Research article
The impact of vehicle parameters on non-exhaust traffic road PM$_{10}$ emissions: A case in South African low-income settlement

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Abstract

About 70% of the roads in low-income settlements are unpaved and close (≤15m) to the residences, thus a major source of ambient and indoor PM$_{10}$ concentrations. International studies have suggested that decreasing vehicle speed and managing vehicle type on paved or unpaved roads can reduce vehicle dust emissions. These mitigation strategies should be examined before being adopted and gazetted into the South African air quality management plan. This study aimed to characterise roads and traffic, emphasising determining the impact of vehicle type on PM$_{10}$ emissions. GIS was used to determine the proportion of paved and unpaved roads. A traffic counter was used to monitor vehicles and to determine traffic composition, diurnal cycles, and average speed per road type. Field campaigns (summer; 6 days; 15 hrs per day) were carried out in Bokamoso to monitor on-road vehicle PM$_{10}$ concentration using a TSI DustTrak DRX® real-time optical aerosol counter. The Box Model method quantifies vehicle PM$_{10}$ emission factors for heavy-duty, medium-duty, and motor vehicles. About 0.88 km of road within Bokamoso is paved with a daily traffic volume of >2000, and 3.6 km is unpaved with >250 daily traffic volume. Paved road heavy-duty vehicle non-exhaust PM$_{10}$ emissions reported a positive medium to strong coefficient of determination to vehicle speed increase with a coefficient of determination of 0.59. Even though there is a positive coefficient of determination between heavy-duty vehicle non-exhaust PM$_{10}$ emission factors and speed on unpaved roads, it is weak (0.2) due to low and less variable vehicle speed. Motor vehicle paved and unpaved road non-exhaust emission factors showed no significant coefficient of determination with increased vehicle speed. Paved road non-exhaust emission factors were not significantly variable with vehicle type. They ranged between an average of 0.15-0.18 g/km/h, with motor vehicles reporting an average of 0.18 g/km/h while heavy-duty vehicles reported an average of 0.15 g/km/h. On the contrary, unpaved road non-exhaust traffic PM$_{10}$ emissions ranged between 0.16-0.3 g/km/h. The emission factors presented may be used to model vehicle traffic emissions, improve on-road vehicle dust emissions impact assessment and as a guide when deciding on local applicable road dust mitigation strategies.

Keywords

Vehicle dust emissions, mitigation strategies, PM$_{10}$, paved-unpaved roads

Introduction

Traffic re-suspended road dust comprises loose soil particles released by moving vehicle friction on paved or unpaved roads. Road emissions can be line sources when a single vehicle travels over a distance or continuous line sources when many closely packed vehicles are moving on the road (Alshetty & Shiva Nagendra, 2021). Jones (2000) estimated vehicle dust (PM$_{10}$) emission per vehicle from the unpaved road to be 0.534 kg/vehicle km, with varying chemical compositions depending on the road soil type. Peaks in traffic activity are between 05:00-09:00, 13:00-14:00 and 17:00 to 21:00 (Nkomo,2018). Traffic peaks result in hourly road dust emission episodes within low-income residential areas. A study characterising respirable indoor particulate matter in South African low-income settlements reported traces of road dust inside residents' homes (Language, 2020). Crustal soil was a major contributor to the total indoor respirable PM, accounting for 34-45% in Agincourt, 13-16% in Giyani, 32-55% in KwaZamokuhle, 9% in kwaDela, and about 25% in Joubertin (Language, 2020). PM from local sources such as construction work, vehicles re-suspended from unpaved roads and regionally transported aerosols were reported to contribute between 19 to 65% to the total ambient fine and coarse particulate matter concentrations (Muyemeki et al., 2021).

Transport has been identified as a fast-growing source of ambient pollutants in African countries, with an annual increase of 4% in on-road vehicle count. (OICA,2014). Due to increased transport demand, South Africa leads the continent with an annual vehicle count increase of 6k to 12k. A number of studies based on African literature report high ambient PM$_{10}$ concentrations (80-360 µg.m^{-3}) attributed to traffic emissions (Terrouche et al., 2016; Zghaid et al., 2009; Lowenthal et al., 2014). Most traffic emissions published studies investigate exhaust emissions (Kirago et al. 2022; Ayetor et al. 2021). This is also true for South Africa; there is a vast body of literature reporting on traffic exhaust emissions (Tongwane et al., 2015; 2021; Mahlangu et al., 2020). However, there is limited literature on non-exhaust traffic emissions. This introduces uncertainties when quantifying the contribution of this source towards degraded ambient air quality and limits the development of non-exhaust traffic emission control strategies, standards and regulations.

In developed countries, non-exhaust vehicle emissions account for 60-90% of measured PM$_{10}$ ambient concentrations (Gilliess et al., 2003). Jones (2000) estimated South African non-exhaust traffic emissions (PM$_{10}$) per vehicle from the unpaved road to be 0.534 kg.km^{-1} with varying chemical compositions depending on the soil type of the road. However, due to international-based emission factors, these estimations do not entirely consider local traffic, road and meteorological characteristics. Worawat Songkitti et al., (2022) reported an increase of 25% in PM$_{10}$ and

PM$_{2.5}$ non-exhaust vehicle emissions when an electric vehicle payload was increased by 60–70 kg. Developing nations depend heavily on public transportation (buses and taxis) for long-distance travel and heavy-duty trucks for transporting goods; this finding is particularly significant.

Land use features, local meteorology (temperature, relative humidity, wind), road surface morphology characteristics (size, shape, pavement, speed humps), traffic flow, composition and vehicle speed have been reported to have an impact on vehicle road dust emissions hence the reported high spatial and temporal variability (Pachon et al., 2021). Vehicle road dust loading can range between 50mg/m^2 and 300 mg/m^2 on the same street or in different lanes of the same street (Gustaffson et al., 2019). This emphasises that several micro-scale factors govern non-exhaust PM traffic emissions and are highly variable over space and time. Considering this high variability, measuring non-exhaust emissions using local road, meteorological, and traffic characteristics is necessary to accurately estimate their contribution.

