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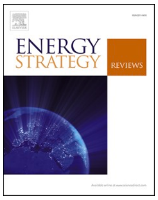

Assessment of the impact of road transport policies on air pollution and greenhouse gas emissions in Kenya

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ABSTRACT

We compile a detailed road transport inventory for greenhouse gases and air pollutants to explore energy emissions from alternative policy scenarios for the Kenya road transport sector. In 2010, road transport emissions accounted for 61% of total nitrogen oxides emissions in Kenya, 39% of fine particulate matter, 20% of carbon dioxide. In the business as usual scenario, road transport emissions increase between 4 and 31-fold from 2010 to 2050, with projected increases of motorcycles accounting for nearly all the increased pollutant emissions. Improved vehicle emission and fuel economy standards, fuel shift and investment in public transport are shown to be effective mitigation options to meet Kenya's climate change goals with the additional benefits of better air quality and improved health.

1. Introduction

The road transport sector is a major contributor to outdoor air pollution, including elevated concentrations of ground-level ozone (O_3), and fine particulate matter ($PM_{2.5}$), mainly through emissions of nitrogen oxides (NOx), and primary $PM_{2.5}$ emissions, including black carbon (BC), as well as carbon monoxide (CO), sulphur dioxide (SO_2), volatile organic compounds (VOCs), organic carbon (OC). Road transport also emits greenhouse gases (GHG) like carbon dioxide (CO_2), Short Lived Climate Pollutants (SLCPs) like Black Carbon (BC), methane (CH_4), hence affects human health, agricultural productivity through degraded air quality and climate through long and short-lived climate forcers [1–8].

Previous emission estimates have identified road transport as an important source of NO_X, CO, BC and VOC emissions in Africa [9–12]. These regional emission inventories highlight historical increases in African road transport emissions, but also the potential for substantially larger increases in the future [9,11–15]. However, while these estimates have been conducted at the continental scale, there is limited analyses at the national level to evaluate the current state of road transport emissions, projected changes into the future and the likely effect of mitigation measures in individual African countries. National road transport analysis in Ghana [16], Nigeria [17], Uganda [18], Côte d'Ivoire [7] and South Africa [19] demonstrate the importance of the road transport sector in meeting national climate goals. Even though the studies cited here do not constitute a systematic review of such studies, they may demonstrate the need for more national and sub-national analysis on the continent. Moreover, multiple pollutant inventories at national scale that are contemporary, robust and accurate potentially improve the downscaling of global, regional climate and chemical transport models [20]. Furthermore, the improvement of national, regional road transport inventories may contribute towards a better understanding and assessment of modelling uncertainties [21].

In sub-Saharan Africa (SSA), vehicle ownership, especially in cities, has increased because of the collapse of formal public transport, lax regulations on vehicle importations, increasing urbanization coupled with increase in gross domestic product (GDP) per capita [9,22]. In addition to the increasing number of vehicles, emissions from road

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transport are exacerbated by the high average age of the fleet which is mainly composed of imported second-hand vehicles (accounting for ~90% of vehicles in SSA [9,10,23–25]), poor fuel quality, poorly maintained roads, lack of vehicle emission regulations and inadequate implementation of vehicle inspection and maintenance programmes [11,22,26–29]. There has also been a rapid increase in the use of informal public transport vehicles [30], for which emissions have not been quantified [10,31]. Combined with often inconsistent vehicle registration, there is currently a large knowledge gap when attempting to quantify air pollution and greenhouse gas emissions [9,10,21]. Therefore, robust national transport emission inventories are needed to design and evaluate suitable policies to mitigate air pollution, that take account of the specific social and policy contexts for road transport within each country [32].

In Kenya, road transport carries 93% of all freight and passenger traffic [33,34]. Public transport is dominated by *matatus* (minibus shared taxis) and *bodaboda* (motorcycles) [33,35–38] and freight by heavy duty trucks which also serve neighbouring landlocked countries [39]. The total number of vehicles has increased nearly four-fold since 1998 to 2014 [[105]40,41]. The vehicle fleet in-use is poorly serviced and old [42], and the share of second-hand imported vehicles has grown to ~97% of all vehicle imports [43,44]. The majority of the vehicles (87% of light duty vehicles between 2010 and 2012) are imported from Japan [44], and Kenya has an 8 year age limit for vehicle importation [25,45]. Kenya also has vehicle exhaust emission limits stipulated in the standard KS1515 and KS1515:2019 [45], but these are not implemented or enforced as the motor vehicle inspection unit (MVIU), the institution mandated to do so, lacks the capacity and resources [46].

Transport is one of the key sectors for GHG mitigation identified by the United Nations Framework Convention on Climate Change (UNFCCC). In 2015, Kenya submitted its first Intended Nationally Determined Contribution (INDC) with the aim of reducing 30% GHGs emissions by 2030 [47]. This was informed by a GHG inventory using fuel consumption as a measure of activity within the road transport sector that identified the transport sector as emitting 10% of Kenya's GHG emissions in 2010 [46,47]. However, this top-down assessment of mitigation options was conducted for long-lived GHGs i.e. CO_2, CH_4 and N_2O. Limited data availability was identified as a hurdle in identifying mitigation scenarios in the transport sector to meet Kenya's 2030 targets [46]. Therefore, additional analysis and the identification of additional data sources to build a bottom-up approach for assessing emissions of both air pollutants and GHGs in the road transport sector may provide a more detailed basis to assess the likely effectiveness of different mitigation strategies.

The aim of this paper is therefore to derive the first 'bottom-up' Kenyan transport emission inventory for emissions of both air pollutants and GHGs. Emissions for the base year, 2010, were estimated for road transport as well as emissions from all other major source sectors in Kenya to set transport within the context of total Kenyan emissions. Road transport emissions were projected to 2050 based on historic trends in vehicle numbers as a function of gross domestic product (GDP) per capita. Mitigation scenarios assessing the emission reductions associated with i) improved vehicle emission and fuel economy standards ii) improved public transport system, and iii) fuel share shift to more renewable energy sources were estimated. This work provides detailed road transport scenario analysis and methodology which may form a basis for future studies on urban air quality, climate, and health impact assessments in African cities.

2. Methodology

To analyse the current and future trends in vehicle emissions from Kenya's road transport sector, a detailed road transport inventory model was created in which economic and demographic drivers were used to project future emissions from 2010 up to 2050. Additionally, to show the relative importance of the road transport sector, a simpler inventory was created for other emission source sectors. Fig. 1, represents the methodology and data sources combined to build a national inventory. The inventory estimated the following 11 emission pollutants: CH_4, SO_2, CO, NO_X, Non Methane Volatile Organic Compounds (NMVOC), Ammonia (NH_3), PM_{10}, $PM_{2.5}$, BC, OC, and CO2.

The data used to construct this inventory are summarised in Table 1, and described in detail in supplementary information, section A. The inventory was constructed using the Low Emissions Analysis Platform (LEAP) software [48].

