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Abstract

Poor air quality is a development challenge. Urbanization and industrial development along with increased populations have brought clear socio-economic benefits to Low-and Middle-Income Countries (LMICs) but can also bring disadvantages such as decreasing air quality. A lack of reliable air quality data in East African cities makes it difficult to understand air pollution exposure and to predict future air quality trends. This work documents urban air quality and air pollution exposure in the capital cities of Kampala (Uganda), Addis Ababa (Ethiopia) and Nairobi (Kenya). We build a situational awareness of air pollution through repeated static and dynamic mobile monitoring in a range of urban locations, including urban background, roadside (pavement and building), rural background, and bus station sites, alongside vehicle-based measurements including buses and motorcycle *t*axis. Data suggest that the measured particulate matter mass concentrations ($PM_{2.5}$, PM_{10}) in all studied cities was at high concentrations, and often hazardous to human health, as defined by WHO air quality guidelines. Overall, the poorest air quality was observed in Kampala, where mean daily $PM_{2.5}$ and PM_{10} concentrations were significantly above the WHO limits at urban background locations by 122% and 69% and at roadside locations by 193% and 215%, respectively. Traffic is clearly a major contributor to East African urban air pollution; monitoring in Kampala and Addis Ababa, on motorcycle *t*axis, in buses and at bus stations indicated that drivers and commuters were exposed to poor air quality throughout their commute. Road-related air pollution can also impact indoor locations near roads. Using one exemplar building located within Nairobi's Central Business District, it is shown that measured outdoor PM concentrations significantly correlate with the indoor air quality ($r = 0.84$). This link between roadside emissions and indoor air pollution within buildings located close to the road should be explored more fully. This study, through a series of case studies, provides clear evidence that roads and traffic need to be a focus for mitigation strategies to reduce air pollution exposure in East African cities.

1. Introduction

Currently, approximately 55% of the global population lives in urban areas. By 2050 this proportion is estimated to reach 68% (UN 2018). Urbanisation has the potential to improve the well-being of societies, yet also presents a number of development challenges including environmental risks, with exposure determined by a range of social, technological, environmental, and behavioural factors. Key environmental health issues include poor

water quality and sanitation, flooding, and the dual risks of indoor and ambient air pollution exposure. Short- and long-term exposure to air pollutants (particles or gases) generated from a range of emissions sources are recognised to exert adverse impacts upon the human respiratory, cardiovascular, metabolic and neurological systems throughout the life course (Kim *et al* 2015, Wong *et al* 2015, Rajak and Chattopadhyay 2020, Shehab and Pope 2019). The World Health Organisation (WHO) reports air pollution is the greatest global environmental health threat contributing to an estimated 7 million premature deaths globally per year, with more than 90% of air pollution associated deaths occurring in Low- and Middle-Income Countries (LMICs), mainly in Asia and Africa (WHO 2014, 2016, GBD Risk Factor Collaborators 2018). Most work has looked at long term impacts of air pollution on health, however, short-term exposure to $PM_{2.5}$ has been shown to increase risk of cardiovascular, respiratory, metabolic and neurological diseases and emergency admissions to hospitals (Orellano *et al* 2020); and ambulance dispatches (Sangkharat *et al* 2019).

East African countries are undergoing rapid economic development, industrialisation and socio-demographic transition, with associated environmental degradation including significant increases in ambient air pollutant levels (Cohen *et al* 2017, Pope *et al* 2018, Rajé *et al* 2018, Kalisa *et al* 2019, Abera *et al* 2020, deSouza, 2020). Available evidence suggests that air pollution will continue to worsen in future years and exert an increasing toll on population health in many cities of East Africa (Petkova *et al* 2013, Gaita *et al* 2014, Pope *et al* 2018, Rajé *et al* 2018, Singh *et al* 2020). In recent years, efforts have been made to understand the air pollution condition, sources and their exposure in East African countries (Vliet and Kinney 2007, Kume *et al* 2010, Gaita *et al* 2014, Schwander *et al* 2014, Ngo *et al* 2015, Egondi *et al* 2016, Amegah and Agyei-Mensah 2017, deSouza *et al* 2017, Pope *et al* 2018, Gatari *et al* 2019, Woolley *et al* 2020, 2021). However, there is still a paucity of air pollution data and well-established air monitoring networks in East African cities, which results in difficulties in understanding both air quality trends and their influences upon public health (Petkova *et al* 2013, Kiggundu 2015, deSouza *et al* 2017, Pope *et al* 2018, Singh *et al* 2020). To establish a nuanced and targeted urban air quality management strategy, information on the temporal and spatial variation in air pollution is required.

With increasing population numbers living in cities, existing urban infrastructure is struggling to cope with the increased demands of urban residents. Rapid expansion and growth has led to urban and suburban sprawl i.e. the unrestricted growth of housing, commercial development, and roads. Urban sprawl is often associated with longer commutes and contributes to traffic congestion and air pollution. According to (Rode *et al* 2017), rapid urbanisation in sub-Saharan Africa has led to intense traffic congestion, as demand for transport has increased faster than cities can provide. In turn, mounting dependency on motorised transport is creating health and safety risks, impeding economic development, and producing more emissions (Abera *et al* 2020). Despite the importance of efficient and effective urban mobility, national and city governments often provide disproportionate levels of investment and institutional support for private vehicle use relative to public and non-motorised transport (Rode *et al* 2017).

Numerous studies have shown that road traffic emissions significantly affect the air quality of urban environments by contributing to the ambient particulate matter (PM) levels (Giugliano *et al* 2005, Borrego *et al* 2006, Pérez *et al* 2010, Kinney *et al* 2011, Pant *et al* 2015). Whilst it is important to understand how air pollution varies between types of location i.e. urban roadside, urban background and rural, it is also important to consider how people engage with the urban environment i.e. locations where people spend significant amounts of time or where significant numbers of people are to be found, as well as how people move around urban areas. Locations with locally increased air pollution are often referred to as hotspots. The elevated pollution levels in such locations may be the product of limited dispersion of pollutants (e.g. a street canyon) or high local emissions (e.g. near a highway, railway station, airport, harbour, or in the case of this paper, a bus station or bus). Alongside hotspots, some groups may be exposed to higher levels of pollution e.g. people who live and work near busy roads and those who travel or commute in heavy traffic. The exposure to air pollutants is itself influenced by choice of transport e.g. drivers, cyclists, and pedestrians as well as the routes used.