Therefore, this study aims to investigate the impact of vehicle weight and speed impact on non-exhaust traffic emissions and quantify PM$_{10}$ emission factors per vehicle class using empirical field measurements. The emission factors presented in this article will reduce uncertainties associated with vehicle traffic emissions' contribution towards ambient air quality.
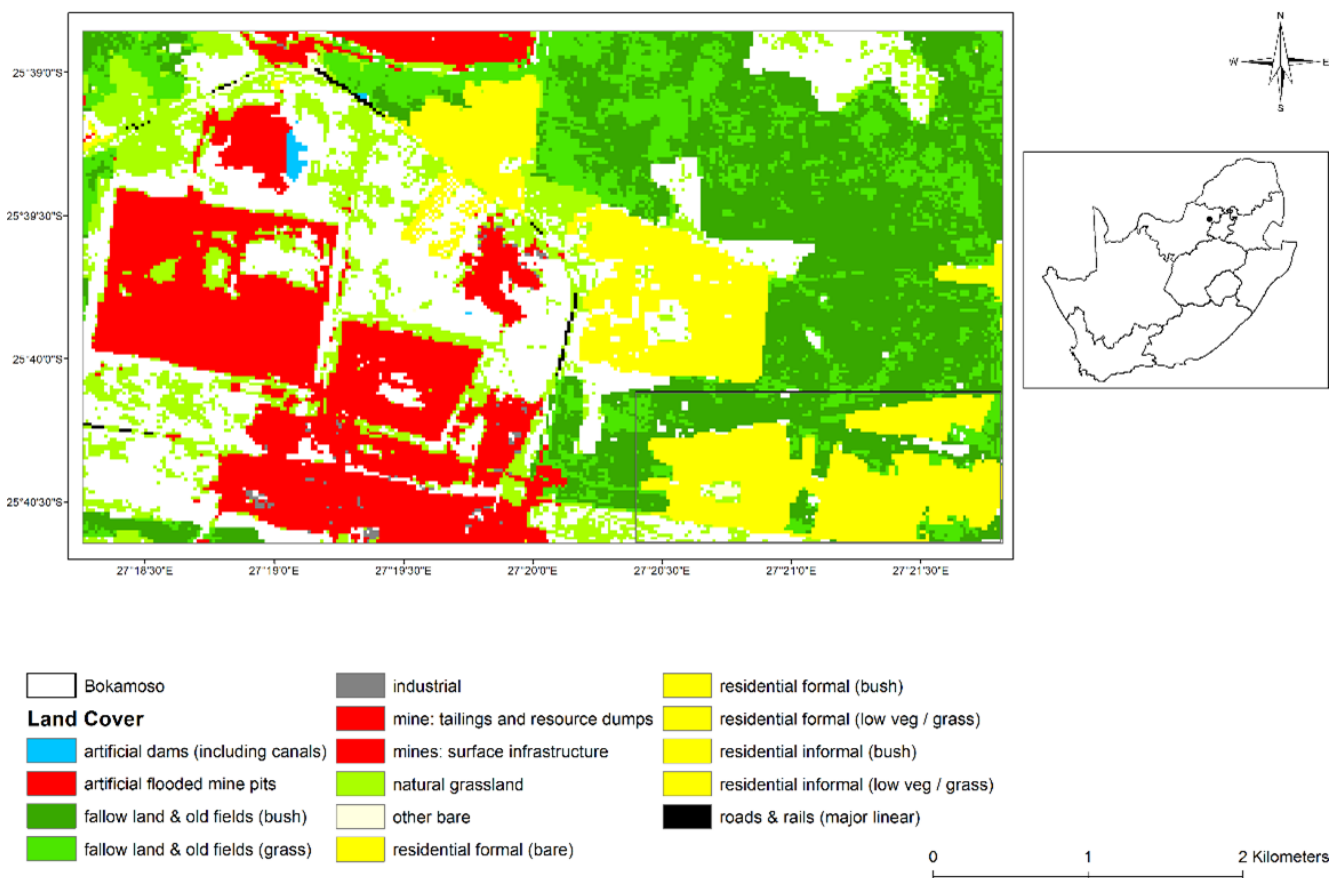

Figure 1: Bokamoso low-income residential area location and land use characteristics.

The reported emission factors add to the dust source emission inventory in South Africa and will reduce uncertainties associated with mobile dust sources and improve road dust particulate matter exposure estimates.

Methods

Study area description and methodology

The North West province is located in a semi-arid area and ranked third in South Africa regarding people living in poverty and lacking infrastructure (Stats SA, 2016). It has a paved road network of 26% and 74% unpaved roads (Department of Public Works and Roads, 2019). Bokamoso (25.6728 S, 27.3455 E) is a low-income residential area within the Rustenburg Municipality selected for the vehicle road dust monitoring campaign due to the presence of unpaved roads observed to be carrying low traffic volumes as well as paved roads observed to have higher traffic volumes. Bokamoso is one of the many low-income residential areas in South Africa; thus, it is important to understand the traffic patterns and the emissions associated with such a

setting. The residential area has a population density of 2724 persons/km^2 (Stats SA General House Survey, 2022). It has been reported to have high levels of unemployment, with 18.7% of the residents having no income (Stats SA Census, 2022). About 30% of the people living in Bokamoso earn between R3 200 - R 6 366 monthly (Stats SA General House Survey, 2022). The residential area is characterised by unpaved roads, unpaved household yards, open soccer fields, and close-by mining and industrial activities. Bokamoso's land use characteristics and high population density (2724km^{-2}) drive the traffic activity within the residential area. The field road dust monitoring campaign took place during the summer.

The road dust monitoring campaign on-site meteorological station reported an average wind speed of 1.5 m.s^{-1} (Figure 2) with an ambient temperature of 25°C and humidity of 42% during the campaign period (Table 2).

Experimental setup and data collection methods

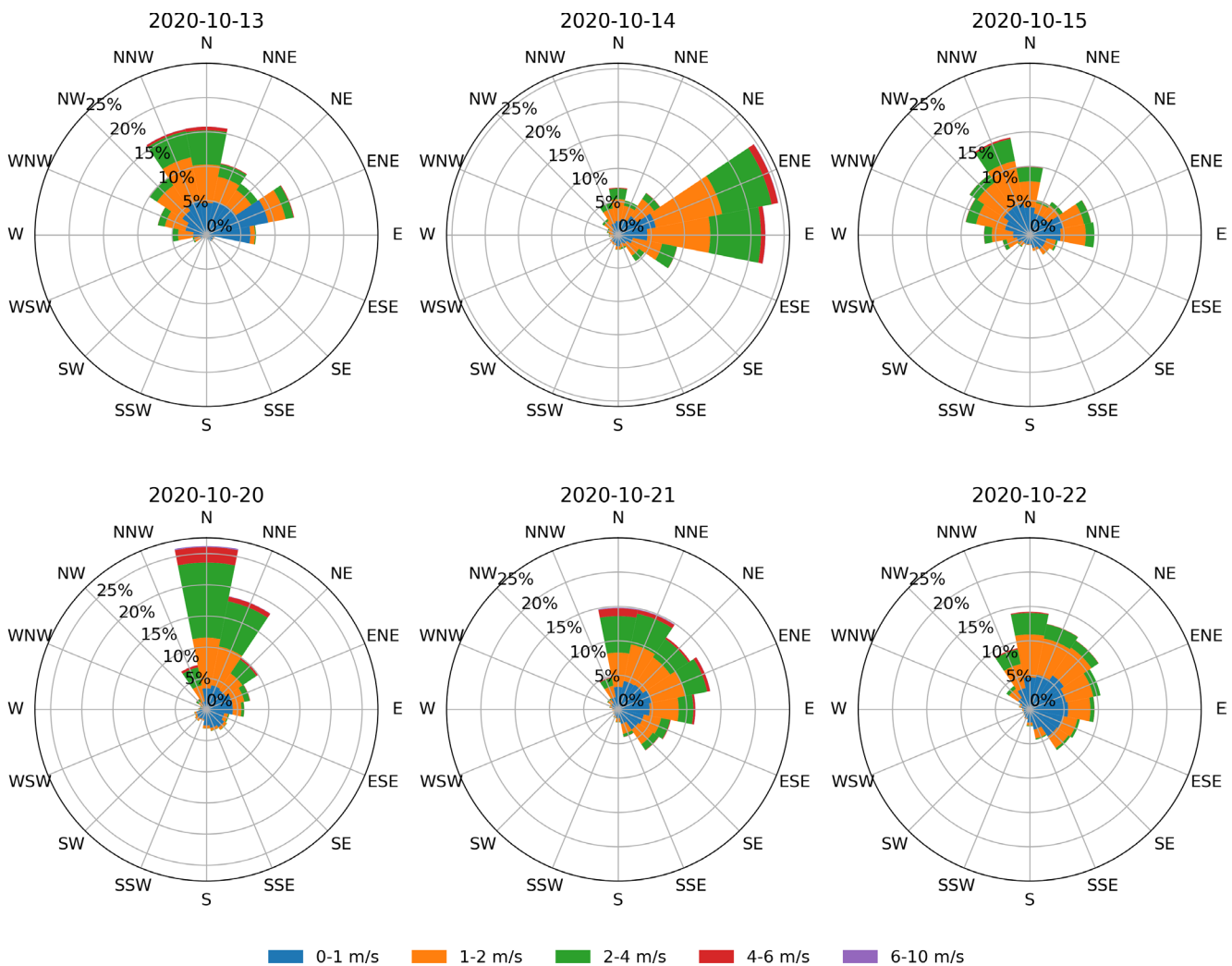The field monitoring campaign aimed to characterise traffic and

