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Full Length Article

Route-Based Emissions Inventory and Energy Consumption of Passenger Vehicles: Case of Addis Ababa, Ethiopia

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ABSTRACT

Emission inventories play a crucial role in identifying the primary sources of atmospheric pollution. In urban environments, including Addis Ababa, elevated concentrations of vehicle emissions pose significant environmental risks. Consequently, measuring vehicle emissions becomes imperative for estimating the impact of passenger vehicles on urban air quality. In 2022, a drive cycle specific to Addis Ababa was developed for the first time; however, it was not utilized for determining both fuel consumption and vehicle emissions. Previous studies on emission inventories primarily focused on vehicle classification, neglecting variations in emissions on different types of roads. This study introduces routes-based emissions inventories and fuel consumption estimates for passenger cars based on the Addis Ababa drive cycle and the Worldwide Harmonized Light Vehicles Test Cycle. To validate the model, an experimental chassis dynamometer setup was employed. The findings of this study revealed that driving in the congested urban areas of Addis Ababa contributes to 56.25 % carbon monoxide, 37.28 % carbon dioxide, 38.19 % nitrogen oxides, 58.25 % volatile organic compound, 29 % particulate matter emissions, along with 37.29 % fuel consumption. Furthermore, congested urban and rural areas in Addis Ababa account for 60 %–73 % of all emissions and fuel consumption from passenger vehicles. The Addis Ababa city administration shall adopt cleaner technologies, improve public transportation access, and implement stricter emissions standards to mitigate vehicular pollution in the city.

1. Introduction

Using a vehicle is necessary to transport both people and goods. Vehicle emissions pose challenges to the climate, the environment, and people's health (El Hafdaoui et al., 2024; Singh et al., 2020). Pollutant emissions have dramatically grown due to the growing number of vehicles on the road; they now account for 23 %–45 % of all traffic emissions (Zhong et al., 2024). The transportation is responsible for about 20 % of global carbon dioxide (CO_2) emissions (Wang et al., 2025). The average driving velocity affects the amount of CO_2 emitted (Rivera-Campoverde et al., 2024). The World Health Organization (WHO) estimates that ambient air pollution resulted in 4.2 million preventable deaths in 2019. Due to incomplete fuel combustion, vehicle emissions are primarily released through the tailpipe, while non-exhaust emissions occur as a result of tire and brake abrasion, road surface deterioration, and dust resuspension (Piscitello et al., 2021). The majority of automobiles run on fossil fuels, contributing to increased atmospheric emissions of gases such as carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM), hydrocarbon (HC), and CO_2 (Muhammad et al., 2024). The emissions levels from vehicles are also influenced by external variables like fuel quality, road conditions, driving cycle, vehicle servicing, driving behavior, ambient temperature, and humidity (Zhong et al., 2024). To develop strategies that can reduce the environmental effects of vehicle exhaust emissions, it is critical to comprehend the relationship between vehicle emissions and the surroundings (Madziel, 2023). Emission inventories serve as a valuable tool for examining the emission characteristics of the pollution source, offering a comprehensive understanding of the source's emission levels over time in the study area. They provide researchers with a strong scientific foundation for creating management plans (Abdulraheem et al., 2023; Cuéllar-Álvarez et al., 2023; Fan et al., 2023). The methods and inputs used in the emissions inventory's computation have a direct impact on the outcomes' quality (Rivera-Campoverde et al., 2024). Recently, emission inventories were employed by (Abdulraheem et al., 2023; Arti et al., 2022; Li et al., 2023; Marques et al., 2021; Zhu et al., 2023).

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List of abbreviations

AADC	Addis Ababa Drive Cycle
AQI	Air Quality Index
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPERT	Computer Program to Estimate Emissions from Road Transport
FC	Fuel Consumption
GHG	Greenhouse Gas
HBEFA	Handbook on Emission Factors for Road Transport
HC	Hydrocarbon
NO_X	Nitrogen Oxides
PM	Particulate Matter
VOC	Volatile Organic Compounds
WHO	World Health Organization
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

A chassis dynamometer is an effective tool to support vehicle emissions measurements in a laboratory equipped with gas analyzers (Yang et al., 2018). In this process, a vehicle is driven through a predetermined driving cycle on a chassis dynamometer to measure its emissions. The pollutant emissions are then collected, evaluated, and expressed as the mass of pollutant species developed over a specified distance (Alves et al., 2015; Andre, 2004; Lairenlakpam et al., 2018). The Worldwide Harmonized Light Vehicles Test Cycle (WLTC), introduced in 2015, is not universally suitable for emission testing across all automotive industries worldwide (Gebisa et al., 2021; Wang et al., 2023). WLTC is based on the average driving conditions of a few countries, which may not reflect the specific traffic patterns, road infrastructure, and driving habits in many regions. In contrast to WLTC, emission factors derived from local drive cycles have the potential to offer a more realistic picture of emission characteristics. (Gebisa et al., 2022; Zhang et al., 2021). Previous studies, such as those conducted by Zhang et al. (2021), Kumar Pathak et al. (2016), and Ho et al. (2014) utilized local driving cycles to estimate vehicles' emissions.

To assess the impact of the sector's emissions, evaluate the effects of current regulations, and emphasize the urgency of taking action to achieve environmental goals, it is essential to estimate the sector's emissions (Singh et al., 2020). In Europe, the two most widely used macroscopic emission models are the Handbook on Emission Factors for Road Transport (HBEFA) and the Computer Program to Estimate Emissions from Road Transport (COPERT) (Tsanakas et al., 2020). For determining macro-scale emissions the COPERT-based model considers factors such as mileage, driving velocity, vehicle type, and weather conditions (Madziel, 2023). Government agencies use COPERT to calculate emissions from road vehicles (Boveroux et al., 2021; Lozhkina & Lozhkin, 2015). Recently, Cuéllar-Álvarez et al. (2023), and Winther (2020), employed COPERT to estimate road vehicle emissions. Executing emissions control strategies will need reliable assessments of existing and future emissions linked roadways in the urban, rural, and highway routes. However, previous studies primarily focused on emissions from various vehicle categories, often neglecting the impact of different roadways within study areas.

In most developing countries, including Ethiopia, vehicles are not tested for emission and fuel economy in domestic laboratories, using domestic test cycles due to the unavailability of standards and facilities. The Addis Ababa Transport Authority reported 627,460 registered cars in the city in 2021, comprising passenger cars (41 %), light commercial vehicles (34 %), heavy-duty vehicles (18 %), motorcycles (3.96 %), and buses (2.99 %), with 43.43 % powered by gasoline and 56.57 % by diesel fuel, as shown in Fig. 1. Despite the alarming increase in vehicles in Addis Ababa, emissions from these vehicles have received limited attention.

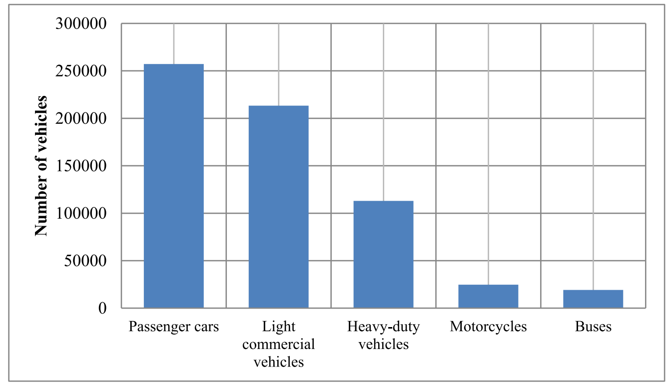

Fig. 1. Distribution of vehicles category in 2021 *(Addis Ababa transport office, 2021)*.