The work reported in this paper addresses the highlighted transport related data gaps in three East African capitals (Addis Ababa, Kampala and Nairobi). An assessment of air quality trends, sources and their exposures is provided, through a series of air quality case studies related to transport in different geographical locations and roadside/traffic-related hotspots.

2. Data and methods

PM mass concentration was measured in three East African cities (Addis Ababa, Kampala and Nairobi) using low cost sensors. PM was chosen as the study pollutant because it is recognised to exert the greatest health impact of any air pollutant in East Africa (Pope *et al* 2018). PM was measured in two size fractions - $PM_{2.5}$ and PM_{10} (PM with aerodynamic diameters less than 2.5 and 10 μm respectively), which have relevant health-based WHO guideline concentrations (WHO, 2006). The effect of the measured PM concentrations upon health was

visualized using the US Environmental Protection Agency (EPA) primary health standard for $PM_{2.5}$ air quality index (AQI), which is shown in table S1 (https://www.airnow.gov/aqi/aqi-basics/ and https://www.airnow.gov/aqi/aqi-calculator-concentration/). This EPA AQI level for health is based on daily mean average (24-hour) concentration of $PM_{2.5}$ data.

It is noted that in several of the figures shown in the paper, the EPA AQI grading of pollutants in used when the measurement duration is shorter than 24 h averages, and hence, strictly the AQI is not valid. However, the AQI provides a useful visualization tool to easily observe spatial and temporal heterogeneity in pollution concentrations.

2.1. Low cost particle sensor

Over the last few years, there has been a revolution in the use of low-cost air quality sensors, with many different models now available on the market. In this study, we use the Alphasense Optical Particle Counter (OPC-N2) (www.alphasense.com) to measure PM mass concentration in the PM_{10} and $PM_{2.5}$ fractions. This sensor model was chosen for a variety of reasons. Firstly, it is currently the low-cost PM sensor with the most independent testing in the scientific literature e.g. (Sousan *et al* 2016, Crilley *et al* 2018, Crilley *et al* 2020). Secondly, the OPC-N2 device is small in size (dimensions 75 $\times$ 60 $\times$ 65 mm), low in weight (under 150 g), and has relatively low power requirements (175 mA when operating), which allows for their installation in a variety of locations with either mains power or a combination of battery and solar power. Supplementary figure S1 (available online at stacks.iop.org/ERC/3/075007/mmedia) provides a diagram with dimensional specification. The unit cost of this miniaturised OPC is also relatively low (approximately £250 GBP) when compared to comparable reference grade optical particle counter (OPC) instruments, with a cost ratio (OPC-N2: reference grade OPCs) on the order of 50. The cost of reference grade instruments which provide absolute PM mass concentrations (gravimetric devices) is significantly higher again.

The OPC-N2 measures particles in the size range of 0.38 to 17 μm, with a maximum particle count of 10,000 per second. The available size range allows for capturing the mass of both $PM_{2.5}$ and PM_{10} fractions. It has a minimum sampling time resolution of less than 1 s, but practically data is usually averaged over longer time periods. In this study, data was sampled at a 10 s resolution, then averaged over longer timescales: hourly or daily, dependent on the analysis required. The OPC-N2 measures size dependent PM concentration through measurement of the light scattering properties of the particles, this approach requires several approximations: particles are spherical and have uniform density and shape. These assumptions are not valid for all particles in the urban environment, but on average, they provide a good approximation. Measured particle number concentration were converted to PM mass concentrations in the $PM_{2.5}$ and PM_{10} size fractions via on-board-factory calibration according to European Standard EN481 (Alphasense 2015, Sousan *et al* 2016). It is noted that the on-board calibration is only valid for the conditions under which the instrument was calibrated. Hence, calibration in similar conditions to the deployment conditions, as in this study, is highly recommended prior to operational deployment.

2.2. Calibration of OPC sensors

To ensure the accuracy and quality of PM mass data, calibration of the OPC sensors is required. Previously, (Crilley *et al* 2018) demonstrated effective calibration of the OPC sensors. The calibration involves an absolute PM concentration scaling, which is dependent on local PM properties. The OPC readings also exhibit a strong dependence on local relative humidity, especially when relative humidity is above 85%, due to the hygroscopicity of PM, (Crilley *et al* 2018). There are various reference grade instruments available for calibration but the availability of these instruments in East Africa is currently limited. It is important that these reference instruments are properly calibrated and serviced themselves. Previous studies have shown that the OPC sensors can suffer from drift and a number of other interference artefacts in addition to relative humidity (Mead *et al* 2013, Crilley *et al* 2018), which cannot be neglected.

For this work, the OPC sensors were calibrated using gravimetric measurements of $PM_{2.5}$ and $PM_{10.}$ Usually, gravimetric analysis method is preferred over the other methods for the calibration of light scattering instruments because it provides an absolute weight measurement (O'Connor *et al* 2014), and weight can be measured with greater accuracy than other fundamental properties. It is also necessary to ensure that calibration is performed under optimum conditions i.e. low relative humidity. Calibration of all sensors was performed in Nairobi using gravimetric calibration as previously described in Pope *et al* (2018). The observed scaling factors between the OPC-derived PM2.5 masses and gravimetric analysis were in the range of 1.8 $\pm$ 0.40, similar to previously observed in Pope *et al* (2018). The calibration was performed for a period of 72 h by collocating the OPCs against an Andersen Dichotomous air sampler on the top of a building in the University of Nairobi (17 m above ground level). The correction/scaling factors were calculated through comparison of the mass concentrations from the OPCs and the gravimetric instrument.