Figure 2: Wind speed and direction for monitoring Bokamoso paved and unpaved road dust.

Table 1: Averaged daily meteorological conditions during the road dust monitoring campaign (On-site meteorological station)

Road dust Monitoring campaign dates for October 2020	Paved road non-exhaust PM$_{10}$ traffic emissions monitoring campaign days			Unpaved road non-exhaust PM$_{10}$ traffic emissions monitoring campaign days		
	13	14	15	20	14	15
Wind Speed (m/s)	122	1.2	NO data	1.56	1.51	0.96
Temperature (°C)	21.51	25.7		31	26.9	26.96
Relative Humidity (%)	55.51	41.6		28	38	42
Rainfall (mm)	0	0		0	0	Drizzling

quantify non-exhaust PM$_{10}$ emissions from paved and unpaved roads in Bokamoso took place from 13 October 2020 until 22 October 2020 from 05h:00-21h:00. Three days paved road site (Tuesday until Thursday) and three days unpaved (Tuesday-Thursday) road site. Particulate matter concentrations PM$_{10}$ concentrations were monitored using a TSI DustTrak DRX® real-time optical aerosol counter. A meteorological station mounted with a rain gauge, temperature, humidity, and wind sensor was set up next to the aerosol counter to monitor meteorological conditions. A traffic counter (Sierzega SR4) captured vehicle data (type, speed, direction, and count). The experimental setup was positioned 2 m from the road edge.

A traffic counter was placed next to the weather station in order to monitor traffic activity and vehicle characteristics such as speed (km/h), vehicle length (decimeter), and direction (+-). The instrument uses the measured length to class the vehicles into categories. Vehicles with (dm) 0 - 20 are classified as motorcycles or bicycles, vehicles with lengths between 20 – 60 dm are classified as passenger cars, or (Motor Vehicles), vehicles with a length between 65 – 95 dm are classified as Medium Duty Vehicle (buses and taxis). Heavy-duty, multi-trailer trucks were assigned to vehicles with 95 – 255 dm lengths (Palo et al., 2019). This data determined the hourly composition on paved and unpaved roads. Also, determine the emission factor variation per vehicle class (Motorcycles, Motor vehicles, Medium duty and Heavy duty vehicles) as they differ in weight.

Data analysis methods
Bokamoso open streets, https://www.openstreetmap.org road shape file, was uploaded into GIS ArcMap and digitised to determine the proportion of paved and unpaved roads within the residential area. Descriptive statistics and clustering analysis was used to classify the vehicles, record their speed, and determine hourly traffic activity, traffic composition and sum on paved and unpaved road.

A simple box mathematical model was used to determine on-road PM$_{10}$ emission factors as a function of vehicle type, weight, and speed. The model is based on a mass-balanced principle, as in Equation 1 (Font et al., 2014). The source, in this case, the road "box", has a (width), L (length) and H (height).

$$q = \frac{uh(c-b)}{L} \tag{1}$$

Where q= emission factor (mg.m^{-2}s^{-1}); u=wind speed (m.s^{-1}); h= height from the ground where the measurements are taken (m); c= PM concentration during peak periods (mg.m^{-3}) b=PM concentration during non-peak periods (mg.m^{-3}) L= length of the road segment for the sampling point (m).

The model assumes that (i) the particulate matter emission rate from the source and airflow out the "box" is constant and in equilibrium, (ii) the concentration of the pollutant in the atmosphere is well mixed, and the airflow within the box is uniform (ii) other atmospheric processes that lead to secondary formation of particles and deposition by gravitation are suspended and insignificant (Font et al., 2014). Specific case studies from the vehicle counter and DustTrak PM concentration and meteorological datasets were selected to determine the impact of vehicle mass on the PM emission factors.

Results

The road network in Bokamoso
Bokamoso has 81% (3.7km) of the unpaved road network, and 19 (0.9km) is paved. The paved roads are covered with asphalt with an even width of about 6 meters, starting at the residential area entrance with a double-line road network that runs through the residential area towards the exit. The residential areas' unpaved roads are bare soil rough surfaces with multiple road networks varying widths of 4-8 meters, highly connected and ultimately connected to the paved road.
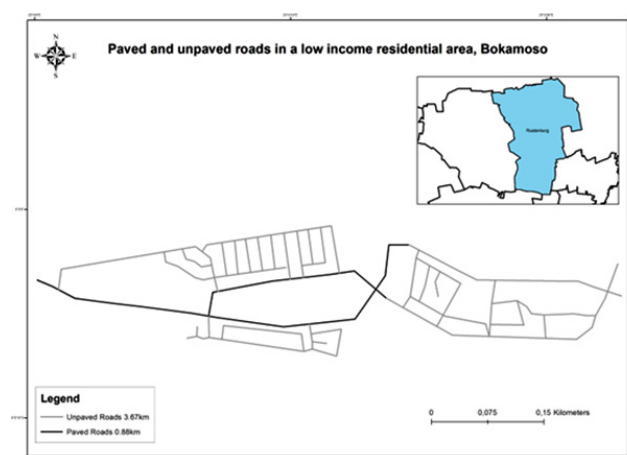
Figure 3: Bokamoso paved and unpaved road network