The emissions for the non-transport energy sectors were quantified by using the IPCC methodology based in the top-down quantification of energy consumption [56]. This were grouped into energy demand from industries, residential including cooking, heating and lighting, commercial and agriculture and transformation through energy use from power generation and charcoal making. The activity data was obtained from energy consumption divided by proportion of energy in each sector consumed as different types of fuel and was obtained from International Energy Agency (IEA) for 2010 [57]. Energy consumption for each sector, for each fuel was then multiplied by emission factors for the 11 pollutants considered. These emission factors were derived from the EMEP/EEA guidebook [58] and the IPCC [56] guidelines. The non-energy sectors including fugitive emissions from industry process, transport dust, agricultural processes (enteric fermentation, residue burning, savannah fires, methane emissions from rice cultivation), and waste incineration were quantified. Agriculture and agricultural related activities, emissions were quantified using data from FAOSTAT on agricultural productivity [59]. Details of the quantification of the non-transport sectors grouped into Energy demand, generation and non-energy sectors are in the supplementary section, A8.

2.1. Transport inventory for Kenya

To quantify emissions from the road transport sector in 2010, the number of vehicles of different categories, fuel use, and emission standards were compiled, along with distance travelled and emission factors for each type of vehicle, as shown in Table 1. There were 1.34 million vehicles registered in Kenya in 2010 [40] and, in the absence of data for vehicles in circulation (in-use vehicle), it was assumed the registered vehicles represent the number of in-use vehicles. The vehicle categories considered were passenger vehicles (private cars, taxis), light duty commercial vehicles (vans, pickups, and small trucks), heavy duty commercial vehicles (lorries and trucks), urban buses (*matatus* and bus coaches), motorcycles (*bodaboda*) and three-wheelers *(tuktuk*). The proportion of vehicles in each category are shown in Table 2. .

The proportion of vehicles in each category using different types of fuel (diesel, petrol, hybrid) for Kenya (Table 2) were determined from ERC [44] for light duty vehicles, and multiple previous studies for heavy duty vehicles ([60,61]; Ministry of Transport Kenya, 2011 [62]).

Imported vehicles manufactured in any particular year would normally comply with an existing standard, or a version of the standard of that year, from the relevant major world vehicle manufacturers in the EU, USA and Japan [63,64]. However, the emission reduction capability of the technology for in-use vehicles can only be maintained if an effective I/M programme is enforced [65]. In Kenya, the absence of enforceable vehicle and fuel economy standards or an effective I/M program meant that the emission standard of all vehicles in Kenya were assumed to be equivalent to pre-Euro standards, even though the vehicles were manufactured to a higher standard initially. Additionally, in the absence of recent national vehicle activity studies for Kenya as a whole for in-use vehicle fleet, we used data from a vehicle activity study conducted in the Nairobi Metropolitan region (NMR) [49], vehicle activity is shown in the supplementary Figures A.3 and A.4. In this it was assumed the vehicle kilometres travelled (VKT) and fuel economy (FE) for NMR were applicable to Kenya as a whole.

The exhaust emissions (g/year) were calculated by multiplying activity data (VKT per year) by the emission factors as shown in equation

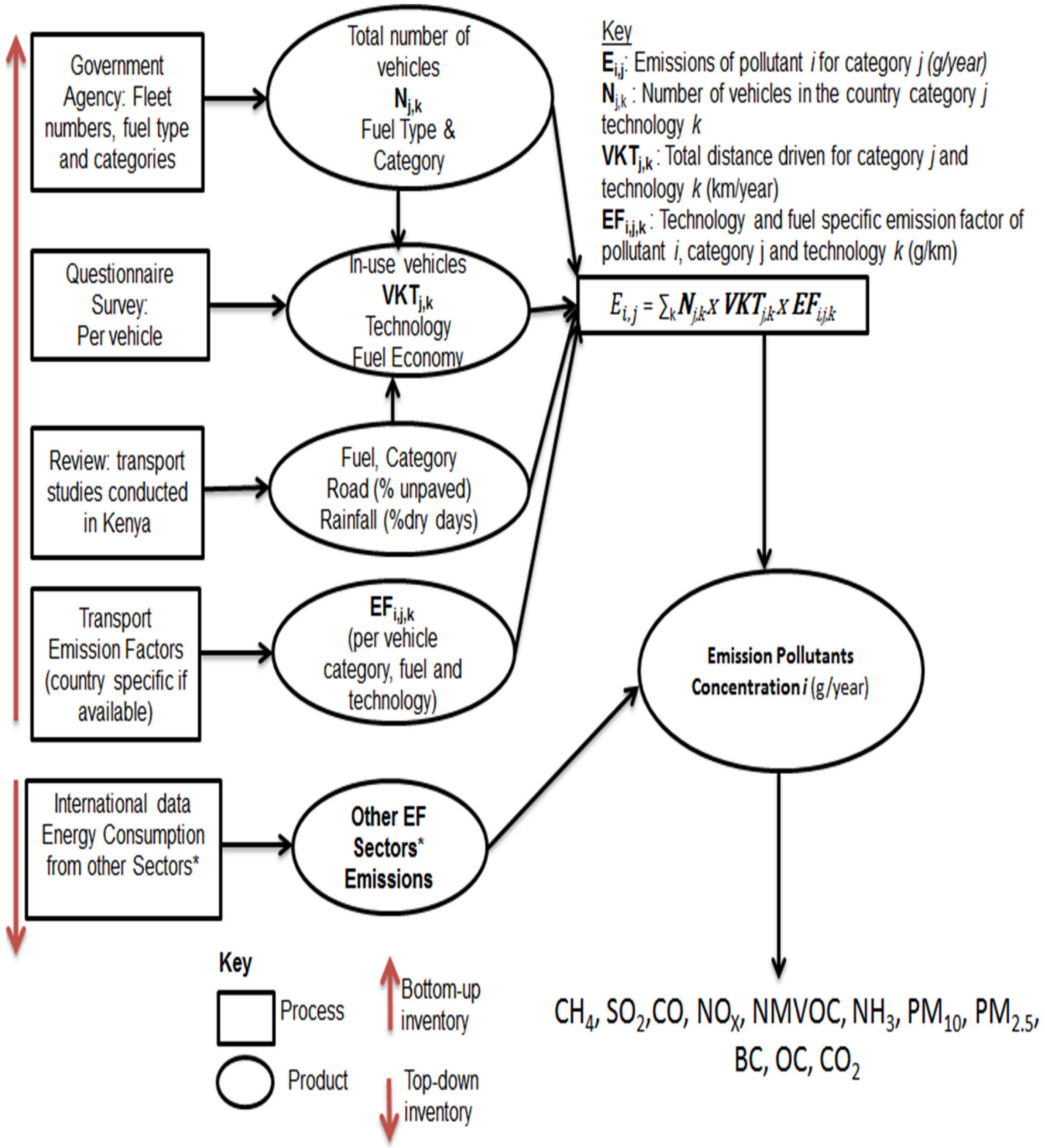

Fig. 1. A representation of the methodology and dataset combination for the estimation of a national inventory of 11 pollutants.

(1):

$$E_{ij} = \sum_k \left(N_{j,k} \times M_{j,k} \times EF_{i,j,k}\right) \tag{1}$$

where,

$N_{j,k}$ = number of vehicles in nation's fleet category j and technology k,

$M_{j,k}$ = average annual distance driven by per vehicle category j and technology k (km/yr),

$EF_{i,j,k}$ = technology specific emission factor of pollutant i for vehicle category j and technology k (gx/km).

In the absence of national vehicle emission factors, default emission factors derived from the Tier 2 emission factors given in the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) emissions guidebook [54,55] were used for all vehicle categories except three-wheelers and motorcycles for which Indian

Table 1

Data for estimating road transport emissions. Numbers in the first column correspond to sections in this paper in the supplementary.