Fig. 1 illustrates the distribution of vehicles in 2021 based on their types.

Various studies conducted in Addis Ababa have identified high emissions pollutants such as CO, NOx, HC, and PM (Bikis & Pandey, 2021; Jida et al., 2020; Tefera et al., 2020). Notably, Ethiopia lacks legally established ambient air quality standards. Despite being a metropolitan city and the seat of the African Union, Addis Ababa lacks air quality monitoring stations. Furthermore, the region lacks previous studies that utilize air quality models to make more precise estimations about air quality.

Emission rates must be developed using data from a specific country to estimate emissions more precisely (Park et al., 2023). Previous emission inventories have mostly depended on emissions variations of different vehicle classes without taking into account the emissions released by vehicles on different types of roads within a specific study area. As a result, such models tend to sacrifice detailed spatiotemporal specificity. Due to this reason it is difficult to identify which roads in the city are responsible for the highest emission levels and which one contribute lower emissions. To address these gaps, this study was developed a methodology for establishing route-based emission inventories that capture the distinct emission trends associated with various road types in Addis Ababa, Ethiopia. This approach aims to provide a more accurate estimation of vehicle emissions released in the city for the year 2022, specifically focusing on passenger cars. Additionally, the Addis Ababa Drive Cycle (AADC) depicted in Figure of Appendix 1 being introduced in 2022, neither its FC nor its emissions have been evaluated. In essence, this study provides an alternative approach to improving the inventory of vehicular emissions based on the local drive cycles. Studying emissions from passenger vehicles in different road types is crucial for implementing practical solutions to reduce air pollution and enhance air quality in the areas of Addis Ababa, Ethiopia.

2. Review of vehicular emissions in Addis Ababa

To evaluate the effects of emissions on air quality concerning changes in vehicle technologies or fleet characteristics, it is crucial to establish a consistent approach and accurately quantify pollutants released by vehicles into the atmosphere, thereby assessing traffic-induced environmental impact. Ethiopia contributed approximately 0.3 % of global emissions and in 2017, the Notre Dame Global Adaptation Initiative country index ranked Ethiopia as the 22^{nd} most vulnerable country to climate change and the 31^{st} least-ready country to enhance resilience, emphasizing the urgent need for action (Wang-Helmreich & Mersmann, 2019). Greenhouse gas (GHG) emissions from passenger cars are projected to increase to 13.1MtCO_2e in 2030, assuming an average fuel efficiency improvement of 10 % (Berhanu, 2017).

At public transportation hubs, elevated concentrations of air pollution from passenger cars, vans, and other types of motor vehicles have been observed (Bikis & Pandey, 2021). The level of air pollution in Addis

Ababa is rapidly increasing due to the growing number of cars on the road. Currently, there are about 630,000 registered vehicles in the city (Mamo et al., 2023). However, the city administration has not enacted any air pollution laws. In Ethiopia, there are no methods for disposing of outdated vehicles, contributing to the deterioration of the urban environment, as older vehicles also release more pollutants into the atmosphere (Bikis & Pandey, 2021). Poor air quality in Addis Ababa is attributed to the city's rapidly expanding transportation industries, rapid urbanization, inadequate, and slow development of the road infrastructure, and the use of fuels with high sulfur content (Tarekegn & Gulilat, 2018).

Table 1 provides reviews of various studies that addressed vehicular emissions in Addis Ababa and highlights the year of study, instruments used, and key findings. Most studies focused on PM, which is a main pollutant in Addis Ababa. This includes the studies by Jida et al. (2020), Tefera et al. (2020), Embiale et al. (2019), and Bikis and Pandey (2021), they identified that PM2.5 and PM10 levels consistently exceeded WHO and air quality index (AQI) standards. Studies by Wondifraw (2018), and Tsegaye et al. (2019), focused on pollutants such as CO, CO_2, NO_2, SO_2, and VOC, analyzing the broader impact of vehicular emissions. Gaseous emissions were quantified using indirect estimations Wondifraw (2018), and Tsegaye et al. (2019), highlighted the increasing emissions intensity over time, suggesting a worsening situation due to fossil fuel dependency and lack of mitigation measures. The previous emissions inventory for Addis Ababa utilized the European drive cycle to estimate vehicle emissions. However, it didn't account for emissions from various route types and was not specific to particular vehicles. In contrast, the current study employed the AADC to analyze the emissions from passenger vehicles in Addis Ababa based on the type of route, and its findings were validated in a chassis dynamometer experimental setup. Overall, this study presents a method for determining emissions from specific passenger vehicles based on real driving conditions in Addis Ababa.

Table 1
Review of Vehicular emissions in AA city.

Reference	Year	Instrument used	Obtained results
Moges and Alemu (2024)	2024	Aeroqual series 500 and LASER	The study found that the levels of CO, SO_2, $PM_{2.5}$, and PM_{10} increased by an average of 19.10 %, 51.61 %, 33.83 %, and 29.07 % during the congested period in Addis Ababa, as compared to the stable condition.
Bizualem et al. (2023)	2023	CW-HAT2005 and Aeroqual series 5000 devices	The study found that the levels of SO_2, NO_2, $PM_{2.5}$, and PM_{10} varied significantly across different locations in Addis Ababa. Notably, the concentration of SO_2 was found exceeding the threshold.
Kebede et al. (2022)	2022	Wager 6500 Digital Smoke Opacity Meter	Analysis of 358 diesel vehicles in the Addis Ababa revealed that 67.9 % exceeded the USA Environmental Protection Agency emission standards with smoke opacity over 41 %. The study also found that minibuses are the primary source of air pollution, more than large and mid-sized buses.
Jida et al. (2020)	2020	Aeroqual series-500 digital analyzer	In comparison to the AQI and the WHO requirements, the city's average 24-h PM2.5 concentration is 13 %–144 % and 58 %–241 % higher, respectively. The PM10 value is likewise above the WHO (8 %–395 %) and AQI (54 %–65 %) guidelines.
Tefera et al. (2020)	2020	Quartz and Teflon filters	90 % of the measured days had $PM_{2.5}$ concentrations above WHO recommendations, with a mean of 53.8 (25.0) g/m^3. 31 % and 36 % of observed days, as compared to the AQI, were harmful for everyone.
Embiale et al. (2019)	2019	SKC 224-PCTX4 and Inductively coupled plasma-optical emission spectroscopy.	The average PM10 values were between 206 and 308 μg/m^3. The main open-market district of the city, Addis Ketema, had the highest pollution levels. The old-town, Arada sub-cities have the lowest concentrations.
Bikis and Pandey (2021)	2021	Air-visual tracking device	The majority of stations had CO_2 levels below 700 ppm, and two of them had average CO_2 levels of up to 1307 ppm during a 30-min air quality measurement. During peak hours, the average PM2.5 at bus and taxi terminals in Addis Ababa exceeds 65 μg/m^3 and 150 AQI, respectively. At AA's main bus stops, PM10 levels rose to 1700 μg/m^3 during peak hours and 970 μg/m^3 during off-peak hours. At peak hours, PM2.5 was increased to 560 μg/m^3 and changed continuously. The minimum concentration was 51 μg/m^3.