Traffic characteristics within Bokamoso
Bokamoso paved roads reported an average of 2 119 vehicles per day and a total of 6 357 in three days. In contrast, unpaved
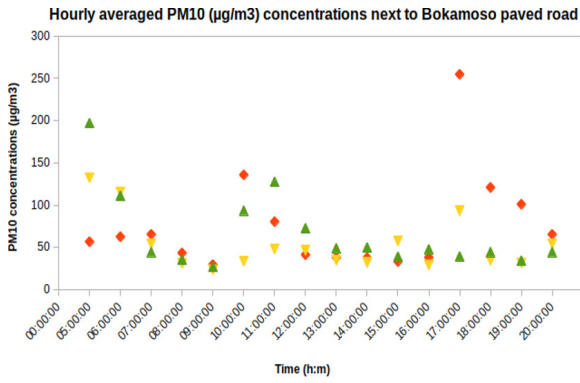
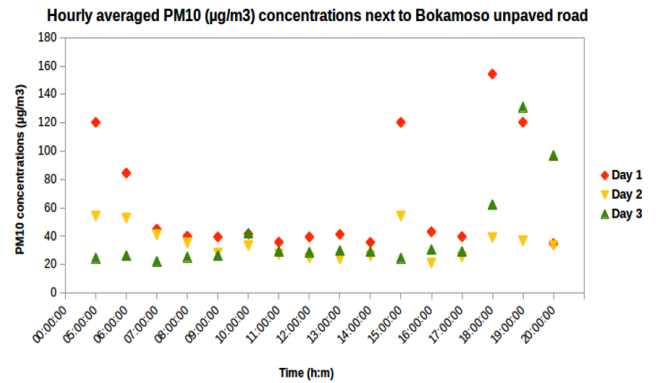***Figure 4A:** Paved roadside PM_{10} concentration measurementsnetwork*

***Figure 5A:** Unpaved roadside PM_{10} concentration measurements*
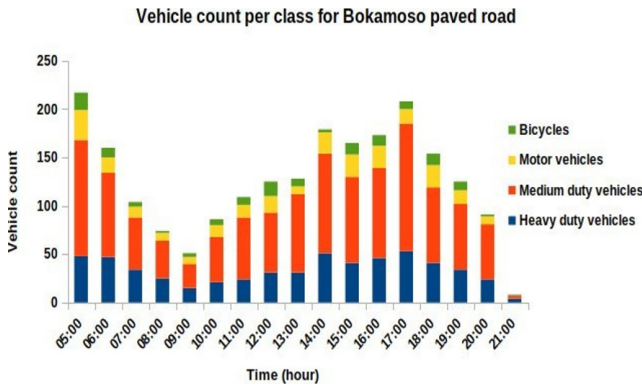

***Figure 4B:** Paved road day 1 (Tuesday) diurnal traffic composition*
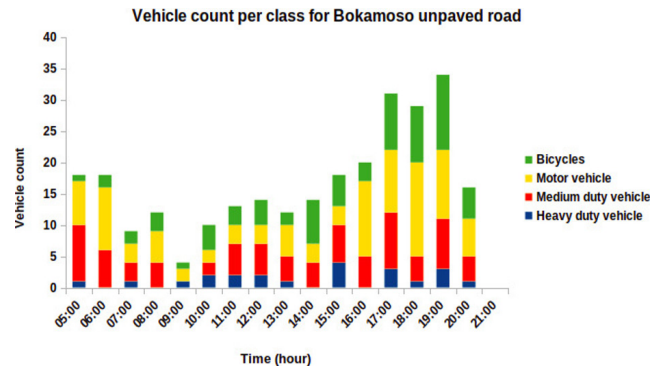

***Figure 5B:** Unpaved road day 1(Tuesday) diurnal traffic composition*

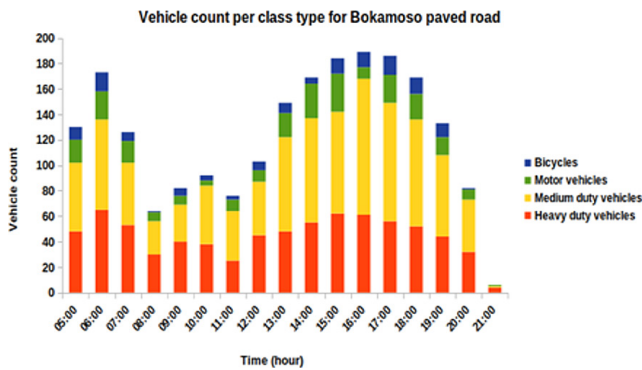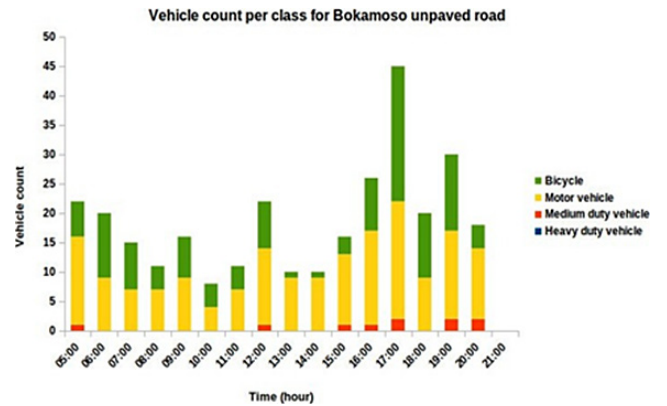***Figure 4C:** Paved road day 2 (Wednesday) diurnal traffic composition*

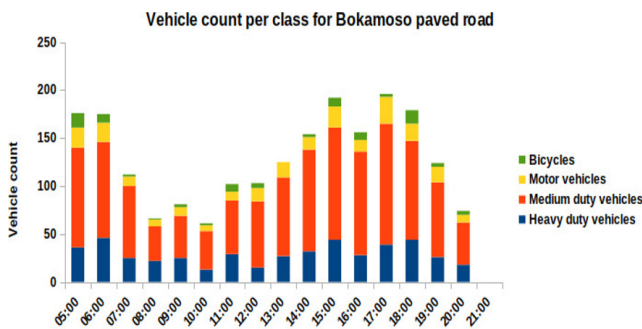***Figure 5C:** Unpaved road day 2 (Wednesday) diurnal traffic composition*

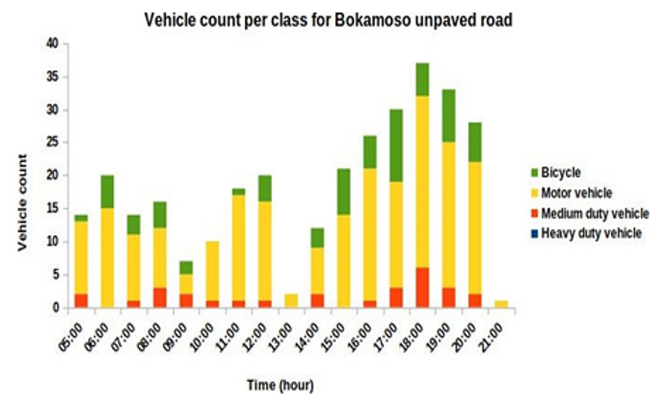***Figure 4D:** Paved road day 3 (Thursday) diurnal traffic composition*

***Figure 5D:** Unpaved road day 3 (Thursday) diurnal traffic composition*

roads have an average traffic volume of 298 per day and a total of 896 in 3 days. Medium-duty commercial and passenger vehicles dominate unpaved roads, while medium and heavy-duty vehicles dominate paved roads. The PM$_{10}$ and traffic count graphs (Figures 4 and 5) show a strong coefficient of determination between traffic density per hour and concentration measured. The paved road monitoring point shows higher concentrations up to averaged 200 µg.m^{-3} with peak concentrations between 05h00-07h00: 09h00-11h00 and 13h00-20h00 (Figure 4A-D). Unpaved road monitoring concentration peaks are up to averaged 160 µg.m^{-3} with peak hours from 06h00-08h00, 10h00-13h00 and 15h30-19h30 (Figure 5A-D). Unpaved roads show lower concentrations compared with paved as multiple unpaved roads (3.7 km) networks feed traffic to the double-line paved roads (0.9 km).