No.	Inputs	Units	Description	Source of information
Figure A.1	Number of vehicles in-use	–	(N): Total number of vehicles in-use	[40,41]
	Category of vehicle		Passenger (M1), light commercial (N1), urban bus (M2), heavy duty (N2, N3, M3), motorcycles (L3e) 3-wheelers (L2e)	[49]
	Vehicle legislation and technology		Conventional (pre-euro), Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6	
Figure A.2	Fuel use	–	Type of fuel in use: petrol, diesel	[40,41,44]
Table A.1	Fuel specifications		Fuel specifications: density and sulphur content	[50,51]
Figure A.3	Average distance travelled per vehicle		(M):Average vehicle mileage also referred to as Vehicle Kilometres Travelled (VKT) per vehicle category	[49]
Figure A.4	Average Fuel Economy (FE)		Average fuel consumption per vehicle category	[49]
Table A.2	Distance travelled on unpaved roads as a percentage of total	%	Average distance travelled on unpaved roads that would contribute to dust particles	[52]
Table A.3	Precipitation average per year	%	% of dry days considered to be < 0.25 mm precipitation per day	[53]
Table A.4	Emission factors: NOX, CO, NMVOC, Exhaust PM10, Exhaust PM2.5, unpaved dust PM10, unpaved dust PM2.5, CO2, BC, OC, SO2		(EF) Default emission factors are shown in Table S9 in supplementary	[54,55]

Table 2

Number and type of fuel for each vehicle category. Data sources [35,40,41,44].

Vehicle category	No. of vehicles	Diesel	Hybrid	Petrol
Passenger Vehicle	553,397	16%	0.01%	84%
Light Duty Commercial	226,876	12%	0.34%	87%
Heavy Duty Commercial	96,355	100%	0%	0%
Urban Buses (Matatu and Coach)	89,708	46%	0%	54%
Motorcycles (Bodaboda)	371,747	0%	0%	100%
Three-wheelers (Tuktuk)	2152	68%	0%	32%

emission factors were used [66]. The emission factors used for each vehicle, disaggregated by vehicle category, fuel type and technology are shown in Table A.4 in the supplementary.

Emissions of PM_{10} and $PM_{2.5}$ from re-suspended dust from unpaved roads were calculated by multiplying the vehicle kilometres travelled on unpaved roads on dry days by a PM_{10} and $PM_{2.5}$ emission factor. Approximately 93% of all roads in Kenya are unpaved [52,67], compared to only 15% in the NMR are unpaved [33]. In addition, it is estimated nearly 67% of the vehicles are in NMR [33]. Table A.2 in the supplementary shows the estimates of the national travel on unpaved roads. Dry days were categorised as those with equal or less than 0.1 mm precipitation per day. The percentage of dry days was calculated from historic meteorology data for Kenya [53], this are shown in supplementary, Table A.3. Equation (2) was used to calculate emission factors for PM_{10} which were converted to $PM_{2.5}$ factors assuming $PM_{2.5}$ is 10% of PM_{10} from unpaved road dust [68,69].

$$PM_{10}\left(Emission\ factor, \frac{g}{km}\right) = 3\ x\ W\ x\ S \tag{2}$$

S: Average speed in km/hr (assume 30 km/h).

W: Average vehicle weight in tonnes (assumed to be 0.4 t for 2-wheelers, 1 t for 3-wheelers, 1.4 t for passenger cars, 2.5 t for light commercial vehicles and 5 t for heavy duty vehicles (trucks and buses).

For the other transport sectors (rail, domestic shipping and domestic aviation), emissions were determined through a top-down inventory based on fuel consumption data [57].

2.2. *Assessment of uncertainties in the road transport emission inventory*

Uncertainty in road transport emissions were estimated by combining individual uncertainties in emission factors and input activity data. Uncertainty in the activity data was available from Ref. [49]. Uncertainty for EMEP/EEA emission factors have been estimated to be between 50 and 200% but these are estimated from emission measurements of a small number of representative vehicles in European driving conditions [54]. In addition, systematic uncertainty may also result from the application of these European-derived emission factors to Kenya, as Kenya driving conditions are dissimilar to European driving conditions. Kenya's driving condition are characterised by heavy traffic congestion in urban areas, poorly maintained roads [33,42] which are mostly unpaved, and even those that are paved often have potholes. We accounted for the emission factor error by assuming 75% uncertainty, but we did not have enough data to account for the magnitude of systematic bias. Moreoverver, we assumed a lower emission standard for the Kenyan fleet even when the newly registered vehicles are less than 8 years old.

In line with the recommendation for EMEP/EEA (2016) for uncertainty calculations we combined the random uncertainty of the emission factors and activity data using Equation (3) in pairs either EF and VKT or FE and VKT depending on the pollutants [54,70,71].

$$U_{total} = \sqrt{U_1^2 + U_2^2 + U_n^2} \tag{3}$$

where.

$U_{1\text{-}3}$: are the percentage uncertainties (half the 95% confidence interval) associated with, vehicle kilometres travelled (VKT) (U_1), Fuel Economy (FE) (U_2) for Kenyan fleet and emission factors (U_3).

U_{total}: is the percentage uncertainty in the product of the quantities (half the 95% confidence interval divided by the total and expressed as a percentage).

2.3. *Future projections of road transport emissions*

The 'Business as usual' (BAU) scenario was used to project vehicle number from 2010 to 2050 based on linear relationship derived between vehicle number, disaggregated by vehicle type, and GDP per capita between 1998 and 2013. The linear relationships derived for this calculation are shown in the supplementary, Figure B1. In the BAU scenario, vehicle emission standards, fuel economy standards and fuel share were kept constant between 2010 and 2050 to reflect current transport sector policy, legislation, regulations, and standards that have been implemented and enforced in Kenya. Here a clear distinction was made for 'implementation', where a relevant plan or system was shown to have been in use and 'enforcement' where laws/regulations were applied and supported by the legislative arm of the country. For example, fuel quality improved in 2016 [44,50,51], this was implemented and enforced thus in the BAU scenario this fuel quality improvement was included, however vehicle emission and fuel economy standards were not enforced, thus in BAU they were kept constant to

2050. Vehicle mileage and fuel share were kept constant from 2010 for all vehicles.

2.4. *Transport mitigation scenarios*

The Kenyan government had made a commitment to reduce approximately 3.5 Mt CO_2 equivalents from the transport sector and 30% GHG from all sectors compared to their BAU by 2030 ([46]; Government of Kenya, 2013 [47]). The transport mitigation actions previously identified to achieve this were to improve vehicle fuel efficiency, fuel use shift to biofuels, improvement of public transport through implementing light rail transport (LRT) and bus rapid transit (BRT) and shift freight from road to rail [46,72]. This study build on the strategy (shown in Table 1) adopted by the government of Kenya and proposed alternate policy to biofuel use; here we proposed to consider increased market penetration of compressed natural gas (CNG) use in urban buses and use of electric motorcycles. In addition, we assessed the policy interventions of strict vehicle emissions standards targeting vehicle technology and fuel quality to further mitigate road transport emissions.

