engine capacity simultaneously (Nzitachristos and Smit, 2014). However when details in terms of fuel type and engine capacity were not present within the database, assumptions had to be made.

These included adding entries on the eNATIS with an engine capacity of zero, none blank or unknown to the smallest available category in COPERT IV (<800 cc category) for the appropriate vehicle type. It was also assumed that such entries would be light passenger vehicles because it primarily used petrol and diesel as a fuel source. Similarly in cases were fuel source was ambiguous entries were allocated to the respective vehicle types based on the available engine capacity which obviously meant such vehicles were generating emissions. These values were also added equally to the petrol and diesel sub-totals, For example it is reasonable to assume that a 21000 cc vehicle would have to be a diesel heavy duty truck. All types of alternate energy sources were added to electric sub-totals for each of the vehicle types. Due to the fact that eNATIS did not provide weight distributions for HCV’s, the total number of entries for each technology was divided and distributed across the 15 sub-classes in COPERT IV equally. Motorcycles with an engine capacity of less than 50 cc was added to the succeeding class (< 250 cc) in COPERT IV because vehicles possessing an engine capacity of less than 50 cc are by law not allowed on public roads of South Africa.

Once completed, this 3 step process yielded the exact figures required for each of the pre-determined sub-classes per vehicle type in COPERT IV. This was carried out and filtered entirely within the eNATIS database and proved to be the biggest input into the model.

4.6.4) Meteorological and Reid Vapour Pressure (RVP) data

The meteorological data obtained from the SAWS for the old Durban Airport (2009-2014) weather station yielded mean maximum temperatures, mean minimum temperature (degrees Celsius), mean relative humidity and mean pressure for the year 2010 (SAWS, 2015). The Reid vapour pressure (RVP) was obtained from (SANS, 2006a,b; SAPIA, 2008). These values were used to determine hot and cold start emission since RVP determines fuel content subject to change throughout the year dependent on temperature. This was sourced in addition to the required model parameters to ensure accuracy of the Tier 2 methodology.

4.6.5) Telematics/Circulation information

The average speed and annual mileage accumulated on urban, rural, and freeway roads (Mij) by individual vehicle classes were crucial inputs into COPERT IV when estimating emissions however these data were not directly available through official statistical records. The circulation data therefore required estimation which according to Ntziachristos and Samaras, (2014), could be sourced from average speed which is representative of each of the road type. This was derived from the National Road Traffic Act 1996 (Act No. 93 of 1996): Chapter IX: Road traffic signs and general limits. The following averages for the different driving environments 40 km/hour for rural, 80 km/hour for urban and 120 km/hour for freeway roads. In terms of the annual mileage for each vehicle category, the mileages of 25000 km, 30000 km, 150000 km and 10000 km for passenger cars, LCV's, HCV's and motorcycles were used respectively. These values were based on a review of findings conducted by Merven (*et al.*, 2012).

4.6.6) Fuel Consumption Data

National fuel sales were obtained for all available fuel types from the Department of Energy (2015). Fuel consumption data (2005-2013) was only available for magisterial districts within the municipality. To differentiate between on road fuel usage and off road fuel usage from national sales data sourced from Department of Energy, fuel consumption data for magisterial districts for the year 2010 was used. Petrol and diesel data (in litres) for eThekwini Municipality and its districts were extracted. The amount of petrol and diesel sold at retail garages had to then be apportioned. The apportionment factors were not available for the municipality thus the level national level apportionment factor from the SAPIA (2008) had to be used. These factors were 95% for petrol and 52% for diesel. These factors were based on how much of the petrol and diesel sold at retail garages is actually sold for use in road transportation only and the quantity of the petrol and diesel that is used for agricultural purposes, construction, mining, marine fishing and energy supply (provision of electrical generators). Only a small amount of fuel is used for off road vehicle use so it is plausible to assume that this is not significant. Likewise fuel is predominately locally produced, so it is plausible to assume that any fuel imported is not significant. The quantity of fuel used was given in litres and had to be converted to tonnes per annum by means of an appropriate conversion factor before being entered into the model.

Current fuel specifications for South Africa were obtained (SA, 1977; SANS, 2006a,b; SAPIA, 2008;). This was sourced in addition to the required model parameters (Figure 12) to ensure accuracy (Ntziachristos and Samaras, 2014).

Given that eThekwini Municipality contains numerous road-freight corridors and is a tourist destination it can be reasonably assumed that significant amounts of fuel purchased outside this municipality are used within the municipality and that fuel purchased within this municipality is being transported into other municipalities. An assumption was therefore made that fuel exports and imports in the municipality balance.

4.7) Post-processing

Once all the data was compiled for the year 2010 it was then entered into the appropriate menus and sub-menus of the model. All other minor options within COPERT IV were accepted with the pre-determined values which matched that of the South African environment (Gkatzoflias *et al.*, 2012). Once all parameters had been compiled it was entered into COPERT IV in accordance with Figure 13. When all calculations were finalised the total emissions for eThekwini Municipality were deduced by COPERT IV, with it being displayed by means of graphs and tables, thus illustrating atmospheric loading in the area.

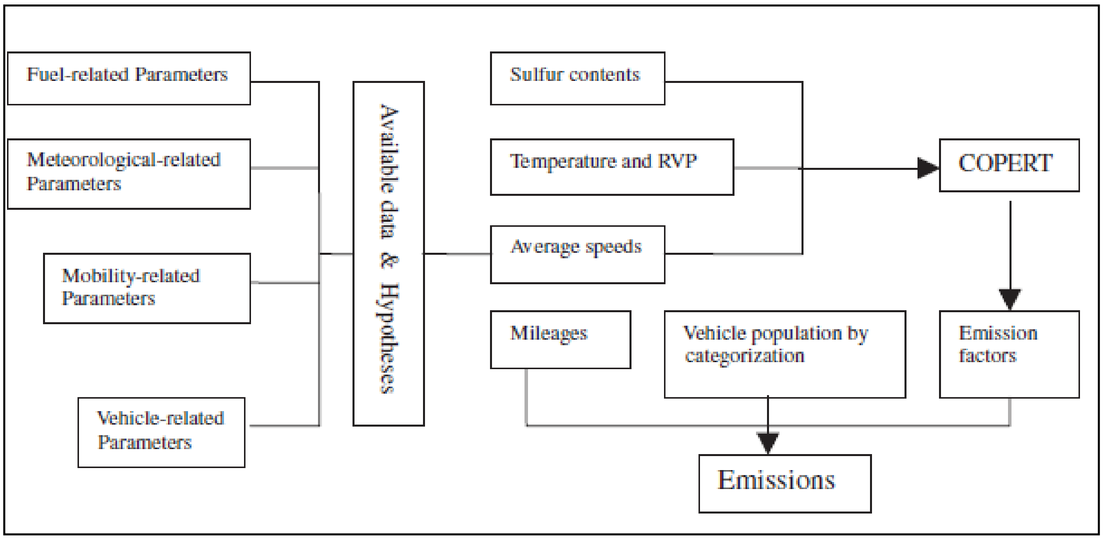

Figure 13: Outline of the procedure required for estimating vehicular emissions in COPERT IV (Ntziachristos and Samaras, 2014)

4.8) Mitigation potential analysis

Upon quantifying all emissions, the current inventory was then used as a baseline to enquire into the mitigation potential and the effectiveness of proposed mitigation measures for eThekwini Municipality's road transport sector. This is based on analysis by the DEA (2014) which has its roots in the IPCC's AR5. Such analysis quantified potential emission reduction at the local level within eThekwini Municipality instead of at the national level. This was calculated using the current inventory with only information regarding the vehicle's emission standard/technology and circulation data having been altered to reflect fleet turnover or uptake of a particular mitigation measure under ideal conditions. In most cases this would entail upgrading the fleet to latest Euro 6 standards for a particular fuel or reducing annual mileage travelled by the fleet.

Before proceeding, mitigation measures recommended by the DEA (2014) were assessed for use within COPERT IV. It was found that no allowances were made for the use of fuel cell electric vehicles (FCEV), diesel hybrid vehicles (HEV), diesel plug in hybrids (PHEV) and pure electric vehicles (EV) within COPERT IV. Therefore its effect could not be modelled within COPERT IV for eThekwini Municipality and was excluded. This is negligible considering how few (0.1%) of these vehicles are actually to be found within the fleet. Even if such vehicle numbers were to double in future, it would still prove to be negligible and therefore will be excluded from any further calculations. This is indicated in Table 13. All other remaining mitigation measures were analysed.

Table 13: Mitigation measures analysed and excluded within COPERT IV.

Mitigation measures (DEA, 2014)	**Corresponding COPERT sub-sectors**	**Fuel type concerned**
Road - improved efficiency – petrol internal combustion engine (ICE)	Gasoline	Standard petrol
Road - improved efficiency - diesel ICE	Diesel	Standard diesel
Road - biofuels	E85	Bio ethanol
Road - alternate fuels – compressed natural gas (CNG)	CNG	CNG
Road - shifting passengers from cars to public transport	Not required	Not required
Road - shifting freight from road to rail	Not required	Not required
Road -alternate fuels - petrol HEV and PHEV	Hybrid Gasoline	Hybrid petrol
Road - alternate fuels - diesel PHEV	N/A	None
Road - alternative fuels – FCEV	N/A	None
Road - alternative fuels - diesel HEV	N/A	None
Road - alternative fuels - EV	N/A	None

With data having already been sorted for use in the initial inventory as discussed above, the simulation of the improved efficiency-petrol ICE and secondly the improved efficiency-diesel ICE mitigation measures both entailed the same steps. Both measures entailed tallying all vehicles which applied to those two mitigation measures regardless of whether that vehicle belonged to the passenger vehicle sector, LCV, HCV or motor cycle sector. The tally thus yielded the number of vehicles which possessed petrol ICE and diesel ICE only. Next the number of assumed vehicles expected to enter the consumer market and have Euro 6 standards across all engine sizes in future were estimated and applied within COPERT IV. This estimation was based on findings from the eNATIS database which indicates that approximately 50% of the current fleet is aged and older than 6 years. These values were then entered into the model and the mitigation potential of improved efficiency- petrol ICE and improved efficiency- diesel ICE were simulated respectively. The simulated total emissions produced by improved efficiency- petrol ICE and improved efficiency- diesel ICE were then subtracted from the baseline value. For improved efficiency- petrol ICE the baseline value was achieved by summing all emissions produced by every petrol engine. For improved efficiency- diesel ICE the baseline value was achieved by summing all emissions produced by every diesel engine. This calculation yielded total emissions mitigated against for each measure.

In the initial inventory, zero vehicles consumed biofuels and alternative fuel-CNG. Thus no emissions were recorded for that point in time. However vehicles making use of petrol HEV and PHEV (although few) were present and produced emissions. To simulate the use of biofuels, alternative fuel-CNG and petrol HEV and PHEV usage in future, these measures underwent the same steps to determine the effect that a 20% uptake of biofuel, alternative-CNG or petrol HEV and PHEV would respectively have on the total emissions produced by the entire fleet of eThekwini Municipality. The use of these measures entailed reducing the current fleet which used traditional fuels by 20% and replacing this with a new fleet of the same size (to maintain fleet size) which consisted of vehicles with latest Euro standards and consumed biofuels or alternative-CNG or petrol HEV and PHEV respectively. These mitigation measures applied to all vehicles from the passenger vehicle sector, LCV, HCV and motor cycle sector. Once the fleet had been altered to reflect 20% uptake of biofuel or alternative-CNG or petrol HEV and PHEV the mitigation potential of these fuels were simulated respectively. The simulated total emissions produced by biofuels and alternative fuel-CNG were then both subtracted from the total emissions produced by the entire fleet of eThekwini Municipality. While the simulated total emissions produced by petrol HEV and PHEV were then subtracted from the total emissions produced in the initial inventory. This yielded total emissions mitigated against for each measure.

The shifting of 20% of passengers to public transport and shifting of 20% freight to rail transport results in reduced annual VKT specifically from the passenger vehicle sector and the HCV sector which results in reduced emissions. As such both of the two measures underwent the same steps which required that annual VKT be reduced by 20% for the passenger vehicle sector and HCV sector. These values were adjusted within the circulation data menu within COPERT IV when assessing the effect of a 20% reduction on the total emissions produced by these two sectors in eThekwini Municipality. The simulated total emissions produced by shifting 20% of passengers to public transport and by shifting 20% of freight to rail transport were then subtracted from the baseline value. For a 20% shift of passengers to public transport the baseline value was the total emissions generated by the entire passenger vehicle fleet in eThekwini Municipality. For a 20% shift of freight to rail transport the baseline value was the total emissions generated by the entire HCV fleet in eThekwini Municipality. This yielded total emissions mitigated against for each measure.

Once all simulations were run, the total emissions produced after applying each mitigation measure was then subtracted from it's baseline values which was obtained from the initial inventory in order to reveal total emissions mitigated against. Negative values indicate an increase in emission production rather than a decrease. This is attributable to the lack of a high initial baseline value and the uptake of alternately fuelled vehicles resulting in greater emissions at a later stage. This is justified by Ntziachristos and Samaras (2014) who indicated that alternative fuels for some countries has a negligible contribution to emissions at present given that uptake of alternatively fuelled vehicles has been limited.

4.9) Conclusion

This chapter outlined steps towards the development of an emissions inventory for GHG, precursor gases and acidifying pollutants from the road transport sector within eThekwini Municipality. This included a description of calculation methods, the COPERT IV model and data inputs used in order to develop the emissions inventory. Tier 2 methodologies were used to calculate both the emissions inventory and the mitigation potential simulation which were modelled for comparison to inform implementation of mitigation measures. Steps were also outlined to illustrate the transformation of data to reveal current the state of ambient air quality. This helped identify morning and afternoon trends with regards to the expected peak traffic volumes and areas which exceeded annual vegetation thresholds of NO_2 and SO_2.

CHAPTER 5: RESULTS AND DISCUSSION

5.1) Introduction

The data and method described in the Chapter 4 were used as inputs into COPERT IV, with the goal of developing an inventory of atmospheric emissions focusing on particular GHG, acidifying pollutants and precursor gases for 2010. Of the three aspects that this chapter describes, the first is the trends and temporal variations of measured ambient concentrations of PM, NO_x and SO_2 relative to the NAAQS within eThekwini Municipality from 2004 to 2014. Secondly a description detailing the composition and information derived from eNATIS of the vehicle sectors is presented and lastly the emission estimates for the 8 pollutants derived from COPERT IV are presented. Lastly findings from the mitigation potential scenarios for eThekwini Municipality are discussed.

5.2) Ambient air quality network findings for 2004-2014

5.2.1) Network findings for NO_2

As of 2014, NO_2 is being measured at 9 continuous monitoring stations throughout eThekwini Municipality in order to assess and comprehend industrial and vehicular emissions on ambient air quality (SAAQIS, 2015). Relative to the NAAQS of 40 $\mu g/m^3$ or 21 ppb, the average annual ambient concentrations of NO_2 were rather elevated and sometimes exceeded the NAAQS at most monitoring stations in an erratic manner (DEAT, 2005; uMoya-NILU, 2015). Warwick, City Hall and Ganges primarily reflected traffic emissions, with the annual NAAQS having been exceeded since 2004 particularly at the Ganges station which is positioned adjacent the M4 highway. It is evident that even till 2014 significant quantities of NO_2 are erratically being emitted by traffic for the data set (SAAQIS, 2015).

Although annual average NO_2 concentrations are elevated, in comparison the number of exceedences of the 1-hour limit value is relatively low (SAAQIS, 2015; uMoya-NILU, 2015). The NAAQS allows for 88 exceedences per annum of the 1-hour limit value of 200 $\mu g/m^3$ or 106 ppb (DEAT, 2005). Most exceedences occurred firstly at Warwick, secondly at Ganges and lastly at City Hall with an exceedence of the NAAQS occurring at Ganges in 2009. In 2009 Ganges surpassed NAAQS with 88 exceedences per annum (Figure 14). These 3 stations unsurprisingly corresponded to traffic, sub-urban traffic and CBD traffic. In terms of these 3 stations listed above, exceedences were recorded on average for all 24 hours of the day for the data set. These stations also recorded more exceedences as compared to those which were positioned closer to industrial point sources. With regards to the industrially located stations, most exceedences occurred firstly at Jacobs, secondly at Wentworth, Southern Works and lastly at Ferndale. The exceedences at these 4 stations can be attributed to industrial emissions however these fell within the allowed value of 88 exceedences per annum (DEAT, 2007a; SAAQIS, 2015). For Jacobs, Wentworth, Southern Works and Ferndale exceedences were recorded on average for 16 hours of the day for the data set.

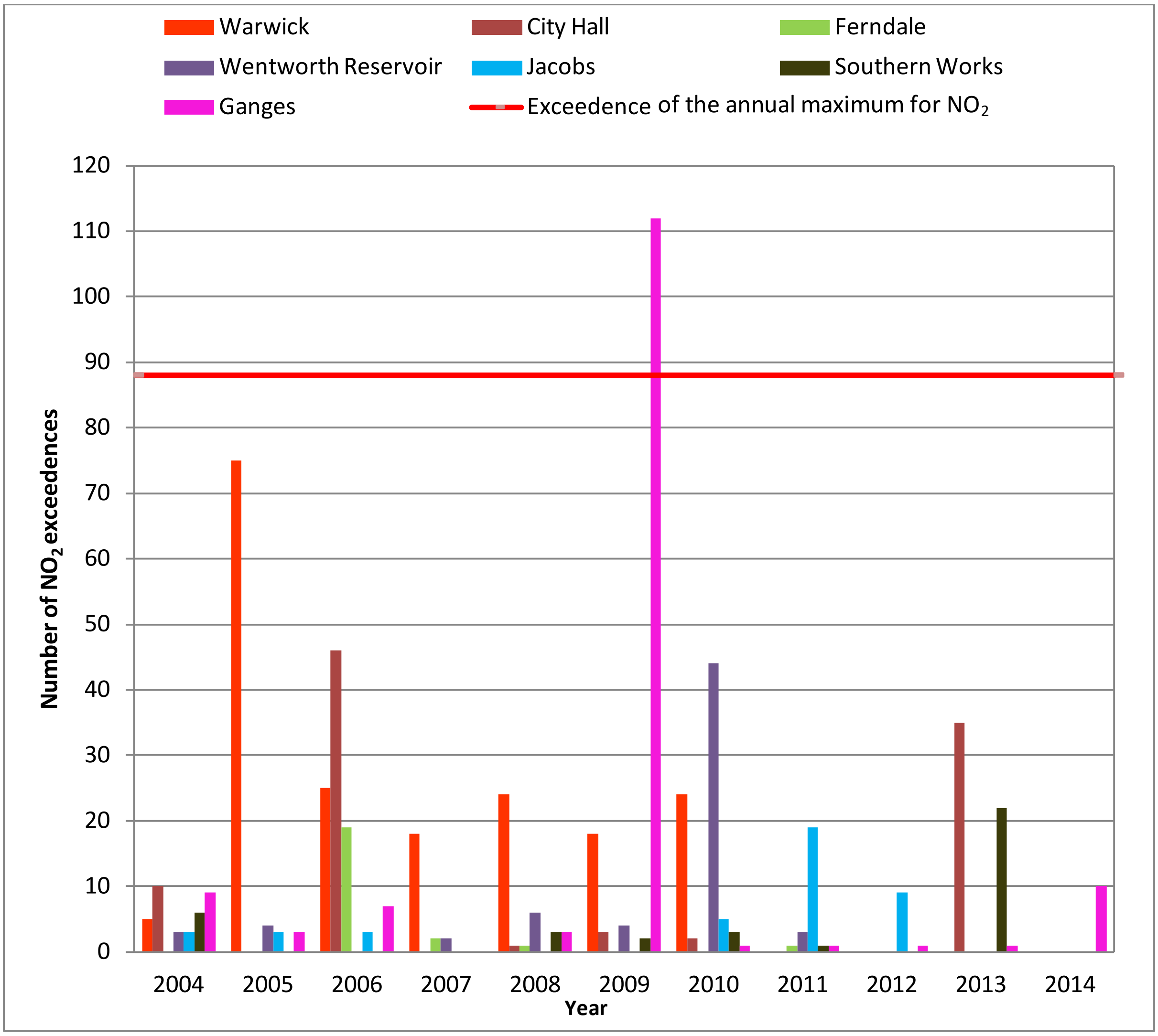

Figure 14: Number of exceedences of the NO_2 NAAQS 1 hour limit value ($\mu g/m^3$) throughout eThekwini Municipality per station from 2004-2014 (SAAQIS, 2015)

Unlike the AQMP the current study sought to identify and attribute trends in the air quality monitoring data. Based on data obtained and analysed, Figure 15 below indicates the diurnal use of vehicles and exceedences which coincide for NO_2 in the mornings from approximately hours 6-10 and afternoons from hours 15-20. This diurnal cycle coincides with findings from Chapter 2, section 2.2.2.1, where it was found that reactions from NO_x to any of the early oxidised products take at least 4 hours to occur. With exceedences spiking between hours 6-10, the rapid drop in the exceedences witnessed at hour 15 is as a result of enough time passing so that equation 6 can occur which oxidises NO_2 after having fulfilled its atmospheric lifetime. This pathway is abundant in summer when the concentrations of photo chemically produced OH radicals are at its peak and oxidises NO_2 to HNO_3 (Seinfeld and Pandis, 2006; Fang 2011). After hour 15, at the end of the business day traffic volumes increase which accounts for the spike between hours 15-20. This continues until the early hours of the morning where NO_2, having fulfilled its atmospheric lifetime is again oxidised by O_3 to produce NO_3 radicals in equation 7 (Seinfeld and Pandis, 2006; Fang 2011). These results in the rapid drop in the exceedences witnessed after hour 1.

