

Modelling ambient vehicle emissions in Zamdela using AERMOD

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Dedication

“He will give you the desires of your heart”. Abba ‘Father, thank you for this time and season I longed for throughout my academic journey. It was all your timing.

This dissertation is dedicated to my mother, Kedumetse Tshisi-Matlaopane. THANK YOU, Mommy, for being my shining star. And to my sister Dorcas Nxumalo, thank you for all the sacrifices. I would also like to thank my family (Kgosimotswedi Nxumalo, Badirileng Tshisi, Onalenna Tshisi, Motheo Nxumalo, Kago Tshisi, Paballo Nxumalo). All that I do is for you; you have been my greatest motivation when times were tough.

Don’t tatazel, just zazazel. You know the vibes.

Officially three degrees hotter.

Abstract

Road transport has become a part of our daily lives in a highly urbanised and globalised world. With the increase in vehicle ownership over the years, on-road emissions are expected to increase. With the growing informal public transportation in poor, disadvantaged areas, it is difficult to keep track of these ever-growing numbers. This is a substantial environmental concern considering that vehicle emissions are synonymous with air pollution. Part of the challenges is the research gap identified in studies focusing solely on the contribution of vehicle emissions to ambient air quality. This results from incompetent emissions laws, lack of vehicle emissions control, and limited monitoring stations to monitor emissions consistently. The gap in knowledge and findings can be solved by incorporating ambient measuring and modelling methods. Developing a representative emissions inventory is one of the most efficient methods to assess and manage vehicle emissions. Estimated emission rates provide information on the activity rate to identify potential sources of concern within a geographic area. Henceforth data from the monitoring station, traffic fleet data and emissions factor are needed to calculate the estimations. The data is an essential input in Gaussian dispersion models. This study makes use of AERMOD to assess the contribution of PM emissions. AERMOD is an atmospheric regulatory model approved by the EPA and DEA as an essential tool in air quality assessment. The model is used to determine the dispersion of atmospheric pollutants under the influence of meteorology. Assessing the concentration and dispersion of linear pollution, such as road paths, is recommended. This study aims to characterise the contribution of vehicle emissions in Zamdela using AERMOD. This study will characterise ambient PM concentrations from 2019- 2021, quantify emissions by developing an emissions inventory and finally use the input data to model the ambient concentrations using AERMOD. The results depict that PM is a pollutant of concern in Zamdela, with regular NAAQS exceedances recorded. Temporal variability concentrations show that two peaks in the morning from 06h00-09h00 and evening from 16h00-20h00 were recorded. Both peaks coincide with domestic solid fuel combustion and vehicular emissions. The source apportionment analysis and traffic count data correlate with the monitored PM concentrations to prove that vehicle emissions are one of the sources of the poor ambient air quality in Zamdela. Emissions from vehicles are often ignored, with a considerable research gap identified on this ground-level source within low-income settlements. Henceforth an emissions inventory per vehicle classification was developed. Sedans are assessed as having a significantly higher contribution to ambient PM than the other vehicle classes. This is a consequence of the increasing ownership of private transport driven by poor public transport in low-income settlements.

LDVs also showed a significant contribution, followed by mini-buses. Thereof, AERMOD was run from 2019-2021 to assess PM concentrations per vehicle classification for both PM₁₀ and PM_{2.5}. The predicted annual and daily PM₁₀ concentrations are below the NAAQS annual (40 µg/m³) and daily (75 µg/m³) standard across the township. The modelled isopleths show a range between of 0.07 µg/m³ - 6.78 µg/m³ for the annual average and 0.99 µg/m³ - 38.3 µg/m³ daily average. The

modelled annual $PM_{2.5}$ attributed to vehicle emissions are between $0.1 \mu g/m^3$ - $12.1 \mu g/m^3$ which complies with the annual $20 \mu g/m^3$ NAAQS standards. The daily average range from $23 \mu g/m^3$ – $237 \mu g/m^3$ and exceeds the $40 \mu g/m^3$ standards over most of the township. On extreme days, daily averages can range from $40 \mu g/m^3$ – $237 \mu g/m^3$. The modelled results compared to the monitored results prove that vehicle emissions are one of the sources contributing to the recorded PM exceedances in Zamdela. It is essential to highlight that domestic fuel combustion morning and evening PM peak hours coincide with traffic emission peaks. Both sources can be identified as pollutants of concern in Zamdela.

Keywords: vehicle emissions, particulate matter (PM), low-income settlements, AERMOD.

Preface

Over the years, there has been an increase in vehicle sales not just globally but in South Africa. With the spatial planning in townships (low-income settlements) confined to the urban periphery, industries are usually close to these areas. This is to accommodate low-income residents who travel to work without spending too much on transportation fares. However, longer distances have increased public and private transportation demand.

Therefore, this study looks at assessing the impact of vehicle emissions. A proposed methodology can be developed from this to evaluate the impact of vehicle emissions in densely populated low-income areas using AERMOD. The study area is a residential township Zamdela, part of the Sasolburg Municipality. Industrial, domestic solid fuel burning, commercial activities, and vehicle emissions impact the air quality of this settlement. There have been studies focusing on the impact of these sources. However, there is still limited information on the contribution of vehicle emissions. The gap in the findings creates a need to regulate and monitor vehicle emissions consistently. The focus will be on Particulate Matter (PM), as it is found to be the most problematic pollutant in Zamdela, as is the case in most low-income areas of South Africa.

This study aims to assess the impact of vehicle emissions. From this, a proposed methodology to assess the impact of vehicle emissions on air quality in densely populated low-income areas in South Africa using AERMOD can be achieved. The chosen study area is Zamdela, a township of Sasolburg in the Free State. Industrial emissions, domestic solid fuel combustion, fugitive dust, commercial activities and vehicle emissions impact the air quality. There have been numerous studies focusing on the impact of these sources. However, there is still limited information focusing solely on vehicle emissions. The gap in the findings creates a need to regulate and monitor vehicle emissions consistently. The focus will be on PM as it is found to be the most problematic pollutant in Zamdela and most low-income areas. The following set objectives have been set to achieve the aim:

- Characterise ambient PM concentrations in Zamdela
- Review the understanding of the contribution of traffic emissions to ambient air quality in Zamdela
- Quantify the contribution of vehicle emissions to ambient PM in Zamdela using a dispersion model

Conferences papers have been presented at:

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Declaration

Ethical Clearance

The North-West University Faculty of Natural and Agricultural Sciences Ethics Committee (FNASREC) reviewed and approved the study procedure under ethical clearance number (NWU-01497-20-A9). The researcher completed an online ethics course (Introduction to Research Ethics, Research Ethics Evaluation, and Informed Consent) registered with the Clinical Trial Centre at the University of Hong Kong.

I, Miss Lerato Tshisi (student number: 27032175), declare that the dissertation:

“Modelling ambient vehicle emissions in Zamdela using AERMOD”

is my own work. Information acquired from other sources has been correctly referenced following the NWU Harvard reference style. It is being submitted in partial fulfilment of the requirements for the Degree of Magister Scientiae in Environmental Sciences in the School of Geography and Spatial Sciences at the Potchefstroom Campus of North-West University. This dissertation has not been submitted to the North-West University for any other degree or to any other institution.

X

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CHAPTER 1: INTRODUCTION

The first chapter introduces the study. The background, problem statement, aims and objectives, and significance of the study will be presented.

1.1 Introduction and background

In a highly urbanised and globalised world, road transport has become a part of our daily lives (Castells, 2010; Bharadwaj et al., 2017). With an increasing global population, urban areas are expected to accommodate more inhabitants as the world expects a surge from 7 billion in 2011 to 9.3 billion in 2020 (Gurjar et al., 2016; Jiang & O'Neill, 2017). As a result, vehicle ownership is expected to increase to accommodate the anticipated growth (Wright et al., 2019). This is a huge global problem, considering that transport, mainly on-road traffic emissions, is synonymous with air pollution (Batterman et al., 2014; Meng et al., 2016; Stone & Bennett, 2001). Alongside other pollution sources (domestic solid fuel combustion, biomass burning, industrial emissions), vehicle emissions have been a concern to researchers considering the significance of the deteriorating air quality in urban cities (Guarnieri & Balmes, 2014; Wang et al., 2019). Moreover, traffic-related emissions have been listed among the most important contributors to poor air quality, surpassing other global, regional and local pollution sources. High-income cities in North America typically have moderate exposure, whilst those in densely populated cities in China, India and African countries have high exposures to traffic-related air pollution (TRAP) (Su et al., 2014; Wang et al., 2019).

There is a current concern in African cities considering the deteriorating state of air quality. With the rapid increase in industries and urbanisation, commuters travel daily using some form of transportation (Amegah & Agyei-Mensah, 2016; Ngo et al., 2015). This puts a burden on urban cities due to the increasing vehicle fleet. Part of these challenges are poorly maintained vehicles, lack of vehicle emissions control and unregulated laws for vehicle emissions (Schwela, 2012). However, public transportation has increased in cities like Abuja, Nigeria, where motorcycles have been banned. Additionally, the low ownership of private vehicles (15% in Nairobi, 13% in Accra and 10 % in Dar es Salaam) has increased the demand for taxis. In cities such as Cape Town, Johannesburg, Lagos, Accra and Kampala, many of these taxis are unregulated and not roadworthy (Pirie, 2014). This has become a growing problem considering the surge in vehicle ownership over the years (Posada, 2018).

South Africa has the largest fleet of new passenger vehicles (PV) in Africa and ranks as the 18th largest fleet globally (Posada, 2018). Statistical estimations depict that vehicle demand is expected to increase until 2050. Private transport growth is calculated to double while public

transportation will be constant. Equivalently, the road freight sector is presumed to develop with an increase in heavy vehicles (DEA, 2019).

The growing informal transportation sector, alongside other certified vehicles in South African townships, has increased over the years (Haq & Schwela, 2012). This is because there is an increased demand for public transportation and private vehicles, followed by poorly operated trains and unreliable bus services (Pirie, 2014). The minibus amenities are unvaryingly provided by the informal sector and are unregulated. Even with these issues, vehicle emissions remain a little-studied air pollution source category within townships (DEA, 2019; Thomas, 2009). This has created a gap in literature and research findings to study the contribution of vehicle emissions to the ambient air quality in townships in South Africa.

1.2 Problem statement

Reducing transport emissions while trying to manage the expanding distance commuters have to travel remains a problem in many parts of the world. This is influenced by a surge in vehicle sales where improved zero-emission vehicles are not a realistic solution (Kelly & Zhu, 2016). Over recent years, cities in developed countries have studied vehicle emissions focusing on Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs). However, estimating emissions from vehicles is difficult because of varying dynamic factors. These include vehicle performance (vehicle type, driving behaviour, traffic congestion, fuel type, speed) and environmental conditions (wind speed, rainfall, temperature) (Zhao et al., 2018). These factors must be considered as they indicate the approximate emission of a given area (Su et al., 2014). Regardless, there is still a gap in understanding emissions in most parts of the world.

Before 1988, limited methodologies and data to quantify exhaust particulate emissions existed as there were no regulated requirements (Al-Thani et al., 2020). The insufficiency of vehicle emission controls and limited spatial variability of monitoring stations are some factors resulting in a lack of information (Haq & Schwela, 2012). With few monitoring sites, it is challenging to monitor air quality consistently.

Less than 150 monitoring sites in Africa focus on PM emissions (Subramanian et al., 2020). Only 41 cities in 10 countries in Sub-Saharan Africa (SSA) have real-time monitoring stations assessing air quality (Moeti, 2018). With the available data up to date, most studies primarily focus on industrial and solid fuel combustion emissions (Chidindi et al., 2019; Friedl et al., 2008; Kheirbek et al., 2016; Language et al., 2016; Pauw, 2020; Scorgie et al., 2003; Wagner et al., 2005) with limited research done on other sources. There is a literature gap in studies primarily focusing on-road emissions in contrast to regional sources.

Inclusive and comprehensive observational studies on traffic patterns and emissions started in 1984 in South Africa (Tongwane et al., 2015). This has not been easy due to the insufficiency of vehicle emission controls and the limited number and uneven spatial distribution of monitoring stations (Haq & Schwela, 2012; Schwela, 2012). However, studies by (Chidhindi et al., 2019; Lourens, 2012; Nkosi et al., 2018 van den Berg, 2015) depict that pollution peaks are recorded during domestic solid fuel combustion activity and road congestion hours. Peaks are seen in the early hours of the morning (06:00 - 09:00) and again in the late evening (17:00 - 21:00) (Lourens, 2012). Elevated concentrations are prevalent during dry winter conditions due to the accumulation of pollution influenced by meteorological conditions (Jury, 2017). Regular exceedances against the National Ambient Air Quality Standards (NAAQS) are recorded during this season (Altier & Keen, 2019).

1.3 Aim and objectives

This study aims to characterise the contribution of road traffic to ambient PM in Zamdela. This will help future management plans and provide data on continuous monitoring in densely populated low-income settlements in South Africa. Management strategies will identify the importance of active mitigation measures in place. The following objectives are proposed:

1. Characterise ambient PM concentrations in Zamdela
2. Review the understanding of the contribution of traffic emissions to the ambient air quality in Zamdela
3. Quantify the contribution of vehicle emissions to ambient PM in Zamdela using a dispersion model.

1.4 Significance of the study

The geographical locations of areas highly affected by poor air quality are characterised by densely populated settlements (Language et al., 2016) and those within proximity to high air pollution source densities (van den Berg, 2015). The most significant impact is where the mentioned factors are typical (Chidhindi et al., 2019; Wagner et al., 2005; Wright et al., 2019). Townships in metropolitan areas are highly affected by high concentrations of air pollution. A combination of sources from solid fuel combustion, fugitive dust, industries and vehicle emissions are the prominent sources identified (Mkhonto, 2013). Priority areas have since been declared due to regular exceedances attributed to the above sources.

In 2008 the Vaal Triangle was declared the first air quality priority area in South Africa by the National Environmental Management: Air Quality Act 2004 (Act No. 39 of 2004). Suburbs and townships in the Vaal Triangle Priority Area (VTPA) included Three Rivers, Sharpeville,

Sebokeng and Zamdela (DEA, 2012). This was after studies showed that air pollution was a problem in the Vaal Triangle and consequently regarded as an air pollution hotspot region. A mixture of sources from industries, domestic solid fuel combustion, commercial activities and vehicle emissions within proximity to one another have since been identified as the main emitters (Muyemeki et al., 2020). Previous studies indicate that there are elevated concentrations of PM (Scorgie et al., 2003). There is a big concern in Zamdela of having the highest particulate matter (PM) concentrations in the Vaal Triangle Airshed Priority Area (VTAPA) region (DEA, 2019). Thus, consistently monitoring sources that contribute to PM emissions is essential.

This dissertation focuses on the impact of vehicle emissions on elevated PM concentrations in Zamdela. However, after decades there is still limited literature in South Africa to study the contribution of vehicle emissions in typical densely populated low-income settlements. This can be achieved by studying the concentration and dispersion of pollutants in the atmosphere using models. This will be the first detailed study of this kind in a densely populated low-income settlement in South Africa.

1.5 Dissertation structure

CHAPTER 1: Introduction

The first chapter discusses the background of vehicle emissions and the problems thereof. The problem statement, aim and objectives and overall justification are highlighted.

CHAPTER 2: Literature review

The second chapter outlines the literature background on vehicle emissions and ambient air pollution. Vehicle emissions, source apportionment studies, car mechanics, meteorology parameters and AERMOD theoretical background is explained.

CHAPTER 3: Methodology

The third chapter explains the study area, methods and instrumentations used throughout the study. Calculations, formulas and statistical procedures are covered in this chapter.

CHAPTERS 4: PM and meteorology

Chapter 4 aims to address and answer objective 1. To better understand traffic emissions and PM, it is important to have an overview of the meteorological conditions that influence PM

concentrations. The wind speed, direction, temperature, relative humidity and PM concentrations are discussed.

CHAPTERS 5: Quantifying PM emissions

This section aims to address and answer objective 2. To better understand traffic emissions and PM, it is essential to have an overview of the contribution vehicle emissions have on ambient PM. Source apportionment characterising PM sources will be discussed. This is followed by an emissions inventory proposed for vehicles in Zamdela.

CHAPTERS 6: Modelling PM emissions

Chapter 6 addresses objective 3. This chapter presents the simulated results to determine the vehicular contribution to particulate matter concentrations within Zamdela. Daily and annual averaging period isopleths plots were modelled for 2019 – 2021. Hourly average concentrations were modelled for discrete receptors selected at the location of the monitoring sites to compare the simulated results to the measured concentrations.

CHAPTER 7: Conclusion

This chapter highlights the key findings and summary of the study.

CHAPTER 2: LITERATURE REVIEW

The second chapter outlines the literature background on vehicle emissions and ambient air pollution. Vehicle emissions, source apportionment studies, car mechanics, meteorology parameters and AERMOD theoretical background are presented.

2.1 Introduction

Literature studies indicate that vehicle emissions are a problem of inquiry. However, there has been insufficient research to understand better fundamentals to monitor on-road transport emissions consistently. Available information imposes that vehicle emissions are attributed to health impacts, with limited data linking emissions to ambient air pollution. This has left a vacuum in the available data and literature studies. A review of existing literature and factors that are important to consider when studying on-road transport emissions are discussed in this chapter. PM will be the primary focus of this dissertation, considering the spatial and temporal impact associated with the pollutant.

2.2 Particulate matter: definition and characteristics

Ambient particulate matter (PM) refers to suspended solid and liquid particles in the atmosphere (Tyson & Preston-Whyte, 2000). PM is categorised into two types according to the formative processes: (i) Primary particles form from direct emissions ;(ii) secondary particles result from chemical reactions and gaseous condensation processes. Secondary particles may consist of solid or liquid matter, with the smallest condensed matter having molecular dimensions ($>0.001\ \mu\text{m}$) (Seinfeld & Pandis 1998). Components of PM contain organic compounds and metals (organic compound [OC], inorganic carbon material consisting of black carbon [BC], elemental carbon [EC], sulphate (S), nitrates (N), phosphates (PO_x) and other ions (Adams et al., 2015). Often the particles are characterised by their size property.

By distinguishing their size diameter, PM is classified into two categories (Adams et al., 2015). They are measured by diameter as they have three-dimensional properties (Montoya, 2013). Coarse PM (PM₁₀) is defined to cover the size range from 2.5 to 10 μm , whilst fine PM (PM_{2.5}) consists of particles less than 2.5 μm (Shah et al., 2015). The composition of larger particles (PM₁₀) differs from smaller PM_{2.5} particles (Figure 2-1) (Chow, 1995). Large particles remain suspended in the atmosphere for minutes to days, whereas the atmospheric lifespan of smaller particles ranges from days to weeks (Tyson & Preston-Whyte, 2000). Smaller particles travel longer distances (100-10 000 km) due to their low gravimetric settling rate, whereas larger particles travel shorter distances (1-100 km) as a result of rapid gravimetric settling and

impaction at surfaces (Kelly & Fussel, 2012; Montoya, 2013). The variability in the composition and properties is derived from the emission sources (Adams et al., 2015).

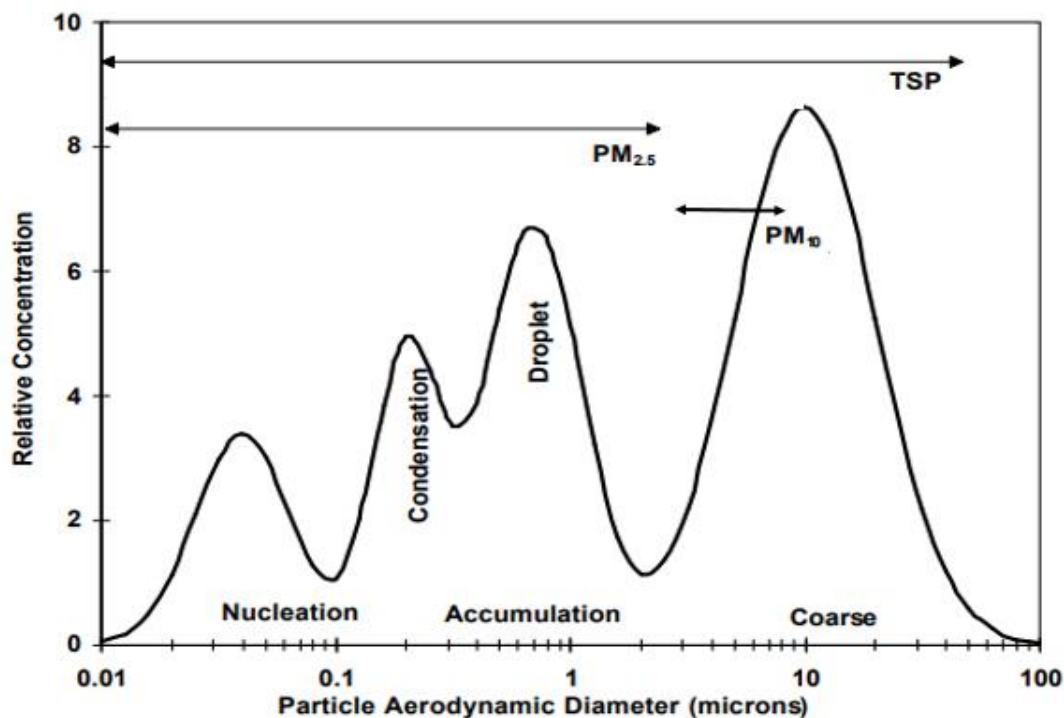


Figure 2-1: The size distribution of PM (Chow, 1995)

Ambient PM can be categorised by assigning particle size to the emission source distinguished by distinctive chemical components (Tyson & Preston-Whyte, 2000; Watson et al., 1997). The source contribution of $PM_{2.5}$ and PM_{10} differ depending on the source of origin (Table 2-1) (Karagulian et al., 2015; Watson et al., 1997). To make a more distinctive source profile, source apportionment studies will be used in this study (Chapter 5). Pollution sources are calculated to determine the contribution of each source to ambient PM. This study's primary focus will be vehicle emission contributions to ambient PM in Zamdela.

Table 2-1: Sources and main components per particle size (Guevara, 2016)

PM Fraction	Source of origin	Main components	Contribution
Coarse particles ($PM_{10-2.5}$)	Agricultural	Agricultural soil, OC	+++
	Traffic resuspension	Road dust	+++
	Windblown dust	Si, Al, Ti, Fe	+++
	Energy and manufacturing industry	EC	++
	Tyre and brake wear	Cu, Zn	++
	Wind-land fires	OC	+
	Biological sources	Fungal debris	+

PM Fraction	Source of origin	Main components	Contribution
Fine particles (PM_{2.5})	Diesel-fuelled vehicle engines	BC	+++
	Biomass combustion	OC, PAHs	+++
	Energy& manufacturing industries	Pb, Cd, As, Cr, V, Ni, Si, SO ₄ ⁻²	++
	Metal processing activities	Pb, Cd, Cr, Zn	+
+++ High contribution; ++ Medium contribution; + Low contribution			

2.3 Health impacts associated with vehicle emissions

Time spent in temporary environmental conditions is linked to higher chances of exposure to air pollution compared to other activities in urban areas (Han & Naeher, 2006). High exposure has been found in indoor and transportation settings (Figure 2-2) (Buonanno et al., 2013; Campagnolo et al., 2019). This comes after prior findings have shown that PM associated with traffic emissions poses serious health implications affecting millions daily (Macêdo & Ramos, 2020). Previous studies show that PM indirectly and directly impacts human health.

Inhaling ambient PM causes more health risks than any other pollutant. This is because of the chemical components found in PM (nitrates, iron, zinc, nickel, sulphates and organic compounds) (Kim et al., 2015; WHO, 2013). PM resulting from vehicle emissions is rich in minerals such as copper (Cu), aluminium (Al), sodium (Na), lead (Pb), zinc (Zn), calcium (Ca), potassium (K), cadmium (Cd) thus making it dangerous to inhale (Lindbom et al., 2006). The severity impact depends on the particle size, whereby fine particles (2.5 µm) are associated with morbidity and mortality rates. The tiny particles can penetrate the respiratory tract and the blood circulatory system, increasing inflammatory cytokines in lung cells (Figure 2-2) (Brown et al., 2013; Jagathlal, 2014; Maddox, 2006; Kjellstrom et al., 2002; Tsai & Chen, 2006). Coarse particles have mass and, once inhaled, can be trapped in the upper respiratory tract by interception or impaction and swallowed, sneezed or coughed out with the mucus. Generally, when inhaling PM₁₀, the cilia and mucus in the nose and bronchial airways act as a filter and will be cleared through the nose or throat (Atkinson et al., 2010).

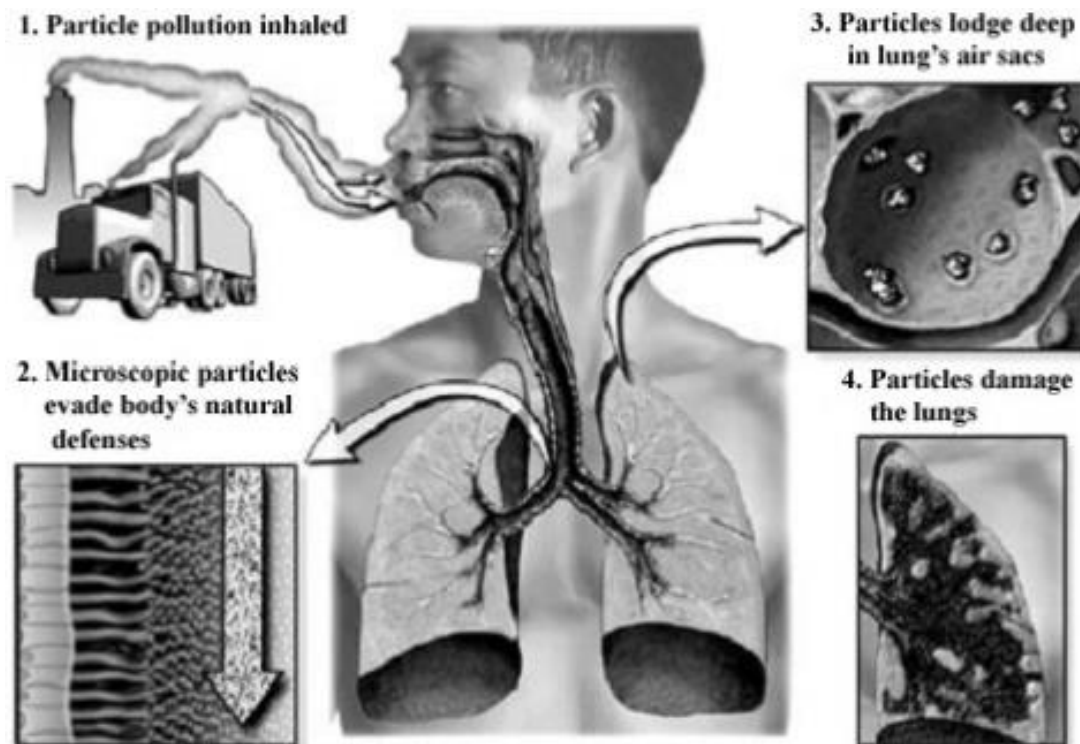


Figure 2-2: Health impacts associated with PM (Maddox, 2006)

Long-term exposure to high ambient PM concentrations is linked to lung cancer and respiratory diseases, whereas short-term exposure worsens respiratory conditions such as asthma, respiratory symptoms, bronchitis, cardiorespiratory implications and premature death (Atkinson et al., 2010; Brown et al., 2013; Shah et al., 2015). Children and women are susceptible to severe respiratory health implications - women spend more time indoors (cooking), whereas children have underdeveloped organs and are more active (Kim et al., 2015). According to studies by Guaita et al. (2011); Kim et al. (2015), children exposed to 65 μm of $\text{PM}_{2.5}$ for 24 hours are at risk of showing respiratory symptoms. Those exposed to >150 μm of PM_{10} show symptoms of reduced lung function (Kim et al., 2015; Sofer et al., 2013).