Five mitigation scenarios were modelled to estimate changes in emissions from different changes to the transport fleet in Kenya (Table 3). Vehicle emission standards in Africa are based on restriction of vehicle age on importation [15], for Kenya that is 8 years [25,44,46]. The Motor Vehicle Inspection Unit (MVIU), under the National Transport and Safety Authority (NTSA) agency, in the Ministry of Transport, have the mandate to enforce Kenya's code of practice for inspection of road vehicles which includes vehicle emissions tests and limits [45], but have limited capacity and resources. Hence in mitigation Scenario 1, we assumed that by 2050 Kenya will have fully implemented better vehicle standards and fuel quality (Euro IV or equivalent) [15,73] and enforced I/M program (Table 1). For the mitigation scenarios, improved fuel standards meant that the sulphur content for diesel will reduce from 500 ppm to 50 ppm from 2016 onwards. By 2050, Fuel Economy (FE) in all vehicles for Scenario 1 was assumed to equal Japanese FE Targets for 2015 [74]: Passenger (44 g/km), Light duty commercial (48.2 g/km), Heavy Duty commercial (122.3 g/km), Urban buses (124.6 g/km) and Indian in-use FE in 2015 [75] (Three wheelers (26.9 g/km), Motorcycles (16.2 g/km). Future vehicle emission standards for Scenario 1 were for passenger vehicles, light duty commercial, heavy Duty and urban buses to meet Euro IV and 4 respectively. The Three wheelers and motorcycles were to meet 4 stroke Euro II standards. Scenario 1 (SC1_FEVES) represents the fuel economy and vehicle emissions standards scenario; Scenario 2 (SC2_CNG) represents the fuel shift to CNG; Scenario 3 (SC3_Electric) represents the shift to electric vehicles; Scenario 4 (SC4_BRT) represents the shift to public transport specifically Bus Rapid Transit (BRT); Scenario 5 (SC5_DIES) represents the shift to newer diesel vehicles. The description of the summary of the scenarios is represented in Table 3.

Table 3
Description of the generation of road transport scenarios for emissions reduction in Kenya.

Kenya GHG scenario	Description of Kenya GHG scenario	This Scenario
Improve fuel Economy (Passenger Vehicles)	Scrap old cars and restrict imports 7% fuel economy improvement by 2030	**Scenario 1: SC1_FEVES (Fuel and Vehicle Standards)** Improve vehicle emission standards and fuel economy standards to meet future emission Strategy (Escalated % of vehicle fleet to meet new standards)
Improve fuel economy (heavy duty vehicles)	Improved efficiency systems in the trucking sector, 2020 (3%), 2030 (10%)	
Fuel shift to Bio-ethanol and Bio-diesel	10% fuel shift to bio-ethanol from 2015 and onwards to 2030	**Scenario 2: SC2_CNG (Fuel shift to CNG)** Fuel shift share from Diesel to CNG Euro III by 2050 [75] Strategy Shift Public Service Vehicles (PSV) buses 2010 (0%), 2020(5%), 2030 (50%), 2050(100%)
	2% fuel shift to bio-diesel from 2015, 10% in 2020 and onwards to 2030	**Scenario 3: SC3_Electric (Electric Vehicles)** Shift to electric motorcycles [76] Strategy (% of electric motorcycle fleet) 2010(0%), 2020 (1%), 2030 (2.5%), 2040 (5%), 2050 (10%)
Improve public transport by introducing LRT & BRT in NMR	5% of public transport demand to be met by BRT and LRT by 2030	**Scenario 4: SC4_BRT (Bus Rapid Transit)** Shift to cleaner public transport [46] % of public transport to be met by BRT 2010 (0%), 2030 (5%), 2050 (10%) Assumptions: 270 BRT buses, 29 km fully implemented in 2030 assumed to pull 100% (11, 000) from 14-seat matatus in Nairobi Strategy Add 270 buses Euro III in 2030 with FE 124.6 g/km, remove 11,000 matatus
		Scenario 5: SC5_DIES (Dieselization of fleets) Importation of Cleaner diesel vehicles Change light duty passenger vehicles to 55% Diesel Euro IV by 2050
		Business As Usual Scenario: BAU vehicle emission standards, fuel economy standards and fuel share were kept constant between 2010 and 2050

3. Results

3.1. *Emissions for base year 2010*

The emission inventory outputs from the emissions inventories of 11 pollutants for 2010 by major source sector are shown in Fig. 2. Transport (road and other forms of transport) dominate NO_x and PM_{10} emissions, and was the majority fraction of $PM_{2.5}$ emission. Smaller contributions were made to CO_2, NMVOC, CO and BC emissions. The dominant contribution of transport emissions to PM_{10} reflects the large estimated emissions of road dust in the coarse fraction of particulate matter, while NO_x emissions were from transport derived from tailpipe emissions. Other source sectors which made substantial contributions to pollutant emissions in Kenya in 2010 include i) residential sector, which contributed the major fraction of estimated BC, OC and CO_2 emissions, ii) cottage industries (Brick kilns and charcoal making) for NMVOC and CO emissions, and iii) agriculture for NH_3 and CH_4 emissions.

The contribution of Kenya's transport sector emissions from road transport, domestic shipping, railway and domestic aviation for 2010, are shown in Fig. 3. International shipping and international flights were not accounted for in the national emissions inventories. Road transport dominates transport emissions of all pollutants. However, the contribution of different modes of road transport varies. Heavy-duty vehicles and urban buses account for 62% of NO_X and 49% of BC road transport emission estimates. Motorcycles dominate NMVOC, OC, CO and $PM_{2.5}$ road transport emissions, while passenger cars contribute most to estimated NH_3, CH_4, and CO_2 road transport emissions.

3.2. *Future trends*

Emission inventory projections were created for the BAU scenario. Different mitigation scenarios, described in Table 3, were also