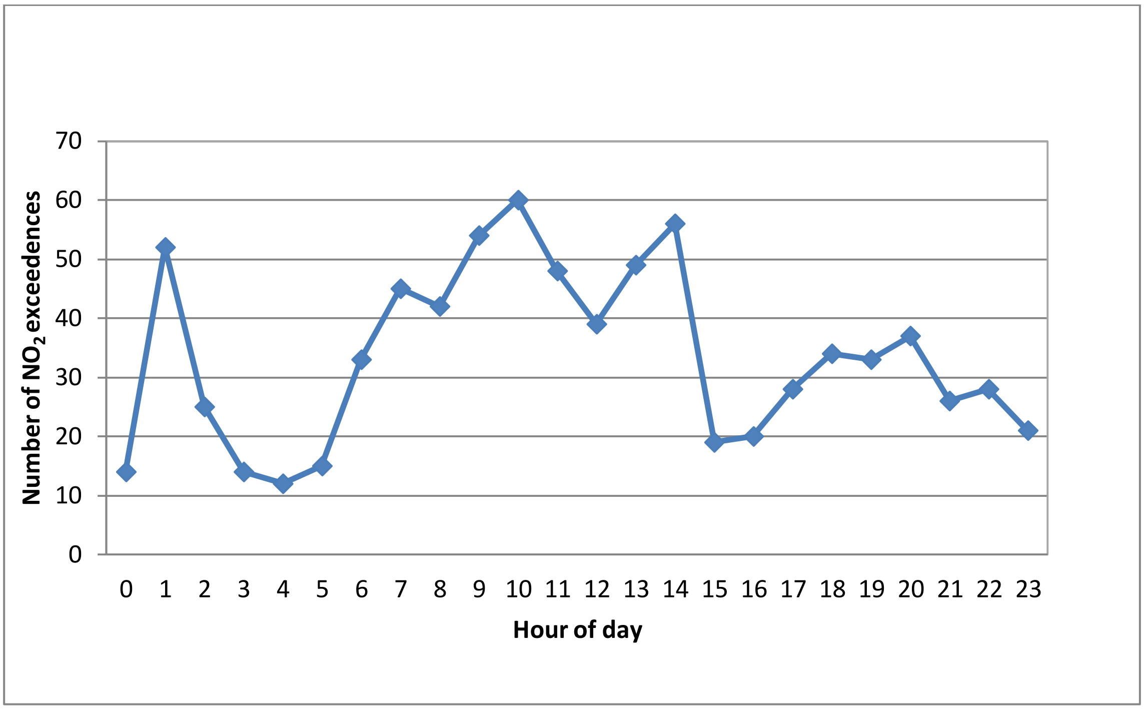

Figure 15: Average number of exceedences of the NO_2 NAAQS 1 hour limit value (µg/m^3) per hour of the day, across all stations from 2004-2014 (SAAQIS, 2015)

It is important to keep in mind that NO_2 is converted to other oxidised products which remain in the atmosphere for a given period of time. These of course are not monitored by the current stations yet these products still have implications for human and environmental health as discussed in Chapter 2, section 2.3. The European Topic Centre on Air Pollution and Climate Change Mitigation (ETCACM) (2011) defines critical levels of NO_2 for the protection of vegetation, unlike the NAAQS which centre on human health. This critical level is 30 µg/m^3 or 11.45 ppb per annum. Analysis of the ambient air quality data set revealed numerous exceedences of annual NO_2 critical levels for the protection of vegetation across all stations for almost all of the years. The numbers of exceedences are indicated in Figure 16.

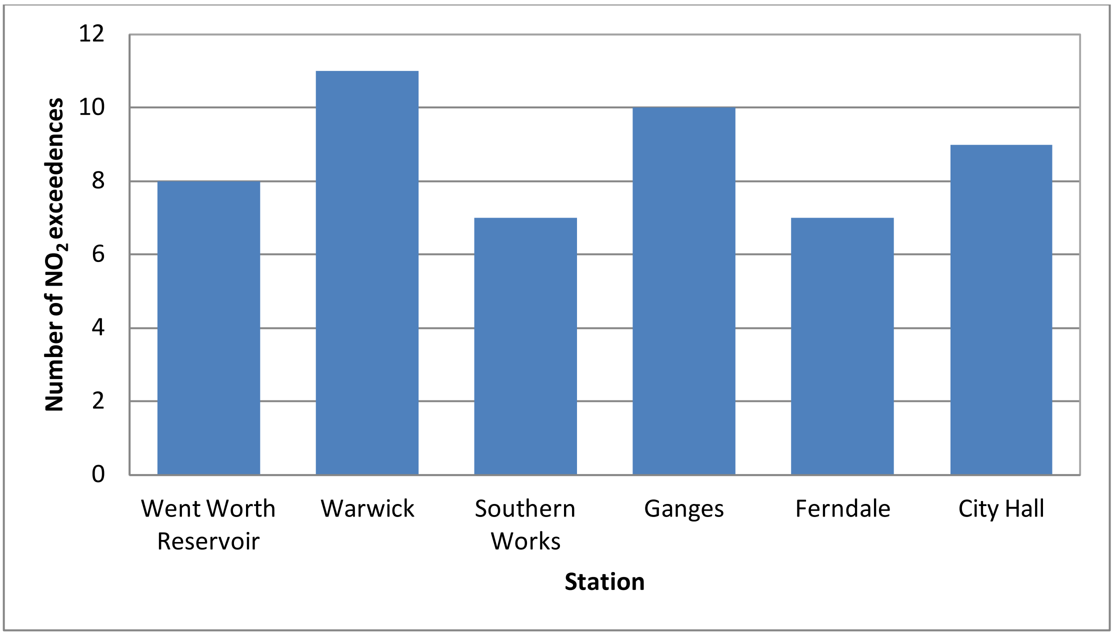

Figure 16: Number of NO_2 exceedences in µg/m^3 of the ETCACM recommended annual standard to prevent vegetation degradation throughout eThekwini Municipality from 2004-2014

Exceedences of the NO_2 ETCACM recommended annual critical level have been occurring throughout the data set at all stations during the monitoring period (2004-2014), with annual concentrations showing a sustained and consistent trend at all stations. This is irrespective of the siting rationale of a station (industrial or urban based). Stations monitoring traffic emissions (Warwick, City Hall, Ganges) seem to experience the highest concentration of NO_2 and highest number of exceedences, often recording concentrations which are twice the recommended annual critical level. This is followed closely by the remainder of the stations despite being positioned to monitor industrial emissions (Figure 17). Such observations can be attributed to vehicular emissions and aged vehicle technologies in use in the municipality.

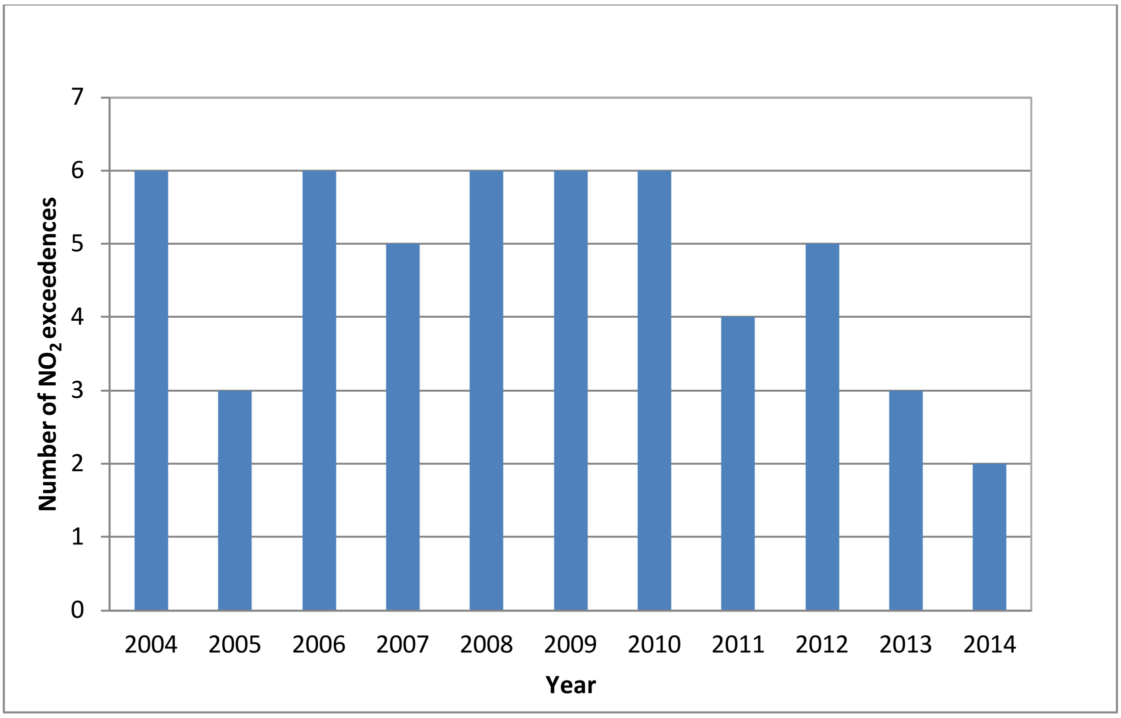

Figure 17: Number of NO_2 exceedences in µg/m^3 of the ETCACM recommended annual standard to prevent vegetation degradation throughout eThekwini Municipality for their respective years

Based on analysis of ambient air quality data in terms of NO_2 degradation of vegetation, key findings indicate that eThekwini Municipality is experiencing medium to high levels of chronic exposure to ambient $NO_{2,}$ which by law is not being regulated. As per the second objective of this study, existing air quality monitoring data in the eThekwini Municipality has identified trends and in areas monitored by the NO_2 stations i.e south Durban to be experiencing high prolonged elevated concentrations of $NO_{2.}$ This is again based on the excessive number of exceedences recorded for the ETCACM recommended annual standard to prevent vegetation degradation and maintain environmental health. It can be concluded that while the NAAQS have helped curb ambient NO_2 concentrations for human health, concentrations and exceedences of ambient NO_2 are yet to be reduced to a level which is safe for environmental receptors such as vegetation. Coupled with local wind circulations and the recirculation of pollutants discussed in Chapter 3, a scenario which is potentially detrimental to the natural environment's health is created. This is particularly of importance for receptors such as vegetation and living organisms. The knock on effects for the acidification of terrestrial and aquatic ecosystems also has to be considered. This has been alluded to in Chapter 2, section 2.3.2.

5.2.2) Network findings for SO_2

As of 2014, SO_2 is measured at 11 continuous monitoring stations. Relative to the NAAQS of 50 µg/m^3 or 19 ppb, average annual ambient concentrations of SO_2 were safely within the NAAQS at most monitoring stations (DEAT, 2005; SAAQIS, 2015). Concentrations of SO_2 were historically elevated at stations in south Durban (Southern Works, Wentworth, Settlers) however these were reduced once the MPP was implemented (DEAT, 2007a). This marked a substantial decrease in concentrations which can directly be attributed to the switch to cleaner fuels and other emission reduction measures by industry. Given such actions, SO_2 concentrations have remained with safe limits of the annual average NAAQS (DEAT, 2007a; uMoya-NILU, 2015).

The reduction in SO_2 emissions in the south Durban was also evident given the scarcity of exceedences (DEAT, 2007a; SAAQIS, 2015). The NAAQS permits for 88 exceedences per annum of the 1-hour limit value of 350 µg/m^3 or 134 ppb (DEAT, 2005). Most exceedences occurred firstly at Southern Works, secondly at Setters School and lastly at Wentworth which reflect industrial sources. The remainder of the stations recorded only a few exceedences; while Prospecton and Ferndale recorded no exceedences of the 1 hour NAAQS throughout the data set (Figure 18). An exceedence of the NAAQS occurred at Southern Works only in the year 2004. In terms of Southern Works, Setters School and Wentworth, exceedences were recorded on average for all 24 hours of the day for the 10 year data set. Apart from this other stations tended to exceed the NAAQS during the usual business hours of the day.

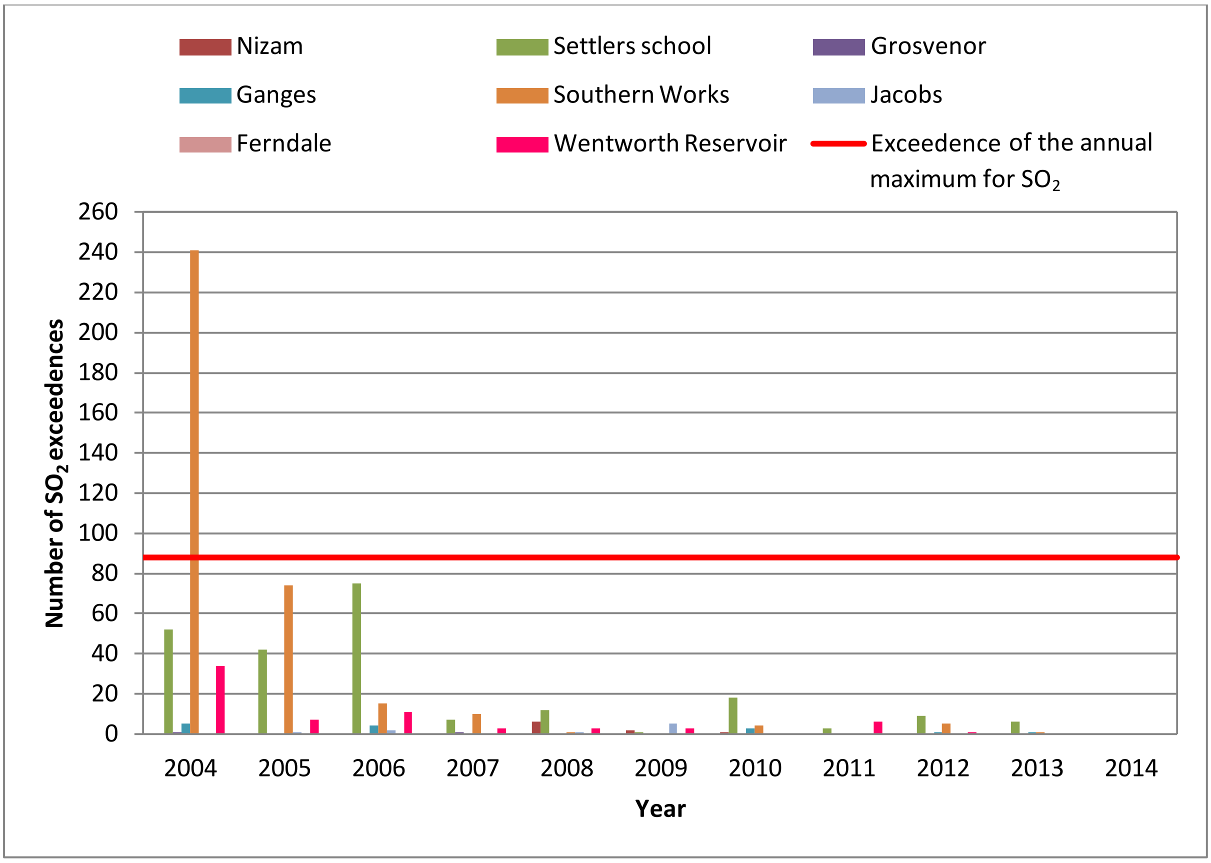

Figure 18: Number of exceedences of the SO_2 NAAQS 1 hour limit value (µg/m^3) throughout eThekwini Municipality per station from 2004-2014 (SAAQIS, 2015)

In Figure 19 the SO_2 exceedences appear to be less erratic relative to NO_2 across the 24 hour averaging period with no drastic variations. SO_2 exceedences remained erratic, making it difficult to assign causality to one emission source at this stage (DEAT, 2007a; SAAQIS, 2015). Based on Figure 19 it is plausible to assume that vehicular traffic does not considerably influence ambient SO_2 in the area as it would have reflected a striking diurnal cycle similar to that observed for NO_2. This is plausible given that it is well established that industries are the main source of SO_2 in the area (uMoya-NILU, 2015). Given that SO_2 typically has a lifetime of one day, this may account for the narrow range in concentrations as illustrated in Figure 19 over an averaged 24 hour period (Seinfeld and Pandis, 2006; Fowler *et al*., 2005). Hence it may not be possible to witness drastic spikes or reductions in exceedence as was the case with NO_2, since SO_2 concentrations are constantly sustained and replenished in the atmosphere.

The effect of the SO_2 remaining in the air for 24 hours has a significant impact on results. The residual SO_2 from the day will combine with the SO_2 emitted at night and vice versa. Even if the actual SO_2 emissions for a given time were lower, the residual SO_2 in the air will act as a buffer and give results that are reflective of a “more constant” SO_2 value. SO_2 is also only effectively converted after a day and does not require the presence of a photolytic reaction unlike the NO_2 conversion process which is restricted by the limiting hours of daylight. Therefore factors such as the light intensity, meteorological conditions discussed in Chapter 3, section 3.2 play a significant role in decomposition of SO_2. While the above is important to note, it does not rule out variations based on traffic volumes and business hours.