Impact of vehicle speed on the paved and unpaved road per vehicle type

Paved and unpaved heavy-duty vehicle emission factors correlate positively with vehicle speed, Figure 6. The speed for unpaved roads ranged between 10-30 km.h^{-1}, mainly due to the national set vehicle speed for heavy-duty vehicles on unpaved roads within residential areas. Therefore, although there is a positive coefficient of determination between heavy-duty vehicle non-exhaust PM$_{10}$ emission factors and speed on unpaved roads, it is weak (0.2) due to low and less variable vehicle speed. Unpaved road emission factors ranged from 0.05-0.2 g/km/h. Paved road heavy-duty vehicles' speed had a wider range of 30-70 km.h^{-1} compared to unpaved road heavy-duty vehicles. However, they reported similar emission factors (0.05-0.3 g/km/h). Paved road heavy-duty vehicle non-exhaust PM$_{10}$ emissions reported a positive medium to strong coefficient of determination to vehicle speed increase with a coefficient of determination of 0.59.

Medium-duty vehicle PM$_{10}$ emissions for paved roads showed a weak linear coefficient of determination (0.2) with vehicle speed, while unpaved road emissions showed a positive, strong linear coefficient of determination (0.89) with vehicle speed (Figure 7A). Overall, paved road medium-duty vehicles reported higher PM$_{10}$ emission factors (0.05-0.325 g/km/h) than unpaved road medium-duty vehicles. This can be explained by the overall high-speed range for paved (24-61 km.h^{-1}) road medium-duty vehicles compared to unpaved road medium-duty vehicles (8-20 km.h^{-1}).

Motor vehicle paved road non-exhaust emission factors showed no significant coefficient of determination with increased vehicle speed (Figure 8). Most of the emission factors were below 0.4 g/km/h with speeds ranging between 10-60 km.h^{-1}. Unpaved road motor vehicle emission also showed no significant coefficient of determination (0.2) with vehicle speed, with most emission factors below 0.25 g/km/h with speeds ranging between 8-22 km.h^{-1}. This might mean further regulating or reducing motor vehicle speed for unpaved and paved roads may not significantly reduce non-exhaust motor vehicle PM$_{10}$ emissions.

Variability of vehicle PM$_{10}$ emission factors per vehicle type on paved and unpaved roads

PM$_{10}$ emission factors for five vehicles per vehicle class were calculated using the box model to investigate paved and unpaved road PM$_{10}$ emissions as a function of vehicle weight for the different vehicle categories. Figure 9 shows a variation of non-exhaust traffic PM$_{10}$ emissions per vehicle type on paved and unpaved road surfaces. Paved road non-exhaust emission factors were not significantly variable. They ranged between an average of 0.15-0.18 g km/h, with motor vehicles reporting an average of 0.18 g/km/h while heavy-duty vehicles reported an average of 0.15 g/km/h. On the contrary, unpaved road non-exhaust traffic PM$_{10}$ emissions ranged between 0.16-0.3 g/km/h. On unpaved roads, medium-duty vehicles reported the lowest average (0.16 g/km/h), followed by motor vehicles (0.18 g/km/h), while heavy-duty vehicles reported the highest (0.3 g/km/h) average non-exhaust PM$_{10}$ emission factor.

The emission factors have a limitation of being a small sample size. Only seven case studies per vehicle type were used to derive the averaged emission factors as this was a real-world field monitoring campaign, and other variables that significantly impacted the emissions, like ambient wind speed and vehicle speed, were difficult to control. Unpaved road monitoring sites had higher emission factors but lower traffic density as there are multiple road networks within the residential area. Paved roads had lower emission factors but higher traffic density as all unpaved road networks within the residential area feed traffic to paved roads. Also, the box model method tends to underestimate emissions calculated when the wind speed is extremely low or high (Haustein et al., 2015).

Discussion

About 80% of Low-income residential area's road network is unpaved and highly connected, thus containing many cross-section braking zones (T junctions, four-way stops) (Gwilliam et al., 2008). This is true for the Bokamoso residential area's road network, as seen in Figure 3. Low-income residential unpaved roads have no flood control infrastructure, poor drainage systems and lack traffic management infrastructures (Nkomo, 2016). They also have a high deterioration rate with a lifespan of less than one year (Saha and Ksaibati, 2017). This decreases overall air quality in surrounding areas as unpaved roads and sidewalks are an infinite source of loose soil particles, especially during non-rainy seasons.

It has been reported that traffic counts have a low coefficient of determination (0.55-0.65) with non-exhaust PM$_{10}$ emissions factors since traffic-heavy paved roads are not effective dust reservoirs (Schaap et al., 2009; Amato et al., 2013; Abu-Allaban et al., 2003; Etyeme-zian et al., 2003). In addition, Padoann et al., (2017) reported higher PM$_{10}$ emissions from secondary paved roads with fewer than 1000 vehicles per day compared with primary roads with over 2000 vehicles per day. These results
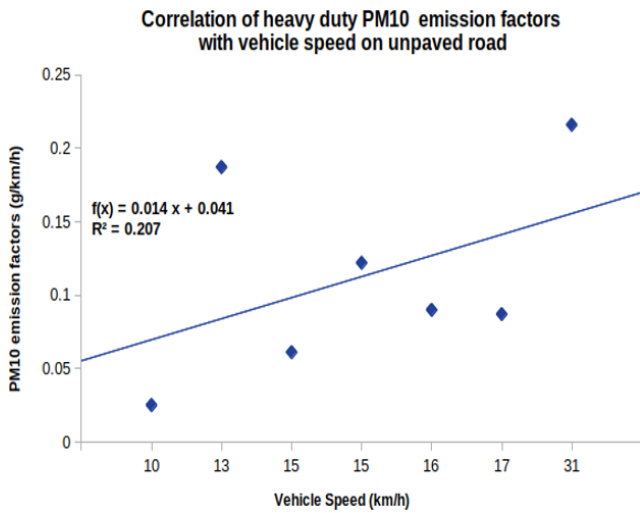
Figure 6A: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for heavy-duty vehicles on unpaved roads
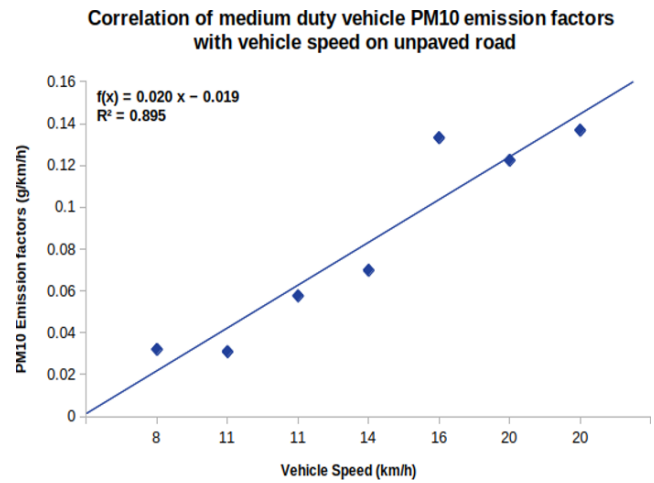