2.4 Other impacts

Apart from health effects, PM has environmental impacts. PM in the upper atmosphere has been found to modify Earth's radiation budget and cloud condensation nuclei (CCN) (Mukherjee & Agrawal, 2017). In the lower atmosphere, high PM concentrations have a negative impact on visibility, as it is a component of photochemical smog (Jagathlal, 2014; Tsai & Chen, 2006). In addition, emissions impact cooling temperatures caused by increased scattering by atmosphere aerosol build-up (Li et al., 2011).

2.5 The relationship between PM and vehicle emissions

There is a current concern regarding vehicle fleets in developing countries that are considerably older than those in developed countries. 65% of vehicle emissions are from combustion, exiting from the exhaust, 20% from the crankcase, 9% due to hydrocarbon volatilisation from the carburettor and the remaining 6% during start-up and braking of vehicles (Barwise & Kumar, 2020; Hung-Lung & Yao-Sheng, 2009). Because of these factors, there are emissions of particles and gases following the combustion of diesel and petrol. Harmful pollutants such as carbon monoxide (CO), black carbon (BC), nitrogen oxide (NO_x), sulphur dioxide (SO₂), hydrocarbons (HC), lead (Pb), volatile organic compounds (VOCs) and particulate matter (PM) are emitted (Batterman et al., 2014; Karagulian et al., 2015). PM is known to have the most detrimental environmental and health impacts of these pollutants.

Road transport emissions are one of the primary sources of ambient PM (Wright et al., 2019). These vehicular emissions are classified into exhaust and non-exhaust emissions. The two sources emit PM with entirely different properties (Ristovski et al., 2012). Exhaust emissions are closely associated with PM_{2.5}, whereas PM₁₀ is linked to both vehicle source categories. Particular attention is focused on diesel emissions as they are the primary source of exhaust black carbon emissions (Al-Thani et al., 2020). Diesel engines are more fuel efficient but may generate prolific black carbon PM. In contrast, petrol vehicles are less efficient but emit more VOCs and less black carbon (Batterman et al., 2014).

A concise study by Karagulian et al. (2015) calculated regional estimates of PM emissions by averaging 419 source apportionment studies in 51 countries worldwide. The results depict that in 2015, global ambient PM_{2.5} was attributed to 25% from traffic emissions, 15% from industrial activities, 18% from natural dust sources, 20% from domestic burning emissions and 22 % from anthropogenic sources. PM₁₀ comprised 25% of traffic emissions, 18% of industrial and power generation activities, 15% of domestic burning, 22% of natural dust sources and 20% of other anthropogenic sources (Karagulian et al., 2015). Traffic contributes more to PM₁₀ than PM_{2.5} in the rest of America (38%), India and Africa (34%). Traffic is one of the main contributors to PM emissions in most regions. The study confirms reports by the World Health Organisation (WHO, 2014) that domestic solid fuel burning and traffic emissions significantly contribute to PM in middle and low-income countries.

2.6 PM in low-income settlements in South Africa

Air pollution in densely populated low-income settlements within South Africa is continuously proven to be a problem (Language, 2016). Available data and analysis depict that PM is problematic, with high concentrations regularly recorded (Moletsane et al., 2021). Identified

sources contributing to the deteriorating air quality include industries, fugitive dust, domestic solid fuel combustion and vehicle emissions (Muyemeki et al., 2020). Low-income areas are susceptible to the mentioned sources, considering the spatial setting and proximity to industries. However, there is still a research gap in the above sources, with vehicle emissions proven to be a concern.

As illustrated in Figure 2-3, particulate pollution remains a major challenge to manage in the area, requiring a detailed source apportionment study to highlight sources that require different management approaches (DEA, 2019). The 10-year trend for PM₁₀ and PM_{2.5} shows non-compliance for most years within the VTAPA. Zamdela PM₁₀ concentrations recorded one of the highest concentrations over the years. The concentrations have been linked to various local sources with domestic solid fuel combustion and vehicle emissions attributing to daily peaks, consequently exceeding the NAAQS. The growth in the number of vehicles on the road creates a need to monitor the impact of vehicle emissions consistently.

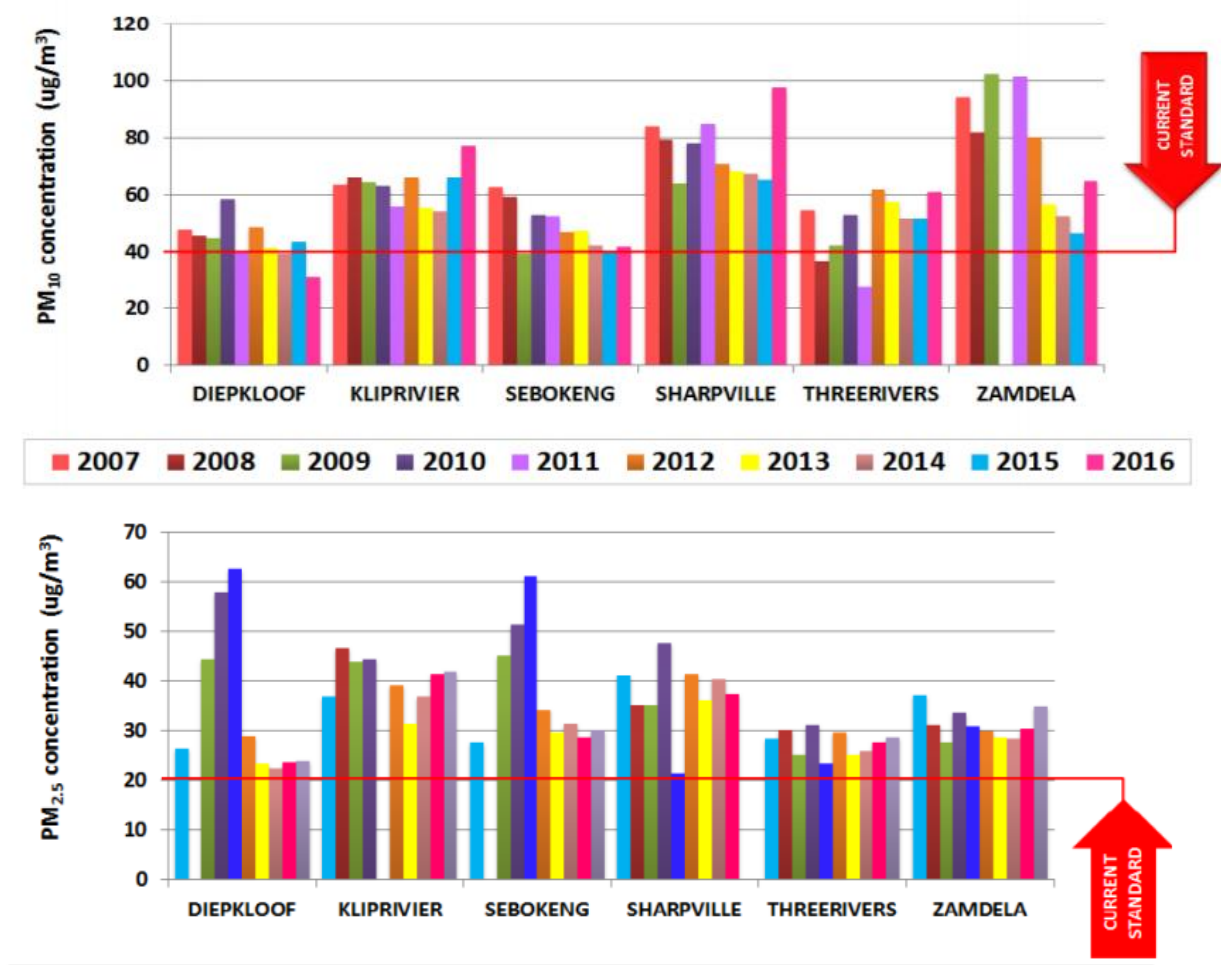


Figure 2-3: Ten-year PM₁₀ and PM_{2.5} annual average trend in the VTAPA (DEA, 2019)

2.7 Vehicles in South Africa

On the African continent, South Africa is the leading automotive industry and one of the largest globally. Like many big global markets, South Africa holds a large fleet of medium, small, and sport utility vehicles (SUVs) (OICA, 2017). According to the National Association of Automobile Manufacturers of South Africa (NAAMSA, 2016), new vehicle sales increased by 22% between 2010 and 2015, growing at an annual average of 4%. The Organization of Motor Vehicle Manufacturers (OICA, 2017) depicts more than 412 000 new passenger vehicle sales in 2015 in South Africa, accounting for more than 37% of the continent's market. This makes South Africa the largest fleet population (Figure 2-4), accounting for approximately 22.6% of the total vehicles in Africa. Subsequently, South Africa is the biggest manufacturing hub, not just in terms of new vehicle sales but as the leading manufacturing country on the continent (Posada, 2018).

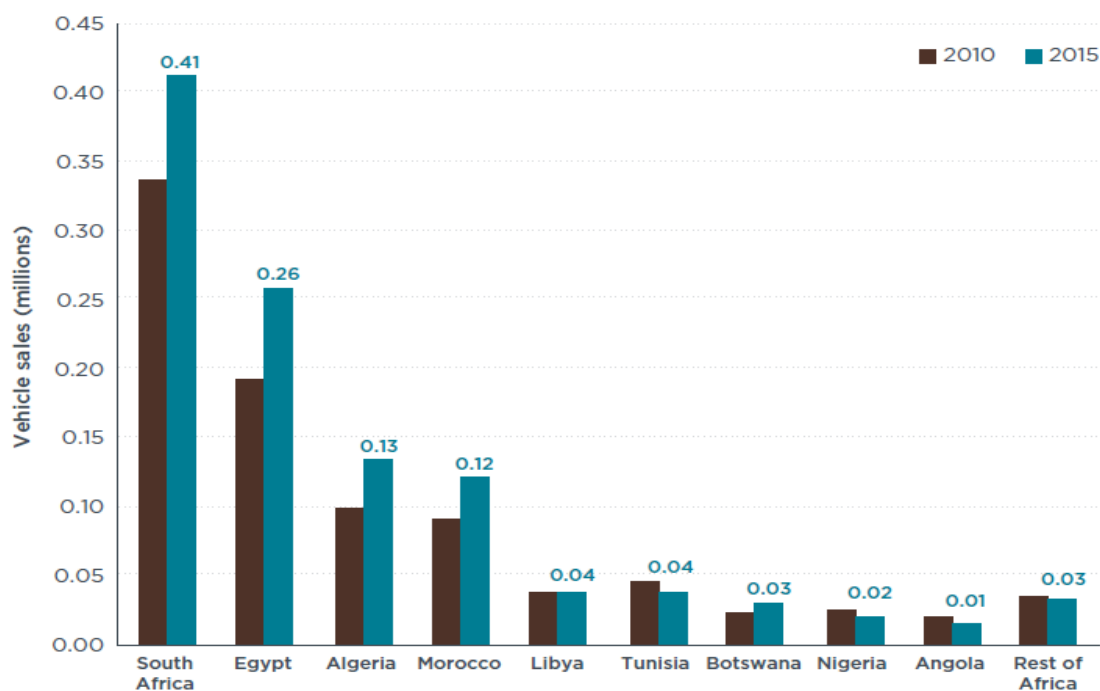


Figure 2-4: Top ten vehicle sales on the African continent (Posada, 2018)

The number of registered vehicles per province in South Africa shows an annual increase from 2015 - 2018 (Table 2-2). Gauteng has the highest number of vehicles registered since it is known as the country's economic hub. The percentage of vehicles registered in 2018 in Gauteng was 38.5%, 16.2% in the Western Cape, 13.3% in Kwa-Zulu Natal, 7.2% in Mpumalanga, 6.6% in the Eastern Cape, 5.7% in Limpopo, 5.1% in Free State, 5.0% in North West and 2.3% in the Northern Cape. From 2017-2018, Limpopo recorded the highest percentage growth of 3.01%, followed by Mpumalanga with 2.78% (RTMC, 2019).

Table 2-2: The total number of registered vehicles per province from 2015-2018 (RTMC, 2019)

Registered vehicles per province	Number registered 2015	Number registered 2016	Number registered 2017	Number registered 2018
GA	4 484 543	4 594 893	4 689 524	4 795 503
KZN	1 556 711	1 593 516	1 627 245	1 660 652
WC	1 839 199	1 900 484	1 977 518	2 022 790
EC	768 945	790 796	811 344	828 069
FS	611 135	619 466	626 744	632 208
MP	815 419	844 935	875 868	900 217
NW	587 354	602 642	617 908	627 847
LI	636 002	661 914	693 109	713 993
NC	267 252	272 507	276 852	281 700
RSA Total	11 566 560	11 881 153	12 205 112	12 462 979

The number of registered roadworthy vehicles in South Africa increased by 257 867 from 2017-2018 (Table 2-3). The classified vehicles (motorcars, minibuses, buses, LDVs, trucks, and others) show an increase from 2015 to 2018, except for motorcycles declining from 2016 to 2018. Most registered vehicles are motorcars for private passenger transport (Goyns, 2008). Registered vehicles increased by 257 867 (2.11%) from 2017-2018. The biggest increase was minibuses from 318 282 (2017) to 330 023 (2018), respectively, showing a 3.69% increment (RTMC, 2019).

Table 2-3: The number of registered roadworthy vehicles per classification in South Africa from 2015-2018 (RTMC, 2019)

CLASSIFICATION	REGISTERED 2015	REGISTERED 2016	REGISTERED 2017	REGISTERED 2018
MOTORCARS	6 697 574	6 942 640	7 172 283	7 340 740
MINIBUSES	295 193	303 180	318 282	330 023
BUSES	58 108	60 525	63 400	64 652
MOTORCYCLES	360 694	363 636	351 756	346 617
LDVS- BAKKIES	2 338 793	2 414 912	2 498 602	2 557 847
TRUCKS	363 281	369 747	372 678	377 090
OTHERS	321 067	272 261	251 192	250 843
TOTAL	10 367 370	10 726 901	11 028 193	11 267 812

The surge in vehicle sales over the years and overall vehicles registered has resulted in increased road emissions. Additionally, several complex operational, environmental and atmospheric factors influence vehicular emissions. These factors are discussed in the following sub-section.

2.8 Factors influencing vehicular emissions

The operation of an internal combustion engine involves chemical and thermodynamic processes. The cycle is driven by the chemical energy obtained from the fuel (petrol or diesel), resulting in a mechanical output. Firstly, the chemical energy stored in the fuel is released as thermal energy. Thermal energy consists of gases and particles in the burning air-fuel mixture. Then the mixture is transferred to mechanical energy through the expanding gases and particles in the combustion cylinder (Dabbas, 2010). Figure 2-5 illustrates the internal combustion in the engine resulting in emissions to the atmosphere.

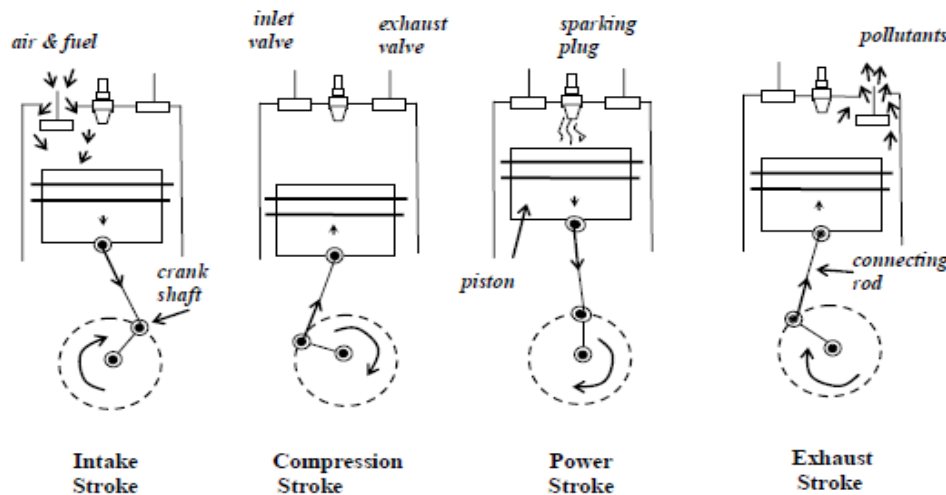


Figure 2-5: Four-stroke internal combustion engine (Dabbas, 2010)

- Intake stroke**: the intake valve opens, and the piston starts moving downward, creating a vacuum. A pre-mixed air-fuel mixture is drawn into the cylinder and mixes with any residual gases from a previous cycle in the cylinder.
- Compression stroke**: At the intake stroke's end, the intake valve closes, and the piston moves upward. This compresses the mixture raising both the pressure and the temperature in the cylinder. As the piston approaches the TC position, a spark plug gives a spark and initiates combustion.
- Power stroke**: the spark ignites the compressed mixture, and combustion occurs. A turbulent flame propagates in the mixture – air, fuel, and residual gases – across the cylinder. The flame raises the temperature in the cylinder and causes the burnt gases in the mixture to expand. The resulting pressure pushes the piston downwards.
- Exhaust stroke**: The exhaust valve opens at the power stroke's end, and the piston starts moving upward. Then, the products of combustion exit through the exhaust valve.

2.9 Factors influencing PM emissions from vehicles

Ambient vehicle emissions vary over time and space (Gately et al., 2017). According to Nicolas (2000) and Dabbas (2010), three linked factors influence on-road emissions, viz., the mix, flow and conditions of traffic. Four factors influencing emissions are discussed, namely, (i) internal combustion engine, (ii) traffic conditions, (iii) driving conditions and (iv) vehicle technology (Figure 2-6).

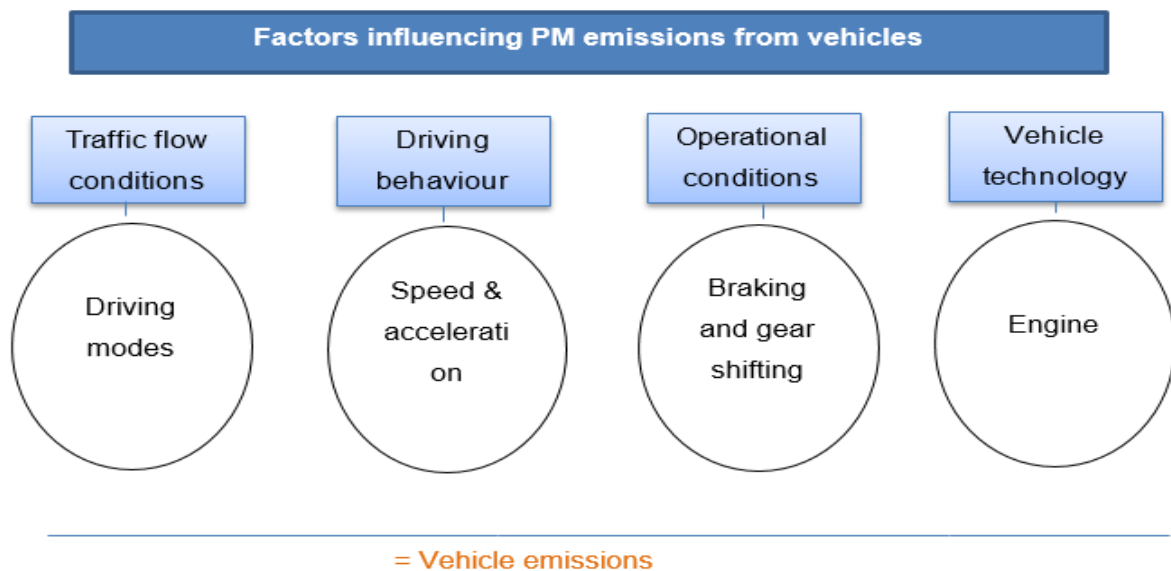


Figure 2-6: Factors influencing vehicle emissions (Dabbas, 2010)

2.9.1 Traffic flow conditions

The driving modes are categorised into four conditions. (i) The idle mode- poor combustion results influenced by low driving speeds. Idling causes the throttle to close, creating a high vacuum in the intake system, consequently increasing fuel-rich mixtures. (ii) During the cruising mode, less fuel is used following a steady engine which requires less power. (iii) The acceleration mode uses more fuel, emitting richer fuel mixtures. (vi) The deceleration mode needs more air at higher speeds. Airflow is limited by the closed throttle resulting in more fuel misfires (Dabbas, 2010).

2.9.2 Operational conditions

Operational conditions alongside ambient atmospheric conditions are known to influence vehicle emissions. These parameters include (i) duration, (ii) average speed, (iii) acceleration standard deviation, (iv) positive kinetic energy, (v) idle period, (vi) number of stops per kilometre, (vii) running speed, (excluding stops), (viii) average speeds, (ix) acceleration and deceleration, (x) average running periods, (xi) number of acceleration and deceleration periods, (xii) relative and joint distribution of speed, and (xiii) relative and joint distribution of accelerations and decelerations (Dabbas, 2010). Literature uses average speeds, or instant

speeds and accelerations, to determine the influence of operational conditions on traffic emissions (Ericsson, 2001).

2.9.3 Driving behaviour

Driving behaviour characterises the relationship between the driver and the vehicle they are driving. This includes how the driver controls the brakes, accelerator and gearbox (Ericsson, 2001). These factors are highly dependent on the type of vehicle structure. Different vehicle modes are affected by varying driving behaviour. As such, hard acceleration and deceleration make vehicles that are low emitters to be high emitters, instantly changing the emission status (Dabbas, 2010)

2.9.4 Vehicular technology

Emissions are elevated as vehicles age. Vehicle age affects emissions in two ways: (i) The older the vehicle, the less likely it is to be adequately maintained. However, the status of maintenance might mask the expected relation with age (Washburn et al., 2001). The differences between emissions of inadequate and well-maintained vehicles of similar ages are significantly greater than the differences between emissions of well-maintained vehicles across various age cohorts. (ii) Age is linked to vehicle technology; the more recent the technology, the more likely the vehicle is fuel-efficient and less polluting (Dabbas, 2010). These emissions have been proven to be influenced by environmental and meteorological conditions.

2.10 Meteorological and atmospheric influence on PM emissions

Meteorology plays a vital role in the dispersion potential, dilution and transportation of atmospheric air pollutants (Godish, 1990; Thomas, 2009). Two factors influencing the factors mentioned above are (i) the average wind speed it takes to transport pollutants and (ii) turbulent velocity fluctuations to disperse in different directions. The wind speed influences the transportation and rate of air pollution dilution. The wind direction variability will determine the flow of air pollutants (Jagathlal, 2014; Tyson & Preston-Whyte, 2000). Turbulence level (depending on how close it is to the boundary layer) determines the accumulation and ability of pollution to disperse vertically and horizontally. Vertical air movement during the daytime is caused by surface heating. Horizontal turbulence is predominantly governed by atmospheric stability and wind speed (Sharan et al., 1996). Meteorological conditions such as temperature, wind speed/direction, precipitation and humidity determine the dispersion capacity of a spatial area.

2.10.1 Wind speed and direction

Pollutants are transported horizontally by wind, a process known as advection (Grundström et al., 2015). The wind speed determines the atmospheric dilution of pollutants, whereas the wind

direction for the direction pollutants travel (Ebenezer, 2019). This is used to identify the relationship between sources and ambient pollution concentration levels (Giri et al., 2008). Wind speed and direction give real-time information about pollutants. Pollutants with long atmospheric residence times ($PM_{2.5}$) are transported over longer distances and potentially to other areas than pollutants with a shorter atmospheric lifespan (PM_{10}). This is influenced mainly by wind speed, whereby pollution concentration from ground-level sources is inversely proportional to wind speed (Grundström, 2015; Triantafyllou & Kassomenos, 2002). The higher the wind speed, the lower the atmospheric pollution concentration as pollution is dispersed. The lower the wind speed, the higher the atmospheric pollution concentration, as pollutants stay suspended and are not diluted or dispersed.

2.10.2 Temperature and solar radiation

Temperature and sunlight (solar radiation) play an essential role in the chemical reactions that occur in the atmosphere. The time of day and geographical location influence the temperature and solar radiation intensity (Ebenezer, 2019). Ambient temperature is important as it determines the mixing rate of pollutants and the depth of the inversion layer. The higher the ambient temperature, the greater the mixing rate of the pollutants, thus enabling them to disperse. The lower the atmospheric temperature, the slower the mixing rate, resulting in higher concentrations as the dispersion is slow (Analitis et al., 2018; Tyson & Preston-Whyte, 2000).

2.10.3 Precipitation

Gases and particles are removed from the atmosphere to the surface by precipitation (rain, snow and fog), a process known as wet deposition (Grundström, 2015; Tyson & Preston-Whyte, 2000). Atmospheric particulates are trapped in rain droplets falling to the ground. The atmospheric pollutants' absorption is proportional to the raindrop frequency and droplet size distribution. The total concentration of pollutants represents a nonlinear process (Shukla et al., 2008). The removal process of pollution involves nonlinear interactions in the atmosphere (Naresh et al., 2007). The effect of rain has shown equilibrium concentrations of pollution in the rain according to a nonlinear mathematical model (Shukla et al., 1992). Studies by Aleksandropoulou & Lazaridis (2004), Pandey et al. (1992), Grundström (2015) and Ebenezer (2019) show that there is a decrease in atmospheric pollution concentrations post-precipitation that improves visibility.

2.10.4 Relative humidity

Water vapour concentration in the atmosphere is represented as a percentage of the saturated pressure at a given temperature, known as relative humidity. The amount of vapour depends on an area's location, wind direction and ambient temperature (Grundström, 2015). Water

vapour plays a vital role in many thermal and photochemical atmospheric reactions. As small and highly polar water molecules can bind strongly to many substances. If absorbed onto suspended particles, condensed moisture can significantly increase the amount of light scattered by the particles. Relative humidity will increase in summer following increased temperatures and expected rainfall (Ebenezer, 2019).