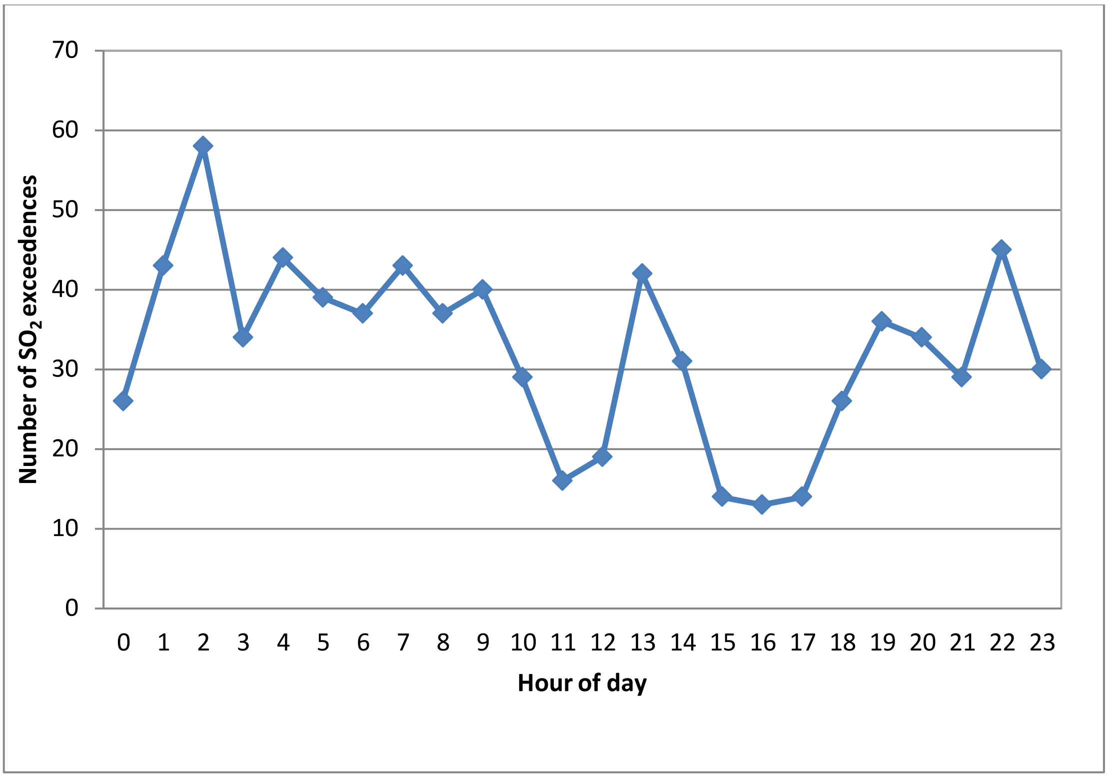

Figure 19: Average number of SO_2 exceedences of the NAAQS 1 hour limit value (µg/m^3) per hour, for 2004-2014 (SAAQIS, 2015)

The ETCACM (2011) defines critical levels of SO_2 for the protection of vegetation. This critical level is 20 µg/m^3 or 10.63 ppb per annum. Analysis of the ambient air quality data set revealed a limited number of exceedences across some stations only. The numbers of exceedences per station are indicated in Figure 20.

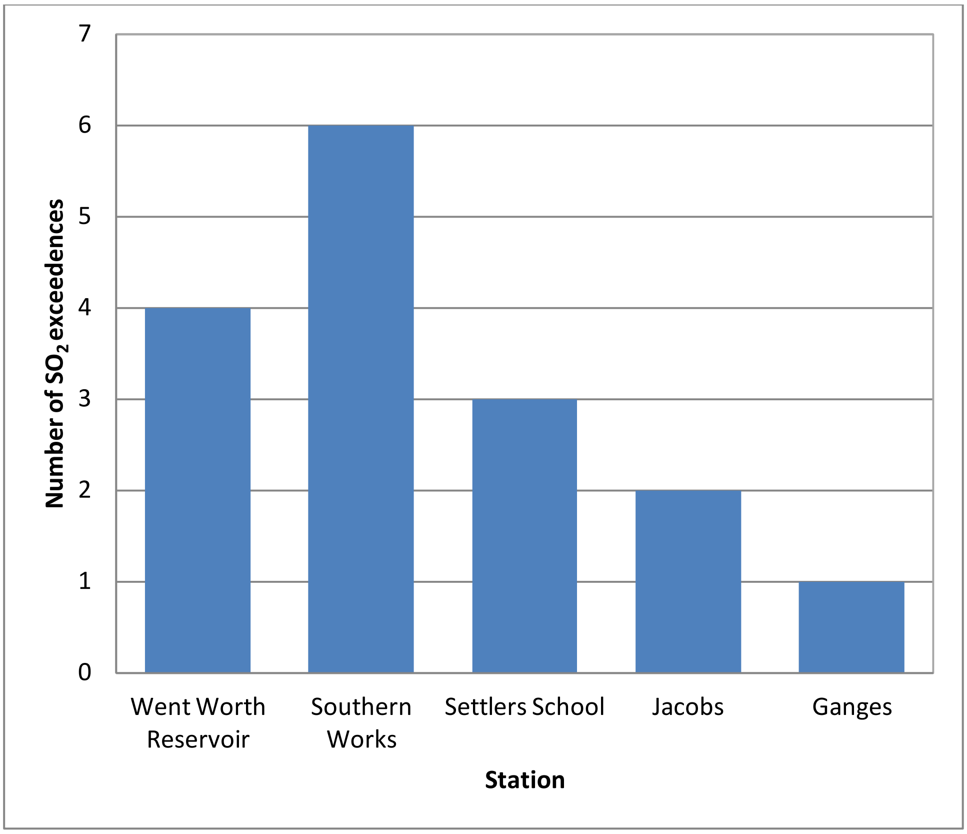

Figure 20: SO_2 exceedences in µg/m^3 of the ETCACM recommended annual standard to prevent vegetation degradation throughout eThekwini Municipality from 2004-2014

In total 13 exceedences of the SO_2 ETCACM recommended annual standard have occurred primarily during the years 2004-2008. After this period only 3 exceedences were recorded showing improved ambient SO_2 concentrations. Wentworth and Southern works stations which were typical of industrial emissions, unsurprisingly accounted for the greatest number of SO_2 exceedences. Settlers school, Jacobs and Ganges only recorded less than 3 exceedences each. Apart from this, annual concentrations were consistently below the recommended critical level at Ferndale and Prospecton with no exceedences being recorded at these stations (Figure 20 and 21). Most of the SO_2 ETCACM recommended annual critical levels were exceeded prior to the implementation of various SO_2 reduction strategies such as the use of cleaner fuels in industry and vehicles. It is this reason that can be attributed to the reduced number of exceedences witnessed in the latter years (Figure 21).

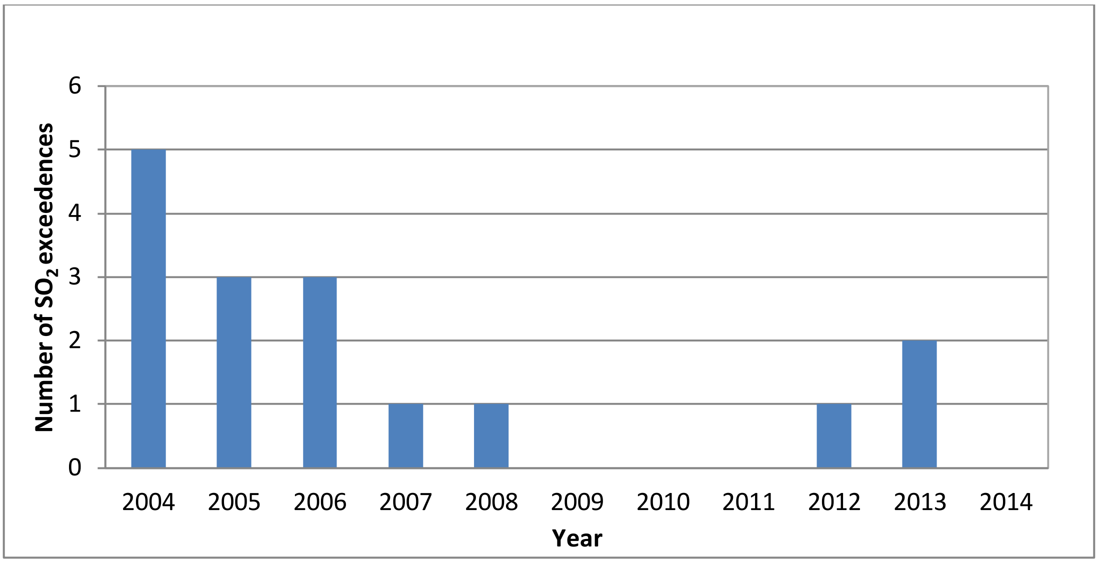

Figure 21: SO_2 exceedences in µg/m^3 of the ETCACM recommended annual standard to prevent vegetation degradation throughout eThekwini Municipality for the respective years

Based on analysis of ambient air quality data in terms of SO_2 degradation of vegetation, it has been found that eThekwini Municipality is experiencing minimal levels of chronic exposure to ambient SO_2 and the natural environment's health is not at immediate risk of degradation from ambient SO_2. In line with the second objective of this study, existing air quality monitoring data in the eThekwini Municipality has not identified elevated SO_2 levels or possible vegetation degradation. This finding is based on the limited number of exceedences of the ETCACM recommended annual standard post 2008. It can also be concluded that the NAAQS along with other key strategies have helped curb ambient SO_2 concentrations for human health and environmental health (uMoya-NILU, 2015).

5.2.3) Network findings for PM

As of 2014 PM is being measured at 10 continuous monitoring stations throughout eThekwini Municipality in order to assess and comprehend the impact of industrial and vehicular emissions on ambient air quality (SAAQIS, 2015). Although the average annual ambient concentrations of PM_{10} were rather substantial at most stations it is still consistently below the NAAQS of 50 µg/m^3. At most stations the annual average concentration remained elevated and erratic yet consistently compliant with the NAAQS (DEAT, 2007a; SAAQIS, 2015). City Hall and Ganges primarily reflected traffic emissions while Wentworth reflected industrial and vehicular emissions. Southern Works mostly reflected industrial emissions (uMoya-NILU, 2015). Similar to NO_2, it is evident that stations monitoring primarily traffic emissions experienced the worst ambient air quality in comparison to stations which primarily monitored industrial emissions (uMoya-NILU, 2015).

The general compliance noted in Figure 22 can be attributed to the use of cleaner fuels and installation of various air filtration systems by industry within south Durban resulting in reduced ambient concentrations of PM observed at Southern Works (uMoya-NILU, 2015). It therefore stands to reason that significant quantities of PM which persist can be attributed to a growing vehicular fleet which have largely been uncontrolled and offset any reductions of PM_{10} from industry. Overall, as of the year 2014 the annual average ambient concentrations of PM_{10} throughout eThekwini Municipality were below the NAAQS of 40 µg/m^3, despite the contribution of a background PM_{10} value of 16 µg/m^3. In addition since 2011 the average annual ambient $PM_{2.5}$ concentrations have not exceeded the NAAQS at Southern works (Figure 22) (SAAQIS, 2015).

The number of exceedences of the 24-hour limit value of 120 µg/m^3 for both PM_{10} and $PM_{2.5}$ allowed for by the NAAQS is 4 per annum and this was exceeded at Wentworth, Ganges, Southern Works and City Hall between 2004 and 2010 (Figure 22 and 23) (DEAT, 2005; SAAQIS, 2015). This was substantially reduced from the year 2011 up to 2014. This can be attributed with a reasonable level of confidence to the phasing-out of leaded petrol and use of low-sulphur diesel in the year 2006 (uMoya-NILU, 2015).

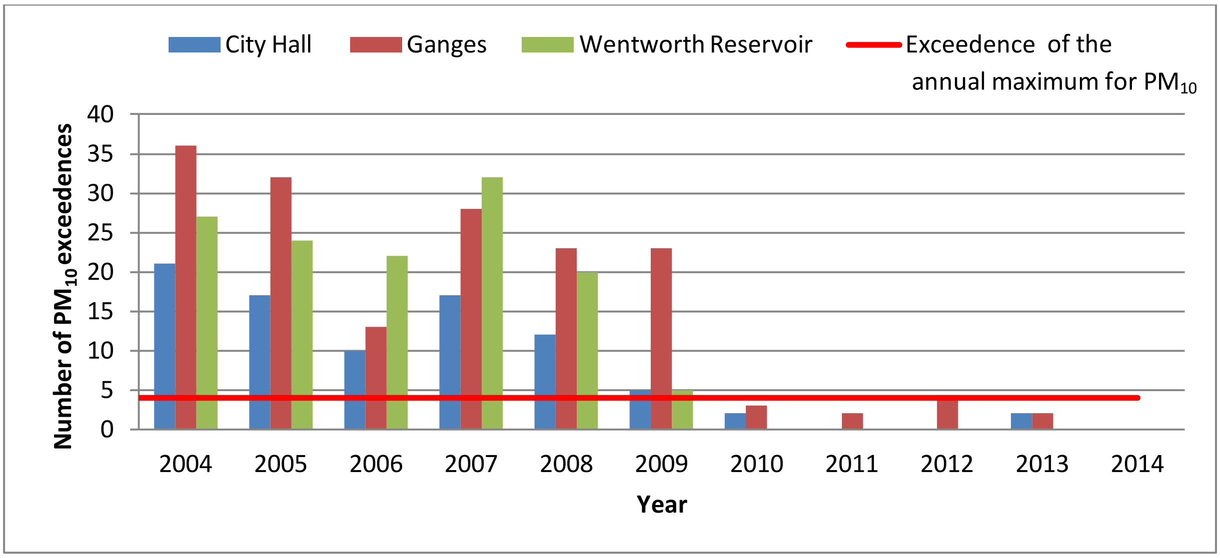

Figure 22: Number of exceedences of the PM_{10} NAAQS 24 hour limit value (µg/m^3) throughout eThekwini Municipality per station from 2004-2014 (SAAQIS, 2015)

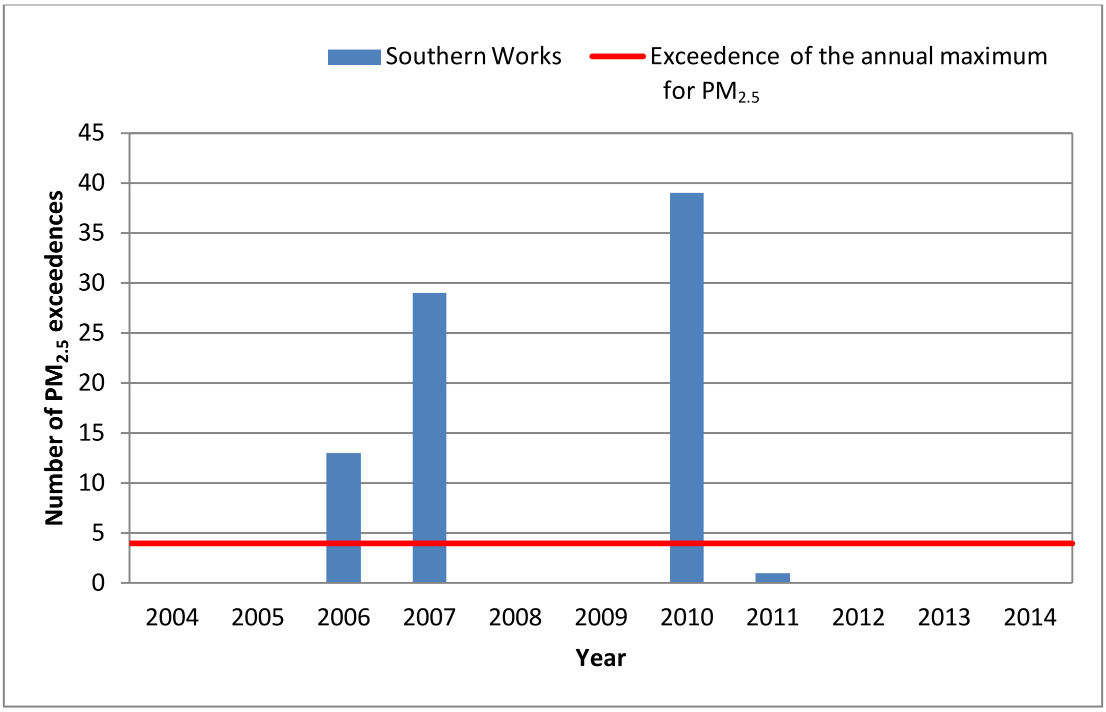

Figure 23: Number of exceedences of the $PM_{2.5}$ NAAQS 1 hour limit value (µg/m^3) at Southern Works from 2004-2014 (SAAQIS, 2015)

Hourly concentration values were employed to identify possible trends in PM_{10} concentrations in relation to vehicular use for each hour of the day across the data set. Overall Figure 24 indicates the cyclical use of vehicles and emission of PM_{10} in the mornings from approximately hours 7-11 and afternoons from hours 17-22. From Figure 24 it is evident that the highest hourly PM_{10} concentrations for all five monitoring stations correspond with peak traffic in the mornings and afternoons. The higher concentrations also appear throughout the business hours during the day. Based on this key finding, it is reasonable to conclude that vehicular use within eThekwini Municipality is primarily responsible for PM_{10} concentrations recorded and its cyclical nature. Given that PM typically have a lifetime of one day to two weeks in the troposphere this may account for the sustained higher concentrations and the narrow range in terms of the highest and lowest concentrations witnessed across all stations.

As per the 2nd objective of this study, existing air quality monitoring data in the eThekwini Municipality has not identified trends which indicate PM_{10} degradation. This finding is based on the limited number of exceedences of PM_{10} and $PM_{2.5}$ since 2011. It can also be concluded that the NAAQS along with other key strategies have helped curb ambient PM_{10} concentrations for human health and environmental health (uMoya-NILU, 2015).

