Research article

Vehicular exhaust emissions from road transport that substantially contribute to air pollution along Thika superhighway, Kenya

Amos Kamau[1*], Elijah Ngumba[1], Paul Njogu[1], George Mwaniki[2], John Kennedy Mwangi[2], William Apondo[2] and Ivy Murgor[2]

[1]Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya
[2]World Resources Institute, Addis Ababa, Ethiopia
*Corresponding author: amoskimondi@gmail.com

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Abstract

Road transportation is one of the anthropogenic sources of greenhouse gases (GHGs) and other air pollutants in Kenya, which have a serious negative impact on human health. The fact that traffic emissions happen directly at ground level in crowded urban areas and expose millions of people to dangerous pollutants like particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), volatile organic compounds (VOCs) among others, at concentrations significantly higher than those from industrial or natural sources makes them a more serious concern than many other emission sources. For the purpose of developing and implementing relevant policies and technology for adequate mitigation measures, an emission inventory needs to be created. The aim of the current study is to estimate the vehicular emissions from different vehicle categories using Thika Superhighway as a case study. The correlation between vehicle population, emission factors, and vehicle kilometer travelled and the levels of emissions were analyzed by use of qualitative and quantitative methods. The bottom-up approach method was used in this study. A total of 398 vehicles were sampled, which included two wheelers, three wheelers, cars and SUVs, Buses, light motor vehicle (passengers), light motor vehicles (goods) and heavy-duty vehicles (HMV). This study reported that the total vehicular emissions of NOX, carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), PM_{10}, $PM_{2.5}$, black carbon (BC) and organic carbon (OC) are 1,971.501, 2,232.053, 293.514, 19.543, 80.080, 80.080, 45,437.969, 1,772.328 t/year, respectively. From the study, buses were the highest contributors of NO_x, PM_{10}, $PM_{2.5}$ and BC emissions, whereas two-wheelers accounted for the majority of CO and NMVOC emissions. LMV passenger (diesel) accounted for the majority of NH_3 and OC emissions. Implementation of car-free days, use of hybrid and electric vehicles and introduction of policies that aim at eliminating unroadworthy automobiles are some of the policies which are recommended to minimize vehicular emissions in Nairobi County.

Keywords

Vehicular emissions, emission factors, emission inventory, pollution, vehicle kilometer

Introduction

Globally, air pollution is the primary environmental health risk. In Africa, ambient air pollution is more harmful than major diseases like malaria, HIV, or diarrhea because it causes almost a million premature deaths annually (Bauer et al. 2019; Burnett et al. 2018). Insufficient policies and support infrastructure coupled with unplanned urbanization at a rapid pace lead to elevated levels of air pollution in cities across sub-Saharan Africa (SSA) (Amegah and Agyei-Mensah 2017; Liousse et al. 2014). The average annual growth rate of SSA cities is 4.2%, while the global average is 1.7%. As a result, it is predicted that by 2040, the population of SSA cities will have doubled (Chen et al. 2022). This necessitates the implementation of efficient pollution control strategies and policies to address the region's air quality issues, lessen the health burden, and guarantee sustainable urbanization.

A significant portion of ambient air pollution, such as elevated concentrations of ground-level ozone (O_3) 60 µg/m³ (8-hr mean, peak-season) and fine particulate matter ($PM_{2.5}$) 8-h concentrations of 25 µg/m³, is caused by the road transportation industry (Maina et al. 2018; Ramachandra and Shwetmala 2009). This is primarily due to emissions of NO_x, CO, sulfur dioxide (SO_2), BC, VOCs, and OC. Furthermore, on-road traffic contributes to the emission of GHGs (Rossi, Ceccato, and Gastaldi 2020). This includes; carbon dioxide (CO_2) and Short Lived Climate Pollutants (SLCPs), including BC and methane (CH_4), which have an impact on agricultural production, human health, and the climate through both long and short-lived climate forcing (Colvile et al. 2001; Gatari et al. 2019; Kinney et al. 2011; Mbandi et al. 2023; Singh, Sharma, and Agrawal 2017; Sitati et al. 2022).

According to studies on the climate change challenge, under strict mitigation, GHGs emissions mostly from transport industry, which includes CO_2 and CH_4, are predicted to account for a growing portion of overall GHGs emissions (Gernaat et al. 2015). The annual average of CO_2 has risen from 280 parts per million in the pre-industrial era to 419 parts per million in 2023; also, CH_4 has more than doubled since the industrial era, to 1,900 parts per billion in recent years (IPCC 2023). As a result, these GHGs may provide a barrier to meeting the Paris Accords of 2015's 2° to 1.5°C climate target (Santos and Ferreira 2022).

Nairobi is the most populous city in Kenya with over 4.4 million residents (KNBS 2019). Nairobi City has the greatest proportion of automobiles and industrial air pollution sources in Kenya. For instance, the contribution of several sectors to the city's particulate matter ($PM_{2.5}$) levels has been reported. About 40% of Nairobi's $PM_{2.5}$ concentrations are caused by road transportation, while approximately 15% of Nairobi's $PM_{2.5}$ concentrations are caused by industrial operations (Oguge et al. 2024). Therefore, the industry and transportation sectors together are responsible for about 55% of $PM_{2.5}$ air pollution in Nairobi City (Oguge et al. 2024). Every year, Kenya's vehicle population grows, making the country's transportation sector one of the main human sources of air pollutants in the atmosphere. The number of registered automobiles grew at a compound annual growth rate (CAGR) of almost 9% between 2011 and 2019, from about 1.6 million to 3.3 million. (Miriam, Jackson, and Faith 2020). Private investors run *Matatus*, which are the primary mode of public transportation in Nairobi (Kiai et al. 2021; Kirago et al. 2022; Maina et al. 2018). Other common modes of transport in Nairobi County includes motorcycles (Mkutu and Mkutu 2019) and heavy duty trucks which serve the neighboring landlocked countries (Sitati et al. 2022). In Nairobi City, walking and public transportation are the primary modes of transport (Basil and Nyachieo 2023). Approximately 40.7% of all trips in Nairobi are made possible by the paratransit system, which is used by the majority of the population (JICA 2014), 39.7% of trips are made by walking, 13.5% by private vehicles (including taxis), and 5.4% by two-wheelers (County Government of Nairobi, CCN, City 2014). Use of railroad transportation is restricted to rush hours (Mukaria et al. 2017).