2.3. Data collection

$PM_{2.5}$ and PM_{10} mass concentrations were measured at three different locations (roadside, urban background and rural) within each city over different timeframes between 2018–2019 (see table S2 and Supplementary section 2.0). Roadside monitoring sites were located very close to the main roads (1–3 m from road edges), where the selected roads were relatively open with no adjacent high buildings and the traffic flow were relatively high and steady. Urban background monitoring sites were away from local / road sources, where OPC sensors were mounted on top of buildings. Rural background sites were located in non-urban areas that were away from point and line sources of air pollution. The sampling heights of the different monitoring stations are not constant and further details are provided in the supplementary material. Synchronous measurements were not always possible due to the lack of instrumentation. In addition to low-cost measurements, one month (Sep 2019) of hourly $PM_{2.5}$ data was used for Addis Ababa from Airnow (www.airnow.gov), which is located at the US embassy. In general, each study city has two distinct rainy and two dry seasons that influence PM concentrations by changing PM sources and sinks, described in (Singh *et al* 2020). Whilst the study cities are distinct from each other in terms of geography; climatology; politics; demographics and other factors, they share rapidly growing population, urbanisation and motorisation trends. Geographical, economical and climatic (including seasonal variability) information of the study cities can be found in supplementary (section 1.0) and (Singh *et al* 2020).

2.4. Influence of traffic emissions on urban PM concentations

To understand the influence of traffic emissions on urban PM concentrations, the urban and roadside increments in PM concentrations were calculated using the 'Lenschow' approach (Lenschow *et al* 2001, Pope *et al* 2018). The Lenschow approach provides an estimate of the contributions of the urban background and roads within the urban area to the total ambient PM mass concentration. Figure S3, provides a schematic profile of PM mass concentrations for different background environment (urban background, roads and regional/ rural background), where it is assumed that the increment in PM mass between urban background and roadside were due to the emissions of the road traffic adjacent to the roadside site (Gianini 2012). Similarly, the increment in PM mass between urban background and regional/rural background were due to PM emission in the urban environment (Gianini 2012). The roadside increment was calculated by subtracting the PM concentrations of the urban background site from the urban roadside site. The urban increment was calculated by subtracting the PM concentrations of the rural background site from the urban background site. Based on these assumptions, this study estimated roadside and urban increment in $PM_{2.5}$ and PM_{10} concentrations using measurements from campaign periods when all sites (roadside, urban and rural) were running simultaneously (table 2). The Lenschow approach removes the influence of regional pollution from urban pollution estimates and allows for more direct comparison between the three study cities, which were measured during different study periods. It is noted, the Lenschow approach views the city simply, as a function of rural background, urban background, and roadside concentrations. The approach could be extended to look at other point air pollution sources, for example biomass and waster burning, but the focus of this study was on the role of roads upon urban pollution.

2.5. Case studies

A series of case studies were performed to explore air quality at different road and traffic related hotspots, including a bus station, road routes and a roadside building, within Kampala, Addis Ababa and Nairobi, where $PM_{2.5}$ concentrations were collected at 10 s time resolution using the OPC-N2 sensor. For the case studies, PM measurements were only collected for the $PM_{2.5}$ size fraction.

2.5.1. Kampala

Boda-Boda motorcycle taxis - $PM_{2.5}$ concentrations were collected on a motorcycle taxi (Boda-Boda) equipped with OPC-N2 sensor, coupled with a Global Positioning System (GPS) device. The sampling campaign consisted of two days (30 April and 2 May 2019) between 07:00 to 21:00 on different road routes in Kampala. The routes taken were dependent on the requirements of Boda Boda's passenger pickup and drop-off locations. It is noted that the motorcycles are a source of pollution as well as being the location for the pollution detector.

2.5.2. Addis Ababa

Bus station –$PM_{2.5}$ concentrations were collected for 8 days (5–12 Sep 2019) at the Addis Ababa International Stadium Bus Station and compared with measurements from an urban background site (Table S2). The collected 10 s data was converted to 1 h averages. The monitor was installed at the Addis Ababa International Stadium Bus Station, close to an assembly point for bus riders at 1.5 m height above ground. This bus station is one of the busiest stations in Addis Ababa, which is located near to the International Stadium and surrounded by busy roads. The bus station data was compared to the hourly mean $PM_{2.5}$ concentration data from the US embassy urban background site obtained via www.airnow.gov.

Table 1. Summary statistics of measured $PM_{2.5}$ and PM_{10} concentrations for all three East Africa measurements sites during the whole monitoring periods, where uncertainties are at 1 standard deviation ($\pm 1\sigma$) of the mean. The range of 24 h average values are provided within the square brackets.

Cities	Sampling locations	Sampling timeframe (day-month-year)	24 h average $PM_{2.5}$ concentration ($\mu g\,m^{-3}$)	24 h average PM_{10} concentration ($\mu g\,m^{-3}$)	% exceedance of WHO 24 h average $PM_{2.5}$ guideline (25 $\mu g\,m^{-3}$)	EPA AQI ranking of air pollution situation
Addis Ababa	Roadside	9 Jul 2019–4 Aug 2019	90.1 ± 38.3 [28.0–221.7]	155.5 ± 48.4 [66.6–296.4]	100.0	Unhealthy
	Urban background	9 Jul 2019–4 Aug2019	47.4 ± 19.7 [16.9–105.4]	82.9 ± 38.21 [25.6–192.1]	86.4	Unhealthy for sensitive groups
	Rural	9 Jul 2019–4 Aug 2019	8.3 ± 4.1 [3.2–22.2]	12.14 ± 6.0 [4.73–32.3]	0.0	Good
Kampala	Roadside	10 Oct 2018–20 Apr 2019	73.1 ± 34.6 [34.6–199.0]	157.2 ± 60.0 [71.3–361.2]	100.0	Unhealthy
	Urban background	10 Oct 2018–21 Oct 2018	55.7 ± 20.3 [28.8–96.7]	84.4 ± 32.7 [43.2–152.0]	100.0	Unhealthy
	Rural	10 Oct 2018–20 Apr 2019	9.3 ± 4.1 [1.8–20.8]	19.5 ± 9.9 [3.7–61.5]	0.0	Good
Nairobi	Roadside	23 Feb 2019–30 Mar 2019	48.5 ± 14.9 [25.6–108.8]	103.6 ± 45.2 [58.6–227.0]	100.0	Unhealthy for sensitive groups
	Urban background	23 Feb 2019–30 Mar 2019	31.6 ± 15.4 [16.5–58.4]	47.1 ± 37.2 [19.0–67.6]	41.3	Unhealthy for sensitive groups
	Rural	23 Feb 2019–30 Mar 2019	4.5 ± 1.4 [3.1–6.7]	12.3 ± 3.0 [8.8–21.7]	0.0	Good