(*continued on next page*)

3. Materials and methods

3.1. Methodology

Emission inventories play a crucial role in air quality studies as they furnish data for air quality models. Vehicle statistics, activity data, emissions control devices on vehicles, and local weather conditions are commonly used to estimate emissions over annual timescales. The method outlined involves generating emission inventories using COPERT. This program was employed to calculate the route-based emissions from passenger vehicles, and the results were validated using an experimental chassis dynamometer setup; a type of work that has not been previously undertaken in this study area. Results of emissions and fuel consumption (FC) from chassis dynamometer tests, with error bars are shown in Fig. A2 under the appendix. To conduct this investigation, vehicle exhaust emissions, and FC were measured and analyzed using the framework shown in Fig. 2 for the chosen AADC and WLTC. A detailed comparison between the developed AADC and WLTC is presented in Table A1 in the appendix section of this study. Compared to the WLTC, the AADC exhibited significantly longer idle times and much higher acceleration and deceleration rates. These prolonged idle times in the AADC were due to frequent vehicle stops and movements caused by traffic congestion and closely spaced traffic light signals. Additionally, the AADC has a shorter cycle length (11.885 km) but a comparatively longer duration (2594 s) compared to the WLTC.

3.2. Secondary data collection

The provided average weather data in Table 2 gives an overview of the climatic conditions in Addis Ababa for the year 2022, highlighting minimum and maximum temperatures as well as humidity levels. The data was obtained from the official website of the Ethiopian Meteorological Service. As Table 2 illustrates, July and August are particularly

Table 1 (*continued*)

Reference	Year	Instrument used	Obtained results
Wondifraw (2018)	2018		Passenger vehicles contribute 40.12 % of CO_2 (0.543 Mtons), 76.59 % of CO (6.025 Ktons), 14.33 % of NOx (0.88Ktons), and 33 % of PM (0.152Ktons) emissions in AA city
Tsegaye et al. (2019)	2016		The overall (mean ± SD) CO, VOC, NO_2, and SO_2 concentration levels were 4.82 ± 3.60 ppm, 317.52 ± 221.52 μg/m^3, 0.12 ± 0.16 ppm, and 0.23 ± 0.20 ppm respectively
Taka et al. (2020)	2020		From 1990 to 2017, the emission intensity grew from 2.46 to 3.22 MtCO_2 per kton of fossil fuels, implying more emissions being generated.

notable for their lower temperatures and exceptionally high humidity, which are signs of intense and regular rainfall during these months; February and March, although they fall within the dry season, have the highest maximum temperatures, making them the warmest months of the year. The data in Table 3 summarizes the key specifications of petrol and diesel fuels standards in Ethiopia, providing insight into their energy content, composition, and quality standards. The Ethiopian fuel requirements show adherence to global standards to promote more effective and clean combustion while lowering hazardous emissions. Due to their different use in compression-ignition and spark-ignition engines, respectively, petrol and diesel have differences in their physical and chemical characteristics.

Table 2
Weather data of Addis Ababa city.

Month	Min Temp [°C]	Max Temp [°C]	Humidity [%]
January	8.4	21.8	53
February	9.9	23.3	51
March	11.2	23.3	53
April	11.8	23.2	63
May	11.4	22.9	62
June	12.1	22.9	65
July	11.6	19.8	81
August	10.8	19.2	85
September	9.1	20.4	79
October	7.5	20.6	63
November	7.4	21.1	60
December	7.6	20.9	56

3.3. *Experimental setup*

During a chassis dynamometer test, exhaust samples from the test vehicle were collected as it was being driven onto the dynamometer platform under WLTC and AADC real-world driving cycles. The experimental investigation on the chassis dynamometer, as shown in Fig. 3 was conducted in Uppsala, Sweden under controlled laboratory conditions. A driver assistance system with tolerance levels was employed to assist the driver in adhering to pre-established cycles. Two vehicles were tested, featuring various engine sizes, fuel types, and technological advancements as listed in Table 4. According to the Addis Ababa transport authority, Toyota holds the top position among passenger vehicles representing over 25 % of registered gasoline cars in Addis Ababa, Ethiopia. Within this category, Toyota Corolla stands out as the predominant brand in terms of quantity. Additionally, Hyundai brand vehicles ranked second in Addis Ababa with approximately 14 % of the diesel passenger vehicles market share.

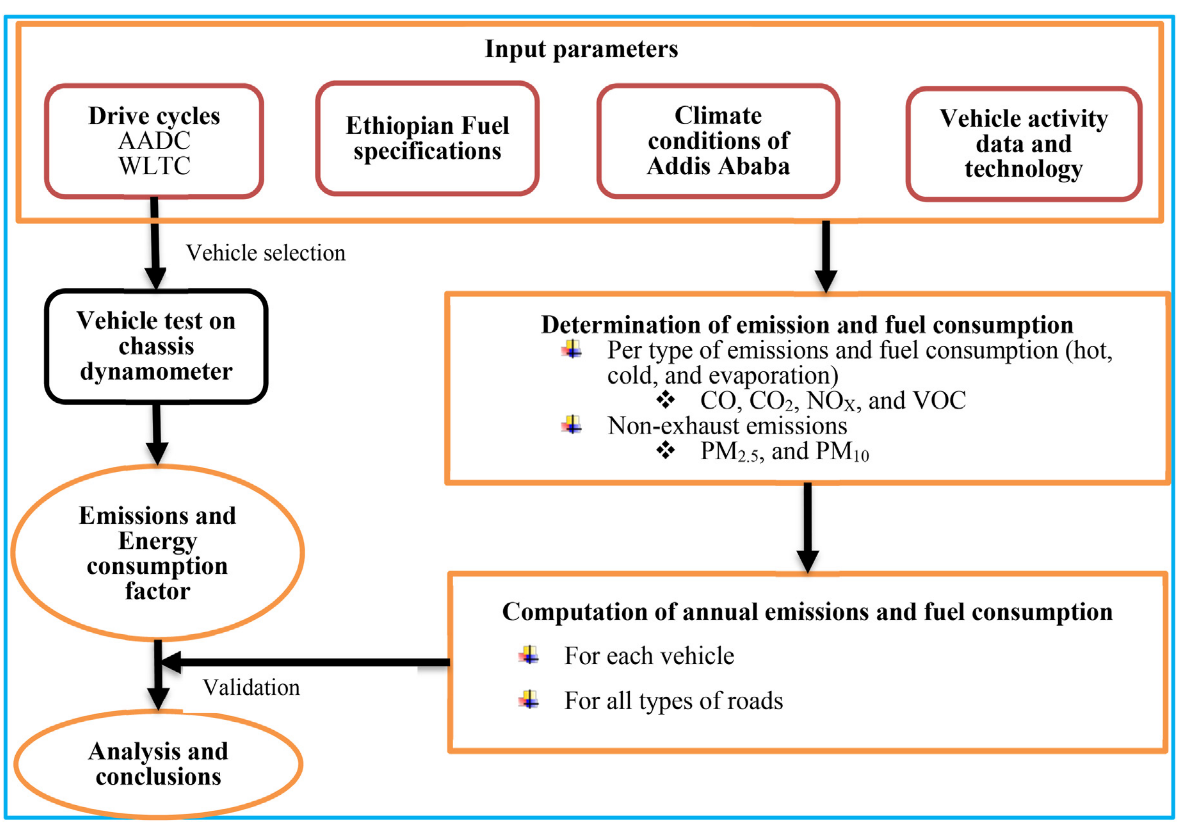

Fig. 2. Study flow chart of the present investigation.