In Nairobi, over 39% of the fine particulate matter is caused by automobile emissions. This comprises emissions that come from mechanical processes, including brake, tire, and road surface wear, as well as resuspended road dust (non-exhaust emissions) and exhaust emissions that are generated by the burning of gasoline through the vehicle's tailpipe (Gaita et al. 2014). Given that 60% of all registered vehicles in Kenya are operated in Nairobi, the high rates of motorization inside the city are mostly to blame for the heavy traffic congestion encountered (Kirago et al. 2022). Compared to other African cities, Nairobi City has one of the longest average commutes to work, which is related to severe traffic congestion (Kinney et al. 2011).

Road transportation has been found to be a significant source of NO_x, CO, BC, NH_3, PM_{10}, $PM_{2.5}$, OC and NMVOC emissions in Africa by previous emission estimations (Bond et al. 2004; Marais and Wiedinmyer 2016). The historical growth in road transport emissions in Africa are highlighted by these regional emission inventories, but there is also room for far higher rises in the future. Although these estimates have been made at the continental level, there haven't been many national evaluations done to assess the situation of road transport emissions today, future changes that are anticipated, and the potential impact of mitigation actions in specific African nations.

The main objective of this study is to determine the vehicular emission profile from both exhaust and non-exhaust emissions that leads to air pollution along Thika Superhighway by various vehicle types travelling along Thika Superhighway. The vehicle types studied included two wheelers, three wheelers, Cars and SUVs, and light motor vehicle (passenger), buses, light motor vehicles (goods) and heavy duty vehicles.

Regulations known as emission standards set a cap on the quantity of pollutants that can be discharged into the environment from a variety of sources, such as automobiles, factories, and other machinery. The purpose of these regulations is to limit the discharge of dangerous substances to safeguard public health and air quality. Emission standards, which are frequently stated as a rate or concentration, specify the highest amount of a certain pollutant that can be discharged from a source. The National Environment Management Authority (NEMA) and the Kenya Bureau of Standards (KEBS) have established standards and policies for vehicle emissions in Kenya. These regulations are intended to protect public health and air quality by limiting non-exhaust emissions from road dust and vehicle wear as well as exhaust pollutants from fuel combustion. The nation has been gradually implementing more stringent pollution limits, switching from previous ones to the greener Euro 4 rules (Ayetor et al. 2021). These guidelines are essential for controlling the pollutants that vehicles release, protecting the quality of the air, and advancing public health. The emission factors used in this study are consistent with the Euro IV emission standards that Kenyan automobiles are currently using (Mbandi et al. 2023).

Materials and methods

Study area

The study was conducted along the Thika Superhighway, located within the Nairobi Metropolitan Region, Kenya. The Thika Superhighway is a dual carriageway approximately 45 km long, forming part of the international trunk route that connects Nairobi City with Ethiopia to the north. The highway begins at Muthaiga Roundabout in Nairobi, proceeds through Kasarani, Githurai Interchange, Kenyatta University, Ruiru Town, and Juja Town, and terminates near the Blue Post Hotel in Thika. This transport corridor traverses Nairobi and Kiambu counties, two of the most densely populated and rapidly urbanizing regions in Kenya and serves as a major conduit for commuter, industrial, and freight traffic.

Land use along the study corridor has undergone rapid transformation over the past decade. Near Nairobi, land is predominantly occupied by high-density residential estates, commercial centers, and light manufacturing industries, particularly around Allsops and Ruiru. In contrast, the Thika end of the highway has transitioned from small-scale agriculture to extensive real-estate developments and industrial estates, reflecting intense urban expansion and industrialization pressure within the Nairobi metropolitan periphery. The corridor also accommodates educational and institutional establishments such as Kenyatta University and several technical institutes, which contribute to high daily human mobility.

According to the 2019 Kenya Population and Housing Census (KNBS 2019), the counties and sub-counties along Thika Superhighway have recorded substantial population growth. Nairobi County had a total population of 4,397,073, while Kiambu County recorded 2,417,735 inhabitants. Within Kiambu, Ruiru Sub-County had 371,111 people, Juja Sub-County 300,948, and Thika Town approximately 279,429 residents in 2019. These populations represent sharp increases from 2009 figures (Ruiru 238,858; Juja 40,446; Thika 136,917) (KNBS 2012), underscoring the rapid urbanization and motorization along the corridor. The highway therefore experiences significant vehicular congestion, dominated by private cars, public service vehicles, and heavy commercial trucks transporting goods between Nairobi, central Kenya, and northern corridors.

Data collection

Two data sources were utilized: traffic count data and a questionnaire survey, as presented in Supplementary Tables S1 and S2. Total vehicle count sampling was considered for all vehicles entering and leaving the Nairobi central district where the sampling station was at the top of the NYS footbridge, Longitude 1°15'21.1926'' and Latitude 36°51'18.54''E. Total Vehicle count sampling was done at three alternate days on 14th, 16th and 18th March 2023, and the average used as the weekly mean. Total vehicle count in Thika road was sampled for 12 hours from 6:30 am in the morning to 6:30 pm in the evening. Sampling was done by twelve research assistants (6 from the inbound and another 6 from the outbound).