Figure 6B: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for heavy-duty vehicles on paved roads

Figure 7A: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for medium-duty vehicles on paved roads

Figure 7B: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for medium-duty vehicles on unpaved roads

Figure 8A: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for Motor vehicles on paved roads

Figure 8B: Coefficient of determination between vehicle speed and PM$_{10}$ emissions for Motor vehicles on unpaved roads
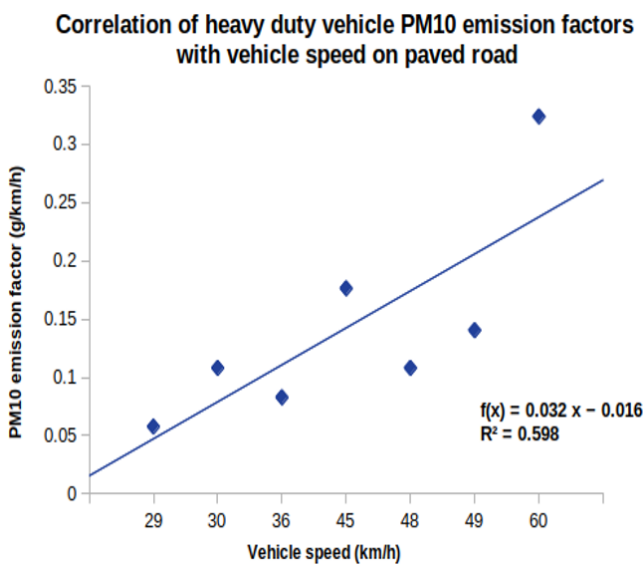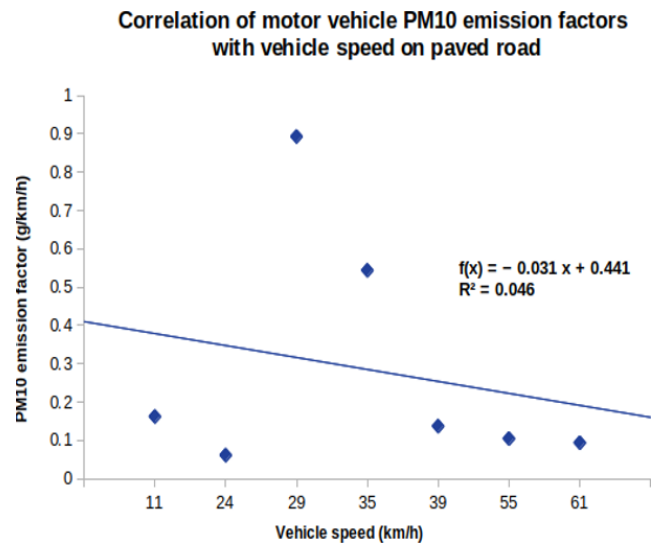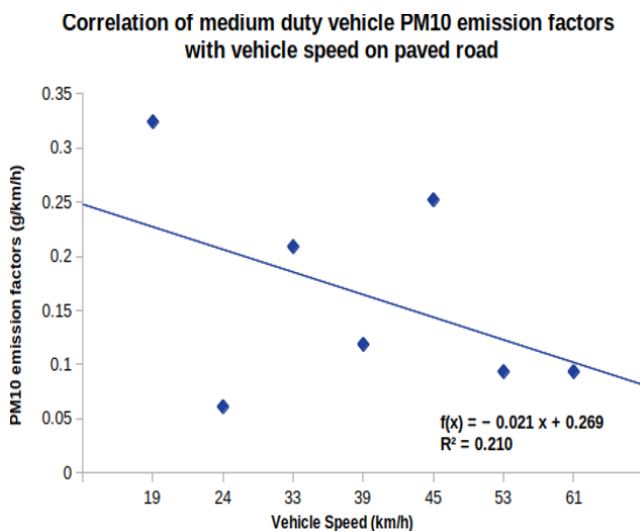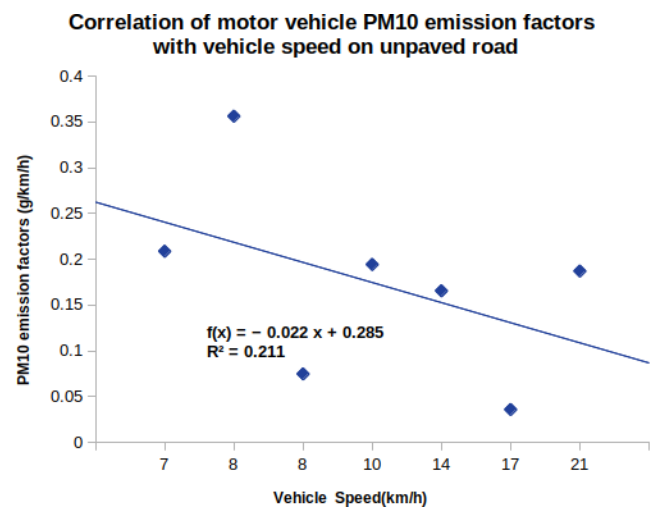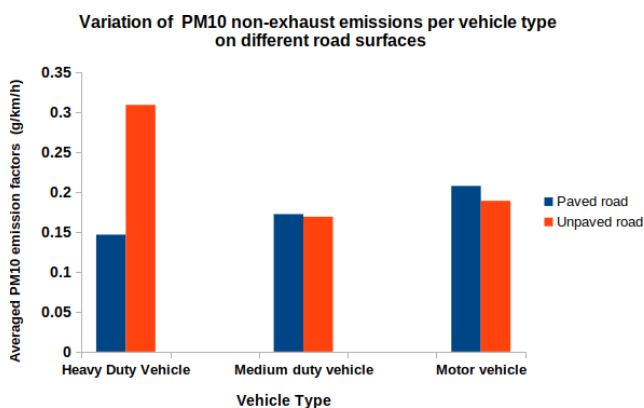
Figure 9: *The impact of vehicle weight on paved and unpaved road PM$_{10}$ emission factors*

may not apply to South African low-income paved residential roads as unpaved sidewalks, household yards, and recreation areas continuously supply loose soil particles to adjacent paved roads. This explains the higher PM$_{10}$ concentrations (0.5-1.5 mg.m^{-3}) on the site of the paved road when compared to the unpaved road (0.2-0.6 mg.m^{-3}) in Bokomo's site.

Local meteorological factors such as ambient wind speed and relative humidity affect non-exhaust traffic emissions. Panchon et al., (2021) investigated seasonal impact on road dust loading for 41 sites within Bagota. The results showed doubled dust loading measurements in the dry season (1.8-45 mg.m^{-2}) compared to the wet season (1-22 mg.m^{-2}). This is because soil moisture decreases road surface dust emission strength and loose soil particle availability (Munkhtsetseg et al., 2016). The results presented in this paper are from summer road dust monitoring field campaigns; hence, they may be applicable only in summer, and non-exhaust traffic emission estimates for paved and unpaved roads in winter are expected to be higher.