Table 3
Ethiopian fuel specifications (Source: Ethiopian Petroleum Enterprise).

Parameters	Petrol	Diesel
Energy Content [MJ/kg]	43.774	42.695
H: C Ratio [−]	1.86	1.86
Density [kg/m^3]	720–740	820–860
S Content [% wt]	Max 0.05	Max 0.05
Pb Content [g/l]	Max 0.013	Not specified
Cd Content [ppm wt]	0.0002	0.00005
Cu Content [ppm wt]	0.0045	0.0057
Cr Content [ppm wt]	0.0063	0.0085
Ni Content [ppm wt]	0.0023	0.0002
Se Content [ppm wt]	0.0002	0.0001
Zn Content [ppm wt]	0.033	0.018
Hg Content [ppm wt]	0.0087	0.0053
As Content [% wt]	Not specified	Max 0.01
RON/Cetane index	Min 92	Min 48

In this study, the selection of vehicles was based on what was commonly available in Addis Ababa, Ethiopia. The annual accumulated mileage values reported in this study were directly recorded from the vehicles' odometers during the data collection process. Additionally, vehicle owners confirmed that the recorded mileage accurately represents their vehicle's annual usage patterns, ensuring that the data reflects the actual circulation and operational characteristics of the sampled vehicles. The measurement system comprises a chassis dynamometer and an emissions analyzer capable of analyzing the concentrations of CO_2, CO, and NOx from the vehicles. Both gasoline and diesel cars underwent testing on the chassis dynamometer, covering the entire AADC and WLTC cycles. Subsequently, considering the cycle distances, the FC and pollutant concentrations were converted into emission factors (g/km).

3.4. COPERT-based annual vehicle emissions estimation

The COPERT approach was employed in this study to determine emissions from passenger vehicles, taking into account emissions during hot, cold, and evaporation phases. Annual mileage information was collected from drivers, and after assessing the necessary AA climate data and the distance covered by each vehicle category, the data were input into COPERT. Subsequently, COPERT generated quantified results for the five most significant pollutant emissions from selected vehicles within the considered period, for each road type of the study area. These top 5 emissions including CO_2, CO, NO_X, PM, and VOC pose threats to both the environment and public health. COPERT 5.6.1 was used to study the emissions levels and FC of hybrid vehicles in addition to gasoline and diesel passenger cars shown in Table 5. This analysis aimed to demonstrate to policymakers how the new hybrid car reduces emissions and FC compared to conventional cars.

The emissions of various vehicle types were determined in tons per year using Equations (1)–(5) (Ntziachristos et al., 2009). Cold start emissions (E_{cold}) pertain to the release of harmful gases when the fuel ignites at the start of the engine. It was determined as equation (1). The ratio of cold to hot emission factors was determined by equation (2).

$$E_{cold} = \beta \times bc \times N \times M \times e_{hot} \times \left(\frac{e_{cold}}{e_{hot}} - 1\right) \tag{1}$$

$$\frac{e_{cold}}{e_{hot}} = A \times V + B \times T + C \tag{2}$$

Where β is the fraction of mileage driven in cold engine condition, bc is the beta reduction factor, N is the number of vehicles under consideration, M is mileage per vehicle, e_{hot} is the hot emission factor, e_{cold}/e_{hot} is

Table 4
Technical data of tested vehicles on a chassis dynamometer.

S/N	Vehicle category	Vehicle Model	Maximum engine power	Accumulated mileage (km)	Technology
1	Passenger car (Euro 4 gasoline)	Toyota Corolla (2010)	96 kW	468,927	Port fuel injection system
2	Passenger car (Euro 6 diesel)	Hyundai 140 (2015)	101 kW	159,370	Particulate filter and Selective Catalytic Reduction

Table 5
Specifications of selected vehicles and collected activity data.

Selected vehicles	Gasoline car	Diesel car	Petrol-hybrid car
Euro category	Euro 4	Euro 6	Euro 6
Vehicle Model	Toyota Corolla	Hyundai StarX	
Maximum engine power (KW)	96	101	
Accumulated mileage (km)	671,086	211,568	0
Mean activity (km/year)	28,800	43,200	28,800
Technology	Port fuel injection system	Common rail diesel	Gasoline direct injection

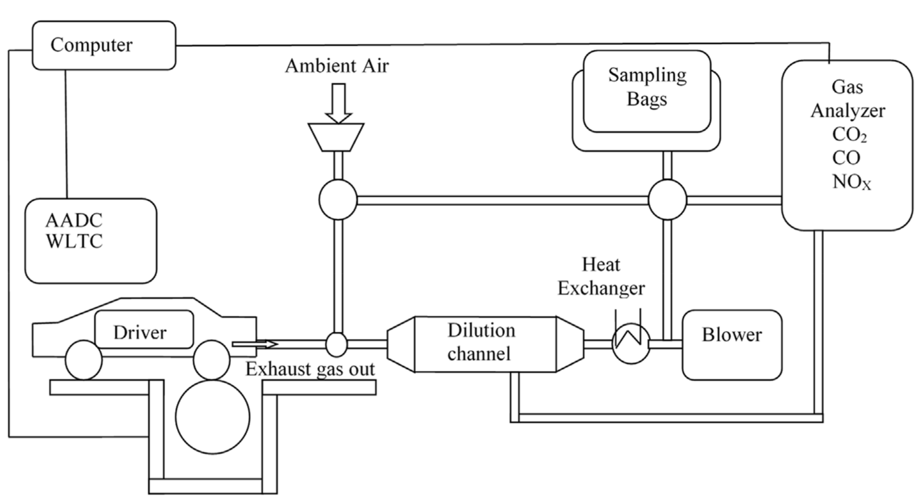

Fig. 3. Experimental set-up of chassis dynamometer for emission and FC measurements.

over-emission level compared to hot emissions, V is vehicle speed in km/h and T is the temperature in ^{o}C.

Hot emissions (E_{hot}) are the pollutants emitted when the engine operates at its designated temperature. This is computed using Equation (3).

$$E_{hot} = NM \times N \times e_{hot} \quad (3)$$

Where NM is km traveled by vehicle (km), and N is the number of vehicles running.

Equation (4) states that COPERT takes into account evaporation from diurnal fuel losses ($E_{diurnal}$), after-use (E_{soak}), and running losses ($E_{running}$).

$$E_{evap} = E_{diurnal} + E_{soak} + R_{running} \quad (4)$$

Finally, the annual total emissions (E_{Total}) were determined using Equation (5).

$$E_{Total} = E_{cold} + E_{hot} + E_{evap} \quad (5)$$

4. Results and discussion

4.1. Emissions factor analysis

The AADC and the WLTC were both utilized in this study to measure the FC, CO_2, CO, and NOx for passenger cars on a chassis dynamometer in Uppsala, Sweden. WLTC and AADC were used as comparison drive cycles for the Gasoline (Toyota Corolla E120) and diesel (Hyundai 140) vehicle types. The emission factors obtained from the chassis dynamometer are presented in Table 6, representing the average of three trial measurements. For passenger cars tested on a chassis dynamometer, it was observed that WLTC underestimated CO_2, FC, and NO_X by 20.43 %, 19.84 %, and 18.76 %, respectively, while CO was overestimated by 34.54 % compared to AADC. The emissions factor findings from the COPERT model and the chassis dynamometer showed a significant difference as shown in Table 5. We believe that the absence of cold start operation in the chassis dynamometer is the main cause of this discrepancy; this explanation is consistent with Alves et al. (2015) findings which found that the absence of cold start emissions could lead emission inventories to understate emissions. The AADC more accurately represents Addis Ababa's city driving condition than WLTC, as indicated by the observed emissions and FC data from experimental findings. Consequently, considering the local weather and traffic conditions, we choose to utilize the AADC to estimate the annual emissions level and FC of passenger vehicles in Addis Ababa.