Random sampling with the help of a questionnaire survey was used to obtain information on the origin and destination (OD) of the vehicles crew, model type, year of manufacturer (YOM), number of trips per day, age of the vehicle and fuel type. To ensure that the survey was representative, vehicles were divided into seven different groups: Cars and sport utility vehicles (SUVs,), buses, light motor vehicle (passenger), heavy duty vehicles (HMV), light motor vehicles (goods), two wheelers and three wheelers.

The sample size was determined based on the population size, confidence interval as well as the margin of error using Yamane formula;

$$n = \frac{N}{1+N(e)^2} \quad (1)$$

Where; n is sample size, N is Population size and e= 0.05 is the margin of error. The average total number of vehicles recorded along Thika Superhighway over the three sampling days was 75,042±10,148, as presented in Supplementary Table S3. The margin of error e was 0.05. Therefore, a total of 398 questionnaires were required at 95% confidence interval (Adam 2020).

Sample size was conducted using both proportionate and disproportionate sampling techniques. In proportionate sampling, vehicles were selected in proportion to their actual representation in the traffic flow, ensuring that the sample reflected the true composition of vehicles on the road. However, in this approach, light motor vehicles (goods) and three-wheelers were underrepresented due to their relatively low occurrence in the traffic stream. Consequently, disproportionate sampling was employed to guarantee that these underrepresented vehicle categories were adequately represented in the dataset. This ensured that all vehicle classes, including those with smaller population shares but potentially significant emission contributions, were properly accounted for in the comparative analysis and emission estimation (Table 1).

The actual distance travelled by various categories of vehicles was obtained using the Global positioning system (GPS) with the help of a Google map where the boundaries of Thika Superhighway were identified as Muthaiga Roundabout and the bridge around blue post hotel.

Based on previous studies (Mbandi et al. 2023; Ramachandra and Shwetmala 2009) the following equation was used in the determination of emission estimation.

$$E_{ij} = \Sigma N_J \times VKT_j \times E_{F\,I,J} \times 10^{-6} \quad (2)$$

Where; E_{ij} is the emission of pollutant i category j (g/day), N_J is the number of vehicles in category j, VKT_j is the total distance driven by category J (Km/year) and EFI_J is the emission factors of pollutant i category j (g/km).

***Table 1:** Total number of vehicles and operating within Thika Superhighway during the study periods (± indicates the standard deviation)*

Vehicle type	Average number of vehicles for the three days	Proportionate Proportion (%)	Sampling Sample size n=398	Disproportionate Proportion (%)	Sampling Sample size n=398
Two wheelers (petrol)	6,551±565	8.7	35	10	40
Three wheelers(Diesel)	602±70	0.8	3	10	39
Car and SUVs (petrol)	38,412±5905	51.2	204	20	80
Cars and SUVs (Diesel)	10,458±1608	13.9	55	10	40
LMV (passengers) (Petrol)	782±11	1.1	4	10	39
LMV (passenger)(Diesel)	6,021±855	8.0	32	10	40
Buses (Diesel)	8,171±491	10.9	43	10	40
LMV (goods) (Diesel)	1,068±204	1.4	6	10	40
Heavy duty vehicle (Diesel)	2,977±439	4.0	16	10	40
Total	**75,042±7909**	**100**	**398**	**100**	**398**

***Table 2:** Emission factors for road vehicles (gkm^{-1})*

Fuel	Vehicle class	NO_x	CO	NMVOC	NH_3	PM_{10}	$PM_{2.5}$	BC	OC emission factor (OC/BC ratio)
Petrol	Cars and Suvs	0.065	0.62	0.065	0.0342	0.0011	0.0011	15	2.31
Petrol	LMV (passenger)	0.064	2.01	0.128	0.0302	0.0011	0.0011	15	2.31
Petrol	Motorbikes	0.317	7.17	0.918	0.0019	0.0035	0.0035	25	2.31
Diesel	Three wheeler	0.51	0.41	0.14	0.001	0.091	0.091	80	0.18
Diesel	Cars and Suvs	0.58	0.092	0.014	0.0001	0.0314	0.0314	87	0.1
Diesel	LMV (passenger)	0.831	0.375	0.035	0.0012	0.0409	0.0409	87	0.1
Diesel	Buses	5.42	0.223	0.220	0.0029	0.0462	0.0462	75	0.154
Diesel	HDV goods	2.85	0.071	0.008	0.0029	0.081	0.081	65	0.154
Diesel	LMV goods	0.831	0.375	0.035	0.0012	0.0409	0.0409	87	0.1

***Table 3:** Vehicle categories based on the engine type*

Vehicle type	Engine capacity (cubic centimeter)
Two wheelers	100-180
Three wheelers	150-350
Cars and SUVs	1,000-3,000
Light motor vehicles (passengers)	2,000-3,000
Buses	4,300-4,500
Light motor vehicles(goods)	800-4300
Heavy duty vehicle	5,000-10,000

Emission factors for NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, BC, and OC were used to calculate emissions based on VKT for different vehicle types, as shown in Table 2.

The emission factors utilized in this assessment were adapted from the dataset presented by Mbandi et al. (2023), who provided detailed, technology-specific values for the Kenyan vehicle fleet.

Results and discussion

Classification based on the engine capacity of different types of vehicles is given in Table 3. The total vehicle counts and vehicle characteristics are presented in the supplementary data (Tables S3–S11).