2.10.5 Influence of seasonal meteorological conditions

High-pressure cells between 25°S and 30°S influence South Africa's climate. Anticyclone conditions are dominant most of the year, with the South Atlantic high-pressure cell to the west, continental high-pressure in the interior and the South Indian high-pressure cell to the east (Lourens, 2012; Tyson & Preston-Whyte, 2000). The variation in seasonal and diurnal changes is important for atmospheric processes (Goldreich & Tyson, 1988; Thomas, 2009). Different atmospheric conditions that prevail during winter and summer influence the dispersion and transport of pollution (Figure 2-7)

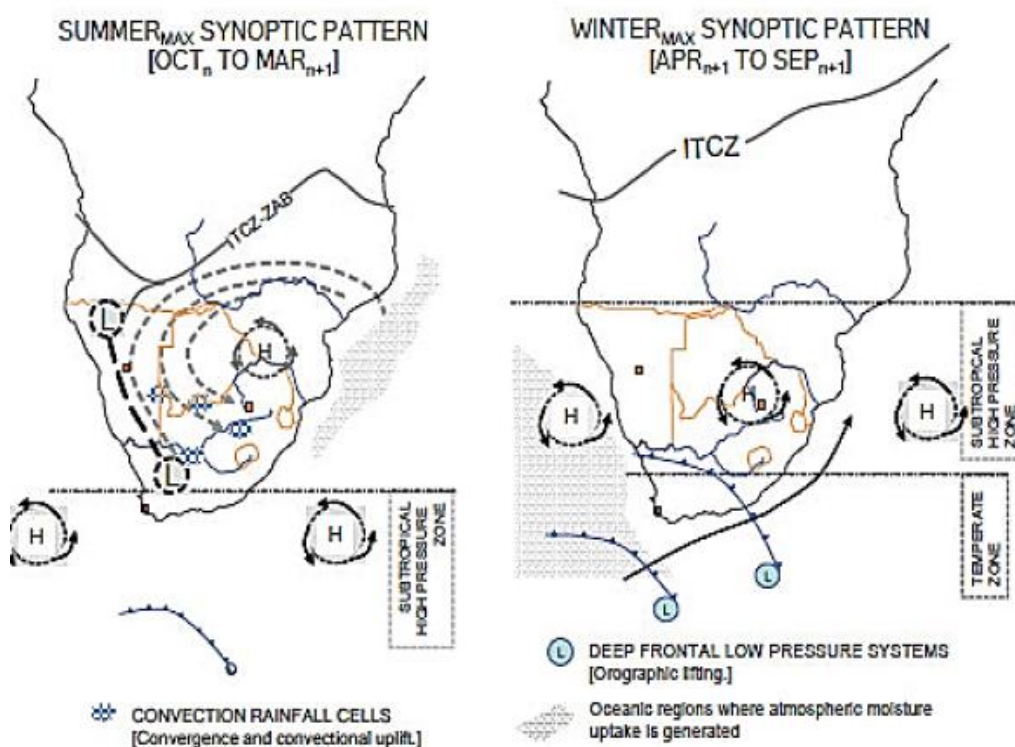


Figure 2-7: Seasonal synoptic pattern in South Africa (Van Wyk, 2011)

In winter, a continental high-pressure cell dominates the country's interior (Figure 2-7). Alongside the westerly wave, ridging anticyclone, the west coast trough is prevalent during the season. The synoptic conditions are associated with low temperatures, a decrease in incoming solar radiation, less relative humidity and low wind speeds (Grundström, 2015; Tyson & Preston-Whyte, 2000). Reducing incoming solar radiation and temperatures means less

mixing, and chemical reactions take longer than usual. For most of the interior, there is less relative humidity and precipitation and limited wet deposition to remove pollution from the ambient air. The haze layer forms in the interior to raise pollution build-up due to less rainfall and low wind speeds. This usually results in higher pollution concentrations as there is less mixing, dispersion and deposition during the season in most parts of the country (Ebenezer, 2019; Tshehla, 2008).

Summer/ spring conditions are characterised by increases in relative humidity, precipitation, wind speeds, temperature and solar radiation. The easterly wave/low and ridging anticyclone systems are predominant in this period in the presence of unstable air bringing good rains to most parts of the country. General good rainfall over the plateau originates from the northerly component (Radaideh, 2017; Tyson et al., 1996). This acts as a removal mechanism of pollution, and concentrations are relatively low during this season. Increasing incoming solar radiation increases surface temperatures to allow more mixing to reduce ambient pollution. An increase in wind speeds is seen in low-pressure systems present during this time to enable the mixing and dilution of concentrations (Tyson & Preston-Whyte, 2000).

Environmental and atmospheric conditions are essential in determining the impact of vehicle emissions on ambient air quality. Alongside these factors, monitoring and legislation play a fundamental role in estimating and regulating emissions.

2.11 PM vehicle emission factors over the years

Emission factors (EFs) are calculated using the ratio of emissions and activity concentrations. Typically, the emissions have a linear proportion compared to the activity level. Henceforth, any given source's final calculated emission factor is the arithmetic average of the specific emission activity (EPA, 2015). Emission factors are used to calculate transport emissions of any pollutant related to the source (Smit et al., 2010).

Vehicular emissions are reliant on many environmental and atmospheric parameters. EFs for vehicles are formulated using sampled data from measurement campaigns. The technique followed often requires a criterion for vehicle selection (vehicle type) and the driving conditions on the road (Franco et al., 2013). From September 1985 until January 1995, the AP-42 formulated calculations for urban paved roads (EPA, 2015). The EF is given in the form of $E = k (sL/0.5)^p$ Equation 1 below:

$$E = k (sL/0.5)^p \quad \text{Equation 1}$$

Where E = particulate emission factor (g/VKT); s = surface material content silt, defined as particles < 75 µm diameter (%); L = surface material loading, defined as the mass of particles

per unit area of the travel surface (g/m²); k = base emission factor (g/VKT); and p = exponent (dimensionless).

Factors k and p are assigned as follows (Table 2-4):

Table 2-4: Values for factors k and p

PARTICLE SIZE FRACTION	K (G/VKT)	P
TSP	5.87	0.9
PM ₁₀	2.28	0.8
PM _{2.5}	1.02	0.6

The emission factor (Equation 1) has been consistent and has not changed since September 1985 and January 1995. Industrial paved road EFs were published in 1983 and revised in 1988. The equation is given in the form of Equation 2 below (EPA, 2015):

$$E = 0.0221 (4/9) (s/10) (L/280) (W/2.7)^{0.7} \quad \text{Equation 2}$$

Where E = emission factor (kg/VKT); L = industrial augmentation factor (dimensionless); s = surface material silt content (%); and W= average vehicle weight (Mg).

The basic $E = 0.0221 (4/9) (s/10) (L/280) (W/2.7)^{0.7}$ Equation 2 dates from the 1979 report initially calculated in Supplement 14 to AP-42. The industrial road EF's primary purpose was to consider that industrial roads have higher emissions than urban roads. For particle size range, factors similar to $E = k (sL/0.5)^p$ Equation 1 were recommended. The equation is given below in the form of Equation 3 (EPA, 2015):

$$E = k (sL/12)^{0.3} \quad \text{Equation 3}$$

Where E = emission factor (kg/VKT); k = base emission factor (kg/VKT); and sL = road surface silt loading (g/m²).

The base emission factor (k) varied with the aerodynamic size range as follows (Table 2-5):

Table 2-5: Aerodynamic range of base emission factor

Particle size fraction	K (g/VKT)
PM ₁₀	2.22
PM _{2.5}	0.081

The paved road emission factors were revised in 1995 to include vehicle weight, particle size and silt as separate variables. The equation is given below in Equation 4 (EPA, 2015):

$$E = k (sL/2)^{0.65} (W/3)^{1.5} \quad \text{Equation 4}$$

Where E = particulate emission factor (having units matching the units of k); k = particle size multiplier for particle size range and units of interest (see below); sL = road surface silt loading (grams per square meter) (g/m²); and W = average weight (tons) of the vehicles travelling the road.

The values of individual variables (Table 2-6) were based on the selection of units of the emission factor dependent on the particle size range (US EPA, 2015).

Table 2-6: Size particle multipliers for paved road equations

Size range	Multiplier k		
	(g / VKT)	(g / VMT)	(lb / VMT)
PM ₁₀	4.6	7.3	0.016
PM _{2.5}	2.1	3.3	0.0073

2.12 Monitoring air pollution in South Africa

2.12.1 Legislation

The South African National Environment Management: Air Quality Act 39 of 2004 mandates permissible concentration of priority air pollutants following the National Ambient Air Quality Standards (NAAQS). National air quality standards are set to regulate air quality in South Africa to protect the environment (DEA, 2012). Production processes such as mining, electricity industries, and production facilities are required to monitor and evaluate their emissions according to the NAAQS. PM has 24-hour and annual concentration limits (Table 2-7 and Table 2-8). Only four exceedances are acceptable for 24-hour averages and none for annual averaging periods. For the daily averaging period, 75 µg/m³ (PM₁₀) and 40 µg/m³ (PM_{2.5}), is permissible whereas 40 µg/m³ (PM₁₀) and 20 µg/m³ (PM_{2.5}) are allowed for the annual period. South Africa does not have vehicle emission standards and therefore uses the NAAQS.

Table 2-7: NAAQS for PM10

Averaging period	Concentration	Exceedance frequency	Compliance date
24 hours	75	4	From from 1 January 2015
1 year	40	0	From from 1 January 2015

Table 2-8: NAAQS for PM_{2.5}

Averaging period	Concentration	Exceedance frequency	Compliance date
24 hours	40	4	From from 1 January 2015
1 year	20	0	From from 1 January 2015

2.12.2 Air quality monitoring stations

Air quality monitoring is an essential primary assessment to measure ambient pollution concentrations (Madruga, 2020). Various measuring techniques depend relatively on the geographical location and the complexity of atmospheric pollutants. These include source-linked monitoring, biological monitoring and fixed monitoring (US EPA, 2017). Fixed monitoring is the most common technique because it provides data over extended periods, which is important in decision-making on air quality management (Madruga, 2020). South Africa has national, provincial and municipal air quality monitoring stations (Figure 2.10). Most stations are in Gauteng and the Highveld, which have the highest air pollution. (Figure 2-8). The stations provide information on air quality to assess compliance with the NAAQS (Gwaze & Mashele, 2018). Data from these stations should be stored in a database, which can later be used to determine air quality using models (US EPA, 2015).

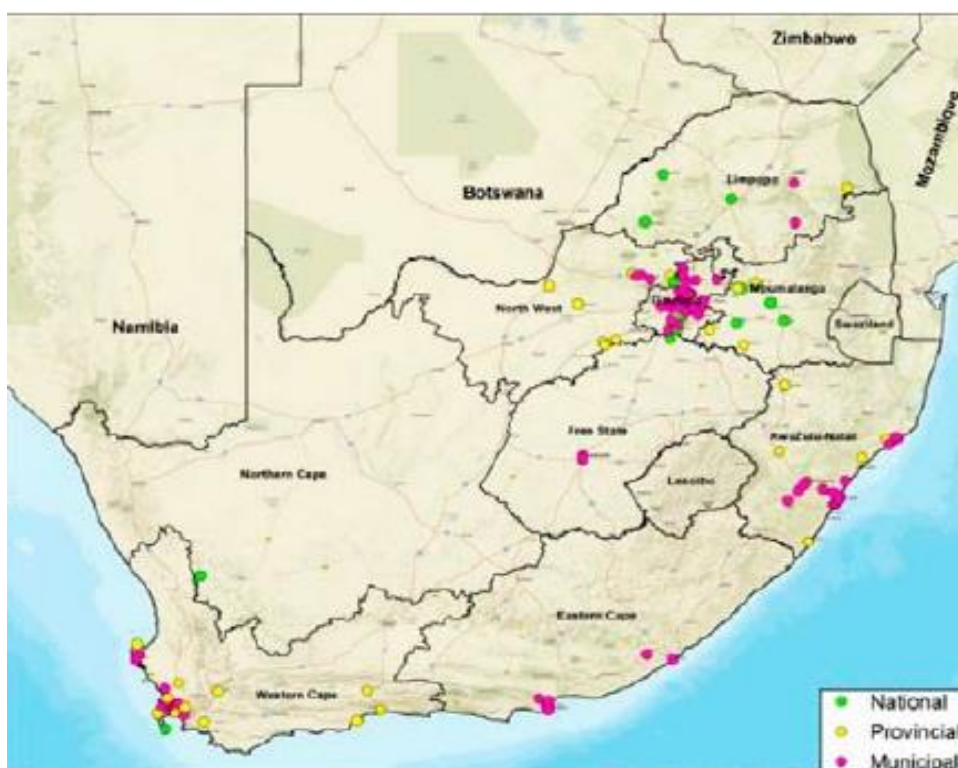


Figure 2-8: Air quality monitoring stations in South Africa (Gwaze & Mashele, 2018)

2.12.3 Source apportionment

Source apportionment is a method used in air pollution studies to categorise and quantify the contribution of emissions from different sources (Hopke, 2016; Tian, 2018). Evidence and information on pollution sources are important to support air quality management and planning. This is vital for policy reports that report and monitor air quality improvement (Thunis et al., 2019; Tian, 2018). Various apportionment techniques are commonly used to quantify sources, viz. receptor models, emission inventories, explorative methods, Lagrangian models, Eulerian models and Gaussian models (Belis et al., 2013).

Principal Components Analysis (PCA) is a statistical factor modelling technique to identify pollution sources and estimate their contribution. Components are extracted from measured pollution concentrations between various species. The sources are interpreted as putative sources based on the analysis of chemical species in several samples. The analyses may detect unaccounted source information from the measured data. PCA assumes that the composition of the emission sources is constant over the sampling period at the receptors, for instance:

- chemical species do not interact with each other, and their concentrations are linearly additive;
- source profiles are linearly independent of each other; measurement errors are random and uncorrelated;
- the number of species is greater than or equal to the number of sources;
- the number of samples is much greater than the number of source types to ensure statistically meaningful calculations;
- the variability of the concentrations from sample to sample is primarily due to differences in source contribution and not due to measurement uncertainty or changes in source composition ; and
- the effect of processes that affect all sources equally (e.g., atmospheric dispersion) is much smaller than the effect of processes influencing individual sources (e.g. wind direction and emission rates).

2.13 Atmospheric dispersion modelling

The atmosphere is composed of dynamic compositions with continuously occurring physical and chemical processes. Pollutants are transported and dispersed over spatial scales. One of the scientific methods to determine the dispersion potential of atmospheric pollution is by using models. Atmospheric dispersion models are used to determine the dispersion of atmospheric pollutants under the influence of meteorology (US EPA, 2005). The South African

Environmental Management Framework Guide states that dispersion modelling is essential in air quality assessment. Ambient data on the pollutants and meteorological parameters are crucial to determine the dispersion at a particular geographical area (DEA, 2014).

Figure 2-9 explains the fundamentals of dispersion models. The models depend on the complexity of the problem distinguished on the chemistry, spatial and temporal scale. Widely used dispersion models are Eulerian, empirical, Gaussian, Lagrangian and receptor models (Zannetti, 1990). For this study, a Gaussian model will be used.

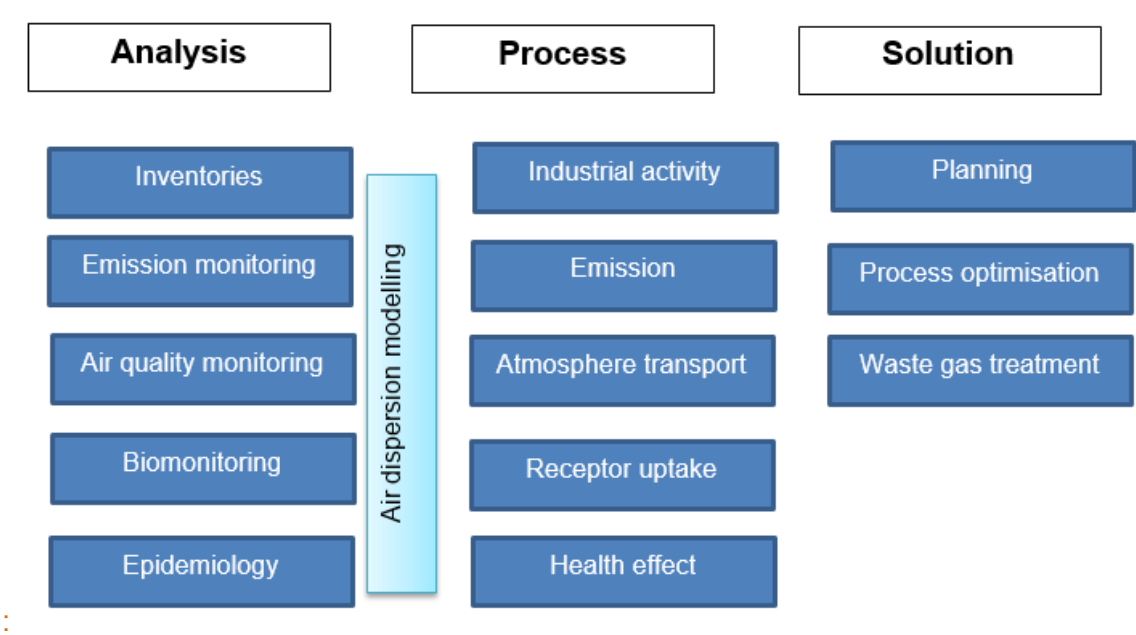


Figure 2-9: Context of air pollution dispersion models

2.13.1 Gaussian dispersion models

Gaussian models are the most common pollutant dispersion models used to analyse data over a long period (Jain, 2015). It uses a fundamental formula to illustrate and explain the three-dimensional field emitted by a source (Zannetti, 1990). The model assumes that the downward ambient concentration follows a statistical horizontal and vertical dimension distribution (Figure 2.10) (Bosman, 2019). Some examples of this model as classified by the EPA are the Offshore and Coastal Dispersion Model (OCD), Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS) and the American Meteorological Society and US Environmental Protection Agency Regulatory Model (AERMOD). AERMOD will be used for this study because it is the most suitable Gaussian model for the study area.

2.13.2 AERMOD as a regulatory tool

American Meteorological Society and US Environmental Protection Agency Regulatory Model (AERMOD) is a regulatory atmospheric dispersion modelling tool used in air pollution studies

(Gibson et al., 2013; Perry et al., 2005). AERMOD is a Gaussian dispersion model designed to cover short-range geographical coverage (<50 km) from point, line and volume sources (Cimorelli et al., 2005). This steady-state dispersion model simulates complex terrain while considering wind speed, temperature and turbulence profiles (Gibson et al., 2013; Langner et Klemm, 2011; Rzeszutek & Szulecka, 2021). Factors such as meteorology, topography, and emissions from sources within proximity need to be taken into consideration (Kumar et al., 2016). The US EPA recommends AERMOD to assess the concentrations and dispersion of linear pollution sources, such as roadways (Macêdo & Ramos, 2020).

Geographical Information System (GIS) is a crucial component incorporated into AERMOD for data analysis provided by monitoring stations (Carbonell et al., 2010). The data provides a representation of the terrain morphology of the area. The road network and vehicle observation count are proven to make the model more accurate (Bosman, 2019). The data characterises input data depending on the terrain and elevated or flat surfaces (Cimorelli, 2005; US EPA, 2005).

The integrated modelling system is divided into two input data processors: (i) the American Meteorological Society/Environmental Protection Agency Regulatory Model Meteorological Processor (AERMET) and (ii) the American Meteorological Society/Environmental Protection Agency Regulatory Model terrain pre-processor (AERMAP). These are highlighted in Figure 2-10.

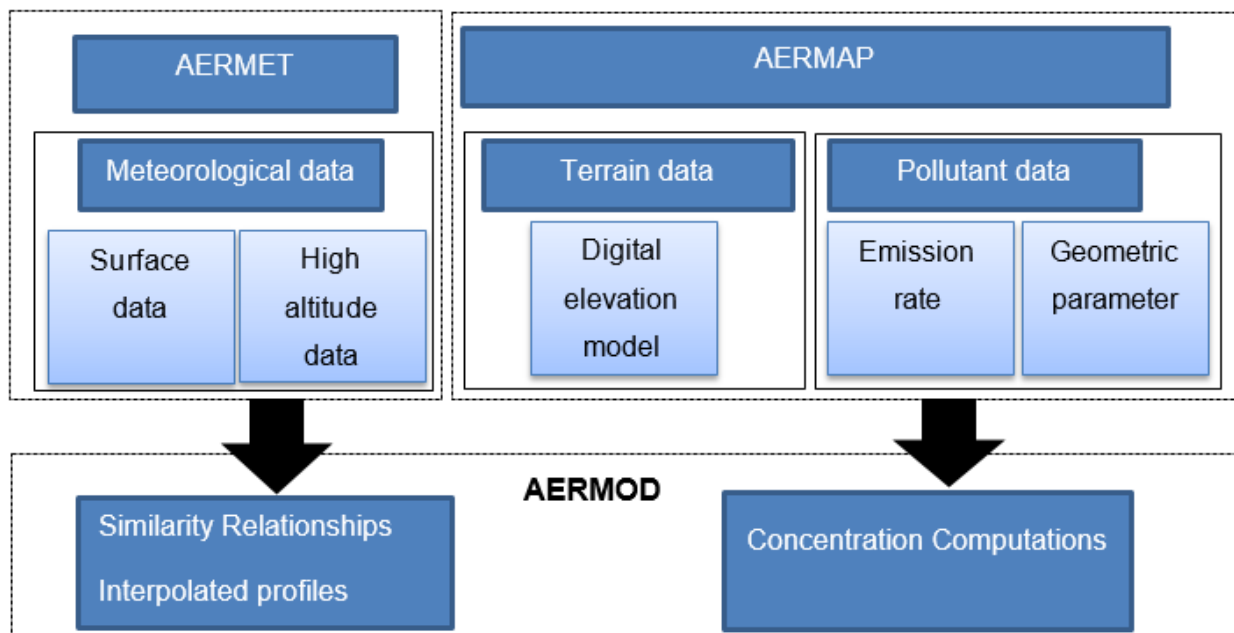


Figure 2-10: AERMOD input flow (Thawonkaew et al., 2016)

AERMAP is a terrain pre-processor component of AERMOD. It is important to visually represent the relationship between the dispersion of pollutants and the terrain. The processor stimulates the atmospheric dispersion effect over topographic scales to provide location and height data for the model receptor (US EPA, 2005). A digital elevation model provided in GIS is important for AERMAP to provide topographic data of the domain to produce adequate resolution dispersion maps (Carbonell et al., 2010). Table 2-9 provides inputs required by AERMAP.

Table 2-9: Possible modelling outcomes of AERMOD (US EPA, 2005)

Capability	AERMOD options
Application	<50 km
Source type	Point, line, area, volume
Source release	Near-surface, surface, elevated
Source location	Urban/rural
Concentration distribution	Gaussian plume model
Plume rise	Briggs empirical expression
Boundary layer structure	LMO scaling
Plume deposition	Dry or wet form gases/particles
Terrain type	Simple/complex
Building effects	PRIME downwash algorithms

AERMET is a meteorological data processor component of AERMOD. The component requires temperature, rainfall, cloud cover, relative humidity, wind speed and direction data (US EPA, 2005). The data are processed to provide mixing height, velocity scale, temperature scale and Monin-Obukhov length data (Cimorelli et al., 2005). The data are obtained from air quality monitoring stations suitable for a particular modelling area (Carbonell et al., 2010; US EPA, 2005).

Specific guidelines are available on AERMOD modelling (US EPA, 2005). However, South Africa has its guidelines, as highlighted in Table 2-10. These are input criteria for intra-urban air quality within South Africa.

Table 2-10: AERMOD input for intra-urban air quality within South Africa (DEA, 2014)

Description	Proposed input
Source	
Type	Urban regions consisting of multiple point sources can be combined to act as an area source.
Emission rate	Emission factors can be used to calculate the emission rate in [g/(s/m ²)]

Background emissions	It can be regional/local background sources. At least one year of monitoring data is advised as significant seasonal differences occur
Variable emissions	Characterise according to hourly/daily /monthly /seasonal variability
Averaging time	Annual/short-term periods (less than 24 hours) in compliance with NAAQS
Receptors and spatial resolution	
Receptor grid	Multi-tier Cartesian grid with predefined grid spacing is recommended, and if necessary, a separate refined grid or discrete receptors should be placed in areas of concern, such as pollution hotspots or sensitive receptors in the modelling domain
Resolution	This is a problem as the pollution concentrations need to be modelled at the same location as the source, for example, in the case of domestic solid fuel burning polluting the direct environment of the residents and not just from 50 meters away
Fence line	Fence lines for industrial sources are advised as a 50 km by 50 km domain, centred on the source, but no fence lines are recommended for domestic sources
Geographical inputs	
Modelling domain	50 km by 50 km centred for flat terrain. For complex terrain, the domain might need to be elongated.
Coordinate system	Universal Transverse Mercator (UTM) and all coordinates should be defined on the World Geodetic System 84 (WGS-84)
Classification of site	An area is defined as urban if it has less than 35% vegetation coverage or the classification method specified by the US EPA guideline should be followed
Meteorology	
Surface data	Hourly sequential is advised, and temperature, relative humidity, wind speed, wind direction, solar radiation, cloud height and cloud cover are needed
Upper air data	At least two daily soundings are required, and temperature, relative humidity, wind speed and wind direction are needed.
Source of MET data	South African Weather Service (SAWS)
Data period	A minimum of 1-year on-site specific data or at least three years of appropriate off-site data must be used. The data should be from a period no older than five years to the year of assessment.

2.13.2 AERMOD limitations

Unfortunately, currently, the AERMOD model only calculates dispersion at some distance away from the source (up to 50 km), which is not satisfactory (Kesarkar et al., 2007), and this is referred to as ‘near source’ dispersion. With intra-urban ambient air pollution, on the other hand, the model is required to calculate the pollutant concentrations at the same location as the source, with, for example, domestic fuel burning, referred to as ‘intra-urban’ dispersion.

CHAPTER 3: METHODOLOGY

This chapter aims to give a comprehensive narrative of the data and methods used in this research. Formulas and calculations are explained. The chapter outlines how dispersion models were run, including the input data. A summary of how the monitored and modelled datasets were analysed is provided.

3.1 Introduction

The study area is a low-income residential township in the Free State province, South Africa. The settlement lies within the Vaal Triangle Airshed Priority Area (VTAPA). It has been declared an air pollution hotspot area in terms of the National Environmental Management: Air Quality Act 2004 (Act No. 39 of 2004). Emissions from industries, domestic solid fuel combustion, commercial activities, biomass burning and vehicles have been identified as contributing sources to poor air quality (Cairncross, 2008; Letsholo, 2020; Muyemeki et al., 2020). The high particulate matter concentrations are linked to these sources (Scorgie et al., 2003). The study focuses on vehicle emissions because there is limited information on the contribution of transport emissions to air quality within low-income settlements. Secondly, PM is a pollutant of concern in the VTAPA. Lastly, there are no proposed methodologies and reports to study the influence of vehicle emissions in a typical South African low-income settlement context.

3.2 Study area description

Zamdela (Figure 3-1) is a densely populated low-income settlement located in Sasolburg in the Metsimaholo Local Municipality (MLM) (26.8662°S; 27.8692°E). The MLM falls under the Fezile Dabi District and is the smallest municipality covering 8% of the geographic area. The township (Zamdela) is adjacent to the town (Sasolburg), with large coal deposits near the Vaal River. The influence of Sasolburg is its proximity to the economically driven city of Johannesburg. It is in a town of significant industrial point sources and is encircled by the SASOL petrochemical plant, Omnia Fertilisers and the Lethabo Power Station. Zamdela is home to 82 339 people with a total of 25 067 households. Approximately 34% (4076) of these households use solid fuels (coal and wood) and liquid fuels (paraffin). Potential air pollution sources have been identified as industries, fugitive dust, vehicles, domestic solid fuel combustion and commercial activities.