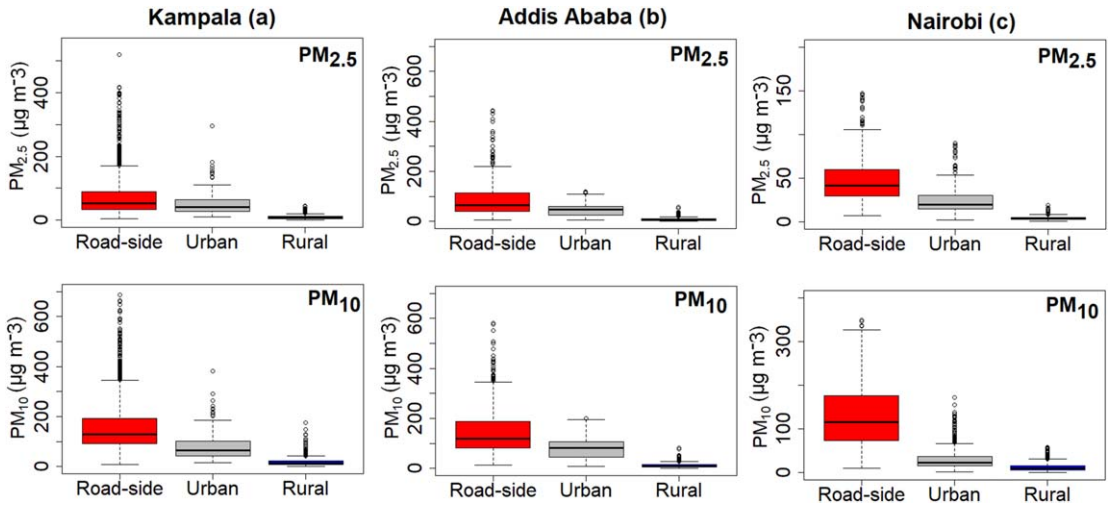

Figure 1. Box and whisker plots of the hourly averaged $PM_{2.5}$ and PM_{10} mass concentrations measured at urban, rural and roadside locations over (a) Kampala (b) Addis Ababa and (c) Nairobi.

Public bus - $PM_{2.5}$ concentrations were measured on board a public bus following three different routes over the course of 1 day (15 Aug 2019): Kara to Merkato (12:07pm–13:30pm), Lamberet to Merkato (17:55pm–19:00pm) and Kara to Anbessa garage (20:00pm–20:50pm) in Addis Ababa. To sample the $PM_{2.5}$ concentrations inside the bus, the OPC-N2 sensor along with GPS device were mounted on the passenger seat near the entrance door.

2.5.3. Nairobi

Building near roadside- $PM_{2.5}$ concentrations were measured at both inside (in a ground floor room) and outside an exemplar building next to a busy road (Moi Avenue) in Nairobi's Central Business District, for eleven days (26 July 2018 to 05 Aug 2018). The building was selected by two major criteria: i) no biomass/household burning sources within the building, and ii) proximity of the building to a busy roadside.

3. Results and discussion

3.1. Air quality in the East African cities

Summary statistics of the measured $PM_{2.5}$ and PM_{10} mass concentrations for all measurements sites during the three study city campaigns are provided in table 1. During the measurement periods, the mean $PM_{2.5}$ and PM_{10} concentrations were highest in Kampala, followed by Addis Ababa then Nairobi for all locations (roadside, urban and rural background) (see table 1). As expected, rural locations in Kampala, Addis Ababa and Nairobi showed cleaner air quality with low PM concentrations compared to roadside and urban backgrounds during the campaign. Figure 1 provides the box and whisker plots of the hourly averaged $PM_{2.5}$ and PM_{10} mass concentrations measured at urban, rural and roadside locations in Kampala, Addis Ababa and Nairobi. These box and whisker plots provide the median averages along with upper and lower quartiles of $PM_{2.5}$ and PM_{10} mass concentrations.

The overall mean mass concentration of $PM_{2.5}$ and PM_{10} at both the roadside and urban background locations were significantly above the WHO limits for $PM_{2.5}$ (25 $\mu g\,m^{-3}$) and PM_{10} (50 $\mu g\,m^{-3}$) for all three study cities, as shown in table 1 and figure 1. Table 1 provides 24 h average data, whereas figure 1 uses average hourly data to highlight the large range of PM concentrations measured during the campaigns. In particular, the daily roadside mean $PM_{2.5}$ mass concentrations exceeded the WHO limits on all days of campaigns in Nairobi and Addis Ababa, in Kampala it exceeded the value 99% of the time (table 1). On many days of the campaign, the daily mean $PM_{2.5}$ concentrations for the urban background sites exceeded the WHO limits in Addis Ababa (86.4%), Nairobi (41.3%) and Kampala (100%).

Using the EPA AQI scale, based upon $PM_{2.5}$, the results, shown in table 1 and figure 1, show that the measured air quality in Kampala, Addis Ababa and Nairobi were typically unhealthy for all residents.