A motorbike also called a motorcycle is a two-wheeled vehicle, having a stronger frame than a bicycle that is driven by a petrol, it has an engine type of 100-180CC. A three wheeler is a "Tuktuk" or a motorized cart three wheeler with an engine size of 150-350cc. Private cars which included, four wheeler drive (4WD) and station wagon with a capacity of four to eight passengers, were all classified as cars and SUVs, and had an engine type of 1,000 to 3,000 CC. All public service vehicle with a capacity of 14 to 18 passengers and ambulances were categorized as light motor vehicles (passengers). They had an engine type of 2,000-3,000 CC. Further, public service vehicle with a capacity of thirty-three passengers, cross country bus and institution buses were categorized as buses with their engine type varying between 4,300-4,500 CC. The category of light motor vehicles (goods) includes all medium-sized vehicles utilized for business purposes. This covers pick up vans, Tata Ace and medium-sized Lorries, with an engine type of between 350-4,900 CC. Heavy duty vehicles included type 2 (6 tyres), 6 tyres (2 axle trucks) and 10 tyres (3 axle trucks), 6 axles and 7 or more axles which had

Table 4: *Total number of vehicles operating within Thika Superhighway during the study periods (± indicates the standard deviation)*

Vehicle type	Engines	Diesel Engine Total	Petrol Engine Total	Grand Total
Two wheeler	100% Petrol	0	6,551±565	6,551±565
Three wheeler	100% Diesel	602±70	0	602±70
Cars and SUVs	78.6% Petrol and 21.4% Diesel	10,458±1608	38,412±5905	48,870±7513
LMV (passengers)	88.5% Diesel and 11.5% Petrol	6,021±855	782±11	6,803±866
Buses	100% Diesel	8,171±491	0	8,171±491
LMV (goods)	100% Diesel	1,068±204	0	1,068±204
HDV (goods)	100% Diesel	2,977±439	0	2,977±439
Total		**29,297±3,667 (39.04%)**	**45,745±6,481 (60.96%)**	**75,042±10,148**

Table 5: *Average Annual VKTS for vehicles that travels along Thika Superhighway (± indicates the Standard deviation)*

Vehicle type	Number of trips per day	Distance covered per trip	Distance (km covered per day	Days in a month the vehicle operated	Days in a year the vehicle operated	Annual VKT (Km)
Two wheelers	8±2	9.50±8.05	76.00±16.10	29±2	348±24	26,448.00±386.40
Three wheelers	3±1	21.30±6.00	63.90±6`.00	26±1	312±12	19,936.80±72.00
Cars and SUVs	1	18.00±12.60	18.00±12.60	29±2	348±24	6,264.00±302.40
Buses	5±2	21.80±13.00	109.00±26.00	28±2	336±24	43,344±720.00.00
Light motor vehicle (passengers)	3±1	43.00±30.00	129.00±30.00	29±2	8,171±491	8,171±491
Light motor vehicle (goods)	2±1	11.52±7.47	23.04±14.94	24±3	288±36	6,635.52±537.84
Heavy Duty vehicle	3±1	22.25±12.00	66.75±12.00	23±3	276±36	18,423.00±432.00

Table 6: *Emissions (t/year)*

Fuel	Vehicle class	NO_x	CO	NMVOC	NH_3	PM_{10}	$PM_{2.5}$	BC	OC
Petrol	Two wheeler	54.924	1242.280	159.053	0.329	0.606	0.606	4,331.521	400.233
Diesel	Three wheeler	11.162	109.938	7.561	0.012	9.386	9.386	660.107	6.481
Petrol	Cars and SUVs	15.640	149.180	15.640	8.229	2.647	2.647	3,609.192	555.815
Diesel	Cars and SUVs	37.995	6.027	0.917	0.066	2.057	2.057	5,568.258	7.861
Petrol	LMV passenger	2.174	68.286	4.349	1.026	0.037	0.037	509.598	78.478
Diesel	LMV (passenger)	18.489	580.674	36.978	8.725	0.318	0.318	4,333.386	667.341
Diesel	Buses	1,679.888	69.117	68.187	0.899	64.158	64.158	21,695.966	47.731
Diesel	LMV (goods)	5.889	2.658	0.390	0.009	0.290	0.290	616.546	0.709
Diesel	HDV	145.340	3.894	0.439	0.159	0.581	0.581	4113.395	7.678
Total emission		**1,971.501**	**2,232.053**	**293.514**	**19.453**	**80.080**	**80.080**	**45,437.969**	**1,772.328**

an engine type of 5,000-10,000 CC (Table 2) (Ramachandra and Shwetmala 2009; Sitati et al. 2022).

The total number of vehicles operating on the Thika superhighway, the percentage of each vehicle type, and the sample size are given in Table 4.

Total vehicle count sampling was conducted over three days on 14th, 16th, and 18th March 2023 and the average was calculated to obtain the weekly mean, as shown in Supplementary Table S3. Cars and SUVs were majority of the vehicles along Thika Superhighway since they accounted for 65.1% of the total number of vehicles. Buses were the second most type of vehicles followed by light motor vehicle (passenger)> two wheeler> Heavy duty vehicle goods (HMV)>light motor vehicle (goods)>three wheelers>. Demand for a better lifestyle, which includes owning a car could account for the majority of the vehicles being Cars and SUVs (Brand, Anable, and Morton 2019).

The average annual VKT for each type of vehicle travels within Thika superhighway are given in Table 5 above.

The origin and destination, number of operating days per month for various vehicle types, and the number of trips per day used in the VKT calculations are presented in the supplementary data (Tables S3–S11). Light motor vehicle (passengers) accounted for the largest distance travelled per day, this was then followed by buses> two wheeler>heavy motor vehicles>light motor vehicle (goods) while cars and SUVs had the lowest distance travelled (Table 5). This is due to the fact that LMV (passenger) and buses are majorly public service vehicles which offer public transport to passengers travelling over relatively long distances. Table 6 shows emissions (t/year) from various vehicle types.