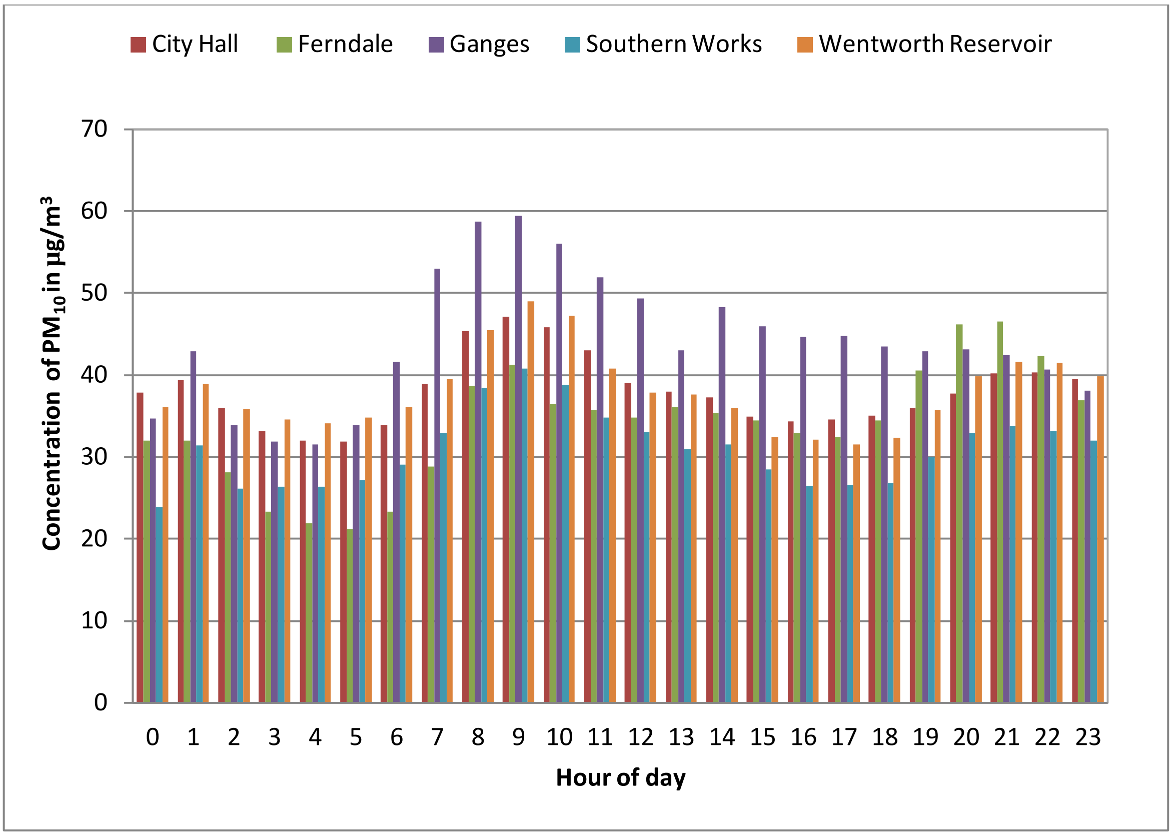

Figure 24: Average hourly PM_{10} concentrations ($\mu g/m^3$) for each hour of the day, from 2004-2014 per station (SAAQIS, 2015)

The effect of horizontal transport from Chapter 3 section 3.2.2.2 on cycles illustrated in Figure 15, 18 and 24 can not be ruled out and maybe superimposed upon these illustrations of exceedences. The culmination of the various winds allows atmospheric pollutants to accumulate over the CBD which occasionally may be supplemented by sources which possibly reflect emissions from areas inland of the municipality. The movement of air at night between the Berea and Bluff ridges poses a potential problem to the city in particular. Decreased velocities, stability and depth of the air mass could serve as a transportation mechanism for pollutants to the city from the south west. Similarly cool drained air masses from the Mgeni River valley may be entrained and transported from the north-east gradient winds (Preston-Whyte, 1970; Preston-Whyte, 1980). Given the occurrence of dominant wind directions and associated pressure systems discussed in Chapter 3 section 3.2, air flow is often reversible which may result in recirculation of pollutants over the CBD and south Durban contributing to the number of exceedences recorded by stations within these areas (DEAT, 2007). Thus pollutants are not merely dispersed, often being influenced by the various transport mechanisms which are subsequently reflected in ambient air quality data.

Information in terms of pollutants emitted and hours of operation by industry may further reveal trends in emissions which may be attributed to industry as a source only, road transport as a source only or both sectors as a source of emissions.

5.3) Analysis of eThekwini Municipality's vehicle fleet

In total 239 723 vehicles were found to be registered in eThekwini Municipality. A vehicle sector's contribution to the emission of certain pollutants varies due to differences in the emission factors of the pollutants, the size of the fleet and the activity data. To investigate emission reduction effectively it is first necessary to identify variations amongst the fleets namely, fleet size and emission contribution of each sector (Cai and Xie, 2007).

5.3.1) Passenger vehicles

Passenger vehicles accounted for 61 % or 145 331 vehicles of the total fleet for eThekwini Municipality (Figure 25). 84 % of this fleet required petrol as a fuel source while 16 % required diesel with the alternative energy fuel sources comprising less than 1 %. 47 % of passenger vehicles complied with Euro 4 standards, 21 % complied with Euro 3 standards, 11 % complied with Euro 2 standards and 10 % complied with Euro 1 standards. The remaining 11 % are comprised of the ECE 15 04 standard and its predecessors.

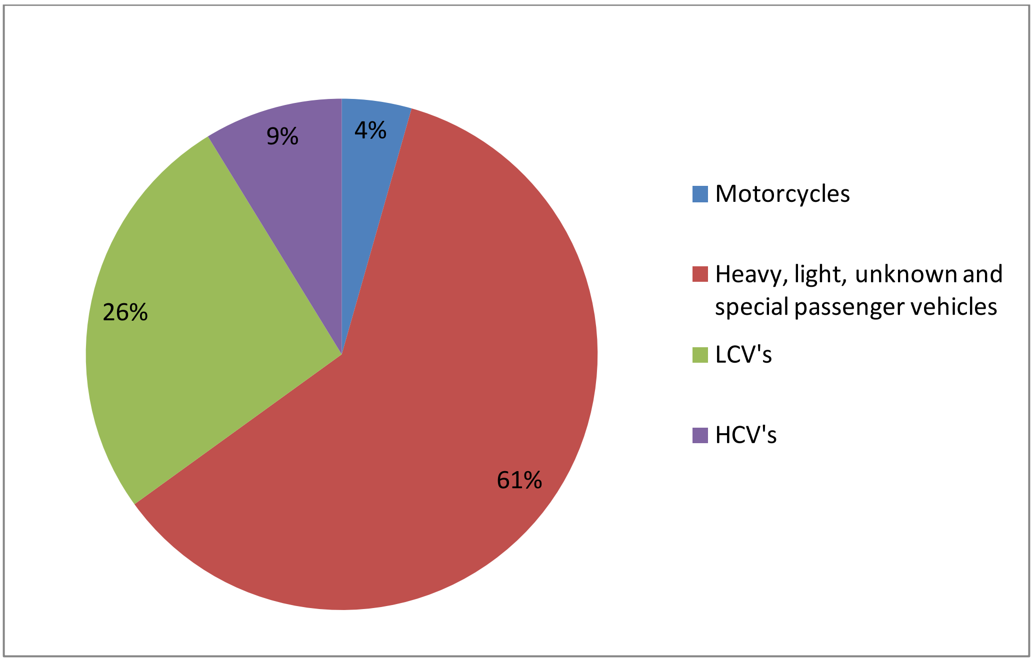

Figure 25: Total composition of eThekwini Municipality's vehicle fleet

5.3.2) LCV's

LCV's made up 26 % or 62 835 vehicles of the total fleet of eThekwini Municipality (Figure 25). 46 % of this fleet required petrol as a fuel source while 54 % required diesel and steam as a fuel source. Overall 24 % of LCV's complied with Euro 4 standards, 28 % complied with Euro 3 standards, 12 % complied with Euro 2 standards and 15 % complied with Euro 1 standards. The remaining 21 % are compliant with Conventional standards. This information revealed that there is an almost equal share of older and newer (≥ Euro 3) LCV's present with future trends being unclear. This has implications for air quality especially since a fair number of LCV's only complied with the older standards contributing more emissions given their activity data (≤ Euro 2).

5.3.3) HCV's

HCV's accounted for 9 % or 20 999 vehicles of the total fleet of eThekwini Municipality (Figure 25). 2 % of this fleet required petrol as a fuel source while 98 % required diesel. Overall 9 % of HCV's complied with Euro V standards, 20 % complied with Euro IV standards, 20 % complied with Euro III standards, 11 % complied with Euro II standards, 14 % complied with Euro I standards and 26 % complied with Euro 0 standards. Similar to the LCV, the information revealed that there is an almost equal share of older and newer (≥ Euro III) HCV's present with future trends being ambiguous. This has implications for air quality especially since most of the HCV's only complied with the older standards contributing more emissions given their activity data (≤ Euro II).

5.3.4) Motorcycle

Motorcycles constituted 4 % or 10 558 vehicles of the total fleet of eThekwini Municipality (Figure 25). 99 % of this fleet used petrol as a fuel source while 1 % required diesel and alternative energy as a fuel source. Overall 29 % of motorcycles complied with Euro 3 standards, 27 % of motorcycles complied with Euro 2 standards, 18 % of motorcycles complied with Euro 1 and 26 % of motorcycles complied with Conventional standards. This information revealed that there is a fewer number of older (≥ Euro 2) motorcycles present with future trends being unclear.

5.4) Aggregated emissions estimates from COPERT IV

Having gained an insight into the composition of the respective fleets in terms of size and activity, aggregated emission contributions of each sector per emission (CO_2, N_2O, NO_x, SO_2, NH_3, $PM_{2.5}$, PM_{10} and total exhaust PM) was calculated using COPERT IV for eThekwini Municipality for the year 2010. This calculation was based upon activity data for the 8 vehicular pollutants calculated by COPERT IV (Cai and Xie, 2007). In order to effectively reduce emissions through informed decision making, it is first necessary to assess the emission contribution of each vehicle sector and subsequently implement measures to control the emissions from that sector. Thus COPERT IV estimates provided an indication of road traffic's contribution to air quality and climate issues.

Table 14: Aggregated emission in tonnes for eThekwini Municipality in 2010

eThekwini Municipality	**GHG**		**Acidifying pollutants and precursor gases**						
Sector	CO_2	N_2O	NO_x	SO_2	NH_3	$PM_{2.5}$	PM_{10}	Total exhaust PM	Total emissions
Passenger vehicles	818485	66	2670	261	91	57	76	31	821736
LCV's	532246	48	1942	169	31	160	175	139	534910
HCV's	2100403	50	18870	665	12	519	564	452	2121535
Motorcycles	12736	0	54	4	0	2	2	1	12800
Total emission	3463869	164	23537	1099	134	737	816	623	3490980

With reference to the total emissions per sector, passenger vehicles account for 24% of the total emissions for eThekwini Municipality, whilst LCV's account for 15% of the total emissions and HCV's account for 61% of the total emissions for eThekwini Municipality. Although less present, motorcycles account for 12800 tonnes or < 1 % of the total emissions for eThekwini Municipality. In total 3490980 tonnes of emission were calculated by COPERT IV to have been emitted in eThekwini Municipality by its fleet (Table 14).

5.4.1) GHG emissions per vehicle sector

Total GHG emitted from the road transport sector was estimated at 3464033 tonnes in 2010, with the CO_2 component constituting the vast majority of the total GHG. With regards to CO_2 emitted across the four sectors, from Table 14 it is evident that the principal contributor of CO_2 for 2010 was the HCV sector, which accounted for about 61% of CO_2 emissions. This was followed by the passenger vehicles which accounted for about 24% of CO_2, LCV's accounted for about for 15% of CO_2 and motorcycles were responsible for < 1% of CO_2. The principal contributor of N_2O was the passenger vehicles sector, which emitted 40% of N_2O emissions. This was followed closely by both the LCV's and the HCV's which accounted for about for 30% of N_2O. Motorcycles were responsible for < 1% of N_2O. Based on these figures passenger vehicles and HCV's combined were responsible for major contributions of GHG, accounting for about 84.27% of the total GHG emissions. This was probably due to the large population of passenger cars and higher annual mileage for HCV's.

5.4.2) Acidifying and precursor gas emissions per vehicle sector

Total acidifying and precursor gases in this study were defined as an aggregate of NO_x, SO_2, NH_3, $PM_{2.5}$, PM_{10} and total exhaust PM. The total amount of acidifying and precursor gases given off by the vehicle fleet of eThekwini Municipality in 2010 was estimated at 26947 tonnes. Of this total value NO_x accounted for the greatest amount of emissions at 23537 tonnes, followed by SO_2, PM_{10}, $PM_{2.5}$, total exhaust PM and lastly NH_3.

The results in Table 14 indicate that the principal emitter of NO_x across the four sectors for 2010 was the HCV sector, which accounted for about 80% of NO_x emissions. This was followed by the passenger vehicle sector which accounted for about 12% of NO_x, LCV's accounted for about for 8% of NO_x and motorcycles were responsible for < 1% of NO_x. The HCV sector emitted 61% of SO_2 emissions. This was followed closely by the passenger vehicle sector which accounted for about 24% of SO_2, LCV's accounted for about for 15% of SO_2, and motorcycles were responsible for < 1% of SO_2. The passenger vehicle sector emitted 68% of NH_3 emissions. The second biggest emitter of NH_3 was the LCV sector accounting for about for 23% of NH_3, HCV's were responsible for 9% of NH_3 and motorcycles were responsible for < 1% of NH_3.

With regards to $PM_{2.5}$ emissions, HCV's were responsible for 70% $PM_{2.5}$., passenger vehicles accounted for about 8% of $PM_{2.5}$, LCV's accounted for about 22% of $PM_{2.5}$, and motorcycles were responsible for < 1% of $PM_{2.5}$.With regards to PM_{10} emissions across the four sectors, HCV's were responsible for 69% of $PM_{10,}$ passenger vehicles accounted for about 9% of PM_{10}, LCV's accounted for about for 22% of PM_{10}, and motorcycles were responsible for < 1% of PM_{10}.With regards to total exhaust PM emissions across the four sectors, HCV's were responsible for 73% of total exhaust PM passenger vehicles accounted for about 5% of total exhaust PM, LCV's accounted for about for 22% of total exhaust PM, and motorcycles were responsible for < 1% of total exhaust PM.

Based on these figures passenger vehicles and HCV's were together responsible for major contributions of NO_x and SO_2 while, while passenger vehicles and LCV's responsible for major contributions of NH_3. LCV's and HCV's are responsible for major contributions of all forms of PM. This was probably due to the large population of HCV and LCV which possess diesel engines and inherently emit more PM as discussed in Chapter 2, section 2.2.2.4.

5.5) Comparison of current emission inventory to other emission inventories

Numerous studies exist which have reported on road transport emissions at lower administrative levels in South Africa. The inventory in the current study was compared to similar inventories undertaken for eThekwini Municipality and cited in Chapter 3, section 3.5, to gauge if it was suitable for further investigations into co-benefits opportunities. Only pollutants which were sampled in other studies were listed for comparison purposes.

In Chapter 3, section 3.5.1 air pollutant emission estimates were conducted by uMoya-NILU using eThekwini Municipality's 2014 on road vehicle fleet in the eThekwini Municipality's Baseline Assessment (uMoya-NILU, 2015). The current study made comprehensive estimations based on the entire on and off road vehicle fleet of eThekwini Municipality which was derived from the eNATIS vehicle database and not a sample, for the year 2010. In Chapter 3, section 3.5.2, the eThekwini Municipality GHG inventory for 2011 and 2012 was based on both on and off-road vehicles within the road transport sector however it did not use an emission inventory model (eThekwini Municipality, 2013; eThekwini Municipality, 2014).

In terms of the GHG, apart from the expected changes to vehicle fleet size, fleet composition and vehicle technology across the years, methodological choice may be the main factor which accounts for differences in GHG estimates (Table 15). Vehicle fleet size, fleet composition and vehicle technology across the years are important to consider as it forms part of key data inputs within any methodology which will ultimately affect emission estimates and result in variations between different studies (Gkatzoflias *et al.*, 2012). The conservative approach employed by Thambiran and Diab (2011) whom allocated all vehicles purchased prior to 1990 as being ECE 15.01 may account for the higher estimates across all emissions for the study. Thus the manner in which Thambiran and Diab (2011) categorised motor vehicles was not consistent with methods prescribed for model input by Gkatzoflias *et al.*, (2012). Apart from this, the current study and that of eThekwini Municipality (2013) seem to be coherent considering changes to fleet size through the study years for CO_2. N_2O emissions from eThekwini Municipality (2013 and 2014) do not seem to be coherent with any other studies (Table 16).

Table 15: Comparison of CO_2 estimates (tonnes) across various studies

Year of study	**2010**	**2008**	**2011**	**2012**
Sector	Current study	Thambiran and Diab (2011)	eThekwini Municipality (2013)	eThekwini Municipality (2014)
Passenger vehicles	818485	2140251		
LCV's	532246	1252630		
HCV's	2100403	2642054		
Motorcycles	12736			
Total emission	3463870	6034935	5610687	6119854

Table 16: Comparison of N_2O estimates (tonnes) across various studies

Year of study	**2010**	**2008**	**2011**	**2012**
Sector	Current study	(Thambiran and Diab, 2011)	(eThekwini Municipality, 2013)	(eThekwini Municipality, 2014)

Passenger vehicles	66	115		
LCV's	48	52		
HCV's	50	71		
Motorcycles	0			
Total emission	164	238	51605	56040

In terms of acidifying pollutants and precursor gases there are similarities between the different inventories despite the age of the studies when comparisons were possible. Higher values of NO_x, SO_2 and PM_{10} estimates by Thambiran and Diab (2011) in 2008 relative to uMoya-NILU (2015) in 2014 can be attributed to the conservative approach mentioned above (Table 17, 18 and 19). Similar to statements made above, when comparing the current study's estimates to uMoya-NILU (2015) 2014 estimates the difference may be attributed to growth and changes in vehicle fleet composition and activity which seems more plausible. In addition to this the difference between estimates seems to stem from the fact that the current study accounted for on and off road vehicles within its methodology. This affects methodology between studies and affects emission estimates resulting in variations. The same can not be said when comparing 2008 estimates to 2014 estimates, since higher estimations across all emissions for the study may have occurred for Thambiran and Diab (2011).

Table 17: Comparison of NO_x estimates (tonnes) across various studies

Year of study	**2010**	**2008**	**2014**
Sector	Current study	(Thambiran and Diab, 2011)	(uMoya-NILU, 2015)
Passenger vehicles	2670	25940	
LCV's	1942	12884	
HCV's	18870	33641	
Motorcycles	54		
Total emission	23536	72465	68292

Table 18: Comparison of SO_2 estimates (tonnes) across various studies

Year of study		**2008**	**2014**
Sector	Current study	(Thambiran and Diab, 2011)	(uMoya-NILU, 2015)
Passenger vehicles	261	670	
LCV's	169	417	
HCV's	665	834	
Motorcycles	4		
Total emission	1099	1921	1585

Table 19: Comparison of PM_{10} estimates across various studies

PM_{10}	**2010**	**2008**	**2014**
Sector	Current study	(Thambiran and Diab, 2011)	(uMoya-NILU, 2015)
Passenger vehicles	77	260	
LCV's	175	610	
HCV's	564	1626	
Motorcycles	2		
Total emission	817	2496	2439

5.6) Study limitations

Within this study assumptions made throughout the development of the emissions inventory as a result of data constraints may result in limitations in the applicability of the emission estimates. Despite this all efforts having been made to collect the detailed statistics required for use with the higher tier method, Tier 3, it was not possible to apply this tier. As such given the data availability and the constraints a Tier 2 methodology was applied when estimating road transport emissions. Given that this is not the highest tier, emission estimates produced via this methodology may vary to a certain degree and may not truly reflect actual emissions produced by the vehicle fleet in 2010.