It is noted that the measured mean $PM_{2.5}$ concentrations in Nairobi were 30% higher in 2019 when compared to similar measurements performed in 2017 for the same months (Feb-Mar) at both roadside and urban sites, while there were minor differences in PM_{10} concentration (Pope *et al* 2018). The differences in observed concentrations between the two measurement campaigns can be due to differences in either, or both,

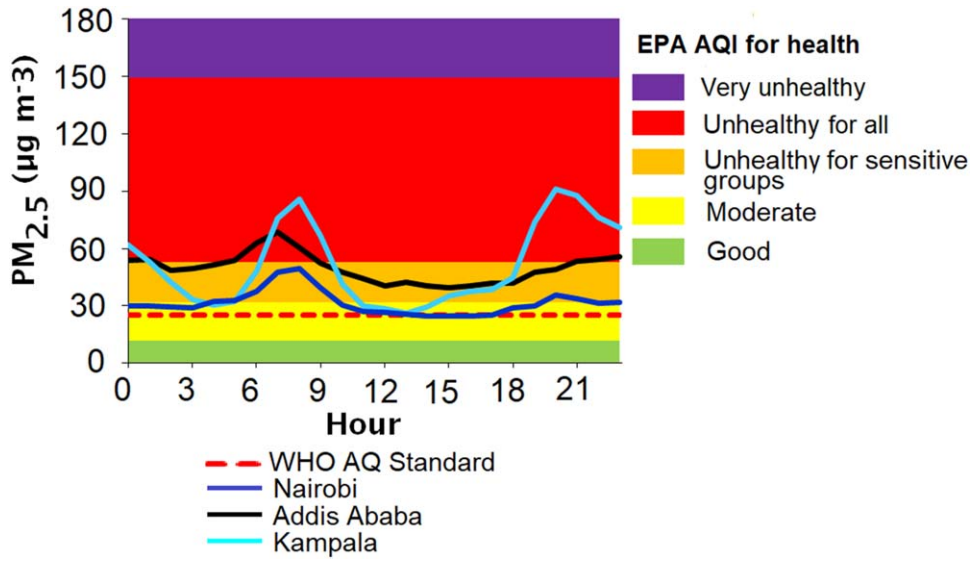

Figure 2. Hourly $PM_{2.5}$ concentrations and WHO air quality guidelines, where different colour backgrounds show the EPA AQI for health.

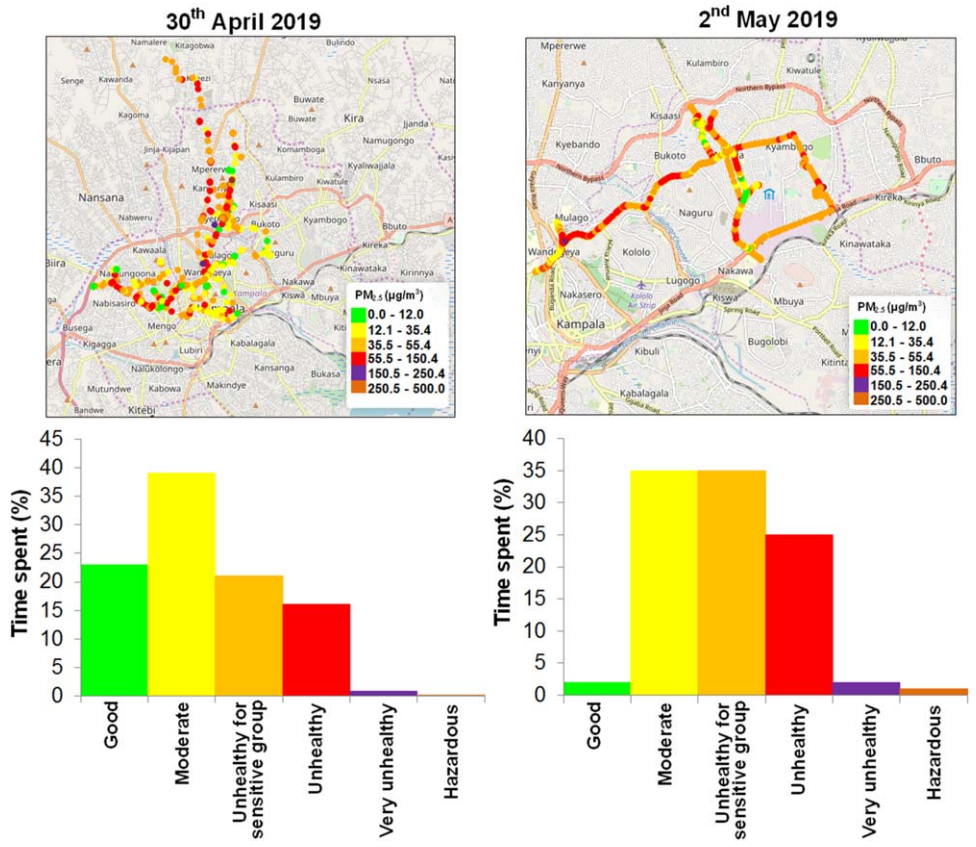

Figure 3. Spatial map of $PM_{2.5}$ concentrations measured on different road routes in Kampala using Boda-Boda taxi, where, colour coding is in accordance with the EPA daily AQI categories.

the sources and losses of the PM. Without detailed information on the meteorology in Nairobi during the two time periods it was impossible to state definitively whether the increased PM concentrations were because of increased sources of PM or decreased losses of PM, or a combination of both source and loss terms. The Singh *et al* (2020) study, which uses visibility as a proxy for air pollution, suggests that PM concentrations are increasing by approximately 4.1% per year in Nairobi. This suggests that the differences in PM during the two field campaigns was likely due to both increased production of PM but also decreased PM losses during the later