Road Traffic Emission Inventory in Thika Superhighway

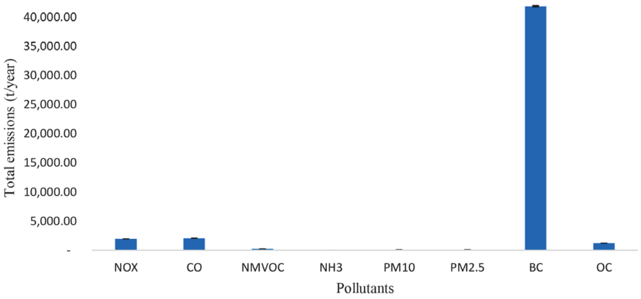

Figure 1: *Total traffic emissions along Thika Superhighway by various pollutants*

BC, a major aerosol produced by burning biomass and fossil fuels, is one of the more harmful types of $PM_{2.5}$ and a powerful climate warmer (Bond et al. 2004; Schaap and Denier van der Gon 2007). The incomplete combustion of organic matter or fossil fuels produces BC, an aerosol made up of fine particle matter. Very varied amounts of BC can be produced by different fuels and combustion processes. For instance, burning natural gas yields very little BC, but burning diesel might yield a sizable quantity. Although the ratio varies based on the fuel type and combustion efficiency, BC and OC are co-emitted. It is crucial to take into consideration both aerosols whenever feasible since, in contrast to BC, OC has a net cooling effect as a climate forcer.

Previous studies reported high concentration of BC emissions (3.9±1.2μgm^{-3}) which was found in Central Business District of Nairobi associated with high traffic rate in traffic congestion. These conditions were observed during morning (6:00 am-9:00am) and evening (4:00pm-8:00pm) traffic peaks (Kirago et al. 2022). As shown in Table 6, high BC emissions (45,437.969 t/year) are attributed to high BC emission factors for both gasoline and diesel vehicles. These findings are consistent with earlier research conducted in urban areas, which highlighted that BC was the primary pollutant in the traffic sector and significantly raised vehicle emission levels as a result of heavy traffic (Gatari et al. 2019; Kirago et al. 2022; Mbandi et al. 2023).

NO_x are a combination of NO and NO_2 gases. Road transport accounts for 61% of the total NO_x emissions (Mbandi et al. 2023). High NO_x emissions (1,971.501 t/year) may be explained by the presence of traffic congestion and old vehicles with no catalytic converters. This may have an impact on human health by contributing to increased respiratory and cardiovascular mortality rates. Apart from three wheelers, Diesel vehicles have a greater NO_x EF than gasoline vehicles, which causes them to produce more NO_x emissions (Table 6). Therefore, the Thika Superhighway fleet composed of 39.04% diesel vehicles (Table 3), contributes to higher NO_x emissions (1,898.763 t/year). Previous studies reported high levels of NO_x emissions which was found to be high in diesel vehicles when compared to gasoline vehicles (Doumbia et al. 2021). Finally, due to outdated diesel vehicles, illegal roadblocks, and inadequate urban traffic management, NO_x concentration measurements in a number of African cities showed an increasing trend (Moselakgomo, Naidoo, and Letebele 2015; Nakajima et al. 2020). Figure 1 also shows that total OC, CO and NMVOC emissions are significant although they are lower than those of BC and NO_x.

Contribution to emissions per vehicle type

Traffic emissions in Thika Superhighway result from various vehicle types. Figure 2 shows emissions Cars and SUVs, two wheelers, three wheelers, LMV (passengers), Buses, LMV (goods) and HDV.

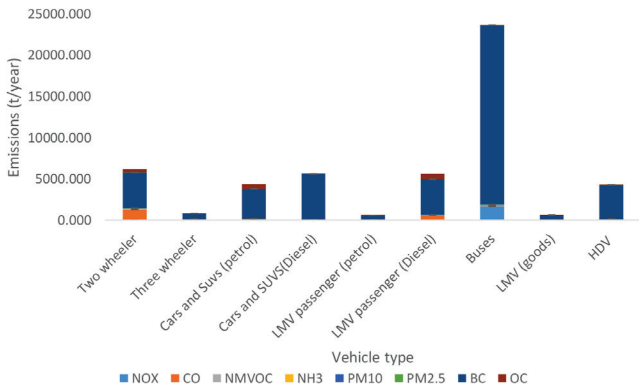

Figure 2: *Stacked bar graph showing emission contribution by different vehicle types operation along Thika Superhighway*

The highest contribution to BC emissions of vehicles on the highway is from Buses (47.8%), which is followed in decreasing order by cars and SUVs (diesel) (12.3%), LMV passenger (diesel) (9.6%), two wheelers (9.6%), HDV (9.1%), Cars and SUVs (petrol) (8.0%), three wheelers (1.5%) and LMV goods (1.4%) and LMV passenger (petrol) with 1.1%. This high contribution by buses is linked to their highest vehicle kilometer travelled per year (37,932±624.00) and their high emission factors (e.g. for BC) (Arevalo-Ascanio and Koech 2025). Further, this might be related to their driving patterns: in general, buses were observed performing several speedups, slowdowns, stops and starts, which result in increased levels of emission. Low contributions are recorded by three wheelers, LMV(goods) and LMV passenger (petrol) i.e. less than 2%, is since their vehicle flow or volume per day is low i.e. 602±70 for three wheelers, 1,068±204 for LMV(goods) and 782±11 for LMV passenger (petrol).