As per Chapter 4, section 4.5.1.2.3 COPERT is classified as a static average speed model which employs the same average speed through very different driving patterns, which does not describe the instantaneous situation of the vehicle. As such the model may under estimate emissions in the current study particularly when comparing it to eThekwini Municipality (2013) estimates (Boubaker *et al.*, 2015). This is another reason that can be attributed to lower emissions being estimated within this study, since not all other studies employed the use of an emissions inventory model. With the number of variables differing between all the studies cited, it is often a difficult task to definitively compare and contrast respective emission estimates given the various methodologies. Critical to this is the manner in which fuel sales were differentiated into on and off road usage according to the apportion factors within this study which affect the results. It can be concluded that the use of on road or on and off road vehicles, nature of the model, changes to vehicle fleet size, fleet composition and vehicle technology across the years and methodological choice may be the main factor which accounts for differences in emission estimates across all studies listed above. Taken as a whole, the current study's estimates seem to associate with eThekwini Municipality (2013) for CO_2 and uMoya-NILU, (2015) for air pollutant emissions even when considering reasons for variations in each study. Thus the inventory for 2010 is acceptable and represents GHG and air pollutant emissions from the road transport sector for eThekwini Municipality. It is fitting enough to justify the need for exploring and implementing for co-benefits opportunities that may be present. Of particular interest is the role of HCV's and passenger vehicles.

5.7) Disaggregated emissions estimates from COPERT IV amongst petrol and diesel fuels

In order to gain a deeper understanding of the emission estimates calculated by COPERT IV in this study and to conclusively attribute emission trends to particular fuels used in the study area, emissions were disaggregated into diesel and petrol components per sector. Table 20 and 15 provide insight into the amount of GHG, acidifying pollutants and precursor gases emissions generated per fuel used within the study location. Using Table 20 and 21 allows one to better explain and account for emissions produced per vehicle sector and fuel type. It is worth noting that the hybrid columns which registered zero tonnes were excluded and that motorcycles were excluded from the discussion as it did not contain a diesel component to compare to.

The fuel sales data within this study was employed by COPERT IV to estimate emissions of CO_2 and SO_2 which are directly related to the amount of liquid fuel that is used. Within the model, the given data worked by assuming that all of the carbon present in the fuel is fully oxidised into CO_2 (Ayemang *et al.*, 2010; (Gkatzoflias *et al.*, 2012). This meant that the quantity of CO_2 emitted primarily depends on the initial carbon content of the fuel utilised and fuel consumption levels.

Table 20: Disaggregated emissions of GHG amongst petrol and diesel engines in eThekwini Municipality

	CO_2			**N_2O**	
Sector	Diesel	Petrol	Hybrid	Diesel	Petrol
Passenger vehicles	130179	688300	6	6	60
LCV's	281337	250909		7	42
HCV's	1974286	126116		48	2
Motorcycles		12736			0
Total	2385802	1078062	6	60	104

The greater proportion of petrol consumed as per the findings from section 5.3.1, by the dominant passenger vehicle fleet and it's annual average mileage, influenced emissions produced by this sector the most. With both these factors considered by the model it is reasonable to accept that a greater quantity of CO_2 and N_2O is emitted by the petrol component of this sector given the nature of the input data and its larger fleet in eThekwini Municipality even when compared to other sectors petrol components (Table 20). Findings from section 5.3.2 indicated that the LCV sector slightly favoured the consumption of diesel fuels, hence the small difference in CO_2 emissions between the diesel and petrol components.

HCV's account for a small proportion of the total fleet and are skewed heavily towards the consumption of diesel fuels. Despite the relatively smaller HCV fleet size, total vehicle kilometres travelled (VKT) and average annual mileages, engine capacity, design, vehicle age, and driving patterns greatly exacerbates the total emissions of CO_2 particularly for the diesel component (Table 20). This accounts for the diesel component emitting more CO_2 and N_2O

Another factor to consider is that of the driving environment. Relative to HCV's, passenger vehicles and LCV's which are often much older as stated in section 5.3 and are driven far less (lower annual mileages), however they spend majority of the time driving within urban areas which often experiences traffic congestion. Bigazzi and Clifton (2015) conducted a review on available literature which indicated that increasing levels of congestion with lower average speeds lead to decreased fuel economy for conventional ICE vehicles which are common in eThekwini Municipality. This insight can be used to help explain and justify the emissions quantified in this study for the petrol component, since it results in extended periods of travel, lowered average velocity, increased vehicle velocity variability and fuel consumption. This is supported by Eckert *et al.*, (2015) who state that these specific routes drastically alters the urban driver profile by placing the engines of passenger vehicles and LCV's under strain. These factors combined with greater acceleration rates required during periods of congestion within an urban environment and use of the "less efficient" first and second gears often means the engine is cycling at a much higher rate, achieving greater revolutions per minute. Thus in this state, the work rate of the engine is greater hence consuming more fuel and producing more emissions (Eckert *et al.*, 2015). Given that higher rates of fuel consumption are directly proportional to the emissions of CO_2, it stands to reason that greater use of passenger vehicles and LCV's in the urban environment plays a considerable role in total emissions recorded for these sectors which must be acknowledged (Gkatzoflias *et al.*, 2012; Li *et al.*, 2015).

Emissions of NO_x in diesel vehicles are generally lower than those for petrol vehicles (Thambiran and Diab, 2011). This statement is in agreement with results for the passenger vehicles sector. However given the number of passenger vehicles making up the petrol component, it is reasonable to accept that a greater quantity of NO_x is emitted here (Table 21). Similar to the GHG, the LCV sector which slightly favours the consumption of diesel fuels accounts for the small difference in NO_x emissions between the diesel and petrol components for the LCV sector. For HCV's the large amount of emissions from the NO_x diesel component is primarily due to the composition of the HCV sector being composed of diesel engines. This explanation follows a similar reasoning to that of the GHG listed above and can be further applied to SO_2, NH_3 and PM.

The concentration of SO_2 increases when diesel fuel consisting of high concentrations of sulphur is used. Given that COPERT IV estimates emissions of SO_2 on fuel quantity and composition and applies the assumption that fuel is fully oxidised into SO_2 it stands to reason that SO_2 emissions trends will mimic that of CO_2 trends given the fleet composition and activity data (Ayemang *et al.*, 2010; Gkatzoflias *et al.*, 2012). This is of course witnessed in both Table 20 and 21, where emission trends for SO_2 were similar to that of CO_2. While trends may be similar, actual quantities of SO_2 produced were considerably reduced relative to CO_2. This is attributed to concentrations of SO_2 which were historically elevated but have reduced within the fuel specifications since 2006 (SANS, 2006a.b). This marked a substantial decrease in emissions which can directly be attributed to the switch to low sulphur fuels (DEAT, 2007a).

It is clear for both the passenger vehicle and LCV sector that the use of petrol fuel is inherently responsible for NH_3 emissions given its composition as alluded to in Chapter 2, section 2.2.2.2. The abundance of diesel HCV's are again responsible for the diesel component emitting more NH_3. PM emissions increased for the diesel components of most sectors which were expected given the inherent designs of diesel engines which produce more carbonaceous emissions during the combustion process (Thambiran and Diab, 2011). This is true for all diameters of PM across all sectors except for passenger vehicles in the $PM_{2.5}$ and PM_{10} column which primarily uses petrol. The substantial differences between the diesel and petrol components for the remainder of the sectors ultimately come down to the emission factors for each PM column which is dependent upon design of that particular vehicle sector. For instance in the HCV sector, break and tyre wear and tear, number of tyres, engine size and axels influence the quantity and diameter of PM emitted more relative to other sectors.

Table 21: Disaggregated emissions of acidifying pollutants and precursor gases amongst petrol and diesel engines in eThekwini Municipality

	NO_x		**SO_2**		**NH_3**		**$PM_{2.5}$**		**PM_{10}**		**Total exhaust PM**	
Sector	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Passenger vehicles	404	2267	41	220	1	90	28	28	32	44	24	7
LCV's	1072	870	89	80	1	30	148	12	156	19	137	2
HCV's	17516	1354	626	40	11	1	516	4	558	6	452	0
Motorcycles	-	54	-	4	-	0	-	2	-	2	-	1
Total	18993	4545	756	344	13	121	692	45	745	71	613	10

Overall reasons for acidifying pollutants and precursor gas emissions can be attributed to the same reasons cited earlier for GHG emissions. This again comes down to the nature of the input data, driving behaviour and real world factors specific to eThekwini Municipality and essential activity data inputs required by the model itself (Boubaker *et al*., 2015). Essential activity data inputs which are responsible for the emissions produced for each sector above in Table 20 and 21 include varying fleet sizes, fuel preferences and varying annual mileages (Gkatzoflias *et al*., 2012). Another essential data input which is responsible for the emissions produced for each sector above but is not easily reflected in Table 20 and 21 above is that of vehicle technology. This is supported by Bigazzi and Clifton (2015) and Boubaker *et al*., (2015) both of whom modelled the energy efficiency and fuel consumption of a variety of new vehicle technologies with the latest Euro standards in traffic congestion against typical ICE vehicles in separate studies. These new technologies include hybrid electric vehicles (HEV's), fuel cell electric vehicles (FCEV's) and electric vehicles (EV's). The researchers concluded that HEV's, FCEV's and EV's are expected to achieve better fuel economy in congestion relative to ICE vehicles, with fuel economy even improving for EV's and FCEV's in highway congestion. In accordance with section 5.3, a significant proportion of the fleet of eThekwini Municipality's fleet is considered to be aged, often lacking emission control devices, maintenance regimes and the use of newer technologies. As a result the current fleet tends to emit a large quantity of emissions as illustrated by the data and indicated by the literature cited.

5.8) Mitigation potential scenarios for eThekwini Municipality

In accordance with objective 3, total emission mitigation potential was calculated using COPERT IV. This was achieved by modelling nationally approved mitigation measures at the local level to determine its suitability and effectiveness. This was based on methods outlined in Chapter 4. Negative values indicate an increase in emission production rather than a decrease. This is attributable to the lack of a larger baseline value initially and the uptake of alternately fuelled vehicles. This is justified by Ntziachristos and Samaras (2014) who indicated that alternative fuels for some countries has a negligible contribution to emissions at present. Table 22 indicates the total emissions mitigated against by each individual mitigation measures and Table 23 provides a final summary of the findings and effectiveness of mitigation measures for eThekwini Municipality ranked in descending order.

Table 22: Total emissions mitigated against per mitigation measure in tonnes per annum

Mitigation scenario	**Baseline emissions per measure**	**Total emissions generated with measure**	**Total emissions mitigated against**
Improved efficiency- petrol ICE	1083302	197939	885363
Improved efficiency - diesel ICE	2407674	2150111	257563
Alternate fuels - CNG	3490980	3475169	15811
Biofuels	3490980	3224335	266645
Shifting passengers to public transport	821736	657388	164348
Shifting freight from road to rail	2121535	1697227	424308
Petrol HEV and PHEV	6	309	-315

Table 23: Summary of mitigation measures and its calculated mitigation potential in tonnes per annum in descending order

Mitigation measures simulated (DEA, 2014)	**Corresponding COPERT IV sub-sectors**	**Total Emissions mitigated against (tonnes)**
Road - improved efficiency - petrol ICE	Gasoline	885363
Road - shifting freight from road to rail	Not required	424308
Road - biofuels	E85	266645
Road - improved efficiency - diesel ICE	Diesel	257563
Road - shifting passengers from cars to public transport	Not required	164348
Road - alternate fuels - CNG	CNG	15811
Road -alternate fuels – petrol HEV	Hybrid Gasoline	-315

The figures in Table 23 are inclusive of direct combustion of fuel and indirect emissions from these fuels. In line with objectives of this study, findings from the simulations conducted within this study and presented in Table 23, further proves and compliments literature cited in Chapter 3, section 3.6. This section cited literature which indicated that reductions in GHG, acidifying pollutants and precursor gas emissions within eThekwini Municipality are possible via technological improvements in efficiencies of engines, modal shifts and a reduction in VKT and carbon intensive fuels (Schoeman, 2010; DEAT, 2014; Buthelezi and Davies, 2015; Chen and Hashim, 2016; Qiu *et al.*, 2016). Although findings from this study does not exactly mimic national rankings found within Table 10 which ranked the use of biofuels first and the shifting of freight from road to rail in seventh place, other mitigation measures at a national level were similarly ranked to that of Table 23. Based on this finding it is safe to assume that even nationally proposed mitigations may be implemented at a local level once appropriately adapted, as it does align itself to locally based mitigation measures.

5.9) Conclusion

Given the number of aged petrol and diesel vehicles found within eThekwini Municipality by this study which lack emission control technologies, it stands to reason that implementation of a fleet renewal programme, in accordance with mitigation measures of Table 23, which comply with latest Euro 6 standards is one option to reduce emissions. If the improved efficiency of petrol and diesel vehicles is coupled with reduced VKT by passenger vehicles and HCV's in the short-to medium-term then it shall result in reduced fuel consumptions, GHG, acidifying pollutants and precursor gas emissions. The knock on effects of such actions if implemented efficiently will most likely reduce GHG, ambient acidifying pollutants and precursor gases which have already been found to have surpassed the safe operating space particularly for vegetation. Having found a considerable link between average daily traffic volumes and emission trends for a 24 hour period for PM and $NO_{2,}$ it can be said that the implementation of mitigation measures listed above will relieve strain experienced by environmental receptors such as vegetation and aid in reducing the number of ETCACM recommended annual exceedences found to be at an elevated level in section 5.2. In conjunction to this, this finding also indicates the need to introduce a South African standard, apart from the NAAQS, which seek to protect critical environmental receptors such as vegetation.

Another key finding from this study was that the uptake of alternative fuels and HEV has been slow within eThekwini Municipality. The reduction in energy and fuel carbon intensity within the road transport sector by substituting oil based products with natural gas, biofuels, electricity or hydrogen produced from low GHG sources could not be quantified with a high level of confidence at present. This is due to the fact that significant time has not yet passed to ensure a large enough fleet size of alternately fuelled vehicles be assembled and analysed to produce a positive benchmark value now which may be compared to in future (Fearnley *et al*, 2015). Because of this current situation, such options to mitigate against vehicular emissions do not seem viable.

It is also important to note that diesel accounts for 68.97% of total emissions in eThekwini Municipality, with HCV's being the main contributor of diesel emissions. Therefore measures aimed at increasing the share of diesel motor vehicles within the passenger fleet could therefore have conflicting environmental implications (especially for PM) and does not seem to be a viable long term solution for eThekwini Municipality. Therefore eThekwini Municipality should explore methods similar to that proposed in section 5.6 and by Qiu *et al.*, (2016), or promote the use of biofuels in order to achieve emissions savings listed in Table 23 instead of increasing the share of diesel motor vehicles.

Based on recommendations by the DEA (2014) and calculations conducted using COPERT IV, it is advised that mitigation potential results found by this study listed in Table 22 and 23 are currently the most effective mitigation measures to be specifically used for the transport sector of eThekwini Municipality. These mitigation measures shall have the greatest direct impact on emission reductions and include improved efficiency of petrol and diesel vehicles, shifting freight from road to rail and shifting passengers from cars to public transport (reduced VKT and modal shift) and biofuels, since it easily accounts for the bulk of emissions from the entire transport sector (DEA, 2014). Thus the road transport sector should intuitively be the primary target for eThekwini Municipality's emission reduction initiatives (Thambiran and Diab, 2011; Buthelezi and Davies, 2015).

CHAPTER 6: CONCLUSION

6.1) Introduction

The road transport sector has been identified as a major contributor of GHG, acidifying pollutants and precursor gases, particularly within urban areas of developing countries. Similar to assessing industrial emissions there is a need to estimate and assess the contribution and implications of such emissions from the road transport sector for ambient air quality. This is required to develop and select pollution mitigation measures which seek to inform decision making, update or re-design current management systems and air quality policies in an attempt to build climate resilience. In municipalities such as the eThekwini Municipality current consumer trends indicate greater ownership of private vehicles which has significant effect on urban lifestyle, GHG, acidifying pollutants and precursor gas emissions. Subsequently issues such as deterioration of air quality, health and climate change become a concern.

6.2) Summary

The current study sought to quantify road traffic emissions for eThekwini Municipality while providing possible co-benefit opportunities to reduce GHG, acidifying pollutants and precursor gases within the road transportation sector. Upon achieving this aim and based on information derived, it would then be possible to identify mitigation measures suited to local driving conditions whilst highlighting possible co-benefits within the recommendations in order to build climate resilience within the municipality in terms of impending climate change.

A literature review was conducted to review the current state of knowledge for the area in an attempt to understand the emission, migration and depositional processes in order to discover potential recommendations and the best possible co-benefit opportunities. This review helped determine the main factors involved in influencing emissions namely chemical characteristics, vehicle activity data, annual vehicle mileage and factors acting upon meteorological dispersion. Contrary to normal practice, results from the literature reviewed indicated the need to estimate emissions other than GHG in order to determine the road transport sector’s potential threat to the environment. Findings from the literature reviewed also indicated that emissions from industrial processes and road transport have been identified as major emitters in eThekwini Municipality and contribute greatly to the pollution plumes experienced in the area (eThekwini Municipality, 2013; eThekwini Municipality, 2014).

Emission factors of 8 GHG, acidifying and precursor gases emitted from eThekwini Municipality's vehicular fleet were calculated by COPERT IV for the year 2010. This was based on statistical data from the eNATIS system, fuel properties, meteorological data, and a compilation of vehicle activity data. The result for the municipality provide an indication of and re-affirms the major contributors of GHG, acidifying pollutants and precursor gases within the motor vehicle fleet.

Road transportation activities produced a total of 3490980 tonnes of emissions in eThekwini Municipality in 2010. Of this total value, 3464033 tonnes of emissions were GHG. Analysis of the contributions of each vehicle sector revealed that passenger vehicles accounted for 24% of the total emissions for eThekwini, whilst LCV's and HCV's accounted for 15% and 61% of the total emissions respectively. Although less present, motorcycles accounted for 12800 tonnes or < 1 % of the total emissions for eThekwini. With regards to CO_2 emissions across the four sectors, the principal contributor of CO_2 for the year 2010 was the HCV sector, which accounted for about 61% of emissions. The principal contributor of N_2O was the passenger vehicles sector, which emitted 40% of N_2O emissions. The principal emitter of NO_x and SO_2 across the four sectors for 2010 was the HCV sector, which accounted for about 80% of NO_x emissions and 61% of SO_2 emissions. The vehicle sector emitted 68% of NH_3 emissions. With regards to $PM_{2.5}$, PM_{10} and total exhaust PM emissions across the four sectors HCV's were responsible for 70%, 69% and 73% of emissions respectively.

The first objective of this study was to compile a disaggregated road transport emission inventory of GHG and acidifying pollutants in tonnes/year in the priority area identified for the year 2010. This objective was carried out to identify which fuel types were responsible for the greatest amount of emissions to better inform decision making and recommendations. From the findings it is evident that both major fuel components contributed unequally to emissions. Diesel was responsible for 68.97% of all emissions in eThekwini Municipality and contributed greatly to air pollution and the potential acidification of the ocean either through acidifying pollutants or through CO_2. Given this finding, it stands to reason that mitigation measures aimed at increasing the share of diesel motor vehicles will have conflicting environmental implications (especially for PM) and does not seem to be a viable long term solution for eThekwini Municipality. As such it is advised that the municipality investigate solutions provided in Chapter 6, section 6.3.

The second objective of this study was to identify possible trends and exceedences of acidifying and air pollutants using existing air quality monitoring data which were either related to human or environmental health. This objective was carried out to assess the state of ambient air quality in relation to the road transport sector. Analysis of the data conducted within this study found a relationship between the diurnal use of vehicles and average number of exceedences of the NO_2 NAAQS 1 hour limit value ($\mu g/m^3$) per hour of the day, across all stations from 2004-2014. Peak vehicular use coincided with NO_2 in the mornings from approximately hours 6-10 and afternoons from hours 15-20. Despite the use of ambient air quality data it is reasonable to assume that vehicular use is to some extent responsible for the levels of NO_2 recorded within the municipality.