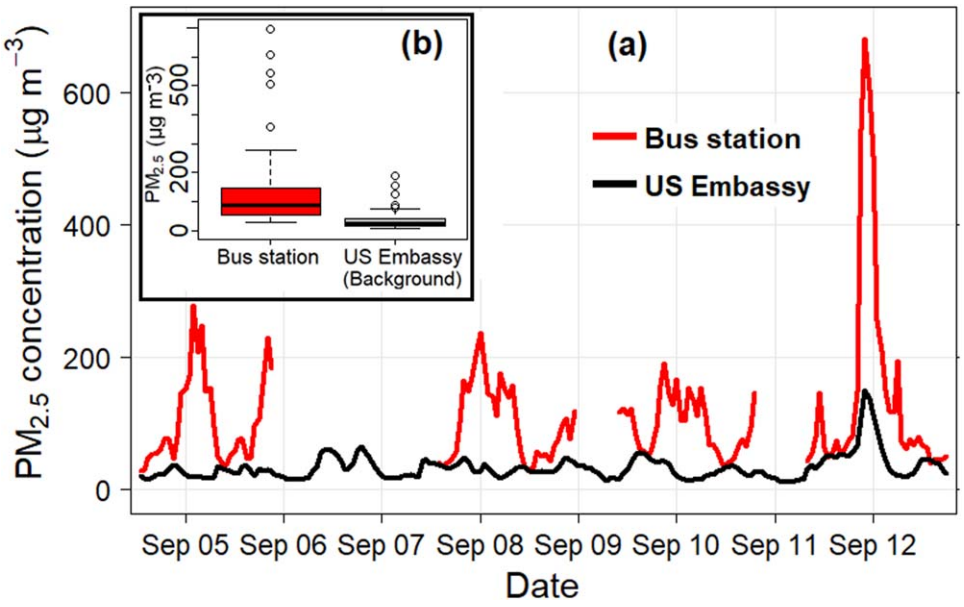

Figure 4. Time series and box and whisker plots of hourly mean $PM_{2.5}$ mass concentration at International stadium bus station and background (US Embassy) sites in Addis Ababa, Ethiopia.

Table 2. Summary statistics of roadside and urban background increment in $PM_{2.5}$ and PM_{10} concentrations during the campaign.

	Roadside 24-hr mean increment in PM level ($\mu g\ m^{-3}$)		Urban background 24-hr mean increment in PM level ($\mu g\ m^{-3}$)	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Addis Ababa	79.5	45.7	65.5	36.3
Kampala	102.0	40.3	66.0	44.6
Nairobi	65.1	23.7	26.4	20.5

field campaign measurement period, when compared to the earlier field campaign. Increased losses can be due to a variety of meteological conditions, including increased wet and dry PM deposition, and horizontal dispersion by wind.

Within the daily average, the air quality situation for Nairobi and Addis Ababa was 'unhealthy for sensitive groups', while for Kampala was 'unhealthy' in reference to the EPA AQI. To enable further exploration of the daily data, hourly diurnal profiles of $PM_{2.5}$ mass concentrations of urban locations are provided in figure 2. There were clear differences between site types when comparing the diurnal profiles. Two peaks were evident during the morning (05:00–10:00 EAT) and evening (16:00–00:00 EAT) periods corresponding to traffic rush hours, indicating a possible dominant PM source related to vehicular emissions at all three sites (figure 2). The evening rush hour period will also likely be impacted by the lowering of the planetary boundary layer, which increases pollutant concentrations. The Planetary boundary layer (PBL) is the region of the lower troposphere, where a layer of warm air is trapped under a layer of cold air, as the result of temperature inversion. The PBL is a function of solar insolation and defines the effective volume that pollution mixes within. The lower the planetary boundary layer height, the smaller the effective volume and hence the greater the pollutant concentration for a given amount of pollution.

The importance of traffic emissions are evaluated by calculating the urban and roadside increment of PM concentrations. The results show a significant roadside and urban increment in $PM_{2.5}$ and PM_{10} concentrations in all study cities (table 2). Overall, the mean roadside increment in $PM_{2.5}$ and PM_{10} concentrations were 49%–55% and 51%–65%, respectively, where Kampala showed the highest increment in roadside $PM_{2.5}$ (55%) and