Effects on human health

While elevated emissions of NO_x, predominantly from diesel-powered buses and heavy-duty vehicles, are known to contribute to respiratory irritation, asthma, and reduced lung function (Krzeszowiak, 2016), the emissions reported in this study (1,971.5 t/year) should primarily be interpreted as indicative of potential sources rather than direct measures of population health risk. Health impacts are more closely linked to ambient pollutant concentrations and human exposure levels than to emission totals alone.

Similarly, the reported BC emissions (45,437.97 t/year) reflect a considerable contribution from traffic, particularly buses, to primary particulate emissions. BC is a key component of fine particulate matter ($PM_{2.5}$), which has been associated with systemic inflammation, ischemic heart disease, and stroke (Nakajima et al., 2020). These findings underscore the need for further assessment of ambient BC levels to better evaluate potential health implications for frequent commuters and roadside populations.

Emissions of PM_{10} and $PM_{2.5}$ (80.08 t/year each) remain a concern, as $PM_{2.5}$ particles can penetrate deep into the respiratory system and impair pulmonary function. Studies in Nairobi (Gaita et al., 2014; Gatari et al., 2019) have reported elevated ambient PM concentrations linked to vehicular activity, highlighting the role of traffic as a major contributor to urban air quality degradation. CO emissions, estimated at 1,242.28 t/year and largely from two-wheelers and gasoline vehicles, can reduce the oxygen-carrying capacity of blood and cause symptoms such as headaches, fatigue, and dizziness under elevated exposure conditions (Duan et al., 2021).

NMVOCs also play an important role by reacting with NO_x to form ground-level ozone, a pollutant known to cause respiratory irritation and reduced lung function (Kim, Kim, and Kim, 2020). Additionally, NH_3 and OC emissions can enhance secondary aerosol formation, indirectly contributing to elevated $PM_{2.5}$ levels and urban haze (Ehrnsperger and Klemm, 2021).

Conclusions

This study quantified vehicular emissions along Thika Superhighway using a bottom-up approach that incorporated locally relevant data on vehicle population, EF, and VKT. The findings provide a comprehensive emission inventory for one of Kenya's busiest transport corridors, contributing valuable baseline information for urban air quality management.

The results revealed that road transport is a major source of air pollutants, with significant annual emissions of BC (45,437.97 t/year), NO_x (1,971.50 t/year), and CO (2,232.05 t/year). Buses were identified as the largest contributors to NO_x, PM_{10}, $PM_{2.5}$, and BC emissions due to their high fuel consumption, frequent stop–go driving patterns, and diesel dependence. Conversely, two-wheelers were the predominant sources of CO and NMVOC, while diesel light motor vehicles (passenger) accounted for most NH_3 and OC emissions. These findings underscore the dominant role of public transport and informal vehicle fleets in shaping the region's pollution profile.

The emission burden observed along Thika Superhighway indicates a substantial contribution of vehicular activities to urban air pollution and public health risks in Nairobi. Exposure to high levels of NO_x, BC, and PM can aggravate respiratory and cardiovascular diseases, especially among populations living or working near major traffic corridors. The results emphasize the urgency of transitioning toward cleaner transport systems and implementing evidence-based mitigation strategies.

Effective policy interventions should include the promotion of low and zero-emission vehicles, enforcement of vehicular emission standards, routine inspection and maintenance of older fleets, and the establishment of dedicated non-motorized and public transit lanes to ease congestion. Additionally, introducing car free days and expanding electric mobility infrastructure could significantly lower the pollutant load. Developing localized emission factors and integrating real-time monitoring and modeling tools would further reduce uncertainties and improve future emission estimations.

Data availability

The datasets and/or analyzed during the current study is available from the corresponding author on request.

Credit authorship contribution statement

Amos Kimondo Kamau: Writing, review and editing, writing original draft, visualization, validation, supervision, resources, project administration, methodology, investigation, formal analysis, data curation, conceptualization.
Elijah Kung'u Ngumba: Writing, review and editing, writing original draft, visualization, validation, supervision, resources, project administration, methodology, investigation, formal analysis, data curation, conceptualization.
Paul Mwangi Njogu: Writing review and editing, writing original draft, resources, methodology, investigation, funding acquisition, data curation, conceptualization.
George Mwaniki: Writing review and editing, writing original draft, visualization, validation, supervision, software, resources, project administration, methodology, investigation, formal analysis, data curation, conceptualization.
John Kenendy Mwangi: Validation, resources, methodology, investigation, data curation.
William Apondo: Visualization, validation, resources, methodology, funding acquisition, conceptualization.
Ivy Murgor: Visualization, validation, resources, methodology, funding acquisition, conceptualization.

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Declaration of competing interests

The authors declare no competing interests.

References

Adam, Anokye M. 2020. "Sample Size Determination in Survey Research Sample Size Determination in Survey Research." (June). doi:10.9734/JSRR/2020/v26i530263.

Amegah, A. Kofi, and Samuel Agyei-Mensah. 2017. "Urban Air Pollution in Sub-Saharan Africa: Time for Action." *Environmental Pollution* 220: 738–43. doi:10.1016/j.envpol.2016.09.042.

Arevalo-Ascanio, Rafael, and Alex Kipkorir Koech. 2025. "Spatio-Temporal Assessment of Polluting Emissions from Transport Commuting in Kenya: The First Step to Inform Mitigation Strategies." *African Transport Studies* 3(May): 100056. doi:10.1016/j.aftran.2025.100056.