This study also made use of the analysis of the ambient air quality data set, which revealed numerous exceedences of annual NO_2 critical levels for the protection of vegetation. This was based on the ETCACM recommended annual standard. Exceedences of the NO_2 recommended annual critical level have been occurring throughout the data set at all stations during the monitoring period (2004-2014), with annual concentrations showing a consistent trend at all stations. A total of 56 annual exceedences have been recorded. Stations monitoring traffic emissions (Warwick, City Hall, Ganges) seem to experience the highest concentration of NO_2 and highest number of exceedences, often recording concentrations which are twice the recommended annual critical level. Such observations can be attributed to vehicular emissions and aged vehicle technologies in use in the municipality. Based on analysis of ambient air quality data in terms of NO_2 degradation of vegetation, key findings indicate that eThekwini Municipality is experiencing medium to high levels of chronic exposure to ambient NO_2, which by law is not being regulated. It can be concluded that while the NAAQS have helped curb ambient NO_2 concentrations for human health, concentrations and exceedences of ambient NO_2 are yet to be reduced to a level which is safe for environmental receptors such as vegetation.

Analysis of the data conducted within this study found no clear diurnal relationship between the diurnal use of vehicles and average number of exceedences of the SO_2 NAAQS 1 hour limit value (µg/m^3) per hour of the day, across all stations from 2004-2014. SO_2 exceedences remained erratic, making it difficult to assign causality to an emission source. Based on this it is plausible to assume that vehicular traffic does not considerably influence ambient SO_2 in the area as it would have reflected a clearer diurnal cycle similar to that of NO_2. Analysis of the ambient air quality data set revealed a limited number of SO_2 exceedences across some stations only, in relation to the protection of vegetation. Only 13 exceedences of the SO_2 recommended annual standard have occurred during the years of 2004-2008. After this period only 3 exceedences were recorded, showing improved ambient SO_2 concentrations. Wentworth and Southern works stations which were typical of industrial emissions, unsurprisingly accounted for the greatest number of SO_2 exceedences. Settlers school, Jacobs and Ganges only recorded less than 3 exceedences each. Apart from this, annual concentrations were consistently below the recommended critical level at Ferndale and Prospecton with no exceedences being recorded at these stations. Most of the SO_2 recommended annual critical levels were exceeded prior to the implementation of various SO_2 reduction strategies such as the use of cleaner fuels in industry and vehicles. It is this reason that can be attributed to the reduced number of exceedences witnessed in the latter years. Based on analysis of ambient air quality data in terms of SO_2 degradation of vegetation, it has been found that eThekwini Municipality is experiencing minimal levels of chronic exposure to ambient SO_2 and the natural environment's health is not at risk of degradation from ambient SO_2 from vehicular or industrial use. It can also be concluded that the NAAQS along with other key strategies have helped curb ambient SO_2 concentrations for human health and environmental health.

Hourly concentration values were employed to identify possible trends in PM_{10} concentrations in relation to vehicular use for each hour of the day across the data set. Peak vehicular use coincided with vehicular use and emission of PM_{10} in the mornings from approximately hours 7-11 and afternoons from hours 17-22. Based on average hourly PM_{10} concentrations (µg/m^3) for each hour of the day, from 2004-2014 per station, it is evident that the highest hourly PM_{10} concentrations for all five monitoring stations correspond with peak traffic in the mornings and afternoons. The higher concentrations also appear throughout the business hours during the day. Based on analysis of ambient air quality data, it is reasonable to conclude that vehicular use within eThekwini Municipality is to some extent responsible for PM_{10} concentrations recorded and its cyclical nature.

The third objective of this study entailed modelling and simulating scenarios based on nationally approved mitigation measures at the local level to determine its suitability and effectiveness in managing atmospheric emissions from the road transport sector within eThekwini Municipality. Simulations were successfully conducted within COPERT IV using nationally approved mitigation measures at the local level. This allowed for the most suitable mitigation measures with the greatest mitigation potential to be specifically identified for eThekwini Municipality. This study found that at present if all technically available mitigation potential measures recommended by DEA (2014) for the road transport sector of eThekwini Municipality are assumed to be implemented, assuming 100% compliance, it was shown that GHG acidifying pollutants and precursor gas emissions could be reduced by 2013723 tonnes in future. The main mitigation measures which account for such figures and should be applied within the municipality include the use of efficient petrol and diesel ICE with the latest Euro 6 standards, modal shifts in the form of reduced vehicle kilometre travelled, shifting freight from road to rail and biofuel usage. At present this is in contrast to national rankings found within Table 10, however it is safe to assume that even nationally proposed mitigations may be initially implemented at a local level as it is does re-align itself to locally based mitigation measures in the long run. Overall it was found that a reduction in the vehicle kilometres travelled, improving the efficiency of road freight transport offered the greatest potential for achieving co-benefits which centred upon the simultaneous reduction of GHG, acidifying pollutants and precursor gases.

The main significance of this study was to provide an emission inventory for the road transport sector of eThekwini Municipality. The inventory quantifies GHG, acidifying pollutants and precursor gases from eThekwini Municipality’s vehicular fleet and further identifies and prioritises vehicle sectors in accordance with the volume and type of emissions it produces. This inventory also serves as a baseline for the road transport sector when justifying the implementation of various mitigation scenarios recommended by DEA (2014). Mitigation potential calculated by scenarios within this study indicates recommended strategies to be employed specifically within eThekwini Municipality to limit GHG, acidifying pollutants and precursor gases by means of the co-benefit approach. Having found a considerable link between average daily traffic volumes and emission trends for a 24 hour period for PM and NO_2, it can be said that the implementation of mitigation measures listed above will relieve strain experienced by environmental receptors such as vegetation and aid in reducing the number of ETCACM recommended annual exceedences found to be at an elevated level in section 5.2. The comprehensive approach employed by this study indicates that through implementation of such measures and by abiding by recommendations it is possible to reduce vehicular emissions and off-set environmental degradation in light of impending climate.

6.3 Recommendations for further research to the reduce vehicular emissions

Based on the preceding 3 objectives, the final objective was to recommend the most suitable interventions to managing and reducing atmospheric emissions from the road transport sector within eThekwini Municipality in order to off-set some of the expected changes brought about by climate change. The following section provides some of the best practice methods and recommendations for further research (apart from mitigation measures assessed in this study) identified for eThekwini Municipality which are borne out of conceptualising issues raised within this study, or through literature reviewed and gaps identified in this study to reduce vehicular emissions in future. It is further recognised that while some options will need to be assessed and implemented through initiatives by national government and the motor manufacturing industry, others options can be implemented by the eThekwini Municipality itself.

6.3.1) Vehicle sectors that possess the greatest potential for mitigation of emissions

Based on findings from this study it is evident that mitigation initiatives should primarily focus on firstly the HCV sector for the greatest effect by increasing the number of fully electric HCV's within the fleet and finding alternative ways to ship goods via freight trains or air cargo. These options would be the preferred since fuel switching to petrol would not currently prove to be an environmental and economically viable solution given the user profile of HCV's. Such changes should be supported by governmental departments which subsidise and incentivise such changes, particularly for large logistic companies. It must be noted that many larger logistic companies have corporate social responsibilities to fulfill; hence adopting any of the mitigation measures listed above can be seen as the company shifting its stance from reactive to a proactive.

Given the large contributions of CO_2, NO_x, NH_3, SO_2 and N_2O from the petrol component for the passenger vehicle and LCV sector it would be efficient to implement a co-benefit approach to simultaneously reduce emissions in these sectors by encouraging modal shifts in the form of reduced vehicle kilometres travelled through public transport or using the improved efficiency of petrol ICE. By implementing a mitigation plan to limit pollutants and GHG from these two sectors it will have a dual effect by also reducing acidifying pollutants and precursor gases. Having already embarked on such initiatives, it is recommended that the municipality should now focus on maintaining and further expanding such initiatives to areas outside of the city in a bid to further reduce vehicular such emissions. This should be supported by appropriate research detailing the sustainability and socio-economic impact of such an endeavour structured under the authority of eThekwini Municipality. Such an approach to further curb GHG would prove to be the most efficient solution to tackle emissions from the road transport sector.

Overall a need for collaboration has been identified by this study, to overcome compartmentalisation of industry, governmental organisations and institutions. It is recommended that synergies between industry, governmental organisations and institutions should ensue in order to generate appropriate research and solutions to collectively reduce vehicular emissions. Examples of such actions include initiatives by appropriate governmental departments which promote, subsidise and incentivise changes through financial institutions and collaborations with the motor manufacturing industry. Collaboration on this scale will encourage the motor manufacturing industry to promote vehicles with latest euro standards and electric engines. Collaboration with financial institutions will allow for greater ease of access to vehicle finance options for the consumer when considering vehicles with latest euro standards and electric engines. This will encourage the selection of an electric vehicle or one with latest euro standards thus reducing emissions. Consumers will be further encouraged to consider such options given the incentives and savings from reduced CO_2 taxes implemented by government. Continual improvements to fuel quality, maintenance schedules, traffic management and pursuing alternative sustainable transport options in future are some of the more common and practical actions which have been proposed for reducing traffic emissions (Peng *et al*., 2015). Thus implementing and action plan which collectively draws upon several options as listed above seems to be the best solution that can be recommended in future.

6.3.2) Improved emission model inputs

While emissions have been calculated from reliable and verified published data sources this study was limited by the lack of on-board emissions measurement devices to provide site specific model inputs. While COPERT IV provides emission factors for a limited number of driving conditions such as vehicle types, capacity classes and regulations, it is common place for most of these driving conditions description to be qualitative and generalised hence preventing the consideration of true local conditions. Quantitative descriptions of real world South African driving conditions need to be employed to truly quantify emissions at the local level. Thus it is recommended that in future research be carried out to compile vehicle emission factors specific to eThekwini Municipality and made available to the public through the use of on-board emissions measurement devices to provide site specific model inputs. This will aid in better reflecting local driving conditions as it would take local driver profiles into consideration thus enhancing the accuracy and precision of future studies by bringing about coherence in the data to be employed by researchers. However such an undertaking requires a great deal of economic and technical resources before it is compiled, which requires approval from eThekwini Municipality.

Another factor to consider which lay outside the scope of this study is that of instantaneous and quantitative vehicle average speed data. Despite speed limits particularly on urban roads and highways, drivers quite often tend to exceed the speed limit, particularly in urban areas where speed limits are often not enforced with cameras and traffic officials. As such emissions calculated by the model may be less then emissions which are actually emitted by vehicles on a daily basis. Emission inventories compiled in future can be enhanced by considering speed dependent emission factors. Hence to remedy and account for these emissions one would once again require the use of on board measurement devices as stated earlier, to collect data and develop a driver profile for each vehicle.

Accurate records of vehicle registrations (eNATIS) are necessary when compiling an emission inventory. Availability of such information for research purposes should be further complimented by reliability through adequate training seminars to ensure synchronicity across all studies with this research space. This can limit potential errors and enhance work efficiency and results.

6.3.3 Financial and management requirements

Although several important findings were made in this study, it did not factor in the economic tools, structures and resources required to implement and quantify proposed mitigation strategies and the associated health benefits there off (from ambient air quality). The cost and benefits of mitigation actions can differ significantly for various geographical areas. In order to fully realise in reality the mitigation potential calculated for eThekwini Municipality, published analyses of such cost will constantly require refinement to update policies and plans in response to a changing market. Considerable research has been conducted on the possible co-benefits within this field, however it is often ignored and overlooked during policy design (Mayrhofer and Gupta, 2016). As such it is often a fruitless effort to merely provide solutions and recommendations which are borne out of considerable research if it is not accompanied by suitability analysis in terms of financial and social structures.

It is thus recommended that in future financial analysis and health impact assessments should be conducted in conjunction with emission inventories to fully assess the co-benefits to human health and ambient air quality (Xi *et al.*, 2015; Chen and Hashim, 2016). This is of particular importance for historical pollution hot spots such as south Durban. Therefore it is proposed that in order to determine the resources required to satisfy financial and health components, future research and analysis be aligned with financial and management structures in order to implement positive changes under a structured management framework. Given that such an undertaking can be completed it will aid in complimenting emission inventories and recommendations put forward within this study (Tobollik *et al.*, 2016).

6.3.4) Comprehensive local legislation

Acidification and precursor gas reduction brought about by the recommended mitigation measures can easily be tied into pre-existing GHG mitigation plans of the subsequent AQMP for eThekwini Municipality in a few years time given that this is currently lacking and that both emissions stem from the same sources. This shall allow for effective management of atmospheric emissions from the road transport sector that simultaneously reduce health issues, air pollutants and GHG (Thambiran and Diab, 2010). The municipality may thus simultaneously satisfy national and international emission reduction targets from this sector and further enhance ambient air quality through efficient strategies. It is recommended that a long term strategy be included within the AQMP which identifies and plans for any unforeseen impact of climate change in future in order to assess any potential threats to climate resilience and to assess if more stringent controls will be needed to prevent undermining of environmental and financial systems in eThekwini Municipality (Thambiran and Diab, 2010).This should be complimented by future mitigation measures formulated in response to causal factors responsible for witnessed emission trends. Such mitigation measures need to be adopted in future in terms of their suitability and benefits to mitigate against unforeseen impact of climate change or emissions from the road transport sector. Some of these measures which were cited and discussed in Chapter 5, section 5.6 went beyond those proposed by the DEA (2014) and included eco-driving, adaptive design, implementing smart traffic signal control and autonomous driving.

From the literature reviewed it is further evident that policy co-benefits are imperative for enhancing horizontal policy amalgamation. Thus adopting a framework in future that adapts to changing institutions, emerging technologies, infrastructure and natural systems, can create key positive insights for urban health and sustainability. As highlighted by section 6.3.3, a management framework which consists of these interconnections and co-benefits can provide a basis for integrated approaches to policymaking and planning in eThekwini Municipality. By investing in this holistic approach, time and financial resources which would have ultimately been used on remediation in future can be saved and used to proactively develop resilience and adaption strategies to cope with climate change (Chapman *et al*., 2016).

Sustainable vehicle mobility constantly requires increased consideration of inter-generational issues which emerge with time. Methods put forward within this study provide an indication of the potential reduction of emissions from the road transport sector that can be achieved. It further represents comprehensive approaches which centre on improving fuel efficiency and modifying vehicle fleets to reduce emissions, which will produce superior health and ambient air quality co-benefits whilst achieving sustainable mobility in anticipation of climate change now and in the near future. It is important to note that while quantifying emissions may not be entirely without uncertainties, the purpose of this study was to make estimations, assess mitigation measures locally and to explore and consider potential future developments within the recommendations not likely realised before in terms of impending climate change. This was to be conducted within a holistic vehicle emission modelling framework and future scenario analysis. The literature put forward by the DEA (2014) while thorough, does not yet include some recommendations made within this study in anticipation of technological trends in future. Thus it is further recommended that eThekwini Municipality, DEA or the

Department of Transport acknowledge and continuously assess emerging solutions for suitability in this country.

REFERENCES

Abiodun, B. J., Ojumu, A. M., Jenner, S., and Ojumu, T. V., 2013. The transport of atmospheric NO_x and HNO_3 over Cape Town. *Atmospheric Chemistry and Physics*, 14(2), 559-575.

Agyemang-Bonsu, K. W., Dontwi, I. K., Tutu-Benefoh, D. A., Bentil, D. E., Boateng, O. G., Asuobonteng, K., and Agyemang, W., 2010. Traffic-data driven modelling of vehicular emissions using COPERT III in Ghana: A case study of Kumasi. *American Journal of Scientific and Industrial Research,* 1(1), 32-40.

Ahmed. F., 2010. Approaches to and tools for managing environmental conflicts in coastal zones in Africa: Challenges and prospects. *African Journal of Conflict Resolution*, 10, (2), 31-47.

Akegbejo-Samsons, Y., 2009. *Demographic trends, resource allocation and climate change in sub-Saharan Africa: Policy implications for sustainability* [online]. Available from: http://www.openmeeting2009.org/pdf_files/Pdf%20papers/Full%20paper%20IHDP%202009%20 A%20version.pdf. [Accessed 2 May 2014].

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen., B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., and Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modelling and policy applications. *Environmental Modelling and Software*, 26(12), 1489-1501.

Amato, F., Alastuey, A., De La Rosa, J., Gonzalez Castanedo, Y., Sánchez de la Campa, A. M., Pandolfi, M., Lozano., A., Contreras González4, J., and Querol, X., 2014. Trends of road dust emissions contributions on ambient air particulate levels at rural, urban and industrial sites in southern Spain. *Atmospheric Chemistry and Physics*, 14(7), 3533-3544.

Amato, F., Pandolfi, M., Viana, M., Querol, X., Alastuey, A., and Moreno, T., 2009. Spatial and chemical patterns of PM10 in road dust deposited in urban environment. *Atmospheric Environment*, 43, 1650-1659.

Aneja, V. P., Roelle, P. A., Murray, G. C., Southerland, J., Willem Erisman. J., Fowler, D., Asman W. A. H., and Patni, N., 2001. Atmospheric nitrogen compounds II: emissions, transport, transformation, deposition and assessment. *Atmospheric Environment*, 35, 1903-1911.

Aneja, V. P., Schlesinger, W. H., and Erisman, J. W., 2009. Effects of agriculture upon the air quality and climate: Research, policy, and regulations. *Environmental Science and Technology*, 43(12), 4234-4240.

Asman, W. A. H., Sutton, M. A., Schjoerring, J. K., 1998. Ammonia: emission, atmospheric transport and deposition. *New Phytologist*, 139, 27-48.

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., and Yoo, K., 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, 9(1), 53-60.

Automobile Association (AA)., 2014. *Euro emissions standards: Progressively tighter exhaust emissions limits to improve air quality and health* [online]. Automobile Association. Available from: https://www.theaa.com/motoring_advice/fuels-and-environment/euro-emissions-standards.html. [Accessed 8 June 2015].

Bader, N., and Bleischwitz, R., 2009. Measuring urban greenhouse gas emissions: the challenge of comparability. *S.A.P.I.E.N.S.*, 2 (3), 1-15.

Baron, J. S., Hall, E. K., Nolan, B. T., Finlay, J. C., Bernhardt, E. S., Harrison, J. A., Chan, F., and Boyer, E. W., 2013. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. *Biogeochemistry*, 114(1-3), 71-92.

Bastianoni, S., Pulselli, F. M., and Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, 49, 253-257.

Bates, N. R., and Peters, A. J., 2007. The contribution of atmospheric acid deposition to ocean acidification in the subtropical North Atlantic Ocean. *Marine Chemistry*, 107(4), 547-558.

Bauer, C., Hofer, J., Althaus, H. J., Del Duce, A., and Simons, A., 2015. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. *Applied Energy,* 157, 871-883.

Beman, J. M., Chow, C. E., King, A. L., Feng, Y., Fuhrman, J. A., Andersson, A., Bates, N. R., Popp, B. N., and Hutchins, D. A., 2011. Global declines in oceanic nitrification rates as a consequence of ocean acidification. T*he National Academy of Sciences*, 108(1), 208-213.

Berntsen, T., and Fuglestvedt, J., 2008. Global temperature responses to current emissions from the transport sectors. T*he National Academy of Sciences*, 105(49), 19154-19159.