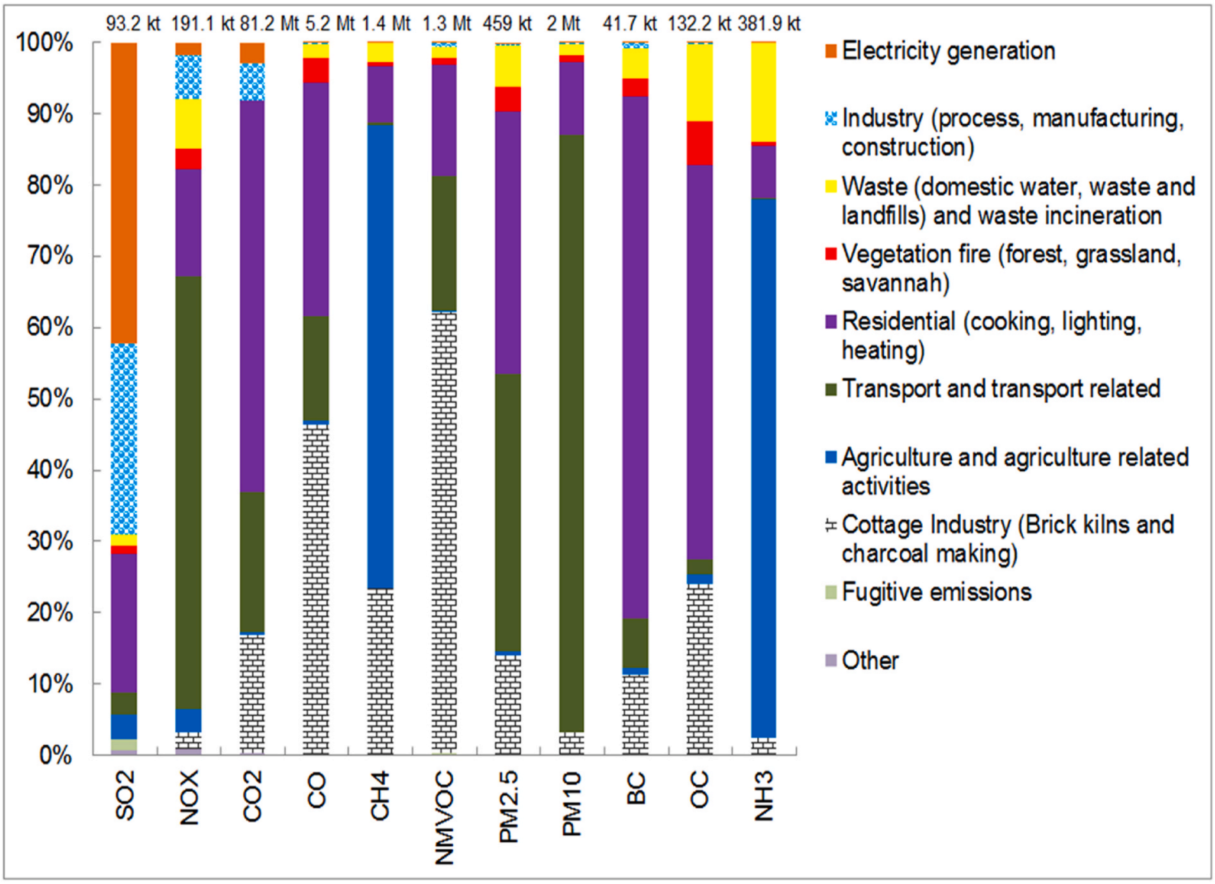

Fig. 2. The 2010 fractional sectorial contribution by emitted species.

constructed and the results are discussed in the sections that follow.

3.2.1. *Business as usual scenario*

The vehicle population growth projection for the BAU scenario is shown in Fig. 4. In 2010, 1.34 million vehicles were registered in Kenya, 40% are passenger vehicles, 27% motorcycles, 16% light commercial, 7% heavy duty, 6% urban buses and 4% three wheeler. By 2030, the vehicle population was projected to increase to 5.7 million vehicles with motorcycles becoming the largest proportion of the vehicle fleet (56%), followed by passenger vehicles (28%). In 2050, Kenya's total vehicle fleet was projected to be 21.6 million vehicles and the motorization rate increases to 226 vehicles per 1000 people, the largest proportion being motorcycles (63%).

BAU emission projections, in response to these changes for different species from Kenya road transport sector up to 2050 were projected to increase approximately 4-fold for SO_2, 9-fold for NO_X, 11-fold for CO_2, 23-fold for CO, 13-fold for CH_4, 31-fold for NMVOC, 19-fold for $PM_{2.5}$, 11-fold BC, 28-fold for OC and 10-fold for NH_3. By 2050, motorcycles dominated estimated road transport emissions of all pollutants except for NO_X and NH_3, contributing 95% of OC and NMVOC, 83% of CO, 81% of $PM_{2.5}$, 56% of BC, 47% of CH_4, 42% of SO_2 and 36% of CO_2. The BAU results from 2010 to 2050 are shown in Fig. 5 and in the supplementary Figure C.2. The rapid increase is largely driven by the disproportionate increase in the motorcycle fleet compared to other vehicles. Heavy-duty vehicles contributed most to estimated NO_X emissions by 2050 (34%), followed by passenger cars (22%) and then motorcycles (21%), whilst passenger cars account for the bulk of NH_3 emissions (87%) from this sector.

3.2.2. *Effect of mitigation scenarios on road transport emissions*

The projections of Kenya's road transport emissions for selected pollutants in the mitigation scenarios from 2010 to 2050 are shown in Fig. 5, and for all pollutants in the supplementary Figures C3.1-C3.10. The most effective scenario for reducing emissions for all pollutants was SC1_FEVES except in reduction of NH_3, for which the most effective scenario was SC5_DIES. SC5_DIES was the second most effective scenario in reducing total SO_2, NO_X, CO_2, CO, CH_4 but this scenario showed increases in total $PM_{2.5}$, BC and OC. The second most effective scenario after SC1_FEVES in reduction of NMVOC, OC and $PM_{2.5}$ was SC3_ELEC, and for BC was SC2_CNG. However, the SC2_CNG scenario showed an increase in total CH_4 emissions, whilst showing substantial emission reductions in NO_X emissions.

SO_2 in all the scenarios initially increased up to 2016, and then decreased to 2020 before increasing again to 2050. However, when compared to the BAU, the SC5_DIES scenario emissions of SO_2 are 4% higher in 2015 then decrease by 11% and 29% of BAU emissions by 2030 and 2050 respectively. Reductions of SO_2 emissions were larger in the SC1_FEVES scenario with decreases of 17% by 2030 and 62% by 2050 relative the BAU. Emission of SO_2 for the other three mitigation scenarios did not differ significantly from the BAU scenario. Estimated emission reduction of CO_2 and CH_4 followed a similar trajectory, whereby SC1_FEVES show the biggest reductions in 2030, 17% for both CO_2 and CH_4, and in 2050, 61% for CO_2 and 63% for CH_4. Emissions from five species; BC, OC, NMVOC, $PM_{2.5}$ showed 93%–98% reduction in the 2050 SC1_FEVES scenario.

The reduction potential of the mitigation scenarios from BAU for different vehicle types for Kenya from 2010 to 2050, are presented in Fig. 6 and in the supplementary, Figures C4.1-C4.10. For NO_X, all scenarios in general showed a decreasing trend from 2010 to 2050 when compared to the BAU scenario (Fig. 6, top left). In scenario SC1_FEVES, NO_X emissions from light commercial vehicles and passenger cars show the largest reductions (>90%) followed by urban buses (73%) and heavy