Ayetor, G. K., Innocent Mbonigaba, Joshua Ampofo, and Albert Sunnu. 2021. "Investigating the State of Road Vehicle Emissions in Africa: A Case Study of Ghana and Rwanda." *Transportation Research Interdisciplinary Perspectives* 11(February): 100409. doi:10.1016/j.trip.2021.100409.

Basil, Paschalin, and Gladys Nyachieo. 2023. "Exploring Barriers and Perceptions to Walking and Cycling in Nairobi Metropolitan Area." *Frontiers in Sustainable Cities* 4. doi:10.3389/frsc.2022.775340.

Bauer, Susanne E., Ulas Im, Keren Mezuman, and Chloe Y. Gao. 2019. "Desert Dust, Industrialization, and Agricultural Fires: Health Impacts of Outdoor Air Pollution in Africa." *Journal of Geophysical Research: Atmospheres* 124(7): 4104–20. doi:10.1029/2018JD029336.

Bond, Tami C., David G. Streets, Kristen F. Yarber, Sibyl M. Nelson, Jung Hun Woo, and Zbigniew Klimont. 2004. "A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion." *Journal of Geophysical Research: Atmospheres* 109(14). doi:10.1029/2003JD003697.

Brand, Christian, Jillian Anable, and Craig Morton. 2019. "Lifestyle, Efficiency and Limits: Modelling Transport Energy and Emissions Using a Socio-Technical Approach." *Energy Efficiency* 12(1): 187–207. doi:10.1007/s12053-018-9678-9.

Burnett, Richard, Hong Chen, Mieczyslaw Szyszkowicz, Neal Fann, Bryan Hubbell, C. Arden Pope, Joshua S. Apte, et al. 2018. "Global Estimates of Mortality Associated with Longterm Exposure to Outdoor Fine Particulate Matter." *Proceedings of the National Academy of Sciences of the United States of America* 115(38): 9592–97. doi:10.1073/pnas.1803222115.

Chen, Shiyin, Qingxu Huang, Raya Muttarak, Jiayi Fang, Tao Liu, Chunyang He, Ziwen Liu, and Lei Zhu. 2022. "Updating Global Urbanization Projections under the Shared Socioeconomic Pathways." *Scientific Data* 9(1): 1–10. doi:10.1038/s41597-022-01209-5.

County Government of Nairobi City. 2014. "The Project on Integrated Urban Development Master Plan for the City of Nairobi in the Republic of Kenya." (May): 82. http://www.nairobi.go.ke/assets/Documents/EI-JR14112-Master-Plan-01-1-1.pdf.

Doumbia, Madina, Adjon A. Kouassi, Siélé Silué, Véronique Yoboué, Cathy Liousse, Arona Diedhiou, N'Datchoh E. Touré, et al. 2021. "Road Traffic Emission Inventory in an Urban Zone of West Africa: Case of Yopougon City (Abidjan, Côte d'ivoire)." *Energies* 14(4): 1–19. doi:10.3390/en14041111.

Duan, Linfeng, Wei Hu, Di Deng, Weikai Fang, Min Xiong, Peili Lu, Zhenliang Li, and Chongzhi Zhai. 2021. "Impacts of Reducing Air Pollutants and CO_2 Emissions in Urban Road Transport through 2035 in Chongqing, China." *Environmental Science and Ecotechnology* 8: 100125. doi:10.1016/j.ese.2021.100125.

Ehrnsperger, Laura, and Otto Klemm. 2021. "Source Apportionment of Urban Ammonia and Its Contribution to Secondary Particle Formation in a Mid-Size European City." *Aerosol and Air Quality Research* 21(5): 1–18. doi:10.4209/aaqr.2020.07.0404.

Gaita, S. M., J. Boman, M. J. Gatari, J. B.C. Pettersson, and S. Janhäll. 2014. "Source Apportionment and Seasonal Variation of $PM_{2.5}$ in a Sub-Saharan African City: Nairobi, Kenya." *Atmospheric Chemistry and Physics* 14(18): 9977–91. doi:10.5194/acp-14-9977-2014.

Gatari, Michael J., Patrick L. Kinney, Beizhan Yan, Elliott Sclar, Nicole Volavka-Close, Nicole S. Ngo, Samuel Mwaniki Gaita, et al. 2019. "High Airborne Black Carbon Concentrations Measured near Roadways in Nairobi, Kenya." *Transportation Research Part D: Transport and Environment* 68(October): 99–109. doi:10.1016/j.trd.2017.10.002.

Gernaat, David E.H.J., Katherine Calvin, Paul L. Lucas, Gunnar Luderer, Sander A.C. Otto, Shilpa Rao, Jessica Strefler, and Detlef P. van Vuuren. 2015. "Understanding the Contribution of Non-Carbon Dioxide Gases in Deep Mitigation Scenarios." *Global Environmental Change* 33: 142–53. doi:10.1016/j.gloenvcha.2015.04.010.

IPCC. 2023. "Summary for Policymakers: Synthesis Report." *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (studies): 1–34.

JICA. 2014. "Nairobi Integarted Urban Development Master Plan."

Kiai, Caroline, Christopher Kanali, Joseph Sang, and Michael Gatari. 2021. "Spatial Extent and Distribution of Ambient Airborne Particulate Matter ($PM_{2.5}$) in Selected Land Use Sites in Nairobi, Kenya." *Journal of Environmental and Public Health* 2021. doi:10.1155/2021/4258816.

Kim, Sun Young, Esther Kim, and Woo Jin Kim. 2020. "Health Effects of Ozone on Respiratory Diseases." *Tuberculosis and Respiratory Diseases* 83: S6–11. doi:10.4046/TRD.2020.0154.