Table 6
COPERT model and chassis dynamometer emission factors.

EstimatedParameters	Vehicle type	Emissions Factor from Chassis dynamometer		Emissions Factor from COPERT	
		AADC	WLTC	AADC	WLTC
CO (g/km)	Petrol	0.68	0.96	0.6712	0.9518
	Petrol Hybrid			1.6169	0.9653
	Diesel	0.069	0.048	0.0711	0.0487
	Average	0.375	0.504	0.6842	0.5686
CO_2 (g/km)	Petrol	213.68	167.01	215.9289	168.755
	Petrol Hybrid			121.0153	120.489
	Diesel	195.43	158.5	194.1663	158.4736
	Average	204.55	162.75	179.4839	150.5584
FC (liter/100 km)	Petrol	8.72	6.82	8.93	6.98
	Petrol Hybrid			5	4.98
	Diesel	6.74	5.56	6.82	5.57
	Average	7.74	6.19	6.93	5.85
NO_X (g/km)	Petrol	0.066	0.06	0.0796	0.0674
	Petrol Hybrid			0.0846	0.0943
	Diesel	0.586	0.47	0.6037	0.4748
	Average	0.326	0.265	0.3056	0.2497
PM 2.5 (g/km)	Petrol			0.0192	0.0149
	Petrol Hybrid			0.0175	0.0138
	Diesel			0.0183	0.0139
	Average			0.0183	0.0142
PM 10 (g/km)	Petrol			0.0371	0.0274
	Petrol Hybrid			0.0333	0.0252
	Diesel			0.0362	0.0265
	Average			0.0356	0.0264
VOC (g/km)	Petrol			0.1375	0.1451
	Petrol Hybrid			0.5633	0.4238
	Average			0.2011	0.1631

4.2. Comparison of the results of this study with previous studies

The comparative findings of this study with the outcomes of previous studies regarding emissions estimation using WLTC are presented in Table 7. Previous studies have shown that standard drive cycles tended to underestimate emissions and FC when compared to local drive cycles, a finding supported by this study. For instance, a study by Zhang et al. (2021), found that the Guangzhou drive cycle's FC, NOx emissions, and CO emissions were, respectively, 1.34, 1.24, and 1.32 times greater than those of the WLTC. In India, Kumar Pathak et al. (2016) reported that local drive cycle-based simulations of HC, CO, and NOx emissions were, respectively, 155 %, 63 %, and 64 % larger than WLTC-based simulations. Additionally, Singapore's driving cycle, when compared to the European driving cycle, had 5 %, 5 %, 8 %, 22 %, and 47 % higher fuel usage, CO_2, CO, HC, and NO_X emissions, respectively (Ho et al., 2014). In general, due to its high average velocity, better road infrastructure, and less traffic congestion the WLTC had the lowest overall emissions (Zhang et al., 2021). Emissions and FC rates increased due to the vehicle's low speed, frequent stops, and high instantaneous speed variability (Tamsanya & Chungpaibulpatana, 2009).

4.3. Route-based annual vehicular emissions analysis

This study utilized COPERT to assess the emissions and energy consumption of hybrid vehicles along with gasoline and diesel passenger cars to demonstrate to policymakers how the new hybrid car reduces emissions and energy consumption compared to conventional cars. Additionally, we determined the amounts of FC and emissions for various road types under the AADC and WLTC for comparison. According to the AADC, the shares of congested urban, urban, rural, and highway distances were 28.61 %, 18.31 %, 44.2 %, and 8.88 %, respectively (Gebisa et al., 2022). The FC and emission levels derived from AADC were significantly dissimilar from those of WLTC, the typical driving cycle, as indicated in Figs. 5–8.

Fig. 4 illustrates the COPERT estimation of annual CO emissions from vehicles for the year 2022 in metric tons per year per vehicle. In the AADC, congested urban (56.97 %) was associated with the highest total

Table 7
Comparing the results of this study with previous studies in relation to emissions estimation based on WLTC.

Local drive cycle	CO	NO_X	HC	FC	Reference
AADC	↑20 %	↑22 %	↑23 %	↑18 %	Present study
Guangzhou drive cycle	↑24 %	↑32 %	–	↑34	Zhang et al. (2021)
India drive cycle	↑63 %	↑64 %	↑155 %	–	Kumar Pathak et al., (2016)
China Light-Duty Vehicle Test Cycle	–	–	–	↑13.5 %	Liu et al. (2020)

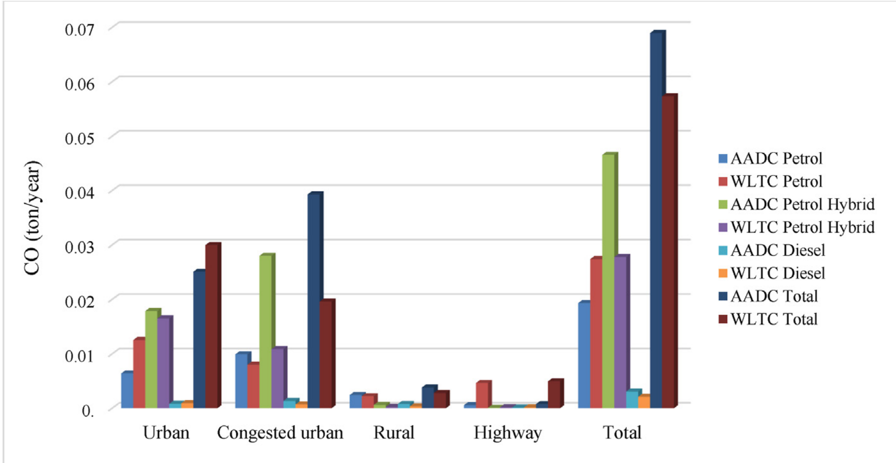

Fig. 4. Annual CO emission levels for various routes.

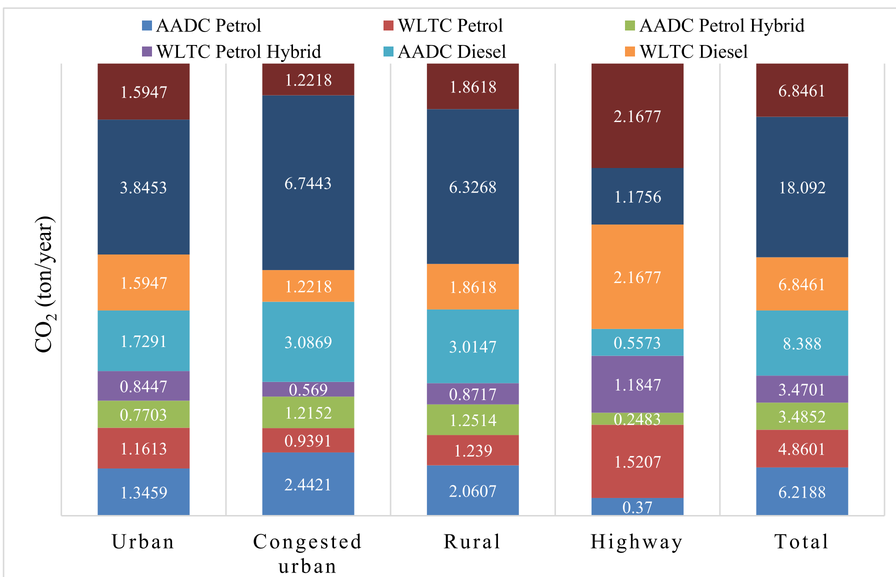

Fig. 5. Annual CO_2 emission levels for various routes.