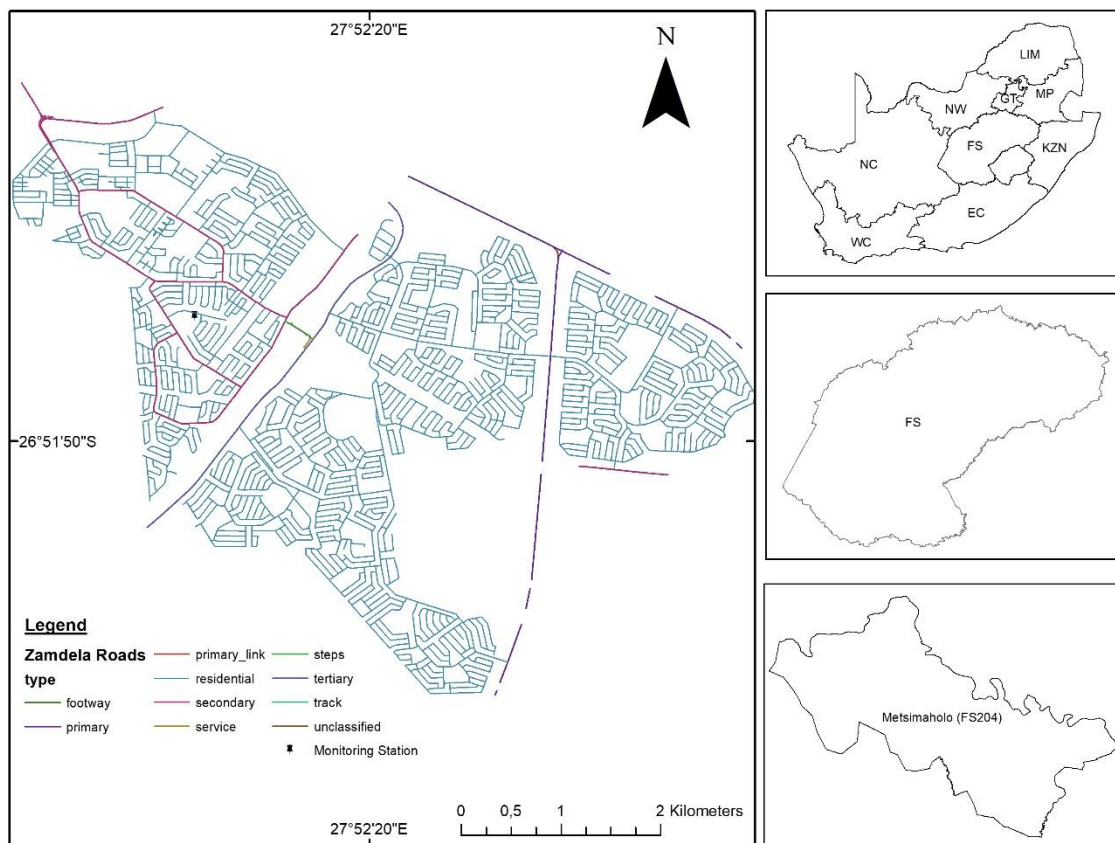


Figure 3-1: Locality map for Zamdela showing road types

Any given area's topography and land use play an important role in the dispersion of atmospheric pollutants through mesoscale systems (Carvalho et al., 2006; Tyson & Preston-Whyte, 2000). In mountainous areas, the wind will cause pollutants to be easily dispersed. In contrast, the pollutants will be trapped in low-level areas such as valleys because the wind does not disperse evenly (Tyson & Preston-Whyte, 2000). Zamdela has a uniform terrain of 1 450 m above sea level (Figure 3-2). It lies on a plateau, and the topography gently slopes downward in the west and southerly direction. The Vaal Basin predominately surrounds the study area, draining colder air from neighbouring high plateau areas (Jagathlal, 2014). The land use surrounding the settlement is predominantly natural grassland, roads, residential areas and industrial point sources.

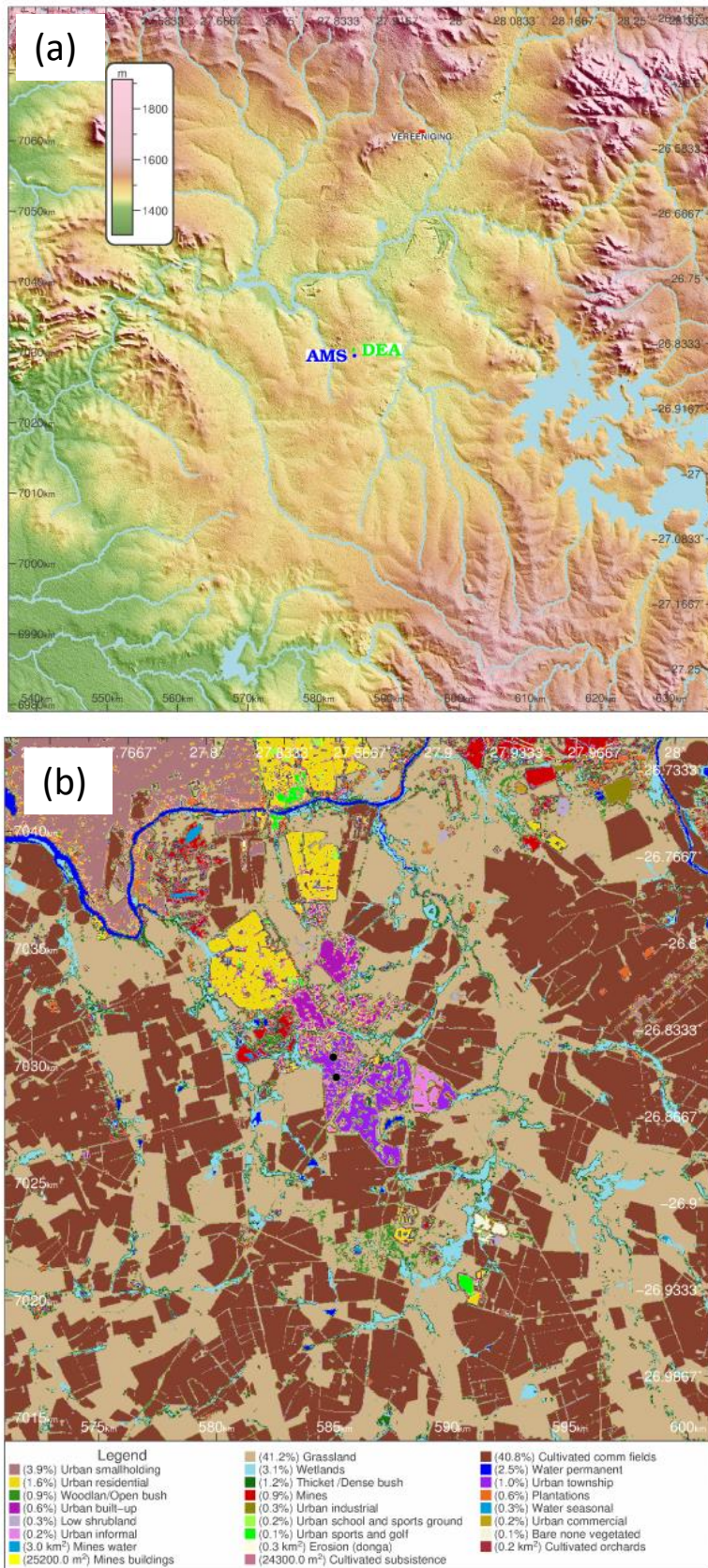


Figure 3-2: Topographic showing terrain differences (a) and land-use map (b) in Zamdela

3.3 Study design

The contribution of traffic emissions in Zamdela was evaluated using data from 2019-2021. The aim is to characterise ambient concentrations of road traffic to ambient PM in a typical densely populated low-income settlement. Figure 3-3 illustrates the steps taken to achieve the methods for the study. Firstly, parameters used to characterise ambient PM, and meteorological data are discussed. Secondly, source apportionment studies in Zamdela are reviewed to evaluate the contribution of vehicle emissions to PM concentrations. Methods and steps to quantify vehicle emissions to PM are calculated. Finally, the contribution of vehicle emissions to PM is modelled using AERMOD.

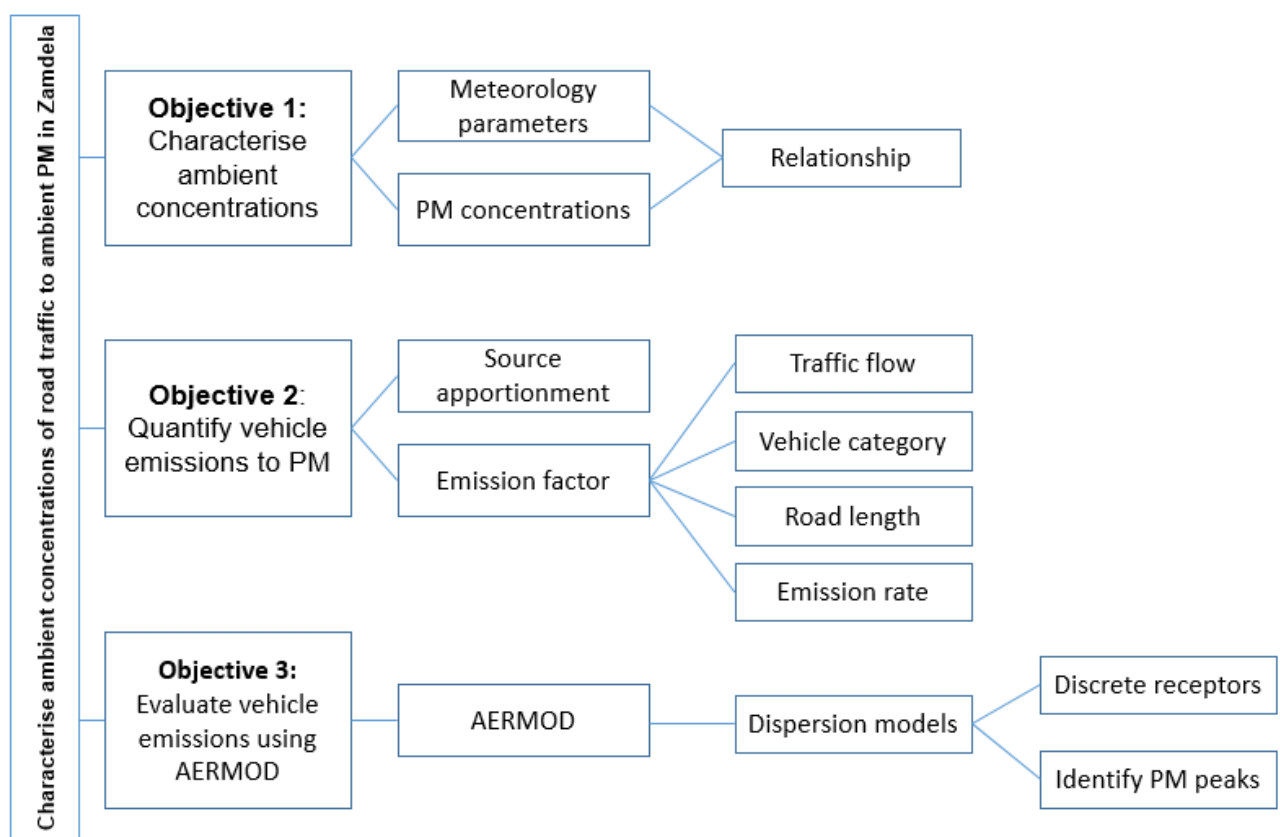


Figure 3-3: Conceptualisation of how to achieve the objectives of the study

3.4 Instrumentation used to measure ambient parameters (Objective 1)

Fixed air quality monitoring stations are essential for measuring atmospheric pollutants, understanding the spatial and temporal variability of pollutants, assessing population exposure and identifying problematic emission sources (Madruga, 2020). For this study, an instrumented caravan was deployed by the Climatology Research Group (CRG) NWU to quantify ambient concentrations (Figure 3-4).



Figure 3-4: Fixed monitoring station in Zamdela showing PM and meteorological analysis used during the sampling campaign

A caravan (owned by the Climatology Research Group North-West University) with equipped ambient air pollution instruments was used to measure PM concentrations and meteorological parameters at a local school (Theha Sejhaba Primary School) north of Zamdela. The school was chosen considering the availability of electricity and security and its location embedded within the township. The mentioned factors are favourable in determining local sources. Data was collected at 1-minute interval averages from 2019-2021 (Table 3-1). Air from outside was pumped into inlets directed towards the PM analysers. Co-located meteorological parameters were recorded - wind direction and speed, temperature, rainfall and humidity. The instruments sampled the meteorological data at 1-minute intervals. Each instrument was calibrated before starting the sampling campaign.

Table 3-1: Measuring parameters for ambient PM and meteorology analysers used during the sampling campaign

Parameter	Instrument	Range	Precision	Sampling rate
PM₁₀	Horiba BAM 1020	0 mg.m ⁻³ to 10 mg.m ⁻³	2.4µg.m ⁻³	60 minutes
PM_{2.5}	MetOne E-Bam	0 mg.m ⁻³ to 65 mg.m ⁻³	2.5µg.m ⁻³	5 minutes
Temperature	Vaisala HMPO60	-10°C to 60°C	± 0.6 °C	1 minute
Humidity	Vaisala HMPO60	0% to 100%	±5%	1 minute
Wind spd/dir	RM Young 05103	0 m.s ⁻¹ to 100 m.s ⁻¹	±3 m.s ⁻¹	1 minute
Rainfall	RM Young 52203	0.1 mm per tip	2% to 3%	1 minute

3.4.1 Continuous PM measurement

Ambient PM is measured using the eBAM for (PM_{2.5}) and the BAM 1020 for measuring (PM₁₀) (Figure 3-5). Both instruments use the same method of using beta attenuation to measure the particles. Hourly measurements at a range of 0–1 000 µg/m³, resolution of ±0.1 µg/m³, and 24-h average lower detection limit of less than 1.0 µg/m³. Carbon 14 emits beta rays on a filter tape at the start of each sample hour. The instrument has a vacuum pump that draws ambient air through to a filter taper, loading the filter with ambient dust particles. The dust particle spots are placed between the beta source and the detector resulting. The deposited particles attenuate the beta rays. The degree of attenuation relative to the unexposed tape can be used to calculate the area density of the deposit, from which the concentration can be derived. The instruments have a measurement range of 5 to 65 530 µg/m³, data resolution of 1.0 µg/m³, an accuracy of ±10% and a 24-h average lower detection limit of less than 1.2 µg/m³ (MetOne Instruments, 2013; Schweizer et al., 2016).

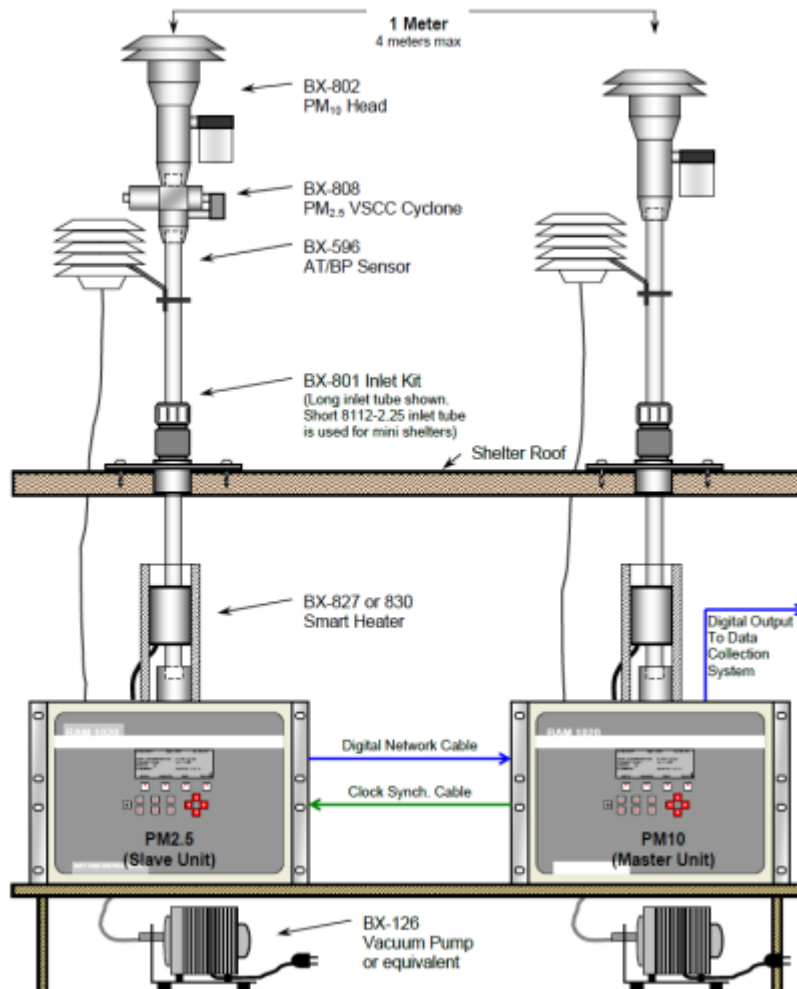


Figure 3-5: PM_{2.5} and PM₁₀ dust monitoring instruments (Met One Instruments Inc, 2009)

3.4.2 Continuous temperature measurement

An RM Young 61302 was used to measure pressure and temperature. The sensor is versatile with high accuracy measurements, low maintenance, low power and calibration power. The resolution of pressure measurements is 0.01 hPa. It has an operational temperature of -40°C to 60°C. It operates immediately, 1 second after the power is on. Data recording starts after a 5-second delay and continues at an 18 Hz rate. With the low power and temperature, the instrument can be used in environments using a battery or solar power.

3.4.3 Continuous wind speed and direction measurement

The RM Young 05103 is used to measure ambient wind speed and direction. An anemometer operating with a pulse generator produces pulses that are proportional to the rotation of the anemometer to detect wind speed. Wind direction is measured using a vane (Meteorological Instrument Guide, 2008). It has a range of 0 to 100 m/s and a 360° mechanical range.

3.4.4 Continuous rainfall measurement

The RM Young 52202 tipping bucket rain gauge was used to measure rainfall. Measured precipitation is released into a collection tube. The gauge has a catchment area of 200 cm² and a 0.1 mm per tip resolution. The magnetic reed switch controls the information data output. It has a built-in heater (+0.75 amps) designed to melt ice (Meteorological Instrument Guide, 2008). The instrument design is the simplest and most effective method used for rainfall estimation. It can perform maximum measurements with little maintenance needed.

3.4.5 Procedures to ensure quality control

Quality control is implemented to improve the data credibility, completeness and consistency (Zhang et al., 2019). This is important to ensure that the data collected is spatially accurate and robust for reporting and analysis (Nyaboga & Mwaura, 2009). The quality control plan for this study includes general conventions on naming variables, files and directories, procedures for site maintenance visits, data management, and data quality assurance. Additionally, the general approach to ensure quality control included regular site visits and calibration and adherence to a quality assurance plan.

Site maintenance was done every two weeks. Data were downloaded, logged to the cloud-based database, reviewed and compared to the data from the previous visit. Data anomalies, such as out-of-range values or gaps caused by power failures, were identified.

The downloaded datasets were merged into one final CSV file. Values above or below the instrument detection limit were flagged out, as stated by Croghan and Egeghy (2003). Values above 1 000 µg/m³ for PM were disregarded as it is unlikely that concentrations can reach that value unless the instrument is faulty. When dealing with outliers and extreme values, these were not set to missing data unless the instrument appeared faulty.

The South African National Accreditation System (SANAS, 2009) recommends that a minimum of 75% of data be available to ensure data quality. Table 3-2 shows the data availability in Zamdela during the sampling period. The data availability is according to standard and is high in confidence. The data was analysed in *Jupyter* using *Python* and **R** for time series plots for the meteorology and ambient illustrations. The meteorological data were also used in *AERMET* to determine the dispersion of PM in the study area. The ambient data analysis was used to validate the monitored PM data, as the monitoring stations were regarded as discrete receptors in the model.

Table 3-2: Data completeness for PM₁₀ and PM_{2.5} from 2019-2021

Monitoring site NWU-SASOL (Zamdela)	2019		2020		2021	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
	77.3%	80.3%	75.1%	77.3%	78.3%	79.6%

3.5 Source apportionment of PM emissions in Zamdela (Objective 2)

It is crucial to know the sources contributing to air pollution to manage the air quality of any area. Hence source apportionment is vital in identifying the origin of problematic sources (Sharmar, 2010).

This study uses existing literature and source apportionment to identify contributing sources of ambient PM in Zamdela. Evaluating source apportionment studies in densely populated low-income settlements is important to understand the contribution of vehicle emissions to ambient air pollution, specifically Zamdela. Source apportionment studies from the North-West University Climatology Research Group are used to understand better the contribution of vehicle emissions to ambient PM in Zamdela.

The source apportionment process involves the identification of sources and calculating the proportion of contribution to the particulate loading of each source. Source apportionment by receptor modelling identifies contributing sources to PM loading at selected receptor sites. This is imperative to comprehend the exposure at each receptor site, identifying the contribution of each source to the ambient particulate loading and the mechanisms associated with their formation (Srimuruganandam and Jose, 2016). This approach may assist in identifying intervention strategies that should be prioritised to target ambient PM pollution sources in areas with significant potential impact on health and the environment in the Vaal Triangle Airshed Priority Area (VTAPA).

It is possible to ascribe ambient PM to their sources as every source may be distinguished by its unique chemical composition. The chemical species frequently found in different source emissions, according to their chemical abundances, are summarised in Table 3-3.

Table 3-3: Chemical species used to identify possible sources contributing to ambient PM

Source	Particle fraction	Chemical abundances in % mass			
		< 0.1%	0.1 to 1%	1 to 10%	> 10%
Paved Road dust	Coarse	CR, SR, Pb, Zr	SO ₄ ²⁻ , Na ⁺ , K ⁺ , P, S, Cl, Mn, Zn, Ba, Ti	EC, Al, K, Ca, Fe	OC, Si
Unpaved road dust	Coarse	NO ₃ ⁻ , NH ₄ ⁺ , K ⁺ , P, S, Cl, Ti	SO ₄ ²⁻ , Na ⁺ , K ⁺ , P, S, Cl, Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si

Construction	Coarse	Cr, Mn, Zn, Sr, Ba	SO ₄ ²⁻ , K ⁺ , S, Ti	OC, Al, K, Ca, Fe	Si
Agricultural soil	Coarse	NO ₃ ⁻ , NH ₄ ⁺ , Cr, Zn, Sr	SO ₄ ²⁻ , Na ⁺ , K ⁺ , S, Cl ⁻ , Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si
Natural soil	Coarse	Cr, Mn, Sr, Zn, Ba	Cl ⁻ , Na ⁺ , EC, P, S, Cl ⁻ , Ti	OC, Al, Mg, K, Ca, Fe	Si
Motor vehicles	Fine	Cr, Ni, Y	NH ₄ ⁺ , Si, Cl ⁻ , Al, Si, P, Ca, Mn, Fe, Zn, Br, Pb	Cl ⁻ , NO ₃ ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , S	OC, EC
Vegetation burning	Fine	Ca, Mn, Fe, Zn, Br, Rb, Pb	NO ₃ ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , S, N ⁺	Cl ⁻ , K ⁺ , Cl, K	OC, EC
Residential combustion	Fine	K ⁺ , OC, Cl, Ti, Cr, Co, Ga, Se	NH ₄ ⁺ , Na ⁺ , Zn, Fe, Si	V, OC, EC, Ni	S, SO ₄ ⁻
Incinerator	Fine	V, Mn, Cu, Ag, Sn	K ⁺ , Al, Ti, Zn, Hg	NO ₃ ⁻ , Na ⁺ , EC, Si, S, Ca, Fe, Br, La, Pb	SO ₄ ⁻ , NH ₄ ⁺ , CO, Cl
Coal-fired boiler	Fine	Cl, Cr, Mn, Ga, As, Se, Br, Rb, Zr	NH ₄ ⁺ , P, K, Ti, V, Ni, Zn, Sr, Ba, Pb	SO ₄ ²⁻ , OC, EC, Al, S, Ca, Fe	Si
Marine	Fine	Ti, V, Ni, Sr, Zr, Pd, Ag, Sn, Sb, Pb	Al, Si, K, Ca, Fe, Cu, Zn, Ba, La	SO ₄ ²⁻ , NO ₃ ⁻ , S, OC, EC	Cl ⁻ , Na ⁺ , Na, Cl

3.6 Emissions inventory calculations (Objective 2)

The manual traffic count method is the most common approach used to record the number of vehicles that pass in an area. This approach is time consuming and expensive but necessary in cases where the vehicles must be classified according to classes. To predict/estimate the traffic flow, it is essential to consider that traffic volumes change throughout the day. Therefore, the counts should not only be done during cyclic peak hours (morning, afternoon, evening) to avoid biased results.

For this study, a manual traffic count was done (Figure 3-6) since there is no SANRAL data or deployed traffic count instrumentation within the settlement. Traffic count data were collected in Zamdela from 6 March 2020- 12 March 2020. The chosen location was Eric Street (27.84254°E; -26.83393°S) (Table 3-4). This street leads into and out of Zamdela, making it a favourable high-volume location to determine incoming and outgoing traffic from the study area. There is a noteworthy discrepancy in this method as the counts were conducted on a distinct road assumed to represent the other roads within the township. With this in mind, weighting was done for the different road classes to obtain a more realistic fleet profile of that area.

The data were collected by counting the number of vehicles passing through the road per hour for sedans, buses, trucks, buses, minibuses, and vehicles accounted as 'other'. For each of the vehicle types, mean volumes were provided for 12-hour daily time windows: 06:00–07:00,

07:00–08:00, 08:00–09:00, 09:00–10:00, 10:00–11:00, 11:00–12:00, 12:00–13:00, 13:00–14:00, 14:00–15:00, 15:00–16:00, 16:00–17:00 and 17:00–18:00. The 12-hour counting period is considered the standard for accurate traffic flow data (Colville et al., 2001). These periods are favourable to highlight the granular separation of peak hours with a higher temporal variability and course separation, which are times affiliated with low traffic volumes. The data were recorded for all weekdays to illustrate the temporal resolution for each datum.

The data were recorded onto log sheets for each classification, date and time, location of the collected road (street name) and the day's weather conditions. A Global Positioning System (GPS) instrument was used to record the coordinates.



Figure 3-6: Manual road traffic sampling campaign

Table 3-4: Traffic count information sheet

Date: 6- 12 March 2020												
Observer: Lerato Tshisi												
Street: Eric Street												
Coordinates: 27.84254°E; -26.83393°S												
Weather: Cloudy/ Sunny/ Partly cloudy												
Vehicle type	6:00-7:00	7:00-8:00	8:00-9:00	9:00-10:0	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00

the shape length for each road type in Zamdela. This is important to estimate emissions which are imported for AERMOD.

3.6.4 Emission factor (Ef)

Emission factors used in the emission rate calculation were validated using the values for PM fraction per vehicle classification (Table 3-5). The classes are separated by motor vehicles, passenger cars, light-duty and heavy-duty vehicles.

Table 3-5: Emission factors per vehicle classification (EEA, 2019)

Vehicle classification	PM fraction	Value
Motor cycle	PM ₁₀	0.0064
	PM _{2.5}	0.0034
PC	PM ₁₀	0.0138
	PM _{2.5}	0.0074
LDVs	PM ₁₀	0.0216
	PM _{2.5}	0.0117
HDVs	PM ₁₀	0.0590
	PM _{2.5}	0.0316

The spatial distribution represents space, time and the geographic relationship that exists (Wang et al., 2020). Dispersion patterns are one of the most common methods to show the spatial distribution within an area. This is important for vehicle emissions because there is a scale effect, as travelling longer distances has a higher spatial distribution than short-distance travelling.

ArcGIS was used to illustrate the estimated spatial distribution of vehicular PM emissions per road length. To calculate PM_{2.5} and PM₁₀ distribution, the average road length and emission rate were used, as explained in Equation 6.

$$EpL = L_{ja} / L_j \times EF_{i,j} \quad \text{Equation 6}$$

Where EpL= Emissions per road length [ton]; L_{aj}= Average total emissions [km]; L_j= Total road length [km]; and TE= Total emissions [ton/km].