Kinney, Patrick L., Michael Gatari Gichuru, Nicole Volavka-Close, Nicole Ngo, Peter K. Ndiba, Anna Law, Anthony Gachanja, et al. 2011. "Traffic Impacts on $PM_{2.5}$ Air Quality in Nairobi, Kenya." *Environmental Science and Policy* 14(4): 369–78. doi:10.1016/j.envsci.2011.02.005.

Kirago, Leonard, Michael J. Gatari, Örjan Gustafsson, and August Andersson. 2022. "Black Carbon Emissions from Traffic Contribute Substantially to Air Pollution in Nairobi, Kenya." *Communications Earth and Environment* 3(1): 1–8. doi:10.1038/s43247-022-00400-1.

KNBS. 2012. "Kenya 2009 Population and Housing Census, Volume XV: Analytical Report on Kenya Population Atlas." XV(March).

KNBS. 2019. II 2019 Kenya Population and Housing Census *Distribution of Population by Administrative Units*. http://www.knbs.or.ke.

Krzeszowiak, Jakub. 2016. "The Impact of Particulate Matter (PM) and Nitric Oxides (NO_x) on Human Health and an Analysis of Selected Sources Accounting for Their Emission." *Medycyna Środowiskowa - Environmental Medicine* Vol. 19(3): 7–15. doi:10.19243/2016301.

Liousse, C., E. Assamoi, P. Criqui, C. Granier, and R. Rosset. 2014. "Explosive Growth in African Combustion Emissions from 2005 to 2030." *Environmental Research Letters* 9(3). doi:10.1088/1748-9326/9/3/035003.

Maina, E. G., A. N. Gachanja, M. J. Gatari, and H. Price. 2018. "Demonstrating $PM_{2.5}$ and Road-Side Dust Pollution by Heavy Metals along Thika Superhighway in Kenya, Sub-Saharan Africa." *Environmental Monitoring and Assessment* 190(4). doi:10.1007/s10661-018-6629-z.

Marais, Eloise A., and Christine Wiedinmyer. 2016. "Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa)." *Environmental Science and Technology* 50(19): 10739–45. doi:10.1021/acs.est.6b02602.

Mbandi, Aderiana Mutheu, Christopher S. Malley, Dietrich Schwela, Harry Vallack, Lisa Emberson, and Mike R. Ashmore. 2023. "Assessment of the Impact of Road Transport Policies on Air Pollution and Greenhouse Gas Emissions in Kenya." *Energy Strategy Reviews* 49: 101120. doi:10.1016/j.esr.2023.101120.

Miriam, Bomett, Wambua Jackson, and Chebet Faith. 2020. "A Utomotive S Ector Profile."

Mkutu, Kennedy, and Tessa Rhodes Mkutu. 2019. "Public Health Problems Associated with 'Boda Boda' Motorcycle Taxis in Kenya: The Sting of Inequality." *Aggression and Violent Behavior* 47(July 2017): 245–52. doi:10.1016/j.avb.2019.02.009.

Moselakgomo, M, M Naidoo, and M Letebele. 2015. "The Indicative Effects of Inefficient Urban Traffic Flow on Fuel Cost and Exhaust Air Pollutant Emissions." (Satc): 851–57.

Mukaria, Samson Murangiri, Raphael G Wahome, Michael Gatari, Thuita Thenya, and Kiemo Karatu. 2017. "Particulate Matter from Motor Vehicles in Nairobi Road Junctions Kenya." *Journal of Atmospheric Pollution* 5(2): 62–68. doi:10.12691/jap-5-2-4.

Nakajima, Teruyuki, Toshimasa Ohara, Toshihiko Masui, Toshihiko Takemura, Kei Yoshimura, Daisuke Goto, Tatsuya Hanaoka, et al. 2020. "A Development of Reduction Scenarios of the Short-Lived Climate Pollutants (SLCPs) for Mitigating Global Warming and Environmental Problems." *Progress in Earth and Planetary Science* 7(1): 1–21. doi:10.1186/s40645-020-00351-1.

Oguge, Otienoh, Joshua Nyamondo, Noah Adera, Lydia Okolla, Beldine Okoth, Stephen Anyango, Augustine Afulo, et al. 2024. "Fine Particulate Matter Air Pollution and Health Implications for Nairobi, Kenya." *Environmental Epidemiology* 8(3): E307. doi:10.1097/EE9.0000000000000307.

Ramachandra, T. V., and Shwetmala. 2009. "Emissions from India's Transport Sector: Statewise Synthesis." *Atmospheric Environment* 43(34): 5510–17. doi:10.1016/j.atmosenv.2009.07.015.

Rossi, Riccardo, Riccardo Ceccato, and Massimiliano Gastaldi. 2020. "Effect of Road Traffic on Air Pollution. Experimental Evidence from Covid-19 Lockdown." *Sustainability (Switzerland)* 12(21): 1–17. doi:10.3390/su12218984.

Santos, Filipe Duarte, and Paulo Lopes Ferreira. 2022. "The Climate Change Challenge: A Review of the Barriers and Solutions to Deliver a Paris Solution." : 1–32.

Schaap, M., and H. A.C. Denier van der Gon. 2007. "On the Variability of Black Smoke and Carbonaceous Aerosols in the Netherlands." *Atmospheric Environment* 41(28): 5908–20. doi:10.1016/j.atmosenv.2007.03.042.

Sitati, Cynthia N, Christopher Oludhe, Leah Oyake, and Aderiana M Mbandi. 2022. "A Street-Level Assessment of Greenhouse Gas Emissions Associated with Traffic Congestion in the City of Nairobi , Kenya The Problem : Nairobi City with Uhuru Highway as a Case Study." *Clean Air Journal* 32(1): 1–12.

Supplementary material

Supplementary material can be accessed at https://cleanairjournal.org.za/article/view/23304