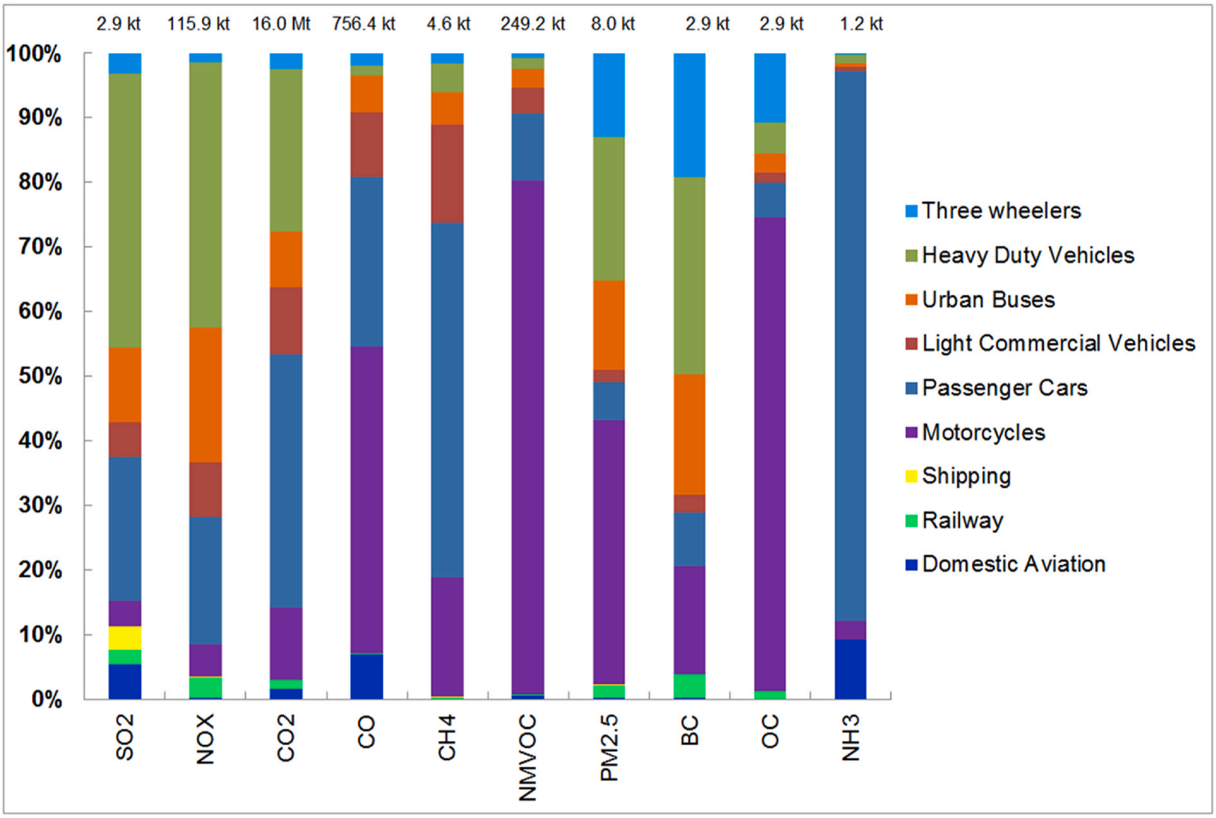

Fig. 3. The 2010 fractional transport sector contribution by emitted species.

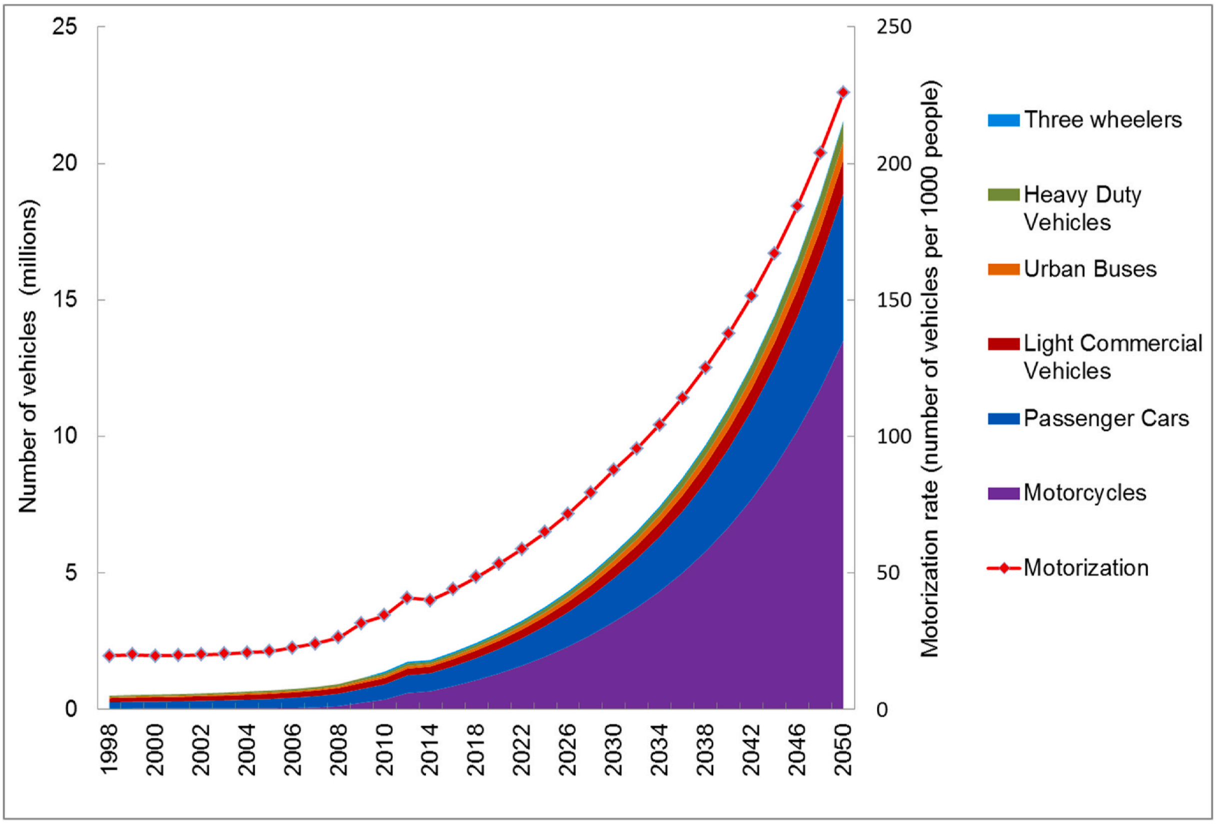

Fig. 4. The historic trend (1998–2010) and future projection (2010–2050) of the total number of vehicles together with motorization rates (number of vehicles per 1000 people) Source data [40,77].