3.7 Modelling traffic contribution to ambient PM using AERMOD (Objective 3)

Modelling the dispersion of atmospheric pollutants is one of the most important components in air quality assessment. Models represent ambient concentrations of source emissions incorporating meteorological parameters and emission estimates (Leelössy et al., 2014). This

represents the spatial and temporal variability of various sources. Because sources such as vehicle emissions are emitted at ground level, exposure to TRAP is widespread. This creates the need to monitor the dispersion of vehicular emissions.

For this study, the contribution of traffic emissions to ambient PM in Zamdela was modelled by looking at different vehicle classifications. For this study, AERMOD was selected because the DEA and US EPA have approved the model as the best tool for air pollution assessment. The model covers a spatial range of up to 50 km, which is appropriate for the study area. Figure 3-7 gives a conceptual outline of the processes in the model, which will be discussed further.

AERMOD requires two input data sets, i.e., emission and meteorological data. Necessary inputs, in addition to the steps illustrated in Figure 3-7, include:

- Inputting of concentrations, wet and dry deposition of gases and particulates.
- Selection of the averaging periods (e.g., hourly, daily and annual) according to the NAAQS
- Output options include the concentrations and depositions at each receptor due to emissions from each group of sources, the average during specific periods (annual and daily) and the maximum in each short averaging period (PLOT-FILE option).
 - i. Application of methodologies to produce the input data required by the model for the description of emission sources, which involved:
 - Defining the pollutants emitted and the size of the particulate matter. In this study, PM_{10} and $PM_{2.5}$ were considered.
 - Determining the source type that best suits the available data and the corresponding release height, velocity, and diameter where applicable.
 - ii. Deciding on locale thus, urban and rural conditions, which in this study was stats SA definition of townships (Zamdela).

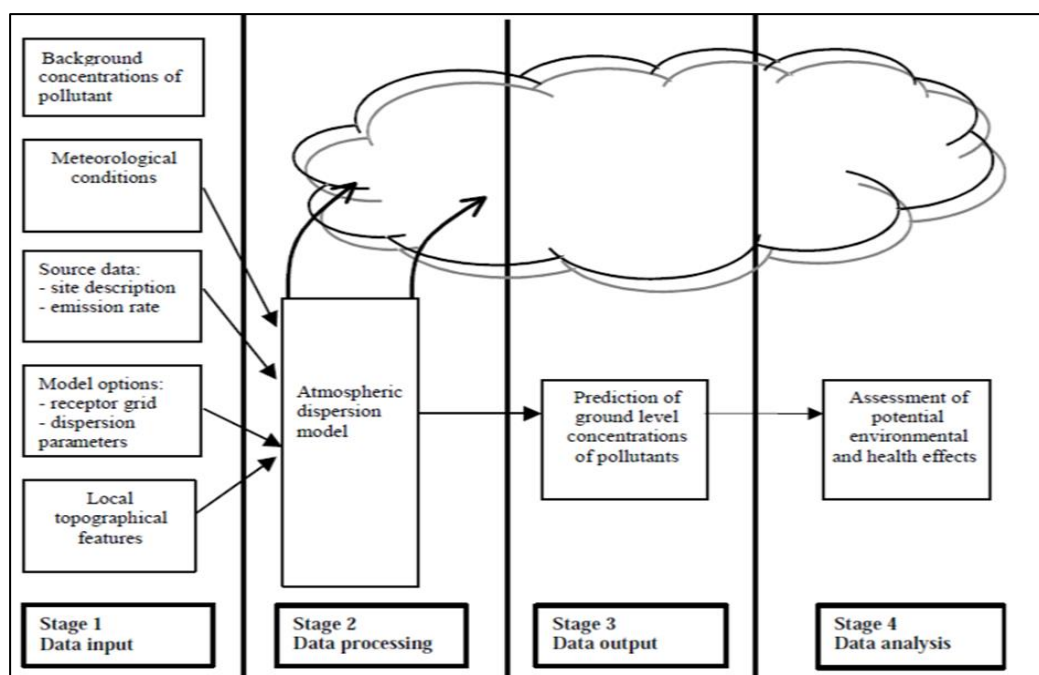


Figure 3-7: Important AERMOD inputs (Ministry for the Environment Manatū Mō Te Taiao, 2004)

3.7.1 Model setup

AERMOD consists of two input processors, namely (i) ARMAP, which is a terrain processor and (ii) AERMET, which is a meteorological processor in the model. ARMAP was run with the geographical inputs, source characterisation, receptors and spatial resolution, including terrain information. The receptors were selected, and the source characterisation emission rate calculations were inputted as required by AERMOD. After that, AERMET was run with all the meteorological data.

3.7.2 Geographical inputs

Geographical inputs include the coordinates, terrain classification and defining the study area type. These inputs are required for ARMAP to process the terrain of the area alongside the source and receptor (US EPA, 2005). The terrain is important because it influences the dispersion of air pollution. The terrain was defined as flat and elevated in Zamdela. Digital Elevation Model (DEM) run ARMAP processor obtained from Shuttle Radar Topography Mission at a resolution of 30 m. The terrain was calculated using the WGS84 datum on the Universal Transverse Mercator (UTM) coordinate system 35°S. Zamdela is defined as an urban area because the area has less than 35% vegetation coverage.

3.7.3 Source characterisation

AERMOD supports various source types from the surface, near-surface and elevated emissions within a study area. These can be represented using source types, i.e., area, point

and volume sources (US EPA, 2017). Road paths are an example of line sources. For this study, roads were assumed to be line volume. Required source parameter input data includes emissions rates, base elevation, coordinates, line type and averaging periods, as explained in Table 3-6.

Table 3-6: Source characterisation input data

Model input	PM ₁₀	PM _{2.5}
Source type	Line volume	Line volume
X coordinate	27.8692°E	27.8692°E
Y coordinate	26.8662°S	26.8662°S
Base elevation (m)	1 450	1 450
Release height (m)	0.3	0.3
Emission rate (t./a)	23	42
Configuration	Adjacent	Adjacent
Pollutant averaging	24 hr NAAQS	24 hr NAAQS

3.7.4 Receptors and spatial resolution

AERMOD was used to run models for PM_{2.5} and PM₁₀ within Zamdela. Areas of concern, such as public schools, were considered discrete receptors for modelling purposes. The domain size was selected to cover the spatial resolution of all the roads in Zamdela. To provide a clear and high resolution, the receptor grid was set to 1000 m by 1000 m. The overall terrain determined the grid size.

3.7.5 Meteorological inputs

AERMET is a stand-alone meteorological data processor in AERMOD. It processes in-situ data from measurements and creates two files, surface data and profile data profile (US EPA. 2017). The two files run separately in different stages to characterise the surface layer and the vertical structure of the PBL. This study used hourly meteorological data for 2019 to 2021. The measured surface profile parameters selected were temperature, relative humidity, wind speed and direction. The data profiles were processed using 24-hour periods by processing the surface data profile and in-situ data. The two sets are merged to provide mixing height data and PBL.

3.7.6 AERMOD input data

The contribution of vehicle emissions of the monitored data was modelled in Zamdela using one-hour ambient data. The methodology used for the AERMOD dispersion tool is summarised in Table 3-7. The important inputs included defining the selected pollutants, concentrations, emission factor selecting receptors and meteorological data.

Table 3-7: AERMOD input data needed to model

Description	Zamdela AERMOD input
Source	
Type	Line volume source
Emission rate	Emission rate calculations per vehicle classification[g/(s/m ²)]
Background emissions	One year PM data
Variable emissions	Hourly
Averaging time	24 hours in compliance with NAAQS
Receptors and spatial resolution	
Receptor grid	1000 m by 1000 m with 100 points
Fence line	No fence line
Geographical inputs	
Modelling domain	10 km by 10 km centred for a flat terrain area
Coordinate system	WGS84 projection datum, with the terrain data calculated based on the Universal Transverse Mercator (UTM) coordinate system (35 South)
Classification of site	Urban area
Meteorology	
Surface data	Hourly temperature, relative humidity, wind speed, wind direction
Upper air data	temperature, relative humidity, wind speed and wind direction
Source of MET data	NWU-CRG monitoring station
Data period	3-year on-site specific data

3.7.7 Comparing modelled data to ambient data

Ambient hourly concentrations from the monitoring station were used as discrete receptors in AERMOD. The station covers the spatial area of the study area to monitor all source emissions in Zamdela. In this study, vehicle emissions are of interest, and it is important to validate the results obtained from the monitoring station and AERMOD.

To validate the study's results, the modelled data will be compared against the ambient monitoring data since the ambient data covered the spatial area of Zamdela measuring all sources at once. Source apportionment vehicle emission percentages will be used to calculate the contribution of vehicles to the overall measured data. Thereof, the vehicle emission modelled results and the contributions of vehicles from the monitored data will be compared.

CHAPTER 4: METEOROLOGY AND PM CONCENTRATIONS

This subsection of chapter 4 aims to address and answer objective 1, as discussed in Chapter 1 (Section 1.4). To better understand traffic emissions and PM, it is important to have an overview of the meteorological conditions that influence PM concentrations. The wind speed, direction, temperature, relative humidity and PM concentrations will be discussed.

4.1 Introduction

An area's climate and meteorology are important in air pollution because it determines the rate of dispersion, deposition and transportation of pollutants (Piketh et al., 1999; Tyson & Preston-Whyte, 2000). The study area is classified as a semi-arid region and is high above sea level. Anti-cyclonic subsidence is prevalent in the VTAPA atmospheric circulation (Thomas, 2009). Subsidence influences the elevated inversions resulting in a limited mixing layer and poor atmospheric dispersion of pollutants. Typically, the summer season is very hot compared to cold winter conditions. Wet and warm summer conditions are attributed to the low-pressure systems (easterly low) prevalent from November to March. Winter months are dry and cold due to the subtropical high-pressure system dominant during the season. This follows from adiabatic warming, which results in atmospheric stability (Liebenberg, 1999; Tyson et al., 1996).

Atmospheric pollutants become airborne from the surface. Once the contaminants are airborne, they are influenced by meteorological conditions (precipitation, temperature, relative humidity, boundary layer, wind speed and direction) in influencing ambient concentrations and dispersion (Giri et al., 2008; Monn, 2001; Tyson & Preston-Whyte, 2000). Analysis of hourly average meteorological data is necessary to facilitate a comprehensive understanding of the dispersion potential of the site. The NWU CRG monitoring station embedded within the township is regarded as representative of the ambient and PM concentrations; data are available from 2019 - 2021. It should be noted that rainfall data could not be analysed due to low data availability.

4.2 Wind speed and direction

Wind speed is a primary determinant for the mixing and dispersion of atmospheric pollutants. The higher the wind speed, the more rapid the dilution and dispersion of atmospheric pollutants consequent low surface concentrations. Conversely, lower wind speed results in less dilution and higher ground concentrations (Thomas, 2009).

The mean wind speeds for Zamdela are represented in Table 4-1. Diurnal patterns and monthly variations are illustrated in Figure 4-1. Wind speeds range from calm to a maximum of 11 m/s in Zamdela. Low wind speeds are recorded during the evenings, night and early morning, especially during winter. Maximum wind speeds are recorded during the day in summer. The maximum average of 9 m/s was recorded at 14:00. Wind speeds decreased throughout the day and evening, reaching a minimum (calm, <1 m/s) at 03:00.

Table 4-1: Wind speed statistical data in Zamdela

Wind speed	Mean	Std	Min	25%	50%	75%	Max
	3	2	0.1	2	3	4	11

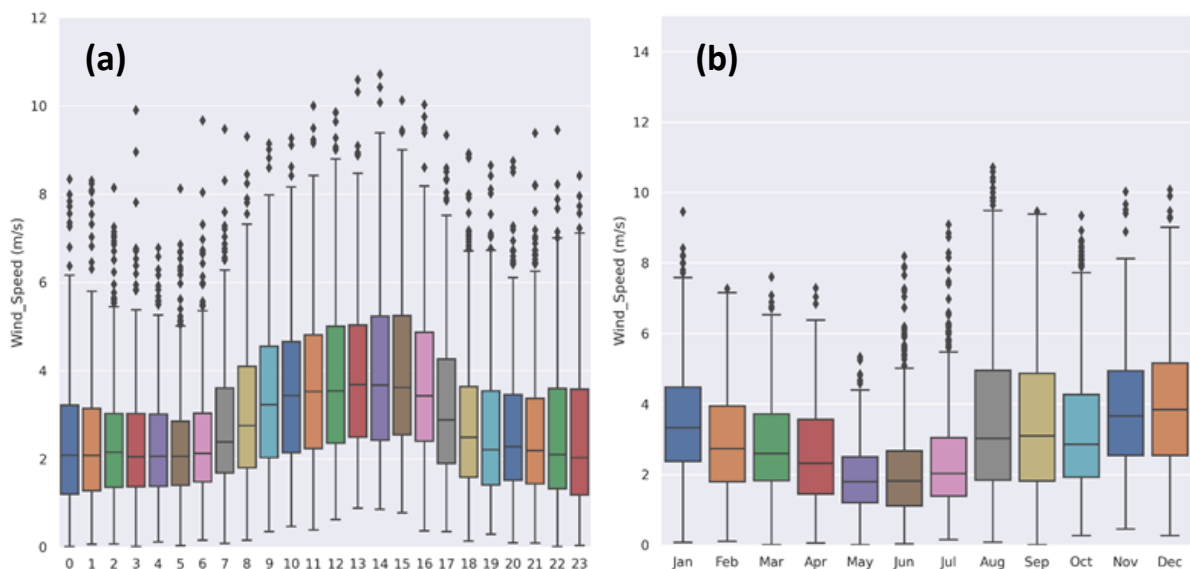


Figure 4-1: Average wind speeds (a) diurnal and (b) seasonal patterns.

4.3 Ambient temperature

Ambient temperatures are essential to determine the mixing rate and inversion layer. The greater the difference between the air and the plume, the higher the pollution plume can ascend. This potentially influences the rate of dispersion of pollutants before reaching ground level. Higher temperatures increase the dissipation rate, resulting in lower ground-level concentrations (Thomas, 2009).

The mean temperatures for Zamdela are presented in Table 4-2. Diurnal patterns and the monthly variations are shown in Figure 4-2. Overall, mean temperatures depict minimum temperatures of -5°C and maximum temperature of 36°C. Temperatures reach 36°C at 14:00 as incoming solar radiation is at its maximum. After that, temperatures decrease to a minimum

just after sunrise. The coldest temperatures occur at 05h00-07h00, reaching below 0°C. The annual pattern profile depicts maximum temperatures in December (36°C) in the summer season. Minimum temperatures are recorded from June- August (0°C) in winter.

Table 4-2: Ambient temperature statistical data in Zamdela

Temperature (°C)	Mean	Std	Min	25%	50%	75%	Max
	17	8	-5	12	17	22	36

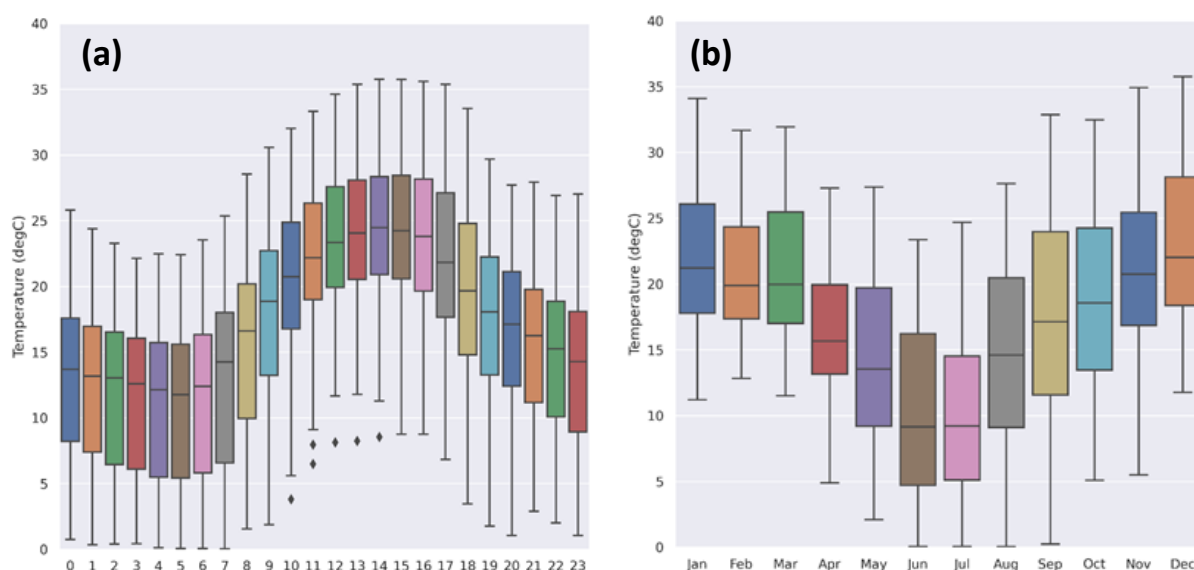


Figure 4-2: Average temperatures (a) diurnal and (b) seasonal patterns

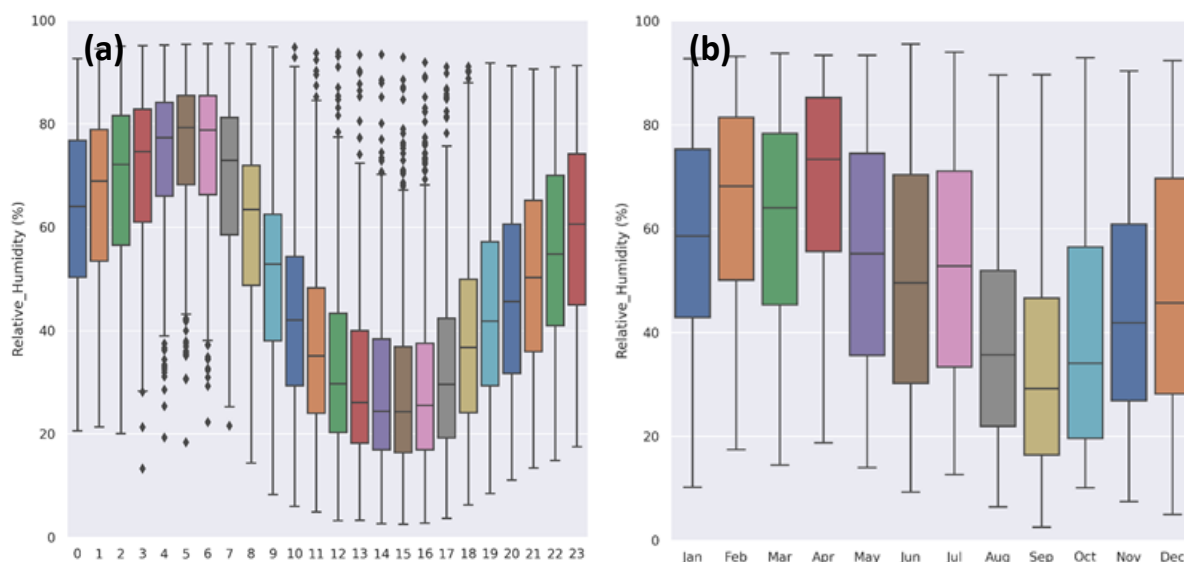
4.4 Relative humidity

The diurnal relative humidity varies inversely to the ambient temperature. When the ambient temperature increases, the relative humidity decrease and vice versa (Thomas, 2009).

The average RH in Table 4-3 depicts a minimum of 3% and a maximum RH of 96% in Zamdela. The maximum RH concentrations are recorded during the early hours of the morning and in the winter months, while minimum temperatures are recorded in the day and summer months. The diurnal pattern (Figure 4-3) shows that RH increases during the night, reaching a maximum (96%) at 07h00 just after sunrise. This accords with the ambient temperature pattern (Figure 4-2). An increase in ambient temperature is inversely proportional to RH. RH reaches a minimum during the day recorded at 15h00 at 3%. The mean monthly pattern decreases during the winter months and increases during the summer months. The maximum RH is recorded in June at 96%, and the minimum is prevalent in September at 4%.

Table 4-3: Relative humidity statistical data in Zamdela

Relative humidity (%)	Mean	Std	Min	25%	50%	75%	Max
	51	23	3	31	51	72	96

**Figure 4-3: Average RH showing (a) the diurnal and (b) the seasonal patterns**

4.5 Ambient monitored PM data

The results shown in Table 4-4 represent the state of ambient air quality in Zamdela for 2019 to 2021. The data are compared against the NAAQS. On average, $PM_{2.5}$ and PM_{10} are not compliant throughout the sampling campaign. Average PM_{10} concentrations were well above $75 \mu g/m^3$ and $PM_{2.5}$ was above the $40 \mu g/m^3$ NAAQS daily limit. $PM_{2.5}$ and PM_{10} daily concentrations were exceeded more than 50% of the time, considering that the median was not in compliance for most days. The daily average for PM_{10} was $102 \mu g/m^3$ and $69 \mu g/m^3$ for $PM_{2.5}$. This implies that PM is problematic in Zamdela.

Table 4-4: A summary of descriptive statistics for PM in Zamdela compared to (NAAQS)

Pollutants	Mean	Std Dev	Min	Median	Max
$PM_{10} (\mu g/m^3)$	102	92	14	72	877
$PM_{2.5} (\mu g/m^3)$	69	51	10	54	832

Table 4-5 represents the frequency of exceedances recorded in Zamdela between 2019 to 2021. PM daily and annual averages recorded at the monitoring station exceed the NAAQS. A total of 831 daily exceedances (i.e. 294 in 2019, 241 in 2020 and 296 in 2021) were recorded

for PM₁₀, and 769 daily exceedances (i.e. 284 in 2019, 234 in 2020 and 251 in 2021) were recorded for PM_{2.5} during the monitoring period. A maximum of four daily exceedances are deemed acceptable for each of these pollutants. This implies that PM exceeds the NAAQS more than 50% of the time.

Table 4-5: The frequency PM exceedances in Zamdela

Pollutants	Period	NAAQS	Exceeds	N exceeds
PM ₁₀ (ug/m ³)	24-h	75	4	831
	Annual	40	0	2
PM _{2.5} (ug/m ³)	24-h	40	4	769
	Annual	20	0	3

4.6 Diurnal PM variations in Zamdela

The diurnal patterns of air pollution concentrations show two peaks throughout the day. The first peak is rerecorded between 05h00 and 07h00, and the second starts at 16h00 and lasts until after 21h00. The elevated concentrations occur for PM_{2.5} and PM₁₀ (Figure 4-4). The peaks reflect a combination of local combustion sources (domestic burning, waste burning and motor vehicle emissions) and mechanical dust resuspension. The two peaks coincide with people leaving their homes and going to and from work, school and other activities. Exhaust fumes from petrol and diesel-fuelled vehicles are at a maximum during peak traffic. Domestic fires are lit morning and evening, linked to people preparing beverages and food before departing for or returning from work (Kovacic et al., 2016). Domestic fires include the combustion of coal, wood and paraffin (Nkosi et al., 2017). In addition, the source apportionment results found suspended dust (fugitive dust and dust from roads), waste burning and traffic emissions to be non-industrial sources of both PM_{2.5} and PM₁₀. Fly ash and secondary sulphate also contributed significantly to the fine fraction (PM_{2.5}) (Muyemeki et al., 2020). Furthermore, the peaks coincide with low wind speeds, low temperatures and a decrease in relative humidity. This is when there is less mixing and dispersion of atmospheric pollutants, consequently resulting in PM concentrations exceeding the NAAQS.

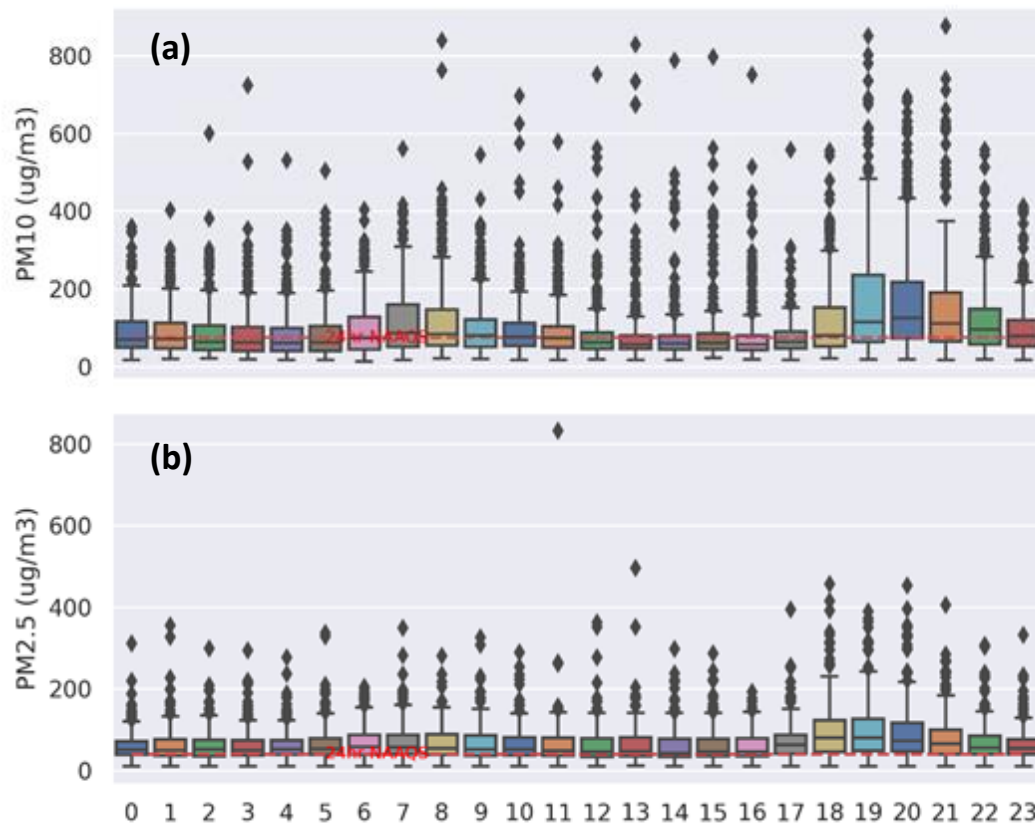


Figure 4-4: Average diurnal PM concentrations for (a) PM₁₀ and (b) PM_{2.5} in Zamdela

4.7 Seasonal PM variations in Zamdela

Seasonal hourly averages depict that winter has the highest PM averages (Figure 4-5). This can be explained by decreasing temperatures, low wind speeds and diminished dispersion potential due to increased atmospheric stability in general and the formation of surface inversion at night. During winter, inhabitants resort to burning solid fuels (coal and wood) because it is cheap and is used as a dual utility to warm the dwellings and cook (Balmer, 2007, Chidindi et al., 2019; Language et al., 2016). Approximately 34% (4 076) of Zamdela households use solid fuels in their homes. In winter, the number of families using solid fuels increases by a factor of almost three; 2 800 households compared to 954 in summer. This is driven by the socioeconomic status of most families in the settlement. Summer and spring months depict lower concentrations, explained by an increase in ambient temperature and higher wind speeds that favour the dispersion potential of atmospheric pollutants. In addition, the source apportionment results found resuspended dust (fugitive dust and dust from roads), waste burning and traffic emissions to be non-industrial sources of both PM_{2.5} and PM₁₀. Fly ash and secondary sulphate also contributed significantly to the fine fraction (PM_{2.5}) (Muyemeki et al., 2020).