Bhargava, S., and Bhargava, S., 2013. Ecological consequences of acid rain. J*ournal of Applied Chemistry,* 5(4), 19-24.

Bhatia, S. C., 2002. *Environmental chemistry.* CBS Publisher and Distributors.

Bigazzi, A. Y., and Clifton, K. J., 2015. Modeling the effects of congestion on fuel economy for advanced power train vehicles. *Transportation Planning and Technology*, 38(2), 149-161.

Bobbink, R., and Hettelingh, J. P., 2010. *Review and revision of empirical critical loads and dose-response relationships*. Proceedings of an expert worksho*p.* Noordwijkerhout.

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Busmante, M., Cinderby, S., Davidson, E., Dentener, F., Emmet, B., Erisman, J. W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., and De Vries, W., 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications*, 20(1), 30-59.

Borges, A., and Gypens, N., 2010. Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. *Limnology and Oceanography*, 55(1), 346-353.

Borken-Kleefeld, J., Fuglestvedt, J., and Berntsen, T., 2013. Mode, load, and specific climate impact from passenger trips. *Environmental Science and Technology,* 47, 7608-7614.

Boubaker, S., Rehimi, F., and Kalboussi, A., 2015. Effect of vehicular technology on energy consumption and emissions. *International Journal of Environmental Studies,* 72(4), 667-684.

Buthelezi, S. A., and Davies, T. C., 2015. Carbon monoxide (CO), ozone (O_3) and nitrogen dioxide (NO_2) exposure from vehicular transportation and other industrial activities in the vicinity of Umlazi Township, South of Durban, KwaZulu-Natal Province, South Africa. *Transactions of the Royal Society of South Africa*, 1-7.

Cai, H., and Xie, S., 2007. Estimation of vehicular emission inventories in China from 1980 to 2005. *Atmospheric Environment*, 41(39), 8963-8979.

Caldeira, K., and Wickett, M. E., 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *Journal of Geophysical Research*. *Oceans*, 110.

Camargo, J. A., and Alonso, Á., 2006. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. *Environment International,* 32(6), 831-849.

Chen, K. S., and Hashim, J. H., 2016. A review on co-benefits of mass public transportation in climate change mitigation. *Sustainable Cities and Society*, 22, 11-18.

Chapman, R., Howden-Chapman, P., and Capon, A., 2016. Understanding the systemic nature of cities to improve health and climate change mitigation. *Environment International,* 1-8.

Chavez, A., and Ramaswami, A., 2011. Progress toward low-carbon: approaches for trans-boundary greenhouse gas emissions foot printing for cities. *Carbon Management*, 2(4), 471-482.

Colvile, R. N., Hutchinson, E. J., Mindell, J. S., and Warren, R. F., 2001. The transport sector as a source of air pollution. *Atmospheric Environment*, 35(9), 1537-1565.

Council of Scientific Industrial Research (CSIR), 2013. 10th Annual State of Logistics Survey for South Africa, 2010 [online]. Available from: http://www.csir.co.za/sol/docs/10th_SoL_Bold_Steps_Forward_web.pdf.

Cui, J., Zhou, J., Peng, Y., He, Y., Yang, H., and Mao, J., 2014. Atmospheric wet deposition of nitrogen and sulphur to a typical red soil agro-ecosystem in Southeast China during the ten-year monsoon seasons (2003–2012). *Atmospheric Environment*, 82, 121-129.

Curran, S., Kumar, A., Lutz, W., and Williams, M., 2002. Interactions between Coastal and Marine Ecosystems and Human Population Systems: Perspectives on How Consumption Mediates this Interaction. *Ambio*, 31(4), 264-268.

D'Angiola, A., Dawidowski, L. E., Gómez, D. R., and Osses, M., 2010. On-road traffic emissions in a megacity. *Atmospheric Environment*, 44(4), 483-493.

Dentener, F., Drevet, J., Lamarque, J. F., Bey, I., Eickhout, B., Fiore, A. M., Hauglustaine, D., Horowitz, L. W., Krol, M., Kulshrestha, U. C., Lawrence, M., Galy-Lacaux, C., Rast, S., Shindell, D., Stevenson, D., Van Noije, T., Atherton, C., Bell, N., Bergman, D., Butler, T., Cofala, J., Collins, B., Doherty, R., E llingsen, K., Galloway, J., Gauss, M., Montanaro, V., Muller, J. F., Pitari, G., Rodriguez, J., Sanderson, M., Solmon, F., Strahan, S., Schultz, M., Sudo, K., Szopa, S., and Wild, O., 2006. Nitrogen and sulphur deposition on regional and global scales: A multi-model evaluation. *Global Biogeochemical Cycles*, 20(4), 1-21.

Department of Energy., 2015. SA fuel sales volume [online]. Department of Energy. Available from: http://www.energy.gov.za/files/energyStats_frame.html. Accessed 8 June 2015. [Accessed 1 February 2015].

Department of environmental affairs and tourism (DEAT)., 2007. *South Durban basin multi-point plan case study report Air Quality Act Implementation: Air Quality Management Planning*. Series C, Book 12.

Department of environmental affairs and tourism (DEAT)., 2009. *Greenhouse Gas Inventory Report for South Africa 1990–2000*. Pretoria: Department of Environmental Affairs and Tourism.

Department of environmental affairs and tourism (DEAT)., 2013. *Greenhouse Gas Inventory for South Africa 2000–2010*. Pretoria: Department of Environmental Affairs.

Department of environmental affairs (DEA)., 2014. *South Africa's greenhouse gas (GHG) mitigation potential analysis: Technical appendix E-Transport sector*. Pretoria: Department of environmental affairs.

Doney, S. C., Mahowald, N., Lima, I., Feely, R. A., Mackenzie, F. T., Lamarque, J. F., and Rasch, P. J., 2007. Impact of anthropogenic atmospheric nitrogen and sulphur deposition on ocean acidification and the inorganic carbon system. *Proceedings of the National Academy of Sciences*, 104(37), 14580-14585.

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A., 2009. Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science*, 1, 169-192.

Doney, S. C., 2010. The growing human footprint on coastal and open-ocean biogeochemistry. *Science*, 328(5985), 1512-1516.

Dong, H., Dai, H., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., FUjii, M., and Masui, T., 2015. Pursuing air pollutant co-benefits of CO_2 mitigation in China: A provincial levelled analysis. *Applied Energy*, 144, 165-174.

Duarte, C. M., Hendriks, I. E., Moore, T. S., Olsen, Y. S., Steckbauer, A., Ramajo, L., Carstensen, J., Trotter, J.A., and McCulloch, M., 2013. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, 36(2), 221-236.

Eckert, J. J., Corrêa, F. C., Santiciolli, F. M., Costa, E. D. S., Dionísio, H. J., and Dedini, F. G., 2016. Vehicle gear shifting strategy optimization with respect to performance and fuel consumption. *Mechanics Based Design of Structures and Machines*, 44(1-2), 123-136.

Elkafoury, A., Bady, M., Aly, M. H. F., and Negm, A. M., 2013. Emissions Modelling for Road Transportation in Urban Areas: State-of-Art Review. In: *Proceeding of 23rd International conference on-environmental protection is a must,* 11-13 May 2013. 1-16.

Environmental Protection Agency (EPA), 2003. *User's guide to MOBILE6.1 and MOBILE6.2: Mobile Source emission Factor Model*. Environmental Protection Agency. Report: EPA420-R-03-010.

Environmental Protection Agency (EPA), 2015. *MOVES2014a User Guide*. Environmental Protection Agency. Report: EPA-420-B-15-095.

Erisman, J. W., Otjes, R., Hensen, A., Jongejan, P., van den Bulk, P., Khlystov, A., Mols, H., and Slanina, S., 2001. Instruments development and application in studies and monitoring of ambient ammonia. *Atmospheric Environment*, 35, 1913-1922.

eThekwini Municipality., 2013. *eThekwini GHG Emissions Inventory 2011* [online]. Available from:http://www.durban.gov.za/Resource_Centre/Current%20Projects%20and%20Programmes/energyoffice/Documents/eThekwini%20GHG%20Inventory%202011%20Technical%20Report%20Final%2020%20March%202013.pdf. [Accessed on 29 July 2015].

eThekwini Municipality., 2014. *eThekwini GHG Emissions Inventory 2012* [online]. Available from:http://www.durban.gov.za/Resource_Centre/Current%20Projects%20and%20Programmes/energyoffice/Documents/eThekwini%20GHG%20Inventory%202011%20Technical%20Report%20Final%2020%20March%202013.pdf. [Accessed on 29 July 2015].

eThekwini Municipality., 2015. Ward Map [online]. Available from: http://www.durban.gov.za/City_Services/engineering%20unit/Surveying_Land_Information/Documents/ETHEKWINI%20WARD%20MAP%20NEW%20BOUNDARIES.pdf. [Accessed 19 May 2015].

European Topic Centre on Air Pollution and Climate Change Mitigation (ETCACM) 2011. Evaluation of current limit and target values as set in the EU Air Quality Directive [online]. Available from: http://acm.eionet.europa.eu/. [Accessed 18 December 2015].

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C., 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science: Journal du Conseil*, 65(3), 414-432.

Fang, Y. T., Koba, K., Wang, X. M., Wen, D. Z., Li, J., Takebayashi, Y., Liu, X. Y., and Yoh, M., 2011. Anthropogenic imprints on nitrogen and oxygen isotopic composition of precipitation nitrate in a nitrogen-polluted city in southern China. *Atmospheric Chemistry and Physics*, 11(3), 1313-1325.

Fang, Y., Wang, X., Zhu, F., Wu, Z., Li, J., Zhong, L., Chen, D., and Yoh, M., 2013. Three-decade changes in chemical composition of precipitation in Guangzhou city, southern China: has precipitation recovered from acidification following sulphur dioxide emission control? *The International Meteorological Institute*, 1-15.

Fearnley, N., Pfaffenbichler, P., Figenbaum, E., and Jellinek, R., 2015. E-vehicle policies and incentives: assessment and recommendations. *The International Council on Clean Transportation*, 1-43.

Forbes, P., and Labuschagne, K., 2009. *The development of South African vehicle emission factors*. Proceedings of the national association for clean air conference, 14-16 October 2009.Vanderbijlpark, South Africa.

Fowler, D., Smith, R. I., Muller, J. B. A., Hayman, G., and Vincent, K. J., 2005. Changes in the atmospheric deposition of acidifying compounds in the UK between 1986 and 2001. *Environmental Pollution*, 137(1), 15-25.

Franco, V., Fontaras, G., and Dilara, P., 2012. Towards improved vehicle emissions estimation in Europe. *Social and Behavioural Sciences*, 48, 1304-1313.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z. C., Freney, J. R., Martinelli, L. A., Seitzinger, S. P., and Sutton, M. A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science*, 320, 889-892.

Gandhi, H. S., and Shelef, M., 1991. Effect of sulphur on noble metal automotive catalysts. *Applied Catalysis*, 77(2), 175-186.

Geng, Y., Ma, Z., Xue, B., Ren, W., Liu, Z., and Fujita, T., 2013. Co-benefit evaluation for urban public transportation sector-a case of Shenyang, China, *Journal of Cleaner Production*, 58, 82-91.

Gkatzoflias, D., Kouridis, C., Ntziachristos, L., Samaras, Z., 2012. *COPERT IV computer programme to calculate emissions from road transport User manual (version 9.0)*. Thessaloniki Greece: EMISIA and EEA.

Greene, D. L., and Plotkin, S. E., 2011. Reducing greenhouse gas emissions from U. S. transportation. *Pew Centre on Global Climate Change*.

Guensler, R. L., Liu, H., Xu, X., Xu, Y., and Rodgers, M. O., 2016. MOVES-Matrix: Setup, Implementation, and Application. *Transportation research board 95th annual meeting*, 10 January-14 January 2016. Washington, 1-18.

Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M., Rowley, S. J., Tedesco, D., and Buia, M. C., 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, 454(7200), 96-99.

Hao, J., and Wang, L., 2005. Improving urban air quality in China: Beijing case study. *Journal of the Air and Waste Management Association*, 55(9), 1298-1305.

Hawkins, T. R., Gausen, O. M., and Stromman, A. H., 2012. Environmental impacts of hybrid and electric vehicles - a review. *The International Journal of Life Cycle Assessment*, 17(8), 997-1014.

Held, G., and Mphepya, J., 2000. W*et and dry deposition in South Africa*. Proceedings, XI Congresso brasiliero de meteorologia. Eskom technology services international.

Hettelingh, J. P., Posch, M., Velders, G. J., Ruyssenaars, P., Adams, M., de Leeuw, F., Lükewille, A., Maas, R., Sliggers, J., and Slootweg, J., 2013. Assessing interim objectives for acidification, eutrophication and ground-level ozone of the EU National Emissions Ceilings Directive with 2001 and 2012 knowledge. *Atmospheric Environment,* 75, 129-140.

Higdon, M. 2007. Durban, South Africa-A full-year study. *Air Force Combat Climatology Centre*, 1-25.

Hillmer-Pegram, K.C., Howe, P. D., Greenberg, H., and Yamal, B., 2012. A geographic approach to facilitating local climate governance: From emissions inventories to mitigation planning. *Applied Geography*, 34, 76-85.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, A., and Hatziolos, M. E., 2007. Coral reefs under rapid climate change and ocean acidification. S*cience*, 318(5857), 1737-1742.

Huang, K., Zhuang, G., Xu, C., Wang, Y., and Tang, A., 2008. The chemistry of the severe acidic precipitation in Shanghai, China. *Atmospheric Research*, 89(1), 149-160.

Huang, Y., Lu, X., and Chen, K., 2013. Wet atmospheric deposition of nitrogen: 20 years measurement in Shenzhen City, China. *Environmental Monitoring and Assessment*, 185(1), 113-122.

Ibrahim, N., Sugar, L., Hoornweg, D., and Kennedy, C., 2012. Greenhouse gas emissions from cities: comparison of international frameworks. *Local environment: The International Journal of Justice and Sustainability,* 17 (2), 223-241.

International Energy Agency (IEA), 2012. *World energy outlook 2012.* Paris, France: OECD/ IEA.

Im, U., Christodoulaki, S., Violaki, K., Zarmpas, P., Kocak, M., Daskalakis, N., Mihalopoulos, N., and Kanakidou, M., 2013. Atmospheric deposition of nitrogen and sulphur over southern Europe with focus on the Mediterranean and the Black Sea. *Atmospheric Environment*, 81, 660-670.

Inter-Governmental Panel on Climate Change (IPCC), 2006. *Guidelines for national greenhouse gas inventories* [online]. Inter-governmental panel on climate change. Available from: www.ipcc-nggip.iges.or.jp [Accessed on 20 December 2015].

Jacob, D. J., and Winner, D. A., 2009. Effect of climate change on air quality. *Atmospheric Environment*, 43(1), 51-63.

Jerret, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahsuvaroglu, T., Morisson, J., and Giovis, C., 2005. A review and evaluation of intra-urban air pollution exposure models. *Journal of Exposure Analysis and Environmental Epidemiology*, 15, 185-204.

Kean, A. J., Harley, R. A., Littlejohn, D., and Kendall, G. R., 2000. On-road measurement of ammonia and other motor vehicle exhaust emissions. *Environmental Science and Technology*, 34(17), 3535-3539.

Kioutsioukis, I., Kouridis, C., Gkatzoflias, D., Dilara, P., and Ntziachristos, L., 2010. Uncertainty and sensitivity analysis of national road transport inventories compiled with COPERT IV. *Procedia-Social and Behavioural Sciences*, 2(6), 7690-7691.

Koupal, J., Cumberworth, M., Michaels, H., Beardsley, M., and Brzezinski, D., 2003. Design and implementation of MOVES: EPA‘s new generation mobile source emission model. *Ann Arbor*, 1001, 1-15.

Kousoulidou, M., Ntziachristos, L., Gkeivanidis, S., Samaras, Z., Franco, V., and Dilara, P., 2010. *Validation of the COPERT road emission inventory model with real-use data*. US EPA 19th Annual international emission inventory conference. emissions inventories-Informing emerging issues.

Krishnamurthy, A., Moore, J. K., Mahowald, N., Luo, C., Doney, S. C., Lindsay, K., and Zender, C. S., 2009. Impacts of increasing anthropogenic soluble iron and nitrogen deposition on ocean biogeochemistry. *Global Biogeochemical Cycles*, 23(3).

Lajtha, K., and Jones, J., 2013. Trends in cation, nitrogen, sulphate and hydrogen ion concentrations in precipitation in the United States and Europe from 1978 to 2010: a new look at an old problem. *Biogeochemistry*, 1-32.

Lárusdóttir, E. B., and Ulfarsson, G. F., 2015. Effect of Driving Behavior and Vehicle Characteristics on Energy Consumption of Road Vehicles Running on Alternative Energy Sources. *International Journal of Sustainable Transportation*, 9(8), 592-601.

Li, C., Ni, A., and Ding, J., 2015. Eco-Driving-Current Strategies and issues, a preliminary Survey. In: *Information Technology and Mechatronics Engineering Conference*. Atlantis Press, 1-9.

Liu, X., Duan, L., Mo, J., Du, E., Shen, J., Lu, X., Zhang, Y., Zhou, X., He, C., and Zhang, F., 2011. Nitrogen deposition and its ecological impact in China: an overview. *Environmental Pollution*, 159(10), 2251-2264.

Liu, T., Wang, X., Wang, B., Ding, X., Deng, W., Lü, S., and Zhang, Y., 2014. Emission factor of ammonia (NH_3) from on-road vehicles in China: tunnel tests in urban Guangzhou. *Environmental Research Letters*, 9(6), 1-8.

Matooane, L., and Diab, R. D., 2001. Air pollution carrying capacity in the South Durban Industrial Basin. *South African Journal of Science*, 97, 450-453.

Mayrhofer, J. P., and Gupta, J., 2016. The science and politics of co-benefits in climate policy. *Environmental Science and Policy*, 57, 22-30.

Menz, F. C., and Seip, H. M., 2004. Acid rain in Europe and the United States: an update. *Environmental Science and Policy*, 7(4), 253-265.

Merven, B., Stone, A., Hughes, A., and Cohen, B., 2012. Quantifying the energy needs of the transport sector for South Africa: A bottom-up model [online].Energy research centre, University of Cape Town. Available from: http://www. erc. uct. ac. za/Research/publications/12-Merven-etal_Quantifying_energy_needs_transport% 20sector. Pdf. [Accessed 3 March 2015).

Migliavacca, D., Teixeira, E. C., Wiegand, F., Machado, A. C. M., and Sanchez, J., 2005. Atmospheric precipitation and chemical composition of an urban site, Guaiba hydrographic basin, Brazil. *Atmospheric Environment*, 39(10), 1829-1844.

Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M. L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R. S., Carslawn, K., Cooper, O. R., Dentener, F., Fowler, D., Fragkou, E., Frost, G. J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H. C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I. S. A., Jenkin, M., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M. G., Lee, J. D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J.J., O’Dowd, C. D., Palmer, P. I., Parrish, D. D., Petzold, A., Platt, U., Poschl, U., Prevot, A. S. H., Reeves, C. E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van der Werf, G. R., Vautard, R., Vestreng, V., Vlachokostas, Ch., von Glasow.,R., 2009. Atmospheric composition change-global and regional air quality. *Atmospheric Environment*, 43(33), 5268-5350.