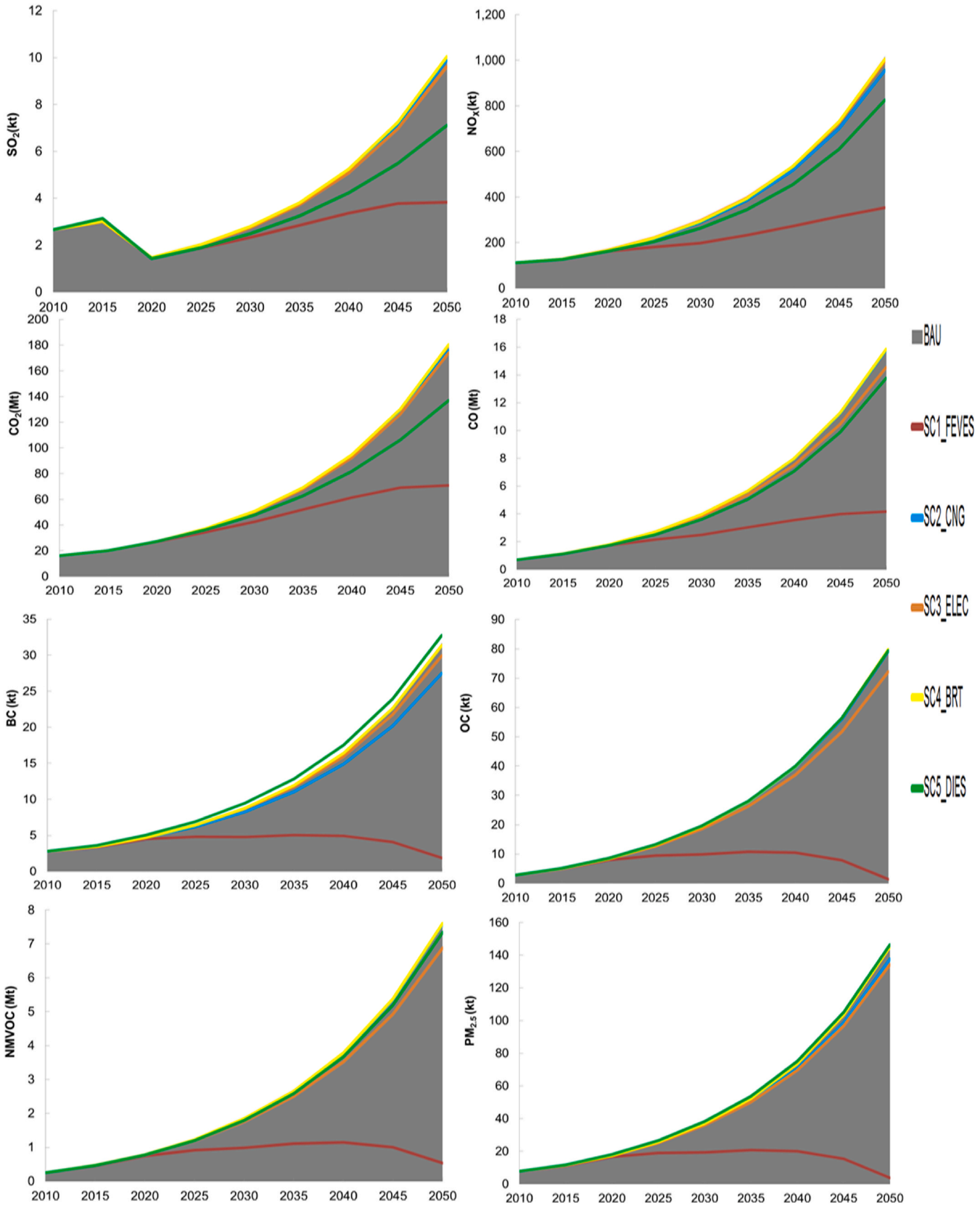

Fig. 5. Total select emissions from Kenya's road transport sector in different scenarios, 2010–2050.

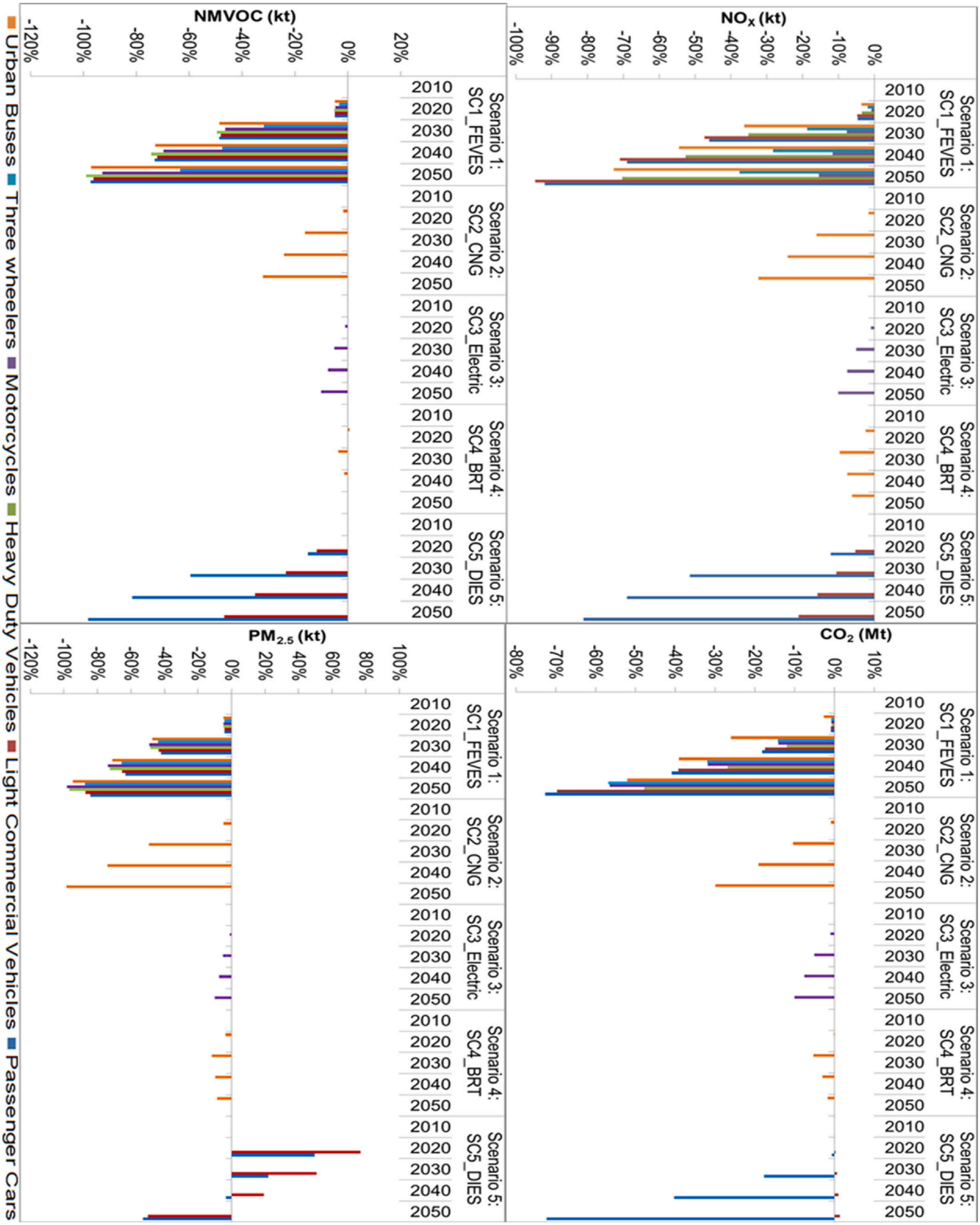

Fig. 6. Select road transport emission reduction in percentage from BAU of the different vehicle types in different scenarios 2010–2050.

duty vehicles (70%). The SC5_DIES scenario shows the second largest NO_x emission reductions in 2050 for both passenger cars (81%) and light commercial vehicles (23%) with the SC2_CNG scenario showing the second largest reduction (16%) for urban buses. SC5_Electric and SC4_BRT show modest reductions, less than 10% by 2050. Carbon dioxide emissions from light commercial vehicles and passenger cars in scenario SC1_FEVES had the largest estimated reductions (>70%) compared to BAU in 2050, whilst motorcycles and three wheelers show over 55% reduction in 2050. The SC5_DIES scenario CO_2 emission reduction for passenger cars was almost as large as for the SC1_FEVES whilst light commercial vehicles showed a slight (1%) increase. For urban buses, the SC2_CNG scenario was the second most effective for CO_2 emission reduction, with a 30% reduction by 2050. SC3_Electric and SC4_BRT show modest CO_2 reductions (<10%) for motorcycles and urban buses respectively by 2050.