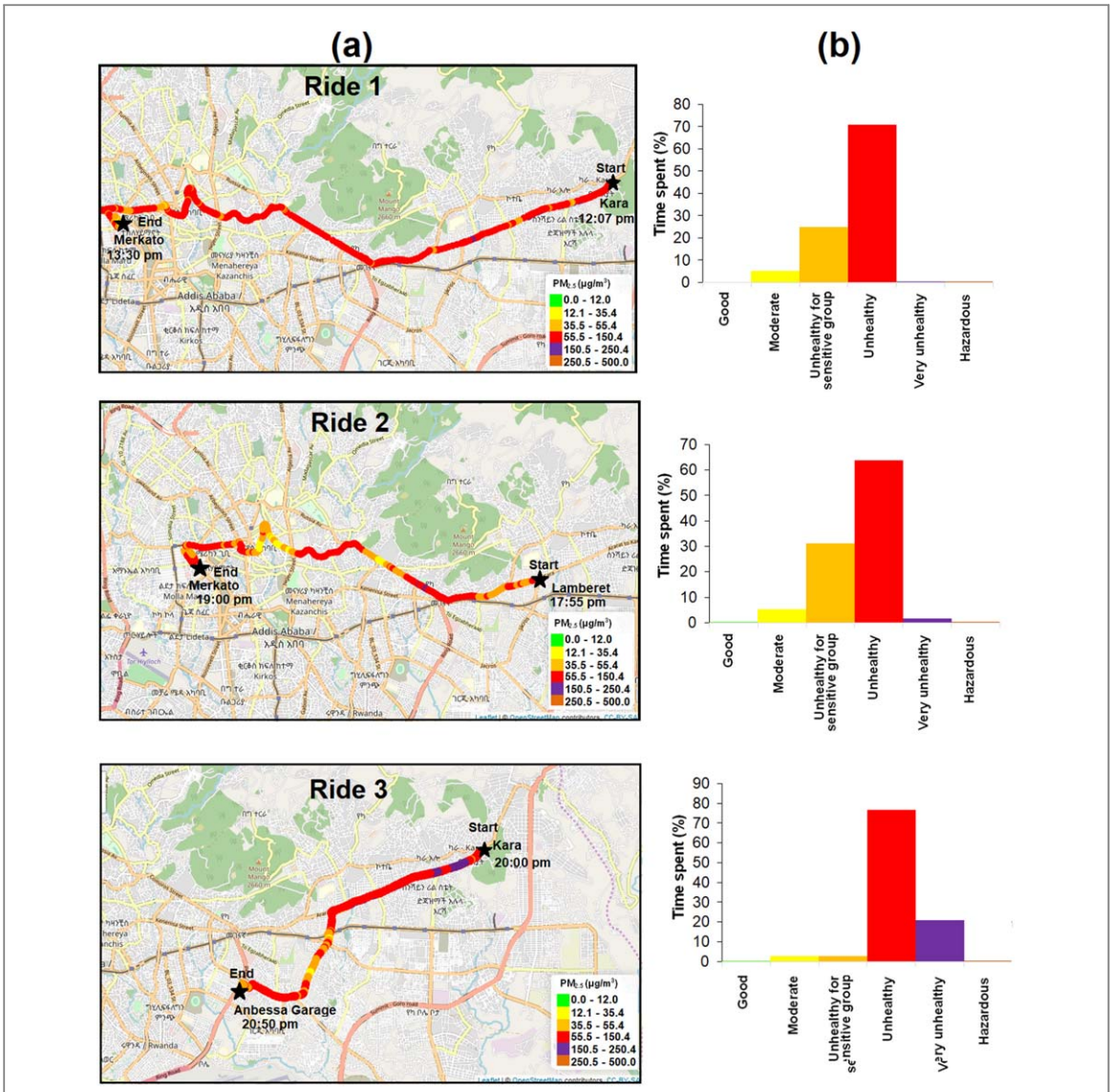

Figure 5. Spatial distribution of $PM_{2.5}$ mass concentrations, which were measured on a public bus (15 Aug 2019) on three distinct routes in Addis Ababa. Here, colour coding is in accordance with the EPA daily AQI categories.

PM_{10} (65%) concentrations as compared to the two other cities. The large roadside increments in all study cities highlight the importance of roads to the urban atmospheric environment in East African cities.

3.2. Case studies within the East African cities

The previous section highlights the importance of road emissions in East African cities upon PM concentrations. In the following sections, $PM_{2.5}$ concentrations were measured at different road and traffic related hotspots (i.e. bus station, road routes and roadside building) within Kampala, Addis Ababa and Nairobi.

3.2.1. Kampala: PM exposure during Boda-Boda ride

PM measurements were collected on a motorcycle taxi (Boda-Boda), where map representations of the $PM_{2.5}$ mass concentrations are shown in figure 3. The range of $PM_{2.5}$ concentration were 1.97–176.5 $\mu g\,m^{-3}$ during the first day and 3.96–504.3 $\mu g\,m^{-3}$ during second day of campaign. For the first day, averaged over all journeys, the mean $PM_{2.5}$ concentration ($\pm 1\sigma$) was 25.2 $\pm$ 24.1 $\mu g\,m^{-3}$, whereas the mean concentration was more than double (51.2 $\pm$ 42.1 $\mu g\,m^{-3}$) during the second day. On the second day heavy traffic jams occured on most routes, which were likely responsible for higher PM emissions. Results showed that the driver and passenger had exposure to poor air quality most of the time during both days of campaign, where 22%–35% of the total travel time was unhealthy for sensitive groups, while an additional 17%–25% of the total travel time was unhealthy for all, according to the EPA daily AQI (figure 3 and table S1).

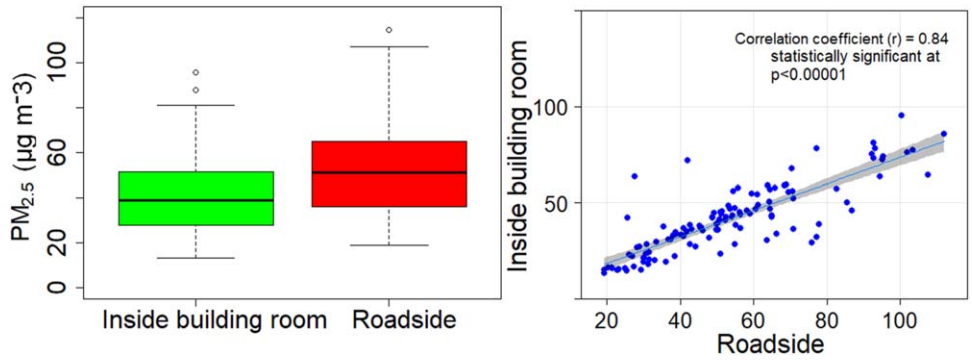

Figure 6. Summary of PM emissions at a building and nearby roadside, where (**a**) hourly mean box plot of $PM_{2.5}$ concentrations (**b**) Correlation between indoor (inside the building room) and outdoor (roadside) $PM_{2.5}$ concentrations.

3.2.2. Addis Ababa: PM exposure at the bus station and on bus

3.2.2.1. Air quality at the bus station

PM air pollution was assessed at the Addis Ababa International Stadium bus station and compared with the background measurement site. The time series of $PM_{2.5}$ concentrations showed that the observed range of hourly $PM_{2.5}$ concentrations were between 28.4–693.2 $\mu g\,m^{-3}$ at the bus station, and 11.0–150.3 $\mu g\,m^{-3}$ at the background site (figure 4). The 24 h mean $PM_{2.5}$ concentration at the bus station (114.4 $\pm$ 50.1 $\mu g\,m^{-3}$) were higher than at the background site (33.0 $\pm$ 8.7 $\mu g\,m^{-3}$) and the bus station values always exceeded the WHO 24-hour average threshold guideline of 25 $\mu g\,m^{-3}$ throughout the eight days of measurement. The overall daily mean bus station $PM_{2.5}$ concentration was found to be at an unhealthy level (using the EPA AQI) and considerably higher (247%) than the measured background concentration (figure 4). $PM_{2.5}$ concentrations were higher over the evening of the 11th September and early morning of the 12th September, compared to the rest of the study days. This high PM period corresponds to the Ethiopian New Year's Eve and celebration day. After the end of the rainy season, Ethiopian New Year (Enkutatash) is celebrated with traditional and cultural activities, including bonfires and fireworks, which was likely responsible for high PM levels on 11th (Singh *et al* 2019).