CO emission levels, followed by urban (36.38 %), rural (5.54 %), and finally, highway routes (1.12 %). The traffic conditions, congestion, speed limits, and unoptimized traffic light operations in AA city have led to a higher percentage of CO emissions in its congested urban areas. However, in the WLTC scenario, urban driving (52.29 %) was where a significant amount of CO was discovered, followed by congested urban (34.18 %), highway (8.65 %), and then the rural route (4.89 %). When the entire route is considered, diesel and hybrid vehicles release more emissions under AADC than under WLTC, while gasoline vehicles release more emissions under WLTC. As shown in Fig. 4, gasoline vehicles emit more CO than diesel vehicles. Similarly, Liu et al. (2022) found that gasoline vehicles in Mongolia, China release more CO than diesel vehicles. In urban areas, a cold start can affect a vehicle's overall CO emissions and FC Weiss et al. (2017), and CO emissions are more susceptible to high speeds, according to (Alves et al., 2015). According to Viteri et al. (2023), a study conducted in the main cities of Ecuador found that the highest daily CO emissions occurred during peak traffic hours. Additionally, Moges and Alemu (2024) found that during congested traffic conditions CO emission levels in Addis Ababa are 19.10 % higher compared to steady traffic flow. The difference in CO emissions between AADC and WLTC can be attributed to factors such as traffic density and lower engine efficiency at low vehicle speeds. Additionally, road slopes may have influenced CO emissions, as the steeper the slope, the greater the acceleration required.

Fig. 5 displays the COPERT estimation of yearly CO_2 emissions from vehicles for the year 2022 in metric tons per year per vehicle. The AADC revealed that driving in a congested urban area (37.28 %) was associated with the highest CO_2 levels, followed by rural (34.97 %), urban (21.25 %), and highway routes (6.50 %). Davison et al. (2021) found that for gasoline passenger cars in the UK, urban routes contributed 54.83 %, rural routes 33.81 %, and motorways 11.39 % of CO_2 emissions, while for diesel passenger cars, the contribution were 37.19 %, 39.85 %, and 22.8 %, respectively. The traffic conditions, congestion, speed limits, and unoptimized traffic light operations in AA city have resulted in frequent stops and travel at low speeds, leading to increased FC. Consequently, a higher percentage of CO_2 emissions was observed in the congested urban areas of AA city. In the WLTC scenario, the highway (31.66 %) had the highest concentration of CO_2, followed by rural areas (27.2 %), urban areas (23.29 %), and finally congested urban areas (17.85 %). Under both WLTC and AADC, hybrid vehicles emit roughly the same amount of CO_2 when considering the entire route, but gasoline and diesel vehicles emit more under AADC than under WLTC. In comparison to a gasoline-powered vehicle, a hybrid vehicle reduces CO_2 gas by 43.95 % for the AADC. This indicates a highly significant impact on GHG reduction. AADC's highest CO_2 emissions share in congested urban areas was mainly caused by frequent stops, slow driving speeds, and rapid acceleration at low speeds. Similarly, Alves et al. (2015), also found that frequent stops and high accelerations cause CO_2 emissions to increase.

Fig. 6 illustrates the COPERT estimation of annual FC from vehicles for the year 2022 in liters per year per vehicle. Driving on rural (34.95 %), urban (21.27 %), and highway (6.5 %) routes resulted in lower FC levels for AADC. In contrast, driving in congested urban areas (37.29 %) led to the highest FC levels due to frequent stops and low-speed travel. In the WLTC scenario, highway driving (31.66 %) had the highest FC, followed by rural areas (27.2 %), urban areas (23.29 %), and finally congested urban areas (17.85 %). When considering the entire route, hybrid vehicles consume roughly the same amounts of energy under both WLTC and AADC. The FC consumption of diesel and gasoline vehicles decreased by 21.83 % and 18.38 %, respectively, under WLTC as compared to AADC. In comparison to AADC, WLTC underestimated FC by 22.34 % when considering the entire route and all vehicles. The energy consumption of the hybrid vehicle was also 44 % lower than that of a gasoline-powered vehicle. This significant difference is attributed to both a generational gap and an efficiency gap between the two vehicles being compared. Despite covering less distance than rural routes, congested urban routes in Addis Ababa tend to consume more fuel than other routes. This is primarily caused by frequent stops, slow average driving speeds, and fast acceleration at low speeds. FC can also be considerably influenced by a cold start in urban areas (Weiss et al., 2017).

Fig. 7 depicts the COPERT-based estimation results of annual NO_X emissions for the year 2022 in metric tons per year per vehicle. Driving in congested urban peak hours (38.19 %) was found to be associated with the highest NO_X gas levels under AADC while driving on rural (33.72 %), urban (22.13 %), and highway (5.96 %) routes were found to be associated with the lowest NO_X gas levels, for AADC. In the WLTC scenario, the concentration of NO_X was highest along the highway (31.63 %), followed by rural areas (26.59 %), urban areas (23.17 %), and finally congested urban areas (18.61 %). When considering the entire route, hybrid vehicles emit 11.39 % more NO_X under WLTC than AADC. Diesel and gasoline vehicles emit 15.33 % and 21.34 % less NO_X under WLTC than under AADC, respectively. WLTC underestimated NO_X emissions by 33.4 % compared to the AADC when considering the entire route and all vehicles. As a result of frequent stops and high acceleration in congested urban areas, the engine temperature increases, which is one of the main reasons for the highest share of NO_X emissions in congested urban areas of Addis Ababa. Studies by Alves et al. (2015) indicated that frequent stops and high acceleration cause NO_X emissions to increase. Davison et al. (2021) found that for gasoline passenger cars in the UK, urban routes contributed 50.85 %, rural routes 36.27 %, and motorways 12.92 % of NO_X emissions, while for diesel passenger cars, the contribution were 34.14 %, 41.42 %, and 24.67 %, respectively.

In this study, road, brake, and tire wear were considered in non-exhaust PM estimation. Table 8 displays the COPERT-based annual PM2.5 and PM10 emissions for 2022 in kilograms per year per vehicle. The AADC cycle results in higher PM2.5 and PM10 emissions than the WLTC cycle for all cars under consideration. In comparison to the AADC, the WLTC underestimated PM10 emissions by 26 % and PM2.5 emissions by 67 % when considering the entire route and all vehicles. The highest contributions of PM2.5 and PM10, 44.27 % and 44.47 %, respectively, came from rural areas. Compared to the WLTC, the AADC has a higher number of stops per cycle. This increase is due to the impact of traffic congestion, speed limits, unoptimized traffic light operations, and insufficient road infrastructure in Addis Ababa city, which have led to more frequent braking, tire wear, and road wear. Similarly, Moges and Alemu (2024) revealed that PM2.5 and PM10 had a significant correlation with increasing traffic volume, the proportion of heavy-duty vehicles, green traffic light time, and temperature.