Moriarty, P., and Honnery, D., 2008. Low-mobility: The future of transport. *Futures*, 40(10), 865-872.

Mphepya, J. N., Galy-Lacaux, C., Lacaux, J. P., Held, G., and Pienaar, J. J., 2006. Precipitation chemistry and wet deposition in Kruger National Park, South Africa. *Journal of Atmospheric Chemistry*, 53(2), 169-183.

Mphepya, J. N., Pienaar, J. J., Galy-Lacaux, C., Held, G., and Turner, C. R., 2004. Precipitation chemistry in semi-arid areas of Southern Africa: a case study of a rural and an industrial site. *Journal of Atmospheric Chemistry*, 47(1), 1-24.

National Climate Assessment (NCA), 2014. *Ocean Acidification* [online]. Available from: http://nca2014.globalchange.gov/report/our-changing-climate/oceanacidification. [Accessed 10 July 2015].

National Research Council (NRC)., 2010. *Ocean Acidification: A national strategy to meet the challenges of a changing ocean*. Washington: National Academies Press.

Nieuwenhuijsen, M. J., Khreis, H., Verlinghieri, E. and Rojas-Rueda, D., 2016. Transport and health: A marriage of convenience or an absolute necessity. *Environment International*, 88, 150-152.

Nilsson, J., and Grennfelt, P., 1988. *Critical loads for sulphur and nitrogen. Air pollution and Ecosystems* , 15, 85-91.

Ntziachristos, L., and Smit, R., 2014. Estimation of road transport emissions for Australia. In 26th *ARRB Conference*, 2014. *Sydney, New South Wales, Australia*.

Ntziachristos. L., and Samaras, Z., 2014. *Methodology for the calculation of exhaust emissions* [online]. European environmental agency. Available from: www.emisia.com/products/copert-4/documentation.

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., Gnanadesikan, A., Gruber, N, Ishida, A., Joos, F., Key, R. M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G K., Rodgers, K. B., Sabine, C. L., Sarmiento, J. L., Schlitzer, R., Slater, R. D., Totterdell, I. J., Weirig, M. F., Yamanaka, Y. and Yool, A., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437(7059), 681-686.

Oxley, T. A., Elshkaki, L., Kwiatkowski, A., Castillo, T., Scarbrough, T., and Apsimon, H., 2012. Pollution abatement from road transport: cross-sectoral implications, climate co-benefits and behavioural change. *Environmental Science and Policy*, 19, 16-32.

Peng, B., Du, H., Ma, S., Fan, Y., and Broadstock, D. C., 2015. Urban passenger transport energy saving and emission reduction potential: A case study for Tianjin, China. *Energy Conversion and Management*, 102, 4-16.

Prata, J., Arsenio, E.. and Pontes, J. P., 2015. Setting a city strategy for low carbon emissions: The role of electric vehicles, renewable energy and energy efficiency. *International Journal of Sustainable Development and Planning*, 10(2), 190-202.

Preston-Whyte, R. A., 1970. *Local atmospheric circulations and the meso-climate of Durban. Thesis* (Doctoral dissertation). University of Natal, Durban.

Preston-Whyte, R. A., and Diab, R, D., 1980. Local Weather and Air Pollution Potential: The Case of Durban. *Environmental Conservation,* 7(3), 241-244.

Qiu, Z., Li, X., Hao, Y., and Deng, S., 2016. Potential of diesel emissions reduction strategies in Xi'an, China. *Clean Technologies and Environmental Policy,* 1-8.

Reşitoğlu, İ. A., Altinişik, K., and Keskin, A., 2015. The pollutant emissions from diesel-engine vehicles and exhaust after treatment systems. *Clean Technologies and Environmental Policy,* 17(1), 15-27.

Rexeis, M., Hausberger, S., Kühlwein, J., and Luz., R., 2013. *Update of emission factors for euro 5 and euro 6 vehicles for the HBEFA version 3.2* [online]. Available from: http://www.hbefa.net/e/documents/HBEFA32_EF_Euro_5_6_TUG.pdf. [Accessed 1 April 2016].

Rockström, J., and Karlberg, L., 2010. The Quadruple Squeeze: Defining the safe operating space for freshwater use to achieve a triply green revolution in the Anthropocene. *Ambio*, 39(3), 257-265.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, S. I., Lambin, E. T. M., Lenton, M., Scheffer, C., Folke, H. J., Schellnhuber, B., Nykvist, C. A., de Wit, T., Hughes, S., van der Leeuw, H., Rodhe, S., So¨rlin, P. K. Snyder, R., Costanza, U., Svedin, M., Falkenmark, L., Karlberg, R. W., Corell, V. J., Fabry, J., Hansen, B., Walker, D., Liverman, K., Richardson, P., and Crutzen., 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, 14(2), 472-475.

Roustan, Y., Pausader, M., and Seigneur, C., 2011. Estimating the effect of on-road vehicle emission controls on future air quality in Paris, France. *Atmospheric Environment*, 45(37), 6828-6836.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T. H, Kozyr, A., Ono, T., and Rios, A. F., 2004. The oceanic sink for anthropogenic CO_2. *Science*, 305(5682), 367-371.

Schoeman. C., 2010. Eliminating extra kilometres results in extra cost savings. S*cience Scope*, 5(1), 12-15.

Schlesinger, W. H., 2009. Planetary boundaries: thresholds risk prolonged degradation. *Nature Reports Climate Change*, 112-113.

Scorgie, Y., and Kornelius, G., 2009. Modelling of acid deposition over the South African Highveld. A*nnual South African National Association for Clean Air Conference*. South Africa.

Scott, G. M., and Diab, R. D., 2000. Forecasting air pollution potential: A synoptic climatological approach. *Journal of Air and Waste Management*, 50, 1831-1842.

Seinfeld, J. H., and Pandis, S. N., 2006. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. 2nd ed. New York: John Wiley.

Sharma, S. K., Datta, A., Saud, T., Mandal, T. K., Ahammed, Y. N., Arya, B. C., and Tiwari, M. K., 2010. Study on concentration of ambient NH_3 and interactions with some other ambient trace gases. *Environmental Monitoring and Assessment*, 162(1-4), 225-235.

Sims, R. R., Schaeffer, F., Creutzig, X., Cruz-Núñez, M., D'Agosto, D., Dimitriu, M. J., Figueroa Meza, L., Fulton, S., Kobayashi, O., Lah, A., McKinnon, P., Newman, M., Ouyang,

J. J., Schauer, D., Sperling, K., and Tiwari, G., 2014. Transport. In: Edenhofer, O. R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., Kriemann, J., Savolainen, S., Schlömer, C., von Stechow, T., Zwickel T., and Minx J.C., eds. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.

Sjödin, Å., and Jerksjö, M., 2008. Evaluation of European road transport emission models against on-road emission data as measured by optical remote sensing. In: *17th International Conference of Transport and Air Pollution*. Göteborg, 1-10.

Smit, R., Ntziachristos, L., and Boulter, P., 2010. Validation of road vehicle and traffic emission models-A review and meta-analysis. *Atmospheric Environment*, 44(25), 2943-2953.

Smith, A. C., Holland, M., Korkeala, O., Warmington, J., Forster, D., Apsimon, H, Oxley, T., Dickens, R., and Smith, S. M., 2015. Health and environmental co-benefits and conflicts of actions to meet UK carbon targets. *Climate Policy*, 1-31.

Solomon, S. D., Qin, M., Manning, Z., Chen, M., Marquis, K. B., Averyt, M., Tignor., and Miller H. L, Eds. IPCC., 2007: *Climate Change. The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York.

South Africa (SA)., 1977. Petroleum products act (No. 49 of 1977), Pretoria.

South Africa (SA)., 1996. National road traffic act (No. 93 of 1996): Chapter IX: Road traffic signs and general limits. Pretoria.

South Africa (SA)., 2004. National environmental management: Air quality act (AQA) (No. 39 of 2004). Pretoria.

South African National Standards (SANS)., 2006a. *South African national standard for unleaded petrol, SANS* 1598, South African Bureau of Standards.

South African National Standards (SANS)., 2006b. *Automotive diesel fuel, SANS 342*. South African Bureau of Standards.

South African Petroleum Industry Association (SAPIA)., 2008. Petrol and diesel in South Africa and the impact on air quality [online]. South African petroleum industry association. Available from: http://www.sapia.co.za/_literature_86491/Petrol_and_Diesel_in_South_Africa_and_the_impact_on_air_quality,_November_2008. [Accessed 1 June 2015].

Speidel, M., Nau, R., Arnold, F., Schlager, H., and Stohl, A., 2007. Sulphur dioxide measurements in the lower, middle and upper troposphere: Deployment of an aircraft-based chemical ionization mass spectrometer with permanent in-flight calibration, *Atmospheric Environment***,** 41, 2427-2437.

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and P. M. Midgley, eds. IPCC., 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York.

Stone, A., 2000. *South African vehicle emissions project: Phase II. Final report: Diesel engines*, February 2000.

Stroe, C, C., Schiavon, M., Panaitescu, V, N., and Ragazzi, M., 2014. Environmental impact modelling of a highway: a case study. *University of Politehnica Bucharest Scientific bulletin, series D*, 76(2), 213-222.

Swart, R., Amann, M., Raes, F., and Tuinstra, W., 2004. A good climate for clean air: Linkages between climate change and air pollution. An Editorial Essay. *Climatic change*, 66(3), 263-269.

Swedish Environmental Protection Agency (SEPA)., 2000. *Environmental quality criteria: coasts and seas*. Stockholm: Sweden. Report Vol. 5052.

Takeshita, T., 2012. Assessing the co-benefits of CO_2 mitigation on air pollutants emissions from road vehicles. *Applied Energy*, 97, 225-237.

Taljaard J. J., Schmidt, *W.*, and van Loon., H., 1961. Frontal analysis with application to the southern hemisphere. *Notos*, 10, 25-58.

Thambiran, T., and Diab, R. D., 2010. A review of scientific linkages and interactions between climate change and air quality, with implications for air quality management in South Africa. *South African Journal of Science*, 106(3-4), 1-8.

Thambiran, T., and Diab, R. D., 2011a. Air pollution and climate change co-benefit opportunities in the road transportation sector in Durban, South Africa. *Atmospheric Environment*, 45(16), 2683-2689.

Thambiran, T., and Diab, R. D., 2011b. Air quality and climate change co-benefits for the industrial sector in Durban, South Africa. *Energy Policy*, 39(10), 6658-6666.

The South African post office., 2015. Postal code tools [online]. Available from: https://www.postoffice.co.za/tools/postalcode.html. [Accessed 19 May 2015].

Tobollik, M., Keuken, M., Sabel, C., Cowie, H., Tuomisto, J., Sarigiannis, D., Künzli, N., Perez, L., and Mudu, P., 2016. Health impact assessment of transport policies in Rotterdam: Decrease of total traffic and increase of electric car use. *Environmental Research*, 146, 350-358.

Tompkins, F., and Deconcini, C., 2015. 2014: A year of temperature records and landmark climate findings [online]. World resource institute. Available from: http://www.wri.org/sites/default/files/2014_Temperature_Records_and_Landmark_Climate_Findings_fact_sheet.pdf.[Accessed 10 March 2015].

Tongwana, M., Piket, S., Stevens, L., and Ramotubei, T., 2015. Greenhouse gas emissions from road transport in South Africa and Lesotho between 2000 and 2009. *Transportation Research part D*, 37, 1-13.

Troost, T. A., Blaas, M., and Los, F. J., 2013. The role of atmospheric deposition in the eutrophication of the North Sea: A model analysis. *Journal of Marine Systems*, 125, 101-112.

Turley, C., and Findlay, H. S., 2009. Ocean acidification as an indicator of climate change. In: Letcher, T. M, Eds. *Climate change: observed impacts on planet earth*. Oxford: *Elsevier*, 367-387.

Tyson, P. D., 1966. Examples of local air circulations over Cato Ridge during July 1965. *South African Geographical Journal*, 48, 13.

Tyson, P. D., 1986. *Climatic change and variability in southern Africa*. Cape Town. Oxford university press.

Tyson, P. D., and Preston-Whyte, R. A., 2000. W*eather and climate of southern Africa*. Oxford University Press.

Tyson, P. D., Diab, R. D., and Preston-Whyte, R. A., 1979. *Stability wind roses for southern Africa*. Johannesburg: Department of Geography and Environmental Studies, University of the Witwatersrand.

uMoya-NILU., 2015. *eThekwini Municipality AQMP review and update: Baseline Assessment.* Durban: uMoya-NILU. Report number uMN032-15.

United Nations (UN), 2001. World Urbanization Prospects: The 2001 Revision. United Nations Population Division [online]. Available from: www.un.org [Accessed 8 April 2015].

United Nations., 2014. World Urbanization Prospects: The 2014 Revision, Highlights [online]. Available from: https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf [Accessed 18 March 2015].

Vanhulsel, M., Degraeuwe, B., Beckx, C., Vankerkom, J., and De Vlieger, I., 2014. Road transportation emission inventories and projections-Case study of Belgium: Methodology and pitfalls, *Transportation research part D: Transport and Environment*, 27, 41-45.

Vestreng, V., Ntziachristos, L., Semb, A., Reis, S., Isaksen, I. S. A., and Tarrasón, L., 2009. Evolution of NO_x emissions in Europe with focus on road transport control measures. *Atmospheric Chemistry and Physics*, 9(4), 1503-1520.

Vet, R., Artz, R. S., Carou, S., Shaw, M., Ro, C. U., Aas, W., Baker, A., Bowersox, V.C., Dentener, F., Galy-Lacaux, C., Hou, A., Pienaar, J.J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P.S.P., and Reid, N.W., 2014. A global assessment of precipitation chemistry and deposition of sulphur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*, 93, 3-100.

von Glasow, R., Jickells, T. D., Baklanov, A., Carmichael, G. R., Church, T. M., Gallardo, L., Hughes, C., Kanakidou, M., Liss, P.S., Mee, L., Raine, R., Ramachandran, P., Raine, R., Ramchandran, P., Ramesh, R., Sundseth, K., Tsunogai, U., Uematsu, M., and Zhu, T., 2013. Megacities and large urban agglomerations in the coastal zone: interactions between atmosphere, land and marine ecosystems. *Ambio*, 42, 13-28.

Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C., and Gobler, C.J., 2014. Coastal ocean acidification: The other eutrophication problem. *Estuarine, Coastal and Shelf Science*.148, 1-13.

Wang, H., and McGlinchy, I., 2009. Review of vehicle emission modelling and the issues for issues for New Zealand. In: *32nd Australasian transport research forum*, 29 September-1 October 2009. Auckland, 1-13.

Water Research Commission (WRC)., 2008. The water wheel. *Water research commission South Africa and the Department of Water Affairs and Forestry*, 7(5), 3-40.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., and Wade, A. J., 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, 54(1), 101-123.

Wong, C. T., and Dutkiewicz, R. K., 1998. Vehicle Emissions Project (Phase II). In: *Main Report, Engineering Research*, November 1998. Pretoria: Report No. CER 161.

Xia, T., Nitschke, M., Zhang, Y., Shah, P., Crabb, S., and Hansen, A., 2015. Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia. *Environment International*, 74, 281-290.

Zunckel, M., Robertson, L., Tyson, P. D., and Rodhe, H., 2000. Modelled transport and deposition of sulphur over southern Africa. *Atmospheric Environment*, 34(17), 2797-2808.

APPENDIX

Table 1: Pollutants for which a detailed methodology exists, based on specific emission factors within COPERT IV.

Group 1
Carbon monoxide (CO),
Nitrogen oxides (NO_x: NO and NO_2)
Volatile organic compounds (VOCs)
Methane (CH_4)
Non-methane VOCs (NMVOCs)
Nitrous oxide (N_2O)
Ammonia (NH_3)
Particulate matter (PM)
PM number and surface area

Table 2: Pollutants which are estimated based on fuel consumption within COPERT IV.

Group 2
Carbon dioxide (CO_2)
Sulphur dioxide (SO_2)
Lead (Pb)
Cadmium (Cd)
Chromium (Cr)
Copper (Cu)
Nickel (Ni)

Selenium (Se)
Zinc (Zn)

Table 3: European standards for passenger vehicles

Diesel and petrol passenger vehicles only	
Technology/emission standard	Period
pre-ECE vehicles	1900 up to 1971
ECE 15 00 and 01	1972 to 1977
ECE 15 02	1978 to 1980
ECE 15 03	1981 to 1985
ECE 15 04	198(6) to 1992
Euro 1	199(3) to 1996
Euro 2	199(7) to 2000
Euro 3	200(1) to 2005
Euro 4	200(6) to 2010

Table 3: European standards for LCV’s and HCV’s and Motorcycles.

Diesel and petrol light duty commercial only (LCV)	
Technology/emission standard	Period
Euro 1	1994 to 1998
Euro 2	199(9) to 2001
Euro 3	200(2) to 2006

Euro 4	200(7) to 2010
Diesel heavy commercial vehicles only (HCV)	
Euro I	1992 to 1996
Euro II	199(7) to 2000
Euro III	200(1)to 2005
Euro IV	200(6) to 2008
Euro V	200(9) to 2013
Euro 0	1988 to 1991
Motorcycles	
Euro 1	1999 to 2004
Euro 2	200(5) to 2007
Euro 3	200(8) to 2017

Table 4: Reid vapour pressure values required by COPERT IV.

Reid Vapour Pressure	Range (kPa)	Taken as (kPa)
Summer	45-65	45
Winter	50-75	75

Table 5: SO_2 exceedences of 10.63ppb vegetation threshold per station.

Year	Went Worth Reservoir	Southern Works	Settlers School	Jacobs	Ganges	Prospecton	Ferndale
2004	17.4	22.46	13.58	14.84	12.54	4.9	3.2
2005	12.24	16.23	10.86	10.11	10.43	4.3	1.91
2006	11.08	12.53	12.69	8.2	7.06	2.8	1.91
2007	9.49	12.23	8.8	6.08	8.07	6.16	2.4
2008	7.99	7.6	6.8	14.43	6.11	5.2	1.32
2009	8.78	8.91	7.54	3.8	4.95	2.86	1.4
2010	7.87	7.69	8.97	4.24	7.37	2.27	1.27
2011	7.8	6.44	6.04	3.53	2.25	1.85	0.44
2012	2.25	18.15	9.93	5.77	7.25	3.22	1.26
2013	10.88	20.27	5.29		3.3	2.21	1.19
2014	7.46	9.1	7.47		2.35	1.08	

Table 6: NO_2 exceedences of 11.45 ppb vegetation threshold per station.

Year	Went Worth Reservoir	Warwick	Southern Works	Ganges	Ferndale	City Hall
2004	12.63	22.97	14.98	21.57	12.54	19.84
2005	10.68	28.47	10.29	19.48	9.9	18.92
2006	13.44	21.45	13.62	22.56	10.66	23.41
2007	14.38	27.73	10.51	18.07	20.63	18.16
2008	13.36	26.86	12.81	19.86	12.74	17.84
2009	15	16.69	14.11	24.58	10.81	19.51
2010	15.77	21.74	14.4	24.41	13.09	17.51
2011	11.38	19.23	10.59	23.47	12.55	
2012	10.3	19.4	12.57	25.02	11.02	19.41
2013		20.49	22.18	9.6		20.14
2014	8.38	18.58	9.73	19.36		9.9