About 63% of South African low-income residents use buses and taxis (Nkomo et al. 2016;2018). The North West province's public transport composition in 2003 was mainly taxis (64%), buses (30) and trains (6%); these statistics increased in 2013 to 67% (taxis) and 21% for buses (National Household Transport Survey, 2003 and 2013). Residents working close to the residential areas use bicycles or private staff public transport (motor vehicles) to work or nearby destinations. According to the National Household Transport Survey, 2013, about 42.4% of low-income South African residents walk to workplaces, 38% use public transport (buses, taxis and trains), while 18.8% use motor vehicles. This correlates well with Bokomo's unpaved road traffic composition as there is a substantial amount of bicycles, especially on unpaved roads. The medium and heavy-duty vehicles on the unpaved road are mostly taxis and buses (public transport); on the paved roads, they are mostly trucks and heavy-duty trucks transporting goods to nearby areas.

There is a portion of low-income residents that prefer private staff transport (motor vehicles) due to public (taxis) transport, long departure waiting periods, and poor road infrastructure

that decreases riding quality (Feikie et al. 2018). This could explain the significant count in motor vehicle class compositions as seen in Bokamoso's residential area paved and unpaved road traffic diurnal cycles. The recent (2021) South African state of traffic report showed a vehicle increase count of 2.28 % (13,712) for the North West province from the year 2019-2021. However, at the national scale, low-income residents (quintile 1) only own 6% of the total registered motor vehicles in South Africa (National Household Transport Survey, 2019).

Kuhns et al. (2003) stated that an increased vehicle weight and speed increases the amount of non-exhaust traffic PM$_{10}$ emitted. This is because an increase in vehicle speed increases ambient wind turbulence between vehicle tires and, therefore, may increase non-exhaust traffic emissions on unpaved roads or paved roads with loose soil particles. Hussein et al. (2008) supported this and reported high dust (10 times greater) concentration measurements for a vehicle travelling at 100 km.h^{-1} compared to a vehicle travelling at 20 km.h^{-1}. (Amato et al., 2017) identified that when speed had increased from 80 to 110 km.h^{-1}, the mean PM concentration was higher with increased vehicle speed. Similar findings are reported for Bokamoso's unpaved roads. A positive coefficient of determination of 0.86 and 0.47 between vehicle speed and PM$_{10}$ emission factors was reported for medium and heavy-duty vehicles, respectively. Both these vehicles showed a positive coefficient of determination on unpaved roads, except for motor vehicles. This difference in the coefficient of determination relationship could be because of the average speed limits and weight differences. Motor and medium-duty vehicle speed limit on unpaved roads ranged between 8-21 km/h. The speed limit for heavy-duty vehicles ranged from 10-32km/h. Motor and medium-duty vehicles showed a low coefficient of determination (0.01;0.19) between vehicle speed and calculated PM$_{10}$ emissions for paved roads. However, there was a positive coefficient of determination for heavy-duty vehicles on paved roads (0.63).

Vehicle type, weight and length mostly determine the vehicle wheel size, count and type. Vehicle wheel type varies per vehicle class, while vehicle wheel count and size tend to increase from lowest vehicle (Motorcycle) class to highest (heavy duty vehicle) (Wenzel,2010). Gillies et al., (2005), found a variation in non-exhaust PM emission factors per vehicle type, with heavy-duty vehicles having higher (48 g km^{-1}h^{-1}) PM$_{10}$ emission factors when compared with light-duty vehicles (0.8 g km^{-1}h^{-1}). Other studies (Schaap et al., 2008 : Amato, 2012) found that heavy-duty vehicles' non-exhaust PM$_{10}$ emissions were up to 9 times higher when compared with motor vehicles, which showed a low coefficient of determination with an almost negative coefficient of determination line.

The study has limitations, several other sources of PM in residential areas, such as domestic burning, and yard sweeping, may lead to an overestimation of the traffic PM$_{10}$ concentration recorded by the aerosol counter. The study was conducted during the COVID-19 lockdown period; therefore, the traffic flow or counts at 05h00 am and 21h00 may be overestimated due to

the lockdown curfew times, which were set to be 04h00- 22h00. Other vehicles use a different road or decrease speed when they see the instrument set up. Therefore, this may result in over and under estimation of the calculated emission factors and may not be applicable under normal traffic conditions. The aerosol counter (DustTrak) has high precision; however, it has been reported to underestimate ambient PM$_{10}$ coarse concentration by 20% and overestimate PM fine fraction by a factor of 2 (Javed and Guo., 2021). In the case of traffic, the traffic counter (Sierzega SR4) could experience vehicle counting and classification errors (Kijewska and Iwan, 2019).

Conclusion
More than 80 % of the roads in Bokamoso low-income residential areas are unpaved and are a daily source of particulate matter, with peak emissions reported during traffic rush hours. The residential area has a high traffic activity driven by the area's land use characteristics. Bokamoso paved roads reported an average of 2 119 vehicles per day and a total of 6 357 in three days. In contrast, unpaved roads have an average traffic volume of 298 per day and a total of 896 in three days. Paved and unpaved heavy-duty vehicle emission factors correlate positively with vehicle speed. Paved road heavy-duty vehicle non-exhaust PM$_{10}$ emissions reported a positive medium to strong coefficient of determination to vehicle speed increase with a coefficient of determination of 0.59. Even though there is a positive coefficient of determination between heavy-duty vehicle non-exhaust PM$_{10}$ emission factors and speed on unpaved roads, it is weak (0.2) due to low and less variable vehicle speed. Motor vehicle paved and unpaved road non-exhaust emission factors showed no significant coefficient of determination with increased vehicle speed. Paved road non-exhaust emission factors were not significantly variable with vehicle type. They ranged between an average of 0.15-0.18 g/km/h, with motor vehicles reporting an average of 0.18 g/km/h while heavy-duty vehicles reported an average of 0.15 g/km/h. On the contrary, unpaved road non-exhaust traffic PM$_{10}$ emissions ranged between 0.16-0.3 g/km/h. The study results will inform decisions regarding road dust emissions interventions in South Africa. The authors recommend a laboratory-based study to further investigate the impact of vehicle characteristics on road dust emissions.

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References
Abu-Allaban M, Gillies J A , Gertler A W, Clayton R, Proffitt D (2003) Tailpipe, re-suspended road dust, and brake-wear emission factors from on-road vehicles. *Atmospheric Environment* (Oxford, England: 1994), 37(37): 5283–5293. https://doi.org/10.1016/j.atmosenv.2003.05.005

Alshetty D, Shiva Nagendra M S, (2021) Urban characteristics and its influence on resuspension of road dust, air quality and exposure. Air Quality, Atmosphere & Health 15(2): 273-287.

Ayetor G K, Mbonigaba I, Ampofo J, Sunnu A (2021) Investigating the state of road vehicle emissions in Africa: A case study of Ghana and Rwanda. *Transportation Research Interdisciplinary Perspectives*, 11(100409): 100409. https://doi.org/10.1016/j.trip.2021.100409

Department of transport, state of traffic report, (2021) https://www.gov.za/sites/default/files/gcis_document/202201/transport-annual-report-2020/21.pdf, accessed 24-08-2023.

Feikie X E , Das D K, Mostafa Hassan M, (2018) Perceptions of the factors causing traffic congestion and plausible measures to alleviate the challenge in Bloemfontein, South Africa. 37th Annual Southern African Transport Conference (SATC 2018) Proceedings, Pretoria, South Africa. 9-12 July 2018.