Estimation of volatile organic compounds (VOCs) takes into account hot, cold, and evaporative emissions, with diesel vehicles not included in this analysis. Determining the trend in VOC emissions becomes challenging when diesel engines are considered, and the amount is also negligible (Alves et al., 2015). Fig. 8 illustrates annual VOC emissions in tons per year per vehicle for each route and drive cycle. When considering the entire route for gasoline, and hybrid vehicles, the WLTC underestimated VOC emissions by 18.9 % compared to the AADC. Under AADC, 96.94 % of the total VOC was concentrated in urban and congested urban areas, while the contribution of rural and highway areas to the total VOC was insignificant.

In the present study, emissions levels obtained from the COPERT model were used to derive emission shares for the various types of routes in Addis Ababa. In the congested urban areas of Addis Ababa, passenger vehicles contributed emissions of 56.25 % CO, 37.28 % CO_2, 38.19 % NO_X, 58.25 % VOC, 29 % $PM_{2.5,}$ and PM_{10}, and 37.29 % FC. In our opinion, frequent stops, slow average driving speeds, and higher acceleration at low speeds were the main causes for higher emissions in the congested urban areas. To reduce road vehicle emissions in congested urban areas, the Addis Ababa city administration shall implement corrective actions that reduce traffic congestion. Possible measures include improving access to public transportation, enhancing road infrastructure, optimizing traffic light operation, imposing road use fees for passenger vehicles, implementing shifts based on even and odd license plate numbers, introducing bridges and flyovers for crossroads, and providing pedestrian underpasses beneath bridges or flyovers. The second area requiring attention in terms of total emissions and fuel use is driving in rural areas, accounting for 34.95 % of fuel use, 34.97 % of CO_2, 33.72 % of NO_X, and 44 % of $PM_{2.5}$ and PM_{10} emissions. Based on our observations in the area, we believe that raising the speed limit here would reduce emissions. When designing roads and establishing speed limits on rural roads, emissions could be considered because vehicle emissions are sensitive to both speed and road slope to improve public health as well as contribute to the reduction of air pollution. Cities such as Addis Ababa could set vehicle speed limitations with the goal of reducing emissions and FC simultaneously in addition to accidents. In general, driving in congested urban and rural areas contributes to 60 %–73 % of all emissions and FC. Focusing efforts on these areas would be crucial for the city administrator of Addis Ababa to effectively decrease air pollution from passenger vehicles.

5. Conclusion

The main emissions from passenger vehicles in Addis Ababa were estimated in this study using AADC and WLTC based on a route-based emission analysis. For each specific vehicle, the emissions of the five most significant gases (CO, CO_2, NO_X, PM, and VOC) as well as FC during the examination period of 2022 were carefully analyzed. This study concluded that the AADC provided more accurate and reliable emissions and FC levels than the WLTC for the driving conditions in Addis Ababa. Therefore, the AADC is the recommended driving cycle for emissions and FC in Addis Ababa. This study found that the AADC, developed in 2022, outperformed the WLTC in emissions estimation. This conclusion was supported by both experimental chassis dynamometer tests and COPERT-based emissions estimations. The emission factors of the understudied passenger cars on a chassis dynamometer test showed that WLTC overestimates CO by 34.54 % compared to AADC and underestimates CO_2, EC, and NO_X by 20.43 %, 19.84 %, and 18.76 %, respectively.

According to the COPERT estimation findings, driving in the congested urban areas of Addis Ababa emits 56.25 % CO, 37.28 % CO_2, 38.19 % NO_X, 58.25 % VOC, 29 % $PM_{2.5}$ and PM_{10}, and 37.29 % in FC. In the AADC, congested urban routes consume more fuel and produce higher levels of CO, CO_2, NOx, and VOCs compared to other routes, despite covering a shorter distance per cycle than rural routes. The combined emissions from the congested urban and rural areas of Addis Ababa contribute to 60 %–73 % of all emissions and FC from passenger vehicles. Notably, there is a significant difference between the emissions

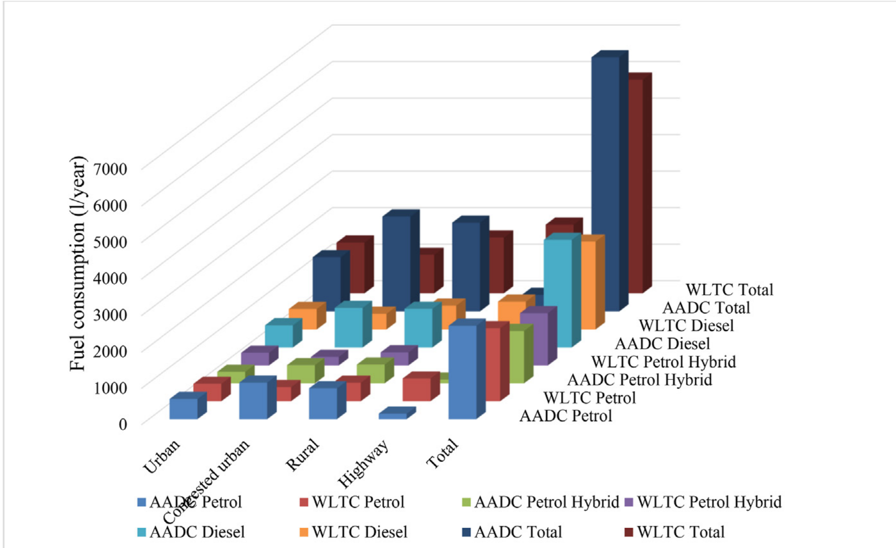

Fig. 6. Annual FC for various routes.

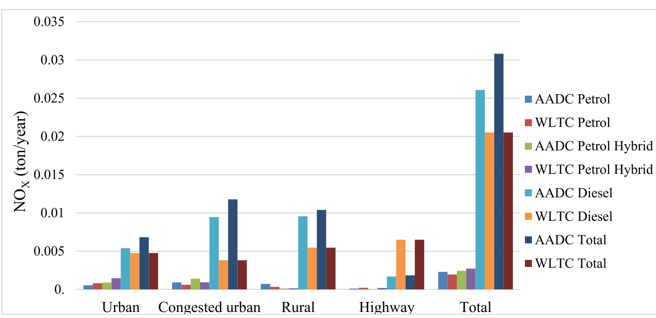

Fig. 7. Annual NO_X emission levels for various routes.

factor results obtained from the chassis dynamometer and those determined by the COPERT model.

The proper application of COPERT following local conditions can aid in formulating policies to reduce air pollution from passenger vehicles and it can provide valuable input to air quality studies. The outcomes of this study revealed that congested urban areas were a major source of emissions from passenger vehicles compared to other types of roadways examined. The city administration of Addis Ababa shall give priority to initiatives that reduce traffic congestion to reduce vehicle emissions in congested urban areas. Emissions monitoring stations shall be placed in the crowded districts of the city, and an emissions reduction plan must be put into action. As part of this strategy, traffic congestion shall be reduced by installing smart traffic lights, introducing bridges and flyovers for crossroads, providing pedestrian underpasses beneath bridges or flyovers, and improving access to public transportation. Additionally, vehicle owners shall be offered incentives to switch to more fuel-efficient vehicles. Furthermore, stricter standards for vehicle emissions shall be introduced to reduce air pollution. This study has the limitation of not considering emission-influencing factors such as mileage degradation, vehicle age, and emission standards. Therefore, future studies shall take these factors into account. Future research on inventories of alternative fuel and energy-based vehicles is required to assess the potential impact of additional power sources from passenger vehicles on air pollution in Addis Ababa cities. To accurately assess current air quality and predict future conditions on Addis Ababa roads, the AADC shall be applied to vehicle emissions and FC tests conducted in the chassis dynamometer and simulation models.