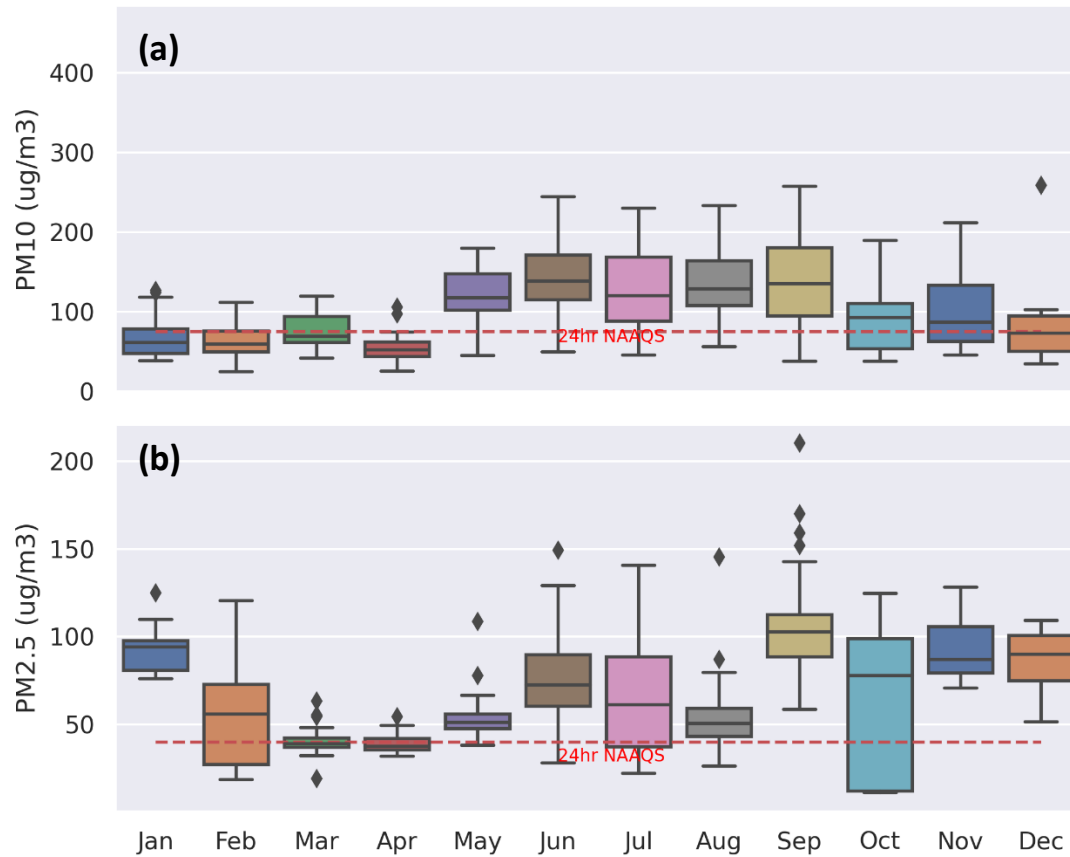


Figure 4-5: Seasonal PM concentrations in Zamdela (a) PM₁₀ and (b) PM_{2.5}.

4.8 Relationship between meteorology and PM

Scatter plots indicate whether two variables have a relationship in any consistent temporal variability (Carslaw, 2012). Figure 4-6 presents correlation plots between ambient PM and meteorological parameters. The only meteorological variable that indicates a correlation with PM is wind speed, with a tendency for increased concentrations at lower wind speeds.

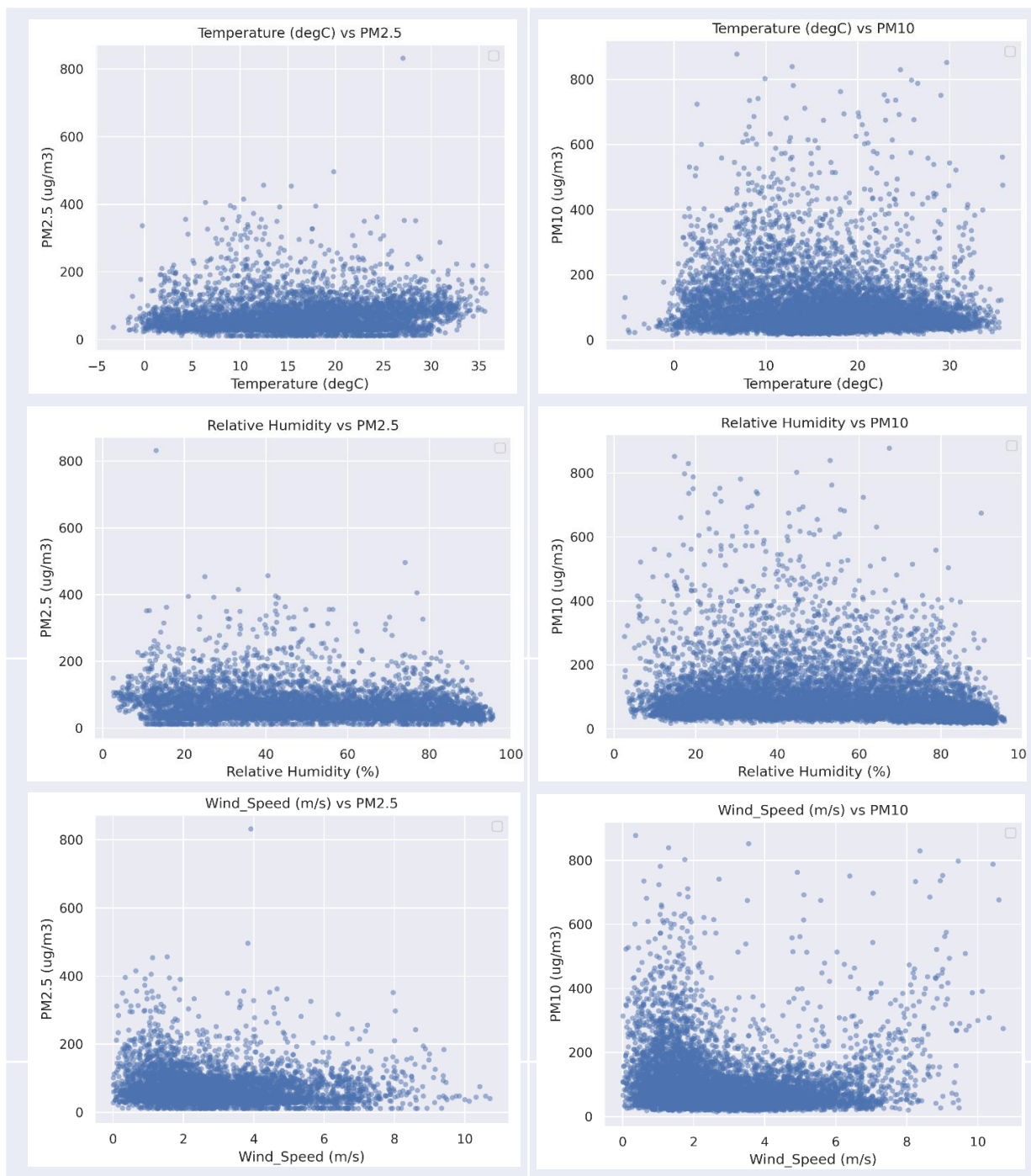


Figure 4-6: Correlation between PM and meteorological parameters: temperature, relative humidity and wind speed

4.9 Conclusion

This chapter depicted a discussion of the first objective (Section 1.3). Ambient PM concentrations were analysed in Zamdela for three years. The observed analyses illustrate that PM is a pollutant of concern, with various sources contributing to the elevated concentrations. Consequently, the NAAQS for PM is frequently exceeded, especially in winter. Of the meteorological parameters, wind speed has the most significant influence on the

dispersion of pollution, controlling the mean seasonal and diurnal temporal variations. An inverse relationship between PM and wind speed is observed. Therefore, source emissions and meteorological conditions influence PM concentrations. Since various sources are identified as contributing to PM, it is important to assess each one individually. Therefore, a source apportionment is necessary to estimate each problematic source's contribution percentage. The analyses and literature findings identify vehicles as one of the contributors to PM. The following chapter will quantify vehicle emissions to PM.

CHAPTER 5: QUANTIFYING PM EMISSIONS

This section of chapter 4 aims to address and answer objective 2. To better understand traffic emissions and PM, it is important to have an overview of vehicle emissions' contribution to ambient PM. Source apportionment characterising PM sources will be discussed. This is followed by an emissions inventory proposed for vehicles in Zamdela.

5.1 Introduction

Quantifying air pollution sources is important when assessing ambient concentrations. This can be achieved by long-term monitoring, source apportionment, estimating emission rates and running dispersion models. An emissions inventory for vehicles was developed in Zamdela. The aim was to understand the impact of vehicle emissions on PM concentrations by estimating emission rates per vehicular classification. Firstly, the contribution of vehicle emissions is characterised and explained by reviewing source apportionment findings. This is followed by traffic volume evaluation per vehicle class to estimate the activity rate.

5.2 Evidence from source apportionment studies

Source apportionment using the chemical mass balance (CMB) receptor model was used to characterise sources contributing to ambient PM. The CRG NWU collected the atmospheric samples in Zamdela for winter and summer campaigns for daytime (10h00- 22h00) and night-time (22h00-10h00) samples. The samples were separated into PM₁₀ and PM_{2.5} fractions. The chemical composition has been analysed with XRF (elemental composition, IC analysis (soluble ions) and thermal desorption and optical analysis (organic (OC)). The model identified elements that were unaccounted for with the available source profiles. Most samples have a threshold below 60%. Through principal components analysis (PCA) analysis, thirteen sources were determined to be problematic in Zamdela.

5.2.1 Summer PM sources

The primary PM₁₀ source during daytime (Figure 5-1a) in the summer months in Zamdela was dust contributing to 33.9% of emissions. Particles of sulphates and nitrates were traced as the second major source, accounting for 27.1%. Other sources of concern identified included wood/biomass burning (14.4%), unpaved/paved roads (11.4%), petrochemical (1.8%), coal combustion (1.2%), waste burning (0.8%), heavy metal dust (0.2%) and excess chlorine (0.1%). Unaccounted sources for the total mass were 9.0% for the daytime summer period. During the night time (Figure 5-1b), dust was the primary source of PM₁₀, contributing 40.7% of emissions. Particulate sulphate and nitrate were found to be the second most abundant

source. Other identified sources included wood/biomass burning (14.0%), unpaved/paved roads (7.3%), excess chlorine (2.3%), coal combustion (1.9%), petrochemical industry (1.5%), heavy metal dust (0.3%) and waste burning (0.2%). Unaccounted sources made up 7.4% of the total mass for the night-time summer period.

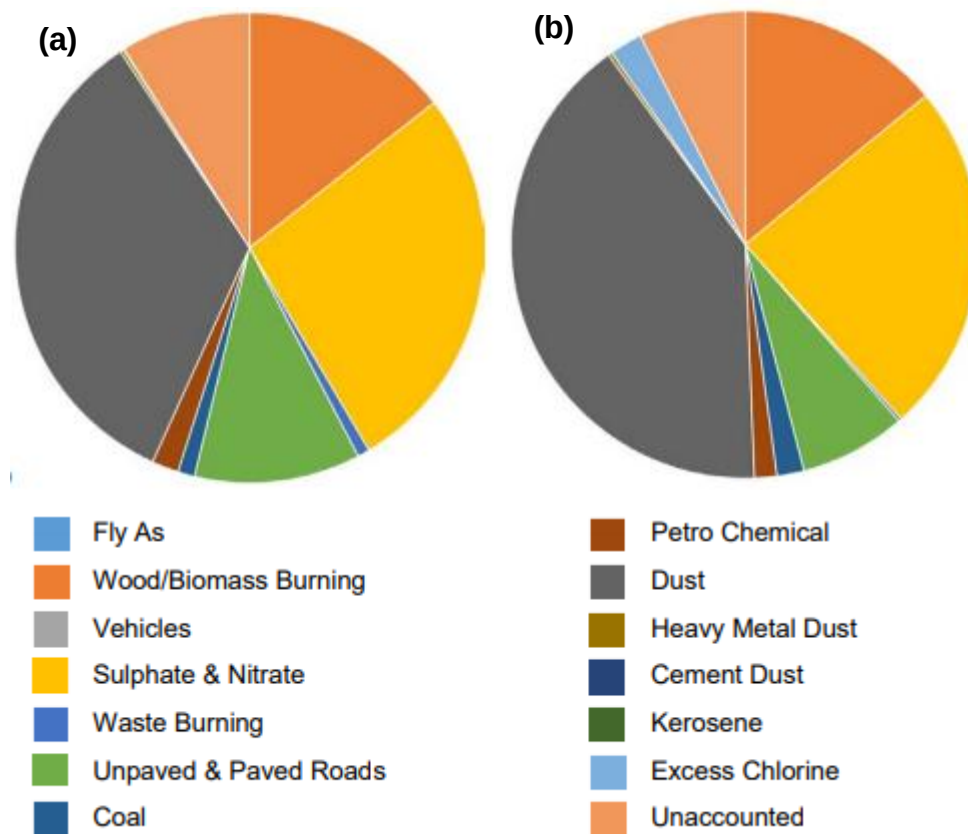


Figure 5-1: PM₁₀ sources identified in summer months during (a) the day and (b) during the night (%)

The primary PM_{2.5} source identified in the summer period during the daytime (Figure 5-2a) sampling was particles of sulphates and nitrates, accounting for 32.8% of emissions. This was followed by vehicle emissions contributing to 6.5%. Other sources of concern included waste burning (3.1%) and heavy metal dust (0.3%). The CMB model did not account for a significant fraction of the emissions (57.3%). During the night-time summer sampling (Figure 5-2b), nitrate and sulphate particles were the primary sources of PM_{2.5}, contributing to 43.3% of the emissions. Other identified significant sources included waste burning (4.0%), vehicle emissions (2.0%) and heavy metal dust (0.6%). Unaccounted sources contributed to a significant fraction (50.1%) of the night-time summer emissions.

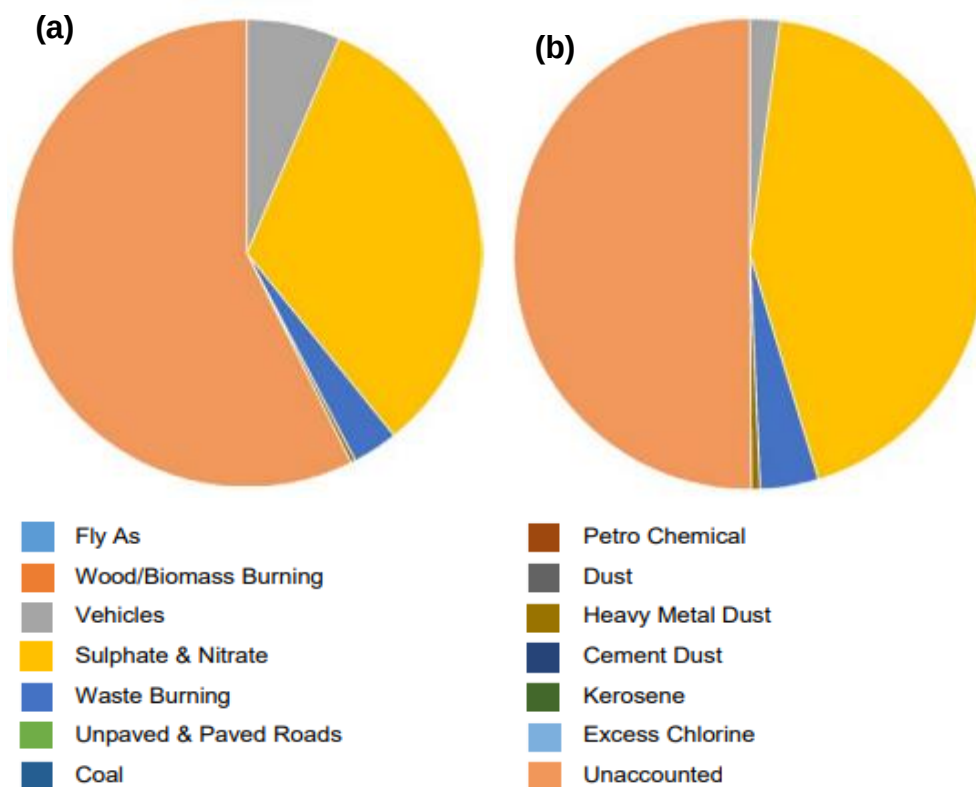


Figure 5-2: PM_{2.5} sources identified in summer months during (a) the day and (b) during the night (%)

5.2.2 Winter PM sources

The primary PM₁₀ source during the day in winter was dust, contributing to 39.2% of emissions (Figure 5-3a). Coal combustion was the second major source accounting for 17.4%. Other sources of significant concern included excess chlorine (8.3%), paved/unpaved roads (7.2%), particles of sulphates and nitrates (6.1%), waste burning (5.4%), petrochemical industry (2.1%) and heavy metal dust (0.1%). Unaccounted sources contributed to 14.12% of the total mass of the daytime PM₁₀ winter sampling emissions. During the night (Figure 5-3b), dust was the primary source of PM_{2.5}, contributing to 29.4% of the emissions. Particles of sulphate and nitrate (15.9%) were significant sources, followed by waste burning (13.2%). Other sources of concern identified included coal combustion (10.4%), vehicle emissions (7.1%), excess chlorine (4.5%), unpaved/paved roads (3.4%), fly ash (2.0%), cement dust (0.3%) and heavy metal dust (0.1%). Unaccounted sources made up 12.0% of the total mass for the nighttime winter emissions.

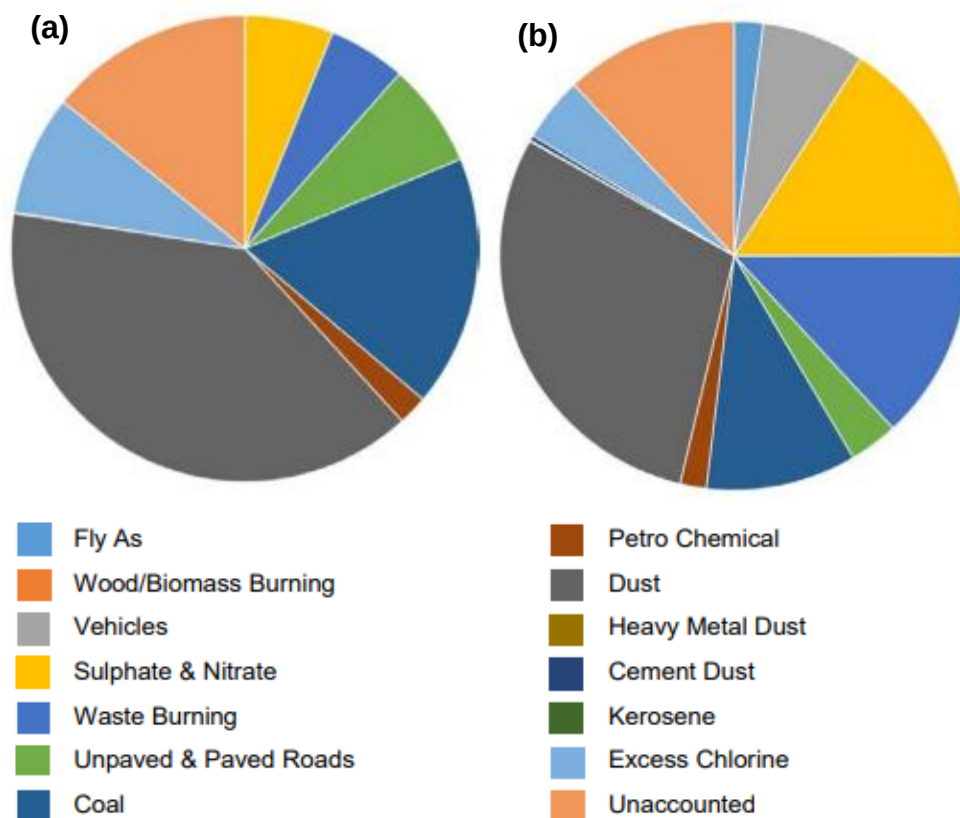


Figure 5-3: PM₁₀ sources identified in winter months during (a) the day and (b) during the night (%)

The primary PM_{2.5} source during the winter daytime sampling campaign (Figure 5-4a) was particles of sulphates and nitrates, contributing 36.1% of the emissions. Waste burning (5.9%) was another significant source, followed by vehicle emissions (1.4%). Other contributing sources identified included unpaved/paved roads (0.6%) and coal combustion (0.1%). A large fraction of the emissions (55.9%) were unaccounted for during the daytime winter campaign. Similarly, the night-time campaign (Figure 5-4b) attributes the same sources as the daytime campaign. Particles of sulphate and nitrates were the primary sources contributing to 37.9%. Waste burning (8.4%) was the second contributing source, followed by vehicle emissions (3.4%). Other contributing sources identified were unpaved/paved roads (1.6%), coal combustion (0.5%) and petrochemical emissions (0.1%). A large fraction of the emissions (48.1%) was unaccounted for during the high-time winter campaign.

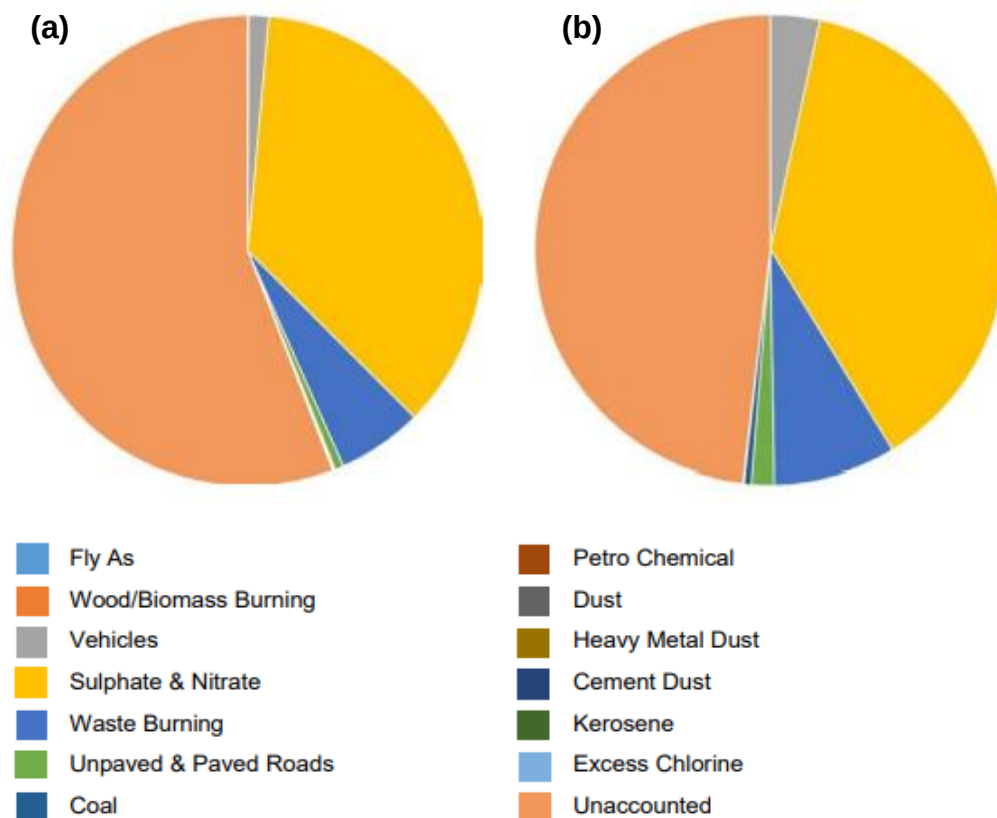


Figure 5-4: PM_{2.5} sources identified in winter months during (a) the day and (b) during the night (%)

The PCA analysis ranks the contributing sources according to their percentage. The analysis for the PM_{2.5} samples depicts seven factors (Table 5-1) for both the summer and winter campaigns. The error indicates how dominant sources vary within the township. This explains the >70% variance in the particulate composition. This implies that there are a large number of prominent sources contributing to the poor air quality in Zamdela and within the VTAPA. The source factors identified by the PCA show a remarkable similarity. The sources can be grouped as follows:

- Wood and biomass burning typically show enrichment in potassium and are important sources of oxalate and formate.
- Secondary inorganic aerosols/coal combustion. The current source profile within the CMB model does not account for the NH₄⁺ in this factor. 161
- Heavy metal industry/vehicles, identified by acetate formic acid, Cr, Fe and Ni
- Suspended dust, Si Al

Table 5-1: Identified PCA factors for PM_{2.5}

	F1	F2	F3	F4	F5	F6	F7
Summer	SO ₄ ⁺²	Formate	Acetate	P	S	Cl ⁻	

	Oxalate	Na	Ca	K	Mn	Cl	
	Na ⁺	Al	Cr	Zn			
	NH ₄ ⁺	Si	Fe				
	K ⁺	Fe					
	Mg ₂ ⁺						
	Ca ₂ ⁺						
Winter	SO ₄ ²⁻	Ca	NO ₃ ⁻				
	NH ₄ ⁺	Cr	Oxalate	Acetate	Ca ₂ ⁺	Na ⁺	Si
	Mg ₂ ⁺	Fe	K ⁺	Formate	Cl	Al	Pb
	S	Ni	K				
		Zn					

Identified sources contributing to ambient PM within the study area include industrial operations, fugitive dust, biomass burning, domestic solid fuel combustion and vehicle emissions (tailpipe and dust from roads). For this study, the focus will be on exhaust vehicle emissions. With the identification of traffic emissions as a significant source of air pollution, in addition to the source apportionment findings, it is necessary to assess the spatial and temporal variability of vehicle emissions.

5.3 Literature on traffic emissions

A previous study reported the contribution of vehicles to ambient air quality in the VTAPA (Thomas, 2009). Vehicle count data was used to assess rush hours on regional roads in the Vaal Airshed. The routes chosen represented largely congested roads within the VTAPA (N4, N1, M1, N12, N17 and N3). The diurnal patterns (Figure 5.6) indicate traffic peaks between 05h00-09h00 and 16h00-18h00. These peaks occur around the same time as the PM peaks depicted in Figure 4-4 (Chapter 4). These findings for the VTAPA are similar to numerous other reports confirming that vehicle emissions are a leading source of urban air pollution (Colville et al., 2001; DEA, 2019; Lourens, 2012; Scorgie et al., 2003; Thomas, 2009).

5.4 Site observational evidence

The Zamdela township has busy roads since it is close to the Sasol industrial plant, the town of Sasolburg and the busy Vaal Triangle. Residents commute daily to work, school and for social activities using various modes of transportation.

During the vehicle count, it was observed that the most common vehicle type is the sedan, supported by RMCT (2019) that sedans are the preferred vehicle on South African roads. In Zamdela Toyota, 'Tazz' vehicles are used as taxis. Many of these vehicles are old and not adequately maintained. Figure 5-5 illustrates different vehicle types on the roads.



Figure 5-5: Image of the traffic volume observed throughout the day in Zamdela

5.4.1 Temporal profiles

Total emissions are estimated annually (tons). However, it is important to assess the diurnal pattern of vehicular activity. This is a significant input for AERMOD. The average hourly traffic volume in Zamdela is shown in Figure 5-6. The morning and evening had the highest traffic volumes. These patterns differed for different vehicle classes. The traffic volume is represented for 12 hours (06h00-18h00); on average, the traffic volume varies depending on peak hours. Distinctively, the peak traffic flow in the morning (total, and specifically for sedans and mini-buses) is sharp, reaching a maximum of only one hour, followed by an immediate drastic drop. The total average daytime traffic flow is relatively steady at ~660 vehicles/h. The evening peak traffic is spread over two to three hours, in contrast to the concentrated one hour in the morning. The overall traffic count data show that the morning and evening peak flows correlate with the PM data in Section 4.6.