3.2.2.2. Air quality on the bus

$PM_{2.5}$ measurements were collected on a public bus following three different routes: Kara to Merkato, Lamberet to Merkato and Kara to Anbessa garage in Addis Ababa to explore the on board PM concentrations, and corresponding exposure to the driver and commuters. We observed significant variability in $PM_{2.5}$ concentrations during all three routes (figure 5). The overall average $PM_{2.5}$ concentrations measured were 69.5 $\pm$ 24.5 $\mu g\,m^{-3}$, 69.0 $\pm$ 27.4 $\mu g\,m^{-3}$, and 104.3 $\pm$ 44.5 $\mu g\,m^{-3}$ during the journeys between Kara to Merkato, Lamberet to Merkatoand Kara to Anbessa garage, respectively. The air quality was poor throughout the extent of all three journeys, where 65%–77% of the total time of journey exposed to an unhealthy level as defined by the EPA daily AQI of $PM_{2.5}$ pollution (figure 5 and table S1), since the measurements were made over a sub 24 h period the AQI is only indicative.

3.2.3. Nairobi: Influence of traffic emission on a building's indoor air quality

The influence of roadside PM emission upon a building's indoor air quality was explored. Summary of PM emissions at both inside (in a ground floor room) and outside of a building next to a busy road (Moi Avenue) in Nairobi's Central Business District is shown in figure 6. Overall, daily mean $PM_{2.5}$ concentration at the indoor (inside the building room) and outdoor (roadside) locations were 41.0 $\pm$ 19.5 $\mu g\,m^{-3}$ and 52.0 $\pm$ 24.25 $\mu g\,m^{-3}$, respectively, with both considerably in excess of the WHO threshold by 64% and 108%, respectively (figure 6(a)). PM concentrations at both locations were at unhealthy levels through most of the campaign time, according to EPA AQI. The ratio between indoor and outdoor $PM_{2.5}$ concentrations was calculated to estimate the relative contribution of indoor and outdoor sources to the indoor air quality (Diapouli *et al* 2008). Roadside PM emissions were significantly associated with the indoor air quality ($r = 0.84$), with indoor to outdoor $PM_{2.5}$ ratio of 0.78 $\pm$ 0.16, thus highlighting the importance of road emissions upon nearby buildings (figure 6(b)).

3.2.4. Overview of case studies and limitations

PM concentrations were measured at different traffic and road related hotspots (a bus station, road routes and roadside building) through detailed mobile and static monitoring case studies. Traffic-related monitoring in

Kampala and Addis Ababa, on motorcycle *t*axis, in buses and at bus stations indicated that drivers and commuters were exposed to hazardous levels of air pollution during most of the routes travelled. This is a serious concern as a significant number of people use bus/motorbike transport for their daily commute in East Africa (Campbell *et al* 2019). Monitoring in an exemplar roadside building in Nairobi highlighted that road-related air pollution can also significantly impact upon those working inside buildings located near roads. The indoor air quality in the building was found to be significantly correlated with roadside PM concentrations. This highlights that road/traffic emissions do not just influence road users. It is noted that many people spend significant amounts of time indoors (i.e. office, schools, shops and homes) (Ashrae 2016), therefore the contribution of road/traffic emissions on indoor microenvironments is of particular concern.

Our findings indicate that key contributions to the East African urban air pollution are local sources, predominantly traffic/road emissions. Hence, air quality management initiatives that rely solely on urban background measurements may significantly underestimate the impact of poor air quality on East African cities. Further to this, this study highlights that hotspot measurement campaigns and dynamic air quality measurement programmes can identify locations where air quality may be particularly poor or where particularly vulnerable groups may be present. These outcomes enable the development of tailored mitigation strategies for improving air quality in East African cities. It is likely that social, political and economic changes are necessary to develop a comprehensive strategy in order to address air pollution challenges in such rapidly industrialising settings, and support sustainable economic development.

For the Lenschow type analysis the locations, heights and measurement periods for the rural background, urban background and roadside measurement sites, in the three study cities, were different. Since PM concentration can vary as a function of location, height and time of year, these differences provide a limitation to the study.

Another limitation is for the measurements that were performed on the Boda boda motorcycles, the motorcycles are a source of pollution as well as being the location for the pollution sensor and hence are not truly independent.

The case study nature of this study introduces limitations to the strength of interpretation possible. Only a limited number of locations were measured, and the measurement periods at the case study locations were relatively short. However, the case studies provide clear evidence for the role of roads as a major source of urban pollution in East African cities. Furthermore, they provide a blueprint for future longer term studies in multiple locations to identify poor air quality urban hotspots, and to discriminate between local and regional sources in these East African cities.

4. Conclusions

This study provides a cross-sectional assessment of contemporary air quality in three East African cities of Kampala (Uganda), Addis Ababa (Ethiopia) and Nairobi (Kenya) through a series of low-cost sensor measurements, focusing on roadside and traffic-related measurements. The key findings show that the daily mean $PM_{2.5}$ and PM_{10} concentrations at roadside and urban background locations in Kampala, Addis Ababa and Nairobi were significantly above the WHO daily health-based limits, as well as at unhealthy levels according to the EPA AQI. During the time periods measured, Kampala showed the poorest overall air quality compared to the other study cities, with mean $PM_{2.5}$ and PM_{10} concentrations exceeding WHO limits by approximately a factor of 2 at urban background and a factor of 3 at roadside locations. Significant urban and roadside increments in PM were observed over all three East African cities, indicating a clear traffic related air pollution contribution to the urban environments. Measurements on motorcycle *t*axis and buses highlight the high pollution levels and hence exposure possible through mobility in East African cities. The measurements at the bus station and building adjacent to the road highlight the importance of road emissions to nearby air pollution levels.

This work provides much needed baseline data with which to improve understanding of air quality for the capital cities of Addis Ababa, Kampala and Nairobi, and the significant influence of roads and vehicles upon the air quality.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:https://doi.org/10.25500/edata.bham.00000608.

Declaration of Competing Interest

The authors have declared that no competing / conflicting interests exist.

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