CRediT authorship contribution statement

Amanuel Gebisa Aga: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Girma Gebresenbet:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Table 8
The COPERT estimation of annual PM2.5 and PM10 emissions for 2022 in kg per year per vehicle.

Pollutant name	Drive cycle	Vehicle Type	Urban (kg/year)	Congested urban (kg/year)	Rural (kg/year)	Highway (kg/year)	Average (kg/year)
PM2.5	AADC	Petrol	0.103	0.161	0.243	0.045	0.552
	WLTC	Petrol	0.110	0.075	0.137	0.105	0.428
	AADC	Petrol Hybrid	0.094	0.146	0.223	0.041	0.503
	WLTC	Petrol Hybrid	0.101	0.068	0.128	0.099	0.397
	AADC	Diesel	0.146	0.228	0.351	0.063	0.789
	WLTC	Diesel	0.157	0.106	0.197	0.142	0.602
	AADC	Average	0.343	0.536	0.817	0.149	1.844
	WLTC	Average	0.157	0.106	0.197	0.142	0.602
PM10	AADC	Petrol	0.199	0.310	0.474	0.086	1.069
	WLTC	Petrol	0.212	0.144	0.259	0.174	0.789
	AADC	Petrol Hybrid	0.178	0.278	0.426	0.077	0.959
	WLTC	Petrol Hybrid	0.191	0.130	0.238	0.167	0.725
	AADC	Diesel	0.290	0.453	0.698	0.124	1.564
	WLTC	Diesel	0.309	0.211	0.379	0.245	1.143
	AADC	Average	0.666	1.041	1.598	0.287	3.592
	WLTC	Average	0.711	0.485	0.876	0.586	2.657

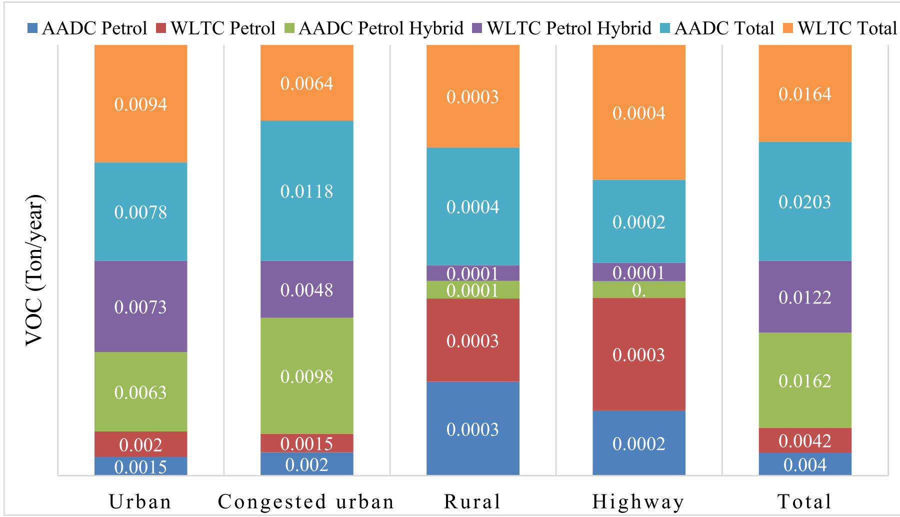

Fig. 8. Annual VOC emission levels for various routes.

Rajendiran Gopal: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Ramesh Babu Nallamothu:** Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Informed consent statement

All participants provided informed consent to participate in this study.

Ethics statement

This study was approved by the ethics committee of Adama Science and Technology University, with ethics approval reference ASTU/SP-R/096/21 the ethics committee approved this experiment are Prof. Balksewrn Singh, Dr. G.K Sing, and Dr. C. Venkatesh.

Data Availability statement

The data presented in this study will be made available on request.

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Conflicts of interest

The authors declare no conflict of interest concerning the authorship and publication of this article.

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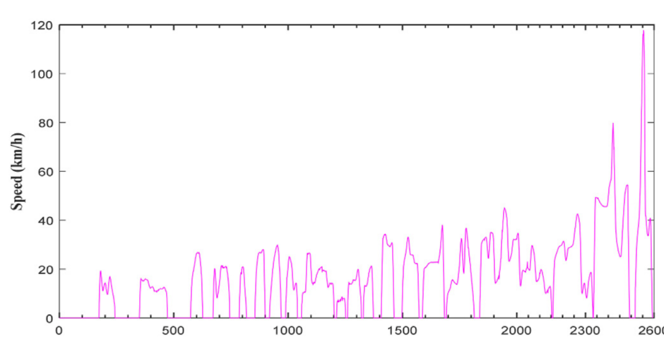
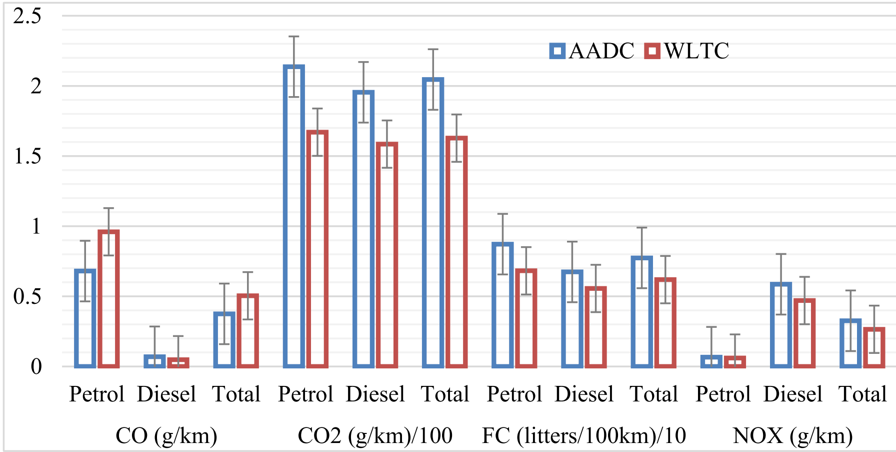
Appendix



Appendix 1. AA driving cycle (Gebisa et al., 2022).



Appendix 2. Results of emissions and FC from chassis dynamometer tests, with error bars.

Table A1
Comparison of the developed AADC with WLTC

Parameter	AADC	WLTC
Cycle length (km)	11.885	23.26
Cycle duration (second)	2594	1800
Maximum velocity (km/h)	117.67	131.31
Cycle average velocity (km/h)	16.495	46.5
Average driving speed (km/h)	23.242	53.15
Maximum acceleration (m/s^2)	2.5	1.75
Maximum deceleration (m/s^2)	−2.5	−1.5
Percentage of acceleration time (%)	0.2	0.309
Percentage of cruising time (%)	0.327	0.278
Percentage of deceleration time (%)	0.182	0.286
Percentage of idle time (%)	0.29	0.127

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