Sedans had the highest hourly vehicle count, followed by LDVs out of the classified category (Figure 5-6). The vehicle volumes are explained by data from the RTCM (2019) that most registered vehicles are motorcars and the preferred mode for private passenger transport (Goyns, 2008).

The average traffic throughout the week is shown in Figure 5-7. The daily averages are calculated from the daily (06h00-18h00) averages. Traffic flow during working days (Monday-Friday) differs significantly from weekends (Saturday and Sunday). Monday is the busiest day for all the vehicle classifications in the settlement. As explained by Sampson (2017), this is the busiest economic day of the week as people return from social activities to work. A second weekday peak is seen on Friday. Thomas (2009) found that a fair amount of the population

travels to neighbouring places for the week, for social events or to visit family. The pattern during the weekend varies considerably. There is a decrease in traffic volumes on the weekend except for sedans on Saturday. Saturday is the busiest social day of the week. Thomas (2009) explains that this is the most favourable day for shopping or leisure activities.

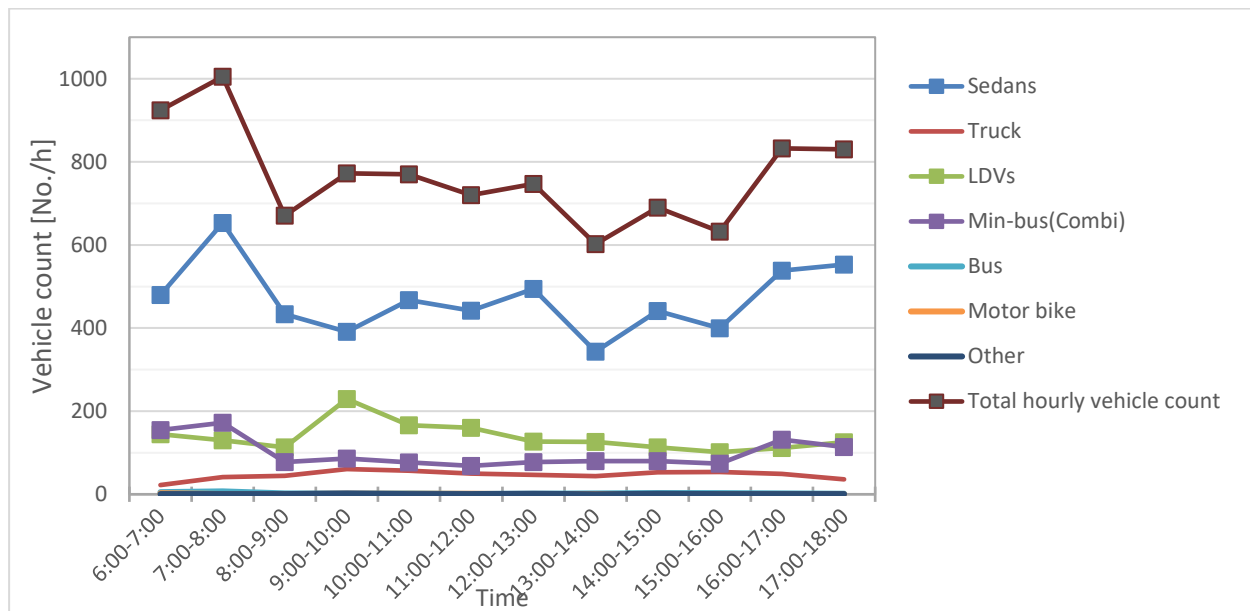


Figure 5-6: Hourly traffic volumes in Zamdela by vehicle type

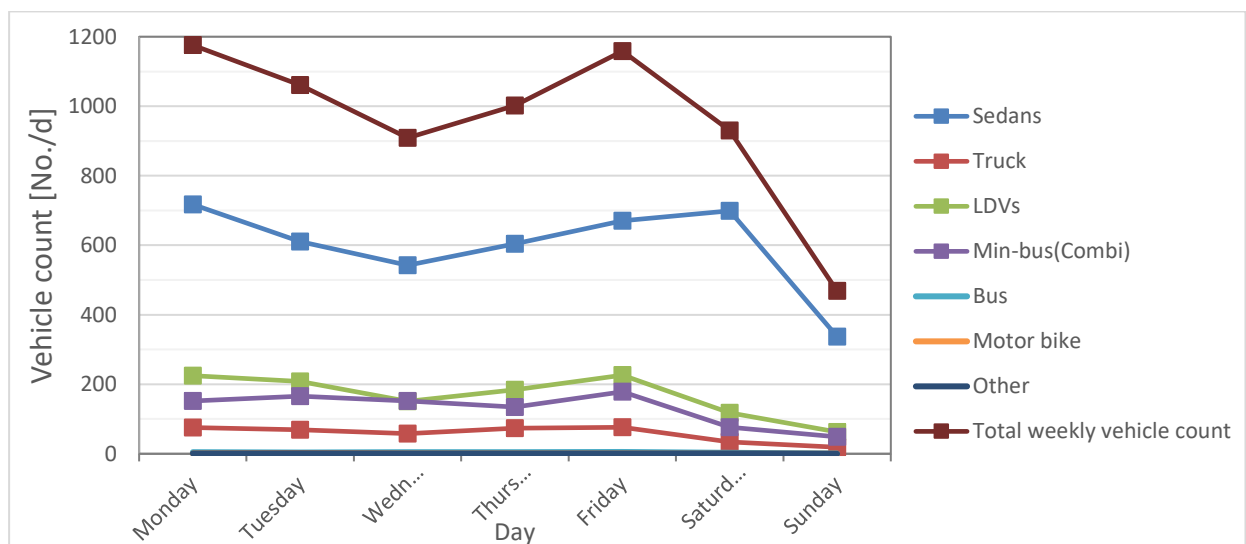


Figure 5-7: Daily traffic volumes in Zamdela by vehicle type

Monthly activity data were unavailable for this campaign; therefore, data were taken from the 2020 VTAPA AQMP. The sites are high-traffic volume sites similar to where the traffic manual count was done. Figure 5-8 illustrates the seasonal, temporal profile recorded in Zamdela. There is a peak in April for HDVs and LDVs, explained by road congestion caused by the Easter break as people travel to homesteads and for religious purposes. An increase during

December for LDVs is observed. This month is the most congested, as explained by the RMTC that people travel for leisure, resulting in high traffic volumes during the festive month.

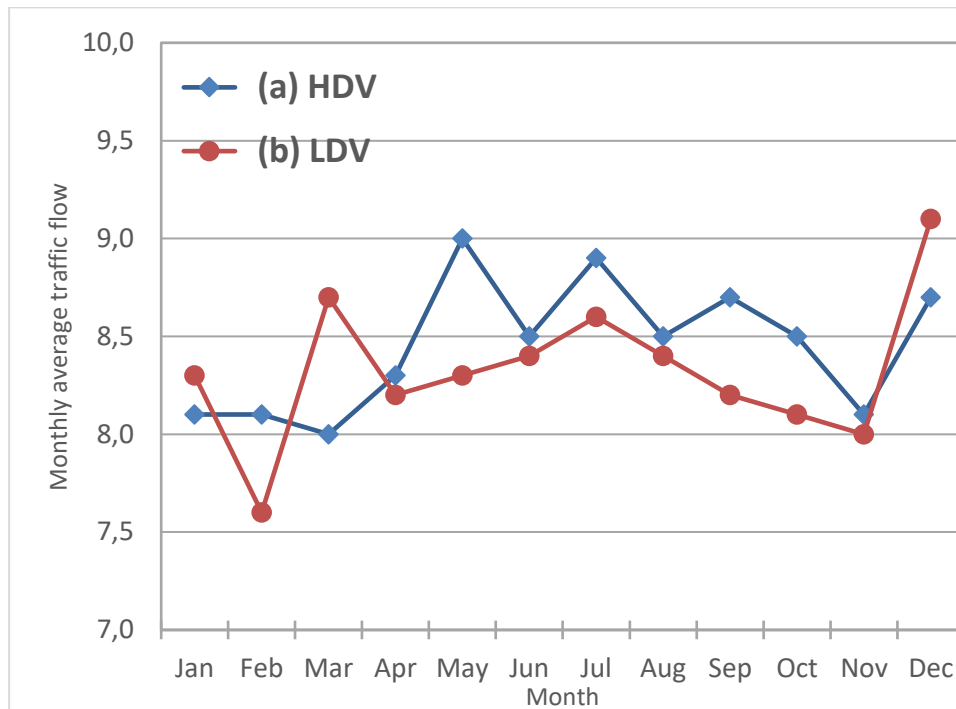


Figure 5-8: Monthly traffic flows in Zamdela showing (a) HDV and (b) LDV

5.4.2 Emission inventory for vehicles

Exhaust emissions from vehicles are identified as a significant source of ambient PM. However, there are no ambient air quality regulations specifically to manage vehicular emissions. Thus, South Africa uses the NAAQS regulations to enforce the contribution of vehicles to ambient air quality. A detailed emissions inventory and dispersion models are required for these regulatory assessments. This is important because of the widespread atmospheric dispersion of vehicular emissions spatially.

Assessing the impact of air pollution sources on ambient air quality is of utmost importance. One of the most efficient methods is developing an emissions inventory within a geographic area. An emission inventory includes emission estimates from a particular source using data from monitoring stations and emission factors. Henceforth, activity rate information can be determined by providing representative macro-emission information (US EPA, 2017; Wang et al., 2020). The data are an essential input in dispersion models such as AERMOD.

For this study, emission rates were estimated using EEA (2019), Thomas (2009) and Colville et al. (2001). These emission calculations are a realistic representation of a densely populated low-income area within South Africa. The emission rates per vehicle classification were based

on representative emission factor values and traffic flow, which were calculated using the manual count data. The Lj (road length) calculations were estimated using the road lengths given on the GIS road data.

5.4.3 Emission calculation per classification

A summary of the contribution of PM_{2.5} and PM₁₀ emissions from different vehicle classes is shown in Table 5-2. Vehicle emissions in Zamdela are one of the most significant sources, confirming the findings of Thomas (2009) and DEA (2019). As anticipated, sedans have the highest PM_{2.5} and PM₁₀ estimates as it has a high traffic volume. This is understandable because of the surge in private vehicles within the country and the settlement. This is because of the unreliability of public transport, whereby people resort to using their private cars to commute and using sedans as public transportation.

Table 5-2: Estimated emission rates per vehicle type in Zamdela

	PM _{2.5} (t/a)	PM ₁₀ (t/a)
Sedans	10.02	18.69
Trucks	4.09	7.64
LDVs	4.77	8.80
Mini-buses	3.43	6.33
Bus	0.22	0.42
Motorbikes	0.01	0.01
Other	0.05	0.11
Total	22.59	42.00

5.4.4 Spatial distribution of vehicle emissions

Figure 5-9 and Figure 5-10 show the estimated annual spatial distribution of PM exhaust emissions in Zamdela. The spatial distributions were calculated based on the vehicle count data, road length and emission rate estimates. The spatial distribution estimates range from 0.000556 t/a to 0.360 t/a (PM_{2.5}) and 0.00103 t/a to 0.67 t/a (PM₁₀).

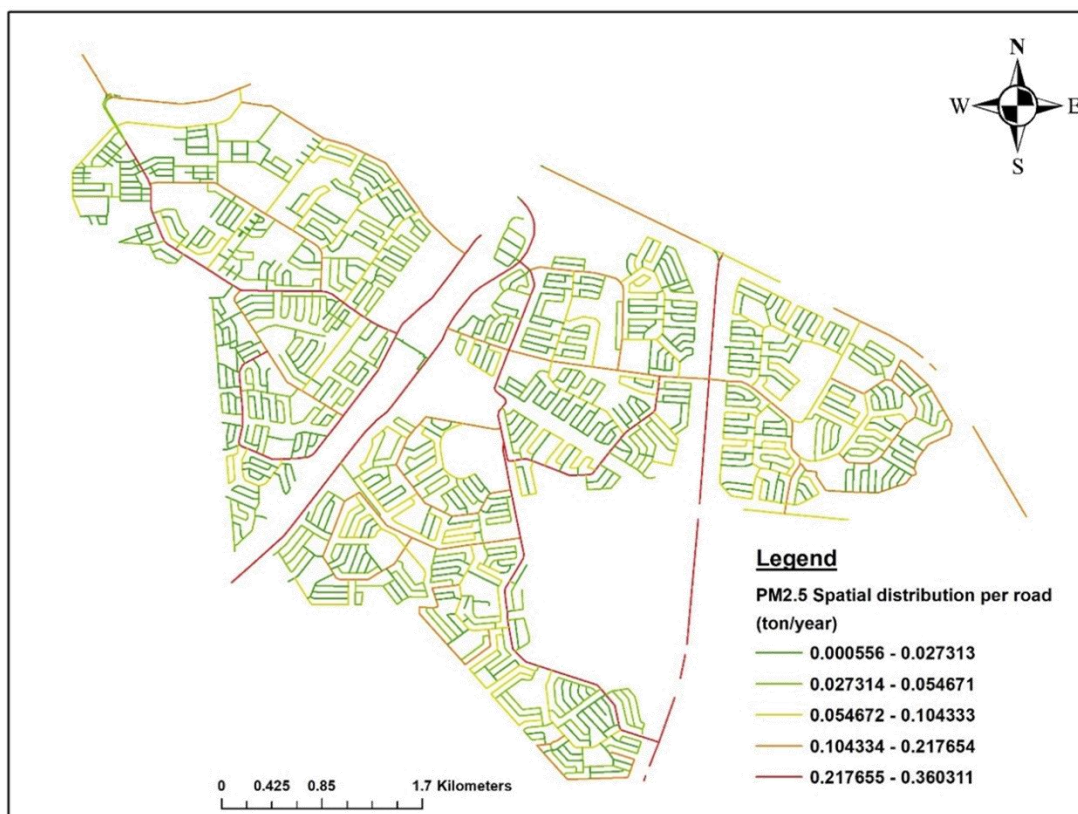


Figure 5-9: Spatial distribution of vehicle tailpipe PM_{2.5} over Zamdela

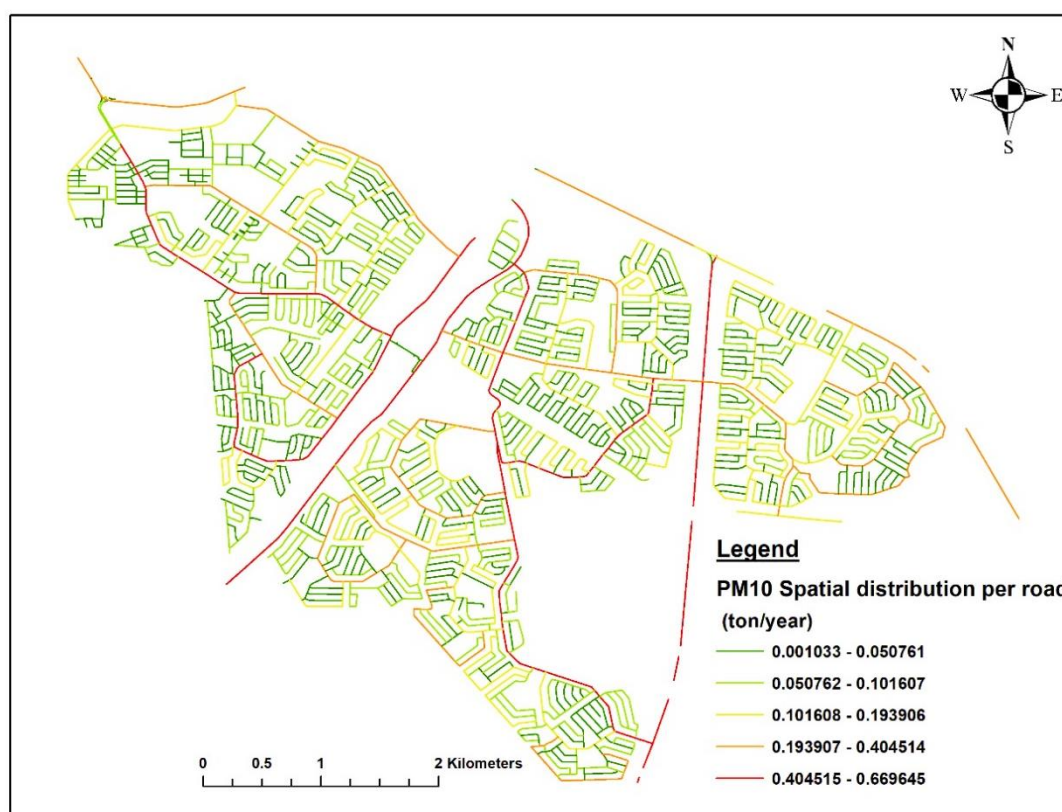


Figure 5-10: Spatial distribution of vehicle tailpipe PM₁₀ over Zamdela

5.4.5 The relationship between traffic flow and PM peaks

Figure 5-11 depicts the hourly diurnal variation of the traffic flow in Zamdela. Since the manual traffic count data was done only from 06:00-18:00, the volume between 18:00-06:00 was assumed using recently available data from the VTAPA report (2018). The peaks identified in the traffic flow data align with the PM peaks observed in the monitored data (Figure 4-4). Both data sets have similar diurnal variations, with peaks in the morning (06:00-10:00) and evening hours (16:00-19:00). These are the hours affected by road congestion when people travel from work, school and other activities.

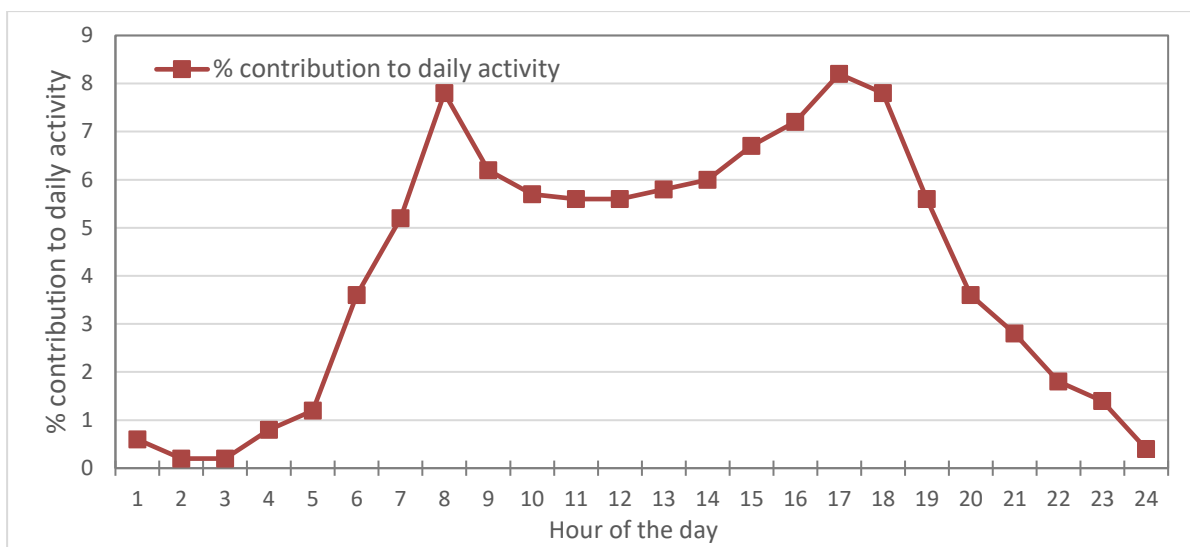


Figure 5-11: Hourly diurnal traffic flow in Zamdela

5.5 Conclusion

This chapter highlights the results and discussion for objective 2. The contribution of vehicle emissions to ambient PM was quantified. The source apportionment results show that vehicles significantly contribute to PM emissions in Zamdela. Statistical analysis, site observations, and temporal and spatial analysis support this. Furthermore, an emissions inventory was developed to estimate the contribution of traffic emissions to the ambient PM. It is concluded that sedans had the highest contribution, explained by the surge in sales of private transportation over the years. Thus, the traffic flow peaks coincide with the PM peaks observed in the ambient data.

CHAPTER 6: MODELLING VEHICLE EMISSIONS USING AERMOD

This chapter presents the simulated results to determine the vehicular contribution to particulate matter concentrations within Zamdela. Daily and annual averaging period isopleths plots were modelled over 2019 – 2021. Hourly average concentrations were modelled at discrete locations to represent the spatial variability of emissions within Zamdela. The modelled average concentration was used to compare with the monitored data to assess the contribution of vehicle emissions to ambient PM in Zamdela.

6.1 Introduction

The contribution of vehicle emissions to ambient PM was modelled in Zamdela over the period 2019 - 2021. The vehicles were classified into sedans, LDV's, mini-buses, trucks, buses and motorbikes. For each vehicle category, emission factors were determined. AERMOD was used to model the contribution and distribution of vehicle emissions to the overall ambient air quality within the settlement. Isopleth plots for hourly and daily concentrations were stimulated according to the NAAQS.

6.2 Modelled results

Modelled annual and daily PM_{2.5} concentrations attributed to vehicle emissions in Zamdela are illustrated in Figure 6-1 and Figure 6-2. The predicted annual concentrations are low over most of the project area modelled. The annual concentrations range between 0.1 µg/m³ - 12.1 µg/m³, which complies with the annual 20 µg/m³ NAAQS standards over the entire township. The daily concentrations range between 23 µg/m³ - 237 µg/m³ with the maximum exceeding the 40 µg/m³ NAAQS standards. It is important to consider that although high maximum daily concentrations are predicted in Zamdela, it is possible for it to be true for one day for the monitoring period. As such the model predicts that on extreme days, daily averages can range from 40 µg/m³ – 237 µg/m³ that exceeds the NAAQS standards. This however is seen over most of the township with high concentrations predicted in the middle of the settlement. Vehicle emissions can be attributed to the daily exceedances recorded in Zamdela.

Modelled annual and daily PM₁₀ concentrations in Zamdela attributed to vehicle emissions are illustrated in Figure 6-3 and Figure 6-4 , respectively. The predicted average contributions are below the NAAQS annual (40 µg/m³) and daily (75 µg/m³) standards over the entire township. The simulated averages range from 0.07 µg/m³ - 6.78 µg/m³ (annual) and 0.99 µg/m³ - 38.3 µg/m³ (daily).

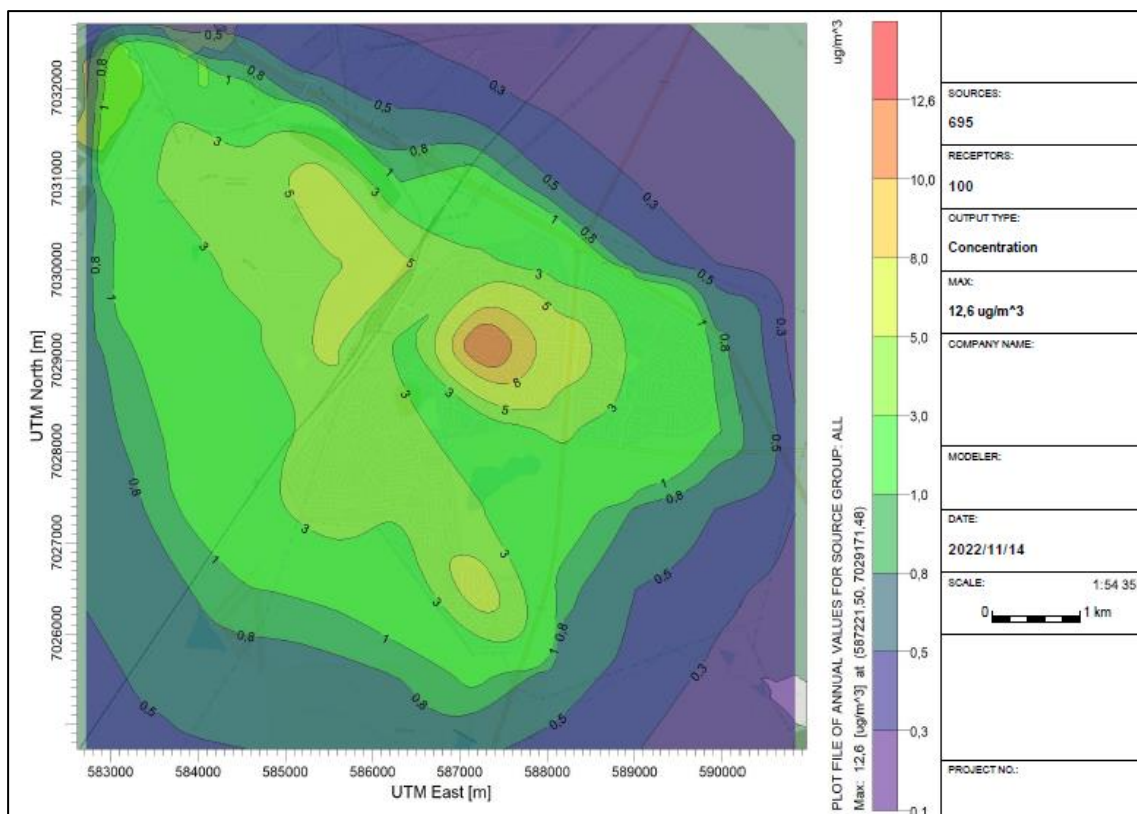


Figure 6-1: Predicted annual PM_{2.5} maximum concentrations for vehicular emissions in Zamdela

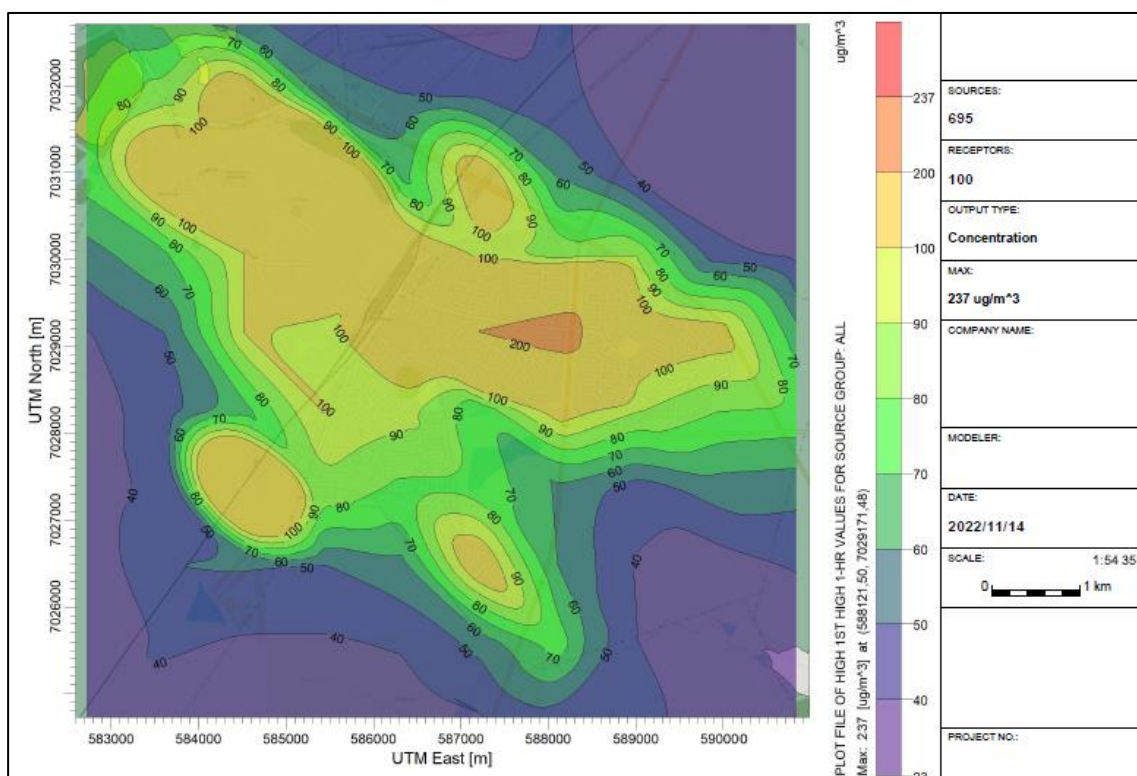


Figure 6-2: Predicted daily PM_{2.5} maximum concentrations for vehicle emissions in Zamdela