Font A, Baker T, Mudway I, Purdie E, Dunster C, Fuller, G, (2014) Degradation in urban air quality from construction activity and increased traffic arising from a road-widening scheme. Science of the Total Environment, 497(498):123–132.

Gillies J A, Etyemezian V, Kuhns H, Nikolic D, Gillette D A, (2005) Effect of vehicle characteristics on unpaved road dust emissions. Atmospheric Environment, 39(13): 2341–2347. https://doi.org/10.1016/j.atmosenv

Gustafsson, M., Blomqvist, G., Järlskog, I., Lundberg, J., Janhäll, S., Elmgren, M., Johansson, C., Norman, M. and Silvergren, S., (2019). Road dust load dynamics and influencing factors for six winter seasons in Stockholm, Sweden. Atmospheric Environment: X, 2, p.100014.

Gwilliam K., Foster V., Archondo-Callao R., Briceño-Garmendia C., Nogales A., Sethi K., (2008) The Burden of Maintenance: Roads in Sub-Saharan Africa, Background Paper 14 (Phase I) 1-58, https://roadsforwater.org/wp-content/uploads/2013/10/the-burden-of-maintenance_roads-in-SSA.pdf, accessed 20-08-2023.

Haustein K, Washington R, King J, Wiggs G, Thomas D, S G, Eckardt, F D, Bryant R G, Menut L, (2015) Testing the performance of state-of-the-art dust emission schemes using DO4 Models field data. Geoscientific Model Development, 8(2):341–362. https://doi.org/10.5194/gmd-8-341-2015.

Jones D, (2000) Road dust: just a nuisance or a significant road management issue. Pretoria, South Africa Transport Conference, Pretoria, 17-20 July:1-13.

Kijewska K, Małecki K, Iwan S (2016) Analysis of data needs and having for the integrated urban freight transport management system. In *Communications in Computer and Information Science* (pp. 135–148). Springer International Publishing.

Kirago L, Gatari M J, Gustafsson Ö, Andersson A, (2022) Black carbon emissions from traffic contribute substantially to air pollution in Nairobi, Kenya. Communications Earth & Environment, 3(1). https://doi.org/10.1038/s43247-022-00400-1

Kuhns H, Gillies J, Watson J, (nd.) Vehicle-Based Road Dust Emissions Measurements. http://www3.epa.gov/ttn/chief/conference/ei12/fugdust/huhns.pdf accessed 06-06-2021.

Language B P (2020) Characterisation of Respirable Indoor Particulate Matter in South African Low-Income Settlements. North-West University, PhD dissertation.

Lowenthal D H, Gertler A W, Labib M W, (2014) Particulate matter source apportionment in Cairo: recent measurements and comparison with previous studies. *International Journal of Environmental Science and Technology: IJEST*, 11(3): 657–670. https://doi.org/10.1007/s13762-013-0272-6

Mahlangu A, Schaberg P, Wattrus M, Forbes P, (2020) Characterisation of semi-volatile hydrocarbon emissions from diesel engines. *Clean Air Journal*, 30(1). https://doi.org/10.17159/caj/2020/30/1.7672

Muyemeki L, Burger R, Piketh S J, Language B, Beukes J P, Van Zyl PG, (2021) Source apportionment of ambient PM$_{10-2.5}$ and PM$_{2.5}$ for the Vaal Triangle, South Africa. *South African Journal of Science*, 117 (5/6): 1–1.

National Household Travel Survey, 2003. file:///home/lapss46/Downloads/ddi-documentation-english-569.pdf accessed 23-08-2023

National Household Travel Survey, 2013. https://www.statssa.gov.za/publications/P0320/P03202013.pdf accessed 23-08- 2023.

National Household Travel Survey, 2020. https://www.statssa.gov.za/publications/P0320/P03202020.pdf accessed 23-08- 2023.

Ncube K, Shackleton C M, Swallow B M, Dassanayake W, (2016) Impacts of HIV/AIDS on food consumption and wild food use in rural South Africa. Food Security, 8: 1135-1151.

Nicholson K W, Branson J R, (1990) Factors affecting resuspension by road traffic. Science of the Total Environment, 93:349–358.

Nkomo S. L, Desai S, Peerbhay K, (2016) Assessing the Conditions of Rural Road Networks in South Africa Using Visual Observations and Field-Based Manual Measurements. Review of Social Sciences, 1(2): 42-55.

Nkomo SL (2018) Assessing the condition of unpaved rural road networks and the associated impacts on the livelihoods of rural communities: A case study of four rural communities in KwaZulu, South Africa. University of KwaZulu-Natal (Thesis-PhD).

Pachon, J., Vanegas, S., Saavedra, C., Amato, F., Silva, L., Blanco, K., Chaparro, R. and Casas, O., (2021). Evaluation of factors influencing road dust loadings in a Latin American urban center. Journal of the Air & Waste Management Association, 71(2), pp.268-280.

Paľo J, Caban J, Kiktová M, Černický Ľ, (2019) The comparison of automatic traffic counting and manual traffic counting. *IOP Conference Series. Materials Science and Engineering*, 710(1): 012041. https://doi.org/10.1088/1757-899x/710/1/012041

Saha P, Ksaibati K, (2017) Developing an optimisation model to manage unpaved roads. J*ournal of Advanced Transportation*, 2017, 1–11. https://doi.org/10.1155/2017/9474838

Schachtebeck C, Mbuya J M, (2016) Assessing the potential benefits of road infrastructure development for poverty alleviation: Lessons Learnt from developing Economies. Southern African Transport Conference, Pretoria, .88-98.

Sehmel G.A. (1973) Particle resuspension from an asphalt road caused by car and truck traffic. Atmospheric Environment, 7:291–309.

Songkitti W, Sa-ard-iam S, Plengsa-Ard C, Wirojaskunchai E, (2022) Effects of payloads on non-exhaust PM emissions from A hybrid electric vehicle during A braking sequence. *Aerosol and Air Quality Research*, 22(7): 220150. https://doi.org/10.4209/aaqr.220150

Statistics South Africa, (2016) General Household water and sanitation: an in-depth analysis of the general Household Survey 2002-2015. Pretoria, South Africa.

Statistics South Africa, (2022) General Household water and sanitation: an in-depth analysis of the general Household Survey 2020-2022. Pretoria, South Africa.

Terrouche A , Ali-Khodja H , Kemmouche A , Bouziane M , Derradji A , Charron A, (2016) Identification of sources of atmospheric particulate matter and trace metals in Constantine, Algeria. *Air Quality, Atmosphere, & Health*, 9(1): 69–82. https://doi.org/10.1007/s11869-014-0308-1

Tongwane M, Piketh S, Stevens L, Ramotubei T, (2015) Greenhouse gas emissions from road transport in South Africa and Lesotho between 2000 and 2009. *Transportation Research. Part D, Transport and Environment*, (37) 1–13. https://doi.org/10.1016/j.trd.2015.02.017

Zghaid M, Noack Y, Bounakla M, Benyaich F. (2009) Pollution atmosphérique particulaire dans la ville de Kenitra (Maroc). *Pollution Atmospherique*, N°203. https://doi.org/10.4267/pollution-atmospherique.1184

10