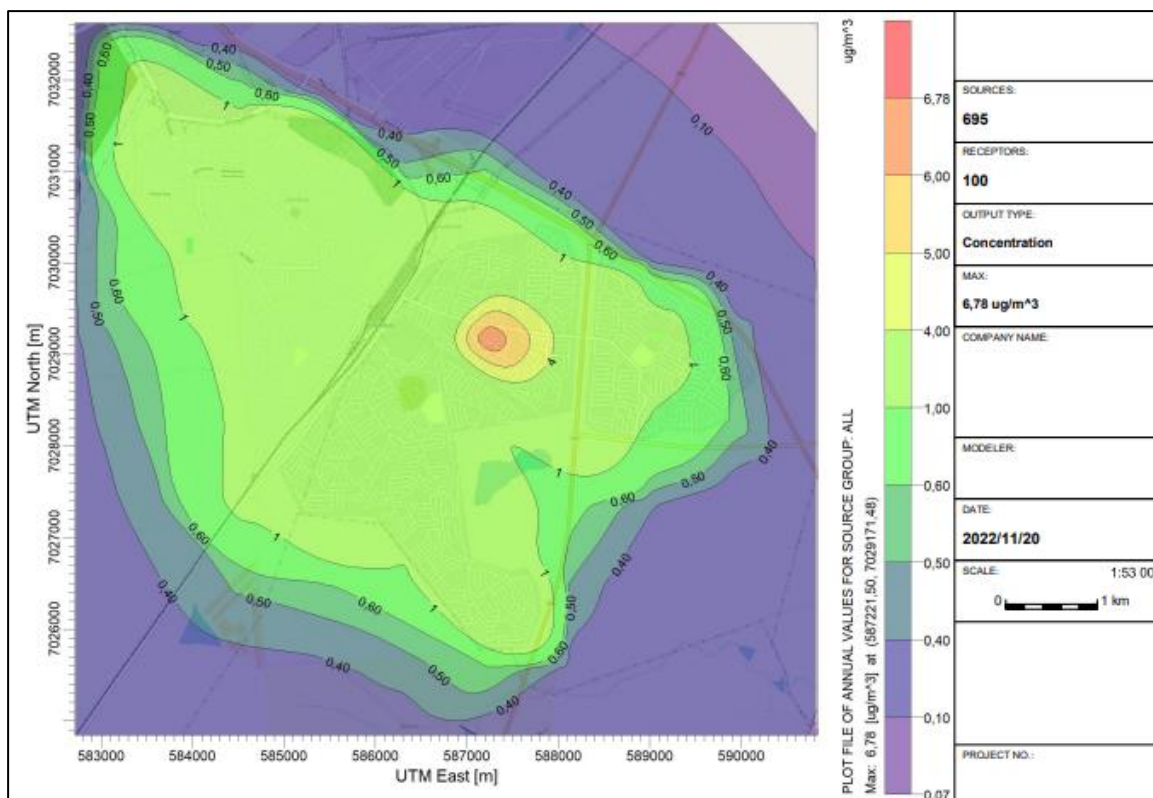


Figure 6-3: Predicted annual PM₁₀ maximum concentrations for vehicle emissions in Zamdela

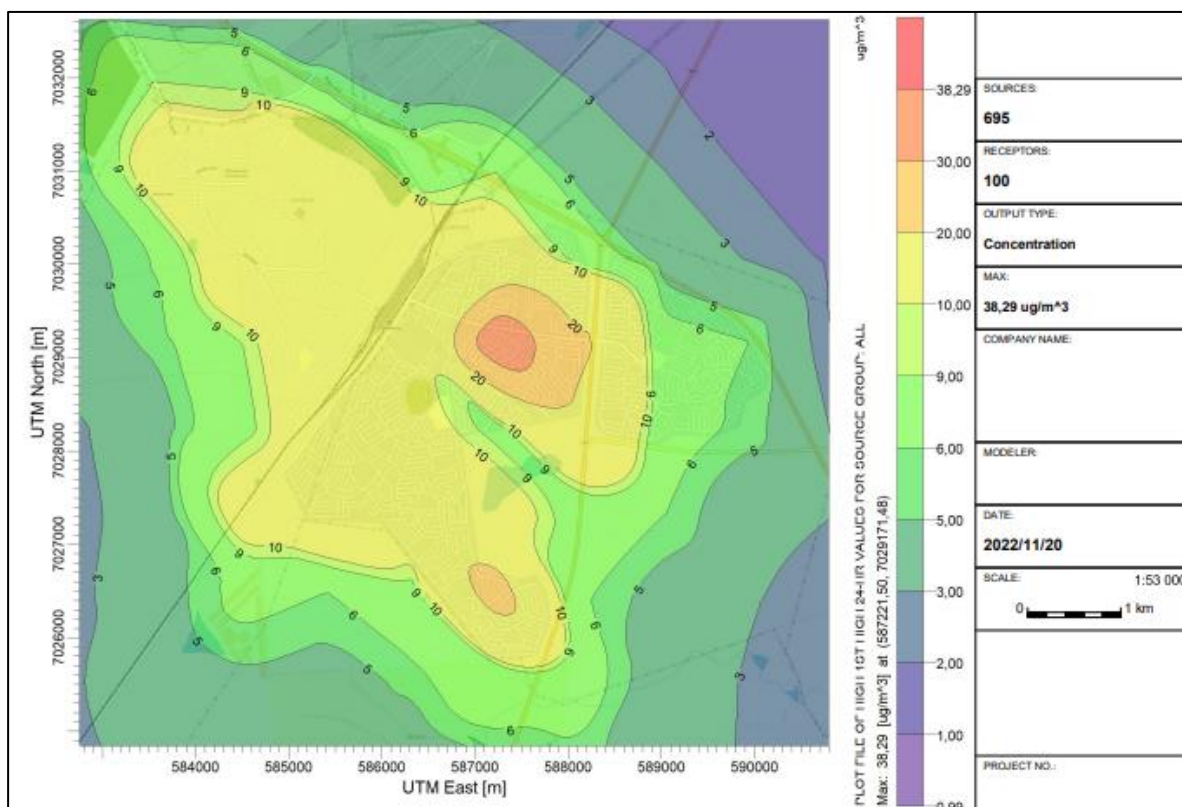


Figure 6-4: Predicted daily PM₁₀ maximum concentrations for vehicle emissions in Zamdela

Discrete receptors are important to represent the spatial distribution of emissions as recommended by the DEA (2014). Figure 6-5 represents the spatial distribution points of the modelled average PM concentrations attributed to vehicle emissions in Zamdela. These points are located at the centre of identified public areas (schools) to determine possible concentrations that could be expected near receptors. Discrete receptors are not plotted for each sensitive receptor but represent a group of sensitive receptors close to each other.

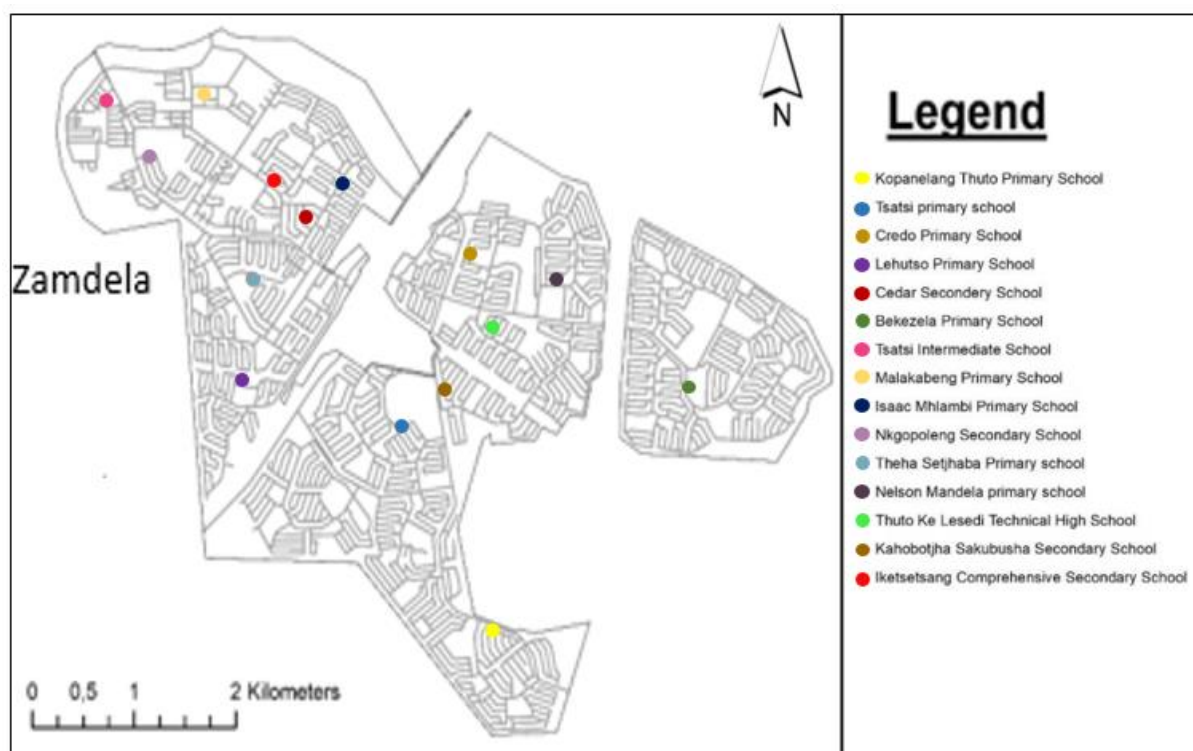


Figure 6-5: Location of discrete receptors identified within Zamdela

Discrete receptors in Table 6-1 were identified during a desktop study to represent the spatial distribution of the modelled concentrations as recommended by the DEA (2014). The spatial distribution of the modelled contribution of vehicle emissions to the ambient PM varies in Zamdela, as demonstrated by Moletsane (2021). The highest predicted concentrations are predicted at Credo Primary School and Theha Setjhaba Primary School. The two schools are embedded within the township where maximum modelled concentrations are predicted.

Table 6-1: Average modelled concentrations for discrete receptors in Zamdela

Discrete receptor	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)	Latitude	Longitude
Kopanelang Thuto Primary School	8.55	3.91	-26.8527	27.8543
Tsatsi Primary School	2.22	1.22	-26.8660	27.8692
Credo Primary School	17.72	6.16	-26.8508	27.8774

Lehutso Primary School	2.40	1.14	-26.8616	27.8558
Cedar Secondary School	2.32	1.24	-26.8427	27.8600
Bekezela Primary School	2.32	1.16	-26.8584	27.8949
Tsatsi Intermediate School	2.20	1.16	-26.8404	27.8423
Malakabeng Primary School	1.97	1.02	-26.8383	27.8485
Isaac Mhlambi Primary School	4.47	2.22	-26.8460	27.8623
Nkgopoleng Secondary School	2.13	1.22	-26.8437	27.8454
Theha Setjhaba Primary School	10.05	4.84	-26.8530	27.8556
Nelson Mandela Primary School	5.31	2.68	-26.8510	27.8773
Thuto Ke Lesedi Technical High School	2.31	1.27	-26.8563	27.8746
Kahobotjha Sakubusha Secondary School	1.79	1.09	-26.8638	27.8723
Iketsetsang Comprehensive Secondary School	4.06	1.83	-26.8455	27.8553

6.3 Validation of the modelled results

Table 6-2 illustrates the contribution of modelled vehicle emission concentrations to the monitored PM concentrations in Zamdela. Average monitored and modelled concentrations over the monitoring period were used to calculate the average PM concentrations. Vehicle emissions contribute to PM emissions and to the NAAQS exceedances recorded in the township. Daily modelled PM_{2.5} concentrations attributed to vehicle emissions significantly and contribute 26% of the total ambient concentrations. Firstly, this is supported by source apportionment studies in Section 5.2.1 that prove that daily vehicle emissions are a leading ground-level source within Zamdela. Secondly, a study by Chidhindi (2022) proves that vehicle emissions contribute to 25% of ground level sources in Zamdela. Thomas (2010) proves that vehicle emissions are one of the important sources that contribute to ambient PM in low-income settlements within the VTAPA. Lastly, daily traffic peaks coincide with PM peaks, as demonstrated in Section 4.6.

Table 6-2: The average contribution of modelled vehicle emissions concentrations to the monitored PM concentrations

			Daily (µg/m ³)	Annual (µg/m ³)
Zamdela	PM _{2.5}	Monitored	180	69
		Modelled	47.04	4.64
		Vehicle contribution (%)	26.13	6.72
	PM ₁₀	Monitored	208	102
		Modelled	13.05	2.14

	Vehicle contribution (%)	6.26	2.10
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Normalised diurnal variations of pollutants help identify possible contributing sources in a given area (Carslaw, 2012). The normalised diurnal, monthly and weekly 1-hour averages for PM in Zamdela were analysed to determine contributing sources to support modelled results.

The diurnal variation (Figure 6-6) depicts peaks between 06h00-09h00 and the evening at 16h00-21h00. These peaks are attributed to domestic solid fuel combustion and vehicular emissions as these are the times people go to or from work, school and other activities. Traffic volumes are high during these hours, coinciding with township domestic combustion (cooking and heating). The monthly variations show that winter months have the highest ambient concentrations. These are affiliated with increased combustion activities due to lower temperatures and less dispersion of atmospheric pollutants during winter. The weekday trend shows an elevated concentration during the weekday and a decrease during the weekend. A reduction in the weekend is explained by less vehicular activity (fewer people going to work and school).

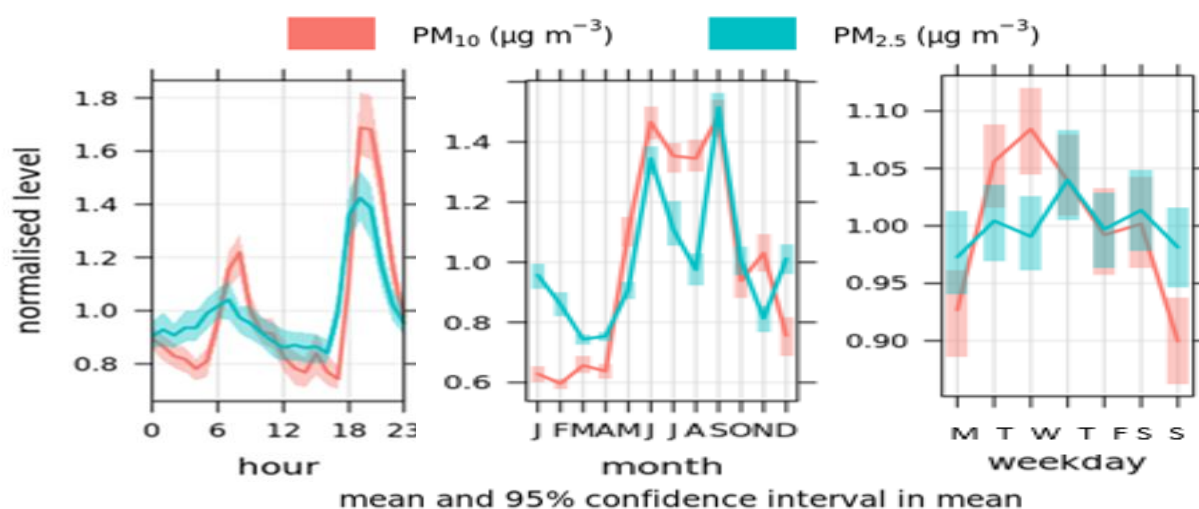


Figure 6-6: Normalised PM concentrations in Zamdela from 2019-2021 diurnal, seasonal and day-of-week averages

6.4 Conclusion

The contribution of vehicle emissions to PM emissions is assessed using AERMOD. There is a spatial variation in concentrations within the township. Maximum predicted concentrations depict that vehicle emissions contribute to ambient PM concentrations, with daily $PM_{2.5}$ showing a significant contribution. Vehicle concentrations coincide with monitored ambient daily concentrations depicted during morning and evening peaks. Even though the focus was solely on vehicle emissions, it is essential to note that domestic fuel combustion coincides with

traffic fleet morning and evening PM peaks. Both sources should be consistently monitored to assess the ambient air quality and develop air quality management plans within Zamdela.

CHAPTER 7: CONCLUSION

This chapter provided a conclusion of the analyses and findings of the study. An overall conclusion is highlighted by answering the research question, “What is the contribution of vehicle emissions to ambient PM in Zamdela?”

7.1 Introduction

The spatial planning in previously disadvantaged townships is confined to residents living on the urban periphery. Large industries are usually in proximity to low-income areas in the VTAPA. This is often presumed to accommodate low-income residents without spending too much on transportation fares. Travelling outside the outskirts of the settlement and longer distances has increased the demand for private and public transportation. Trains are poorly operated, and buses are unreliable, which has helped spawn greater use of private vehicles and the minibus taxi industry. However, the informal sector taxi industry provides an extensive vehicle population, which is poorly unregulated. Considering the growing informal public transportation alongside other certified vehicles, emissions are inevitably expected to increase. This is a significant problem, considering how traffic emissions are synonymous with air pollution. Some challenges concerning traffic emissions are poorly maintained vehicles, continued distribution of high-sulphur diesel fuel, lack of vehicle emission controls and ineffective laws for vehicle emissions.

Industrial, domestic solid fuel burning, commercial activities and vehicle emissions impact the study area's air quality. However, there is still little information focusing on just vehicle emissions compared to the other sources. The gap in the findings creates a need to consistently regulate and monitor the contribution of vehicle emissions to ambient air quality. Therefore, the study aimed to assess the impact of vehicle emissions on PM concentrations in Zamdela. The primary focus is on PM because it was found to be the most problematic pollutant in Zamdela and other densely populated settlements. Firstly, the ambient concentrations were analysed. Secondly, a source apportionment profile was used to determine problematic sources. This was followed by vehicle temporal and spatial variability to quantify PM by estimating the emission rate. Lastly, the contribution of vehicle emissions was modelled, and the results were compared to the monitored data.

7.2 Ambient concentrations in Zamdela

The ambient air quality in a dense low-income settlement on the South African Highveld was assessed from 2019 to 2021. The results depict that PM is a pollutant of concern in Zamdela.

The NAAQS for PM were exceeded throughout the sampling campaign. There were 284 exceedances for PM_{2.5} and 348 for PM₁₀. This is problematic since only four exceedances per year of the 24-hour limit are deemed acceptable. Poor air quality was experienced in the autumn and winter and during the morning (06h00-10h00) and evening peaks (17h00-21h00). The measured diurnal PM peaks coincide with domestic solid fuel combustion and peak vehicle emission. The winter seasonal peaks are associated with increased domestic solid fuel combustion and biomass burning. Other identified sources include windblown fugitive dust (especially in August). As much as these sources are the primary reason for elevated ambient PM concentrations, meteorology is a factor influencing atmospheric pollution levels.

Meteorological parameters have an inversely proportional relationship with PM concentrations. Lower wind speeds and minimum temperatures recorded in the morning and evening resulted in elevated PM concentrations. The stable conditions cause calm atmospheric conditions. Therefore, pollutants (PM) have a longer lifespan and cannot disperse. Conversely, ambient PM concentrations decrease when higher wind speeds, less rainfall and maximum ambient temperatures occur during the day. This happens due to unstable atmospheric conditions resulting in enhanced dispersion of PM.

Therefore, favourable meteorological conditions alongside local sources that are not easily regulated, such as domestic fuel burning, vehicle emissions, biomass burning and wind-blown dust are among the contributors to the poor air quality in Zamdela.

7.3 Contribution of vehicle emissions to the ambient PM in Zamdela

At Zamdela, the fine-to-coarse fraction ratio demonstrates a clear fractionation, with Na, Al, Si, P, K, Ca and Ti having the highest concentrations in the coarse fraction regardless of the time of day and season. The remainder of the metallic elements, namely, V, Cr, Fe Ni Cu, Zn and Pb, have fine to coarse fraction ratios above one, indicating that these elements primarily occur in the fine fraction in both seasons.

A source apportionment analysis demonstrates that multiple anthropogenic sources contribute to ambient PM in Zamdela. Identified sources include fly ash, biomass burning, sulphates and nitrates, waste burning, coal, petrochemical, heavy metal dust, cement dust, kerosene, excess chlorine, dust, paved & unpaved roads and vehicle emissions. The Principal Components Analysis (PCA) analysis shows that vehicles are a major identified source within the settlement. Motor vehicle element Pb was higher in the fine fraction at Zamdela during the day and night in all seasons.

7.4 Traffic fleet in Zamdela

A manual vehicle count was conducted for a week by classifying vehicles in Zamdela. The results depict a large volume of vehicles travelling on the roads of Zamdela. The township is located on the urban periphery of Sasolburg and in proximity to the SASOL plant and other heavy industries. Residents must travel outside the township to work, school, or other social/personal activities.

Given the above factors, there is a high daily volume of private and public vehicles on the roads of Zamdela. Residents from surrounding areas travel to work using private vehicles or minibus taxis. In Zamdela, sedans are used as 'taxis'. However, these unregulated vehicles are not well maintained. With the proximity of industries (Sasol) to Zamdela, trucks and large abnormal vehicles transport chemicals in and out of the plant throughout the day. These heavy vehicles use diesel fuel which is problematic in terms of emissions. Consequently, considering all these vehicles travelling daily, exhaust emissions on the roads of Zamdela increase during the day.

7.5 Vehicle emissions as a contributing source of PM

The diurnal series shows that overall, there are three distinctive traffic volume peaks each day in Zamdela. The morning peak (06h00-10h00) and evening peak (16h00-18h00) are only recorded for sedans and LDVs. These are the times that people travel to and from work, school and other personal/social activities. Sedans and LDVs are the most popular vehicle classes. The dependence of private and public transport within the settlement explains this. Furthermore, the prominent traffic volume peaks correlate to the PM peaks. Vehicle emissions from the traffic volume during the day are well-dispersed in the atmosphere. These observations support the literature (Batterman et al., 2014; Chidindi et al., 2019; Karagulian et al., 2015; Language et al., 2016), ambient data and source apportionment evidence that vehicles influence PM concentrations in Zamdela.

7.6 Emissions inventory for vehicle emissions in Zamdela

Emission rates were calculated per vehicle classification in Zamdela using relevant EPA emission factors. The estimates show that of the vehicles travelling on the road, sedans have the most impact on both PM₁₀ and PM_{2.5}. This is because sedans are the preferred transportation mode within the township. With limited public transport, people have little choice but to opt for private vehicles. Additionally, sedans are used as informal public transport - most of them are old Toyota Tazz models that are poorly maintained as observed during the traffic count sampling campaign.

7.7 Modelled results

The contribution of vehicle emissions to ambient PM was modelled in Zamdela using AERMOD. The modelled isopleths indicate that vehicle emissions do contribute to the ambient PM in Zamdela. The predicted annual and daily PM₁₀ contributions are below the NAAQS annual (40 µg/m³) and daily (75 µg/m³) standard across the township. The modelled isopleths show a range between of 0.07 µg/m³ - 6.78 µg/m³ for the annual average and 0.99 µg/m³ - 38.3 µg/m³ daily average. The modelled annual PM_{2.5} attributed to vehicle emissions are between 0.1 µg/m³ - 12.1 µg/m³ which complies with the annual 20 µg/m³ NAAQS standards. The daily average range from 23 µg/m³ – 237 µg/m³ and exceeds the 40 µg/m³ standards over most of the township and on extreme days, averages can range from 40 µg/m³ – 237 µg/m³. It is important to consider that although high maximum daily concentrations are predicted in Zamdela, it is possible for it to be true for one day for the monitoring period. Vehicle emissions contribute significantly to PM_{2.5} and thus needs to be consistently modelled and monitored.

The modelled results compared to the monitored results prove that vehicle emissions are one of the sources contributing to the recorded PM exceedances in Zamdela. PM_{2.5} modelled concentrations contribute a significant 26% of the total concentrations as supported by source apportionment studies that prove that daily vehicle emissions are a leading ground-level source within Zamdela.

The modelled concentrations are spatially distributed across the township. Even though the study only focused on vehicular emissions, it is essential to highlight that domestic fuel combustion morning and evening PM peak hours coincide with traffic emission peaks. Both sources can be identified as pollutants of concern in Zamdela.

7.8 Assumptions and limitations

The following were the assumptions and limitations made in the study:

- i. Traffic count data were collected at one location, assuming the data represented the whole township. However, the road was chosen because it is a major entry and exit point for the settlement.
- ii. The ambient air monitoring station is embedded in the township and measures all sources, not just vehicle emissions. Thus, a source apportionment was necessary to estimate the contribution of traffic emissions to the overall monitored data.
- iii. Rainfall meteorological data was not presented due to low data availability. Therefore, literature studies are used to explain the influence of precipitation on atmospheric pollutants.

- iv. Traffic count sampling was conducted before the COVID 19 restrictions. Therefore, traffic flow during the COVID19 restrictions was not accounted for.
- v. AERMET does not account for wind speeds <1 m/s. Therefore, wind winds below that are not included in the model.

7.9 Recommendations - Reliable public transport

There is a lack of safe, reliable and accessible public transport; hence there is a large population of unregulated amenities in Zamdela. To ensure that inclusive public transport is provided for residents, minibus taxis, trains and buses should be provided for the community.

(i) Taxis are a popular form of transportation in most townships. They are flexible and convenient for most commuters. (ii) Buses provide a safer, more economical and more efficient service than taxis. (iii) Trains are the most efficient way for many people to travel while reaching longer distances. They are also cost-efficient; however, they only operate during certain hours of the day. This way, people can travel together in larger numbers. This would reduce the road traffic fleet, possibly reducing on-road emissions. However, these amenities will have to be regulated and serviced regularly.

This will help future management plans and provide data on continuous monitoring in densely populated low-income settlements in South Africa. Management strategies will identify the importance of active mitigation measures in place.

7.10 Overall conclusion

Overall, the results depict that vehicle emissions are a noteworthy contributor to ambient PM in Zamdela. However, it is challenging to estimate vehicle emissions because of environmental and atmospheric complexities. These include emission factor estimations and other sources (domestic fuel combustion) that coincide with vehicle emission peaks within the township. Nevertheless, AERMOD can be used to estimate the contribution of vehicle emissions within low-income settlements. The findings show that the estimated contribution of vehicle emissions to ambient PM is significant, particularly PM_{2.5}. Therefore, there is a need to account for vehicle emissions as much as emissions from industries and domestic solid fuel combustion when devising air quality improvement plans.

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