The SC1_FEVES scenario generally produced the highest reductions in NMVOC emissions, compared to BAU in 2050, for all vehicles types: 63% for three-wheelers and >93% for the remaining categories (Fig. 6). However, the SC5_DIES scenario NMVOC emissions reductions for passenger cars (98% by 2050) were higher than in all other scenarios although for light commercial vehicles, the 2050 reduction (47%) was less than half that for SC1_FEVES. For urban buses, the SC2_CNG scenario shows the second largest NMVOC emission reduction by 2050 (32%) after SC1_FEVES and the SC3_Electric scenario show the second highest reduction (~10%) for motorcycles by 2050.

The $PM_{2.5}$ emissions reductions, compared to BAU in 2050, are generally highest in SC1_FEVES at >90% for heavy duty vehicles, motorcycles and urban buses and >80% for all other vehicle categories (Fig. 6, bottom right). However, for urban buses, the highest emission reduction (99% in 2050) is shown in the SC2_CNG scenario. For the SC5_DIES scenario, passenger cars and light commercial vehicles initially show a $PM_{2.5}$ emission increase of 50% and 77% respectively by 2020, but this reduces rapidly to 2050 by which time there is a reduction of over 50% compared with the BAU. The SC3_Electric and SC4_BRT scenarios show modest reductions in $PM_{2.5}$ emissions from motorcycles and urban buses respectively, both less than 15% by 2050.

4. Discussion

4.1. Transport policy implications for Kenya

This study estimated that a substantial fraction of total national CO_2 emissions (20%) came from road transport in 2010, and these emissions were projected to increase substantially into the future. Hence, to achieve the stated goals of Kenya's NDCs, controlling emissions from transport was shown to be important. This study shows that the implementation of a BRT system as proposed may have modest GHG emission reductions, but focussing on improving vehicle emissions standards, and fuel economy across the entire Kenyan vehicle fleet may be more effective in achieving this. Carbon dioxide was the main long-lived GHG to which transport contributed, while emission reductions in other sectors would be more effective in reducing other GHGs such as CH_4 (e.g. agriculture). In addition to climate impacts, increased motorization in Kenya has also led to increased congestion, road accidents and air pollution especially in urban areas [23,33,42,46,78,79]. An outdoor ambient air apportionment study conducted in Nairobi in 2009, found vehicle emissions contribute 39% of $PM_{2.5}$ [25].

Kenya's government efforts to reduce road transport pollution through national regulation and standards align with their international commitments and Kenya's 'vision 2030' policy [46,72]. To curb vehicle emissions the government has used a vehicle and fuel standards approach: firstly, introducing a vehicle age limit for importation to 8 years and harmonizing fuel quality standards together with the other East African communities to achieve 50 ppm sulphur content for diesel and 150 ppm for gasoline [44]. Legislation for vehicle emission limits and inspection exists [45], however government inspectorate lacks resources and capacity, therefore it is poorly implemented. Furthermore, without inspection and maintenance (I/M) programs in Kenya, newer fleet (less than 8 years) emissions also increase significantly [65,80]. This study shows that the effective enforcement of vehicle and fuel economy standards on imported vehicles, to achieve the Euro IV standard to which the vehicles currently imported into Kenya are manufactured, would be the most effective action to reduce air pollutant and GHG emissions from the road transport sector. Implementation of the SC1_FEVES, SC2_CNG, SC4_BRT and SC5_DIES scenarios require strict vehicle emission standards up to Euro IV to be implemented and enforced by 2020 so that the fleet's standards start to improve gradually. These standards go hand in hand with better fuel standards and implementation of an I/M program for all vehicles in Kenya. Under the KS1515:2000 standard, commercial and public vehicles should undergo annual tests and private vehicles should have bi-annual tests if they are 5 years or older upon registration. These emission standards resemble the UK Ministry of Transport (MOT) vehicle tests and limits and are therefore I/M tests.

Fuel economy standards are often decoupled from vehicle emissions standards [63]. However, Kenya could implement these concurrently given its improved fuel quality and vehicle imports from countries with Euro IV standards or higher. In Kenya, a study in NMR estimated in-use vehicle fleet economy characterised by vehicle category [49]. Assuming the Kenya's fleet fuel economy is similar to NMR for 2010, then the SC1_FEVES scenario was implemented such that Kenya's vehicle fleet will have an average annual improvement rate until it reaches the Japanese fuel economy standards [74] by 2050. SC1_FEVES required these improved FE standards to be implemented by 2020, so that the fleet FE gradually changes. However, the annual FE improvement estimated for this scenario (5–100%, by 2050) was higher than some previous studies: a 1% annual improvement of fuel economy for the South African fleet [81], and 0.3–1.3% for Chinese fleet [76]. Both of these countries, unlike Kenya, have a large automotive manufacturing sector and have existing vehicle emission and fuel economy standards [76,82], whilst Kenya's projected improvement would be from standards that do not exist, therefore this difference was deemed to be justifiable in the Kenyan context.

Prior studies have shown increasing the share of compressed natural gas (CNG) in buses and hybrid electric vehicles decreases vehicle emissions [76,81,83,84]. China and India are global leaders in the use of CNG, and in both countries, there were deliberate government efforts to build infrastructure to support CNG use through tax incentives and subsidies in addition to domestic availability of CNG [85]. In this study's SC2_CNG scenario, a widespread adoption of CNG urban buses was envisaged by 2050, contributing to reductions of $PM_{2.5}$, CO_2, NMVOC, BC and NO_X (see Figs. 5 and 6). The estimated $PM_{2.5}$ emission reduction in SC2_CNG was similar to India's reduction on initial introduction of CNG for buses and three-wheelers in the past decade [84]. Kenya does not have a domestic supply of CNG, but neighbouring Tanzania has abundant CNG reserves and has been utilizing it for transport, targeting nearly 500,000 conversions by 2040 [86]. The implementation of this scenario could therefore be facilitated by imported natural gas from Tanzania, and CNG-fuelled buses from China or India, countries that are already Kenya's trading partners. Furthermore, government commitment would also be needed to build required infrastructure for CNG use such as filling stations [85,86]. The Kenyan government had considered tax incentives for hybrid electric vehicle imports [46], therefore it is likely the percentage (~0.01% in 2010) of hybrid vehicles, will grow by 2050. However, in this study, we did not explore the hybrid vehicle scenario because emission factors for second-hand hybrid vehicles were not available.

BRT has been successfully implemented in over 200 cities worldwide [87] as it has advantages in increasing access to safe, convenient and affordable public transport [88] while reducing intensive use of private cars. In SSA, BRT has been implemented in Nigeria [89], South Africa [81,90] and Tanzania [88]. BRT systems are often complementary to existing informal transport systems in Africa [87]. Kenya is in the process of implementing BRT systems in Nairobi [46], although there have been delays it is now at an advanced stage. The current study, explored the implementation of the proposed BRT for Kenya in the SC4_BRT scenario. The scenario was modelled based on the data from a BRT system implemented in Tanzania that carried 120,000 passengers using a 21 km road with 177 buses [91]. The results showed emission reduction for $PM_{2.5}$ and BC and modest reductions for other emissions compared to SC1_FEVES (see Figs. 5 and 6). Greater emission reductions could be achieved for Kenya from BRT by increasing the scale (road network, number of buses, routes) of the proposed project whereby Kenya would start to see benefits in reducing vehicle ownership, decreasing vehicle mileage, which in turn reduces vehicle emissions and provides sustainable transport.

In previous studies, the key source of PM emissions in the transport sector has been light and heavy duty trucks with diesel engines [6], especially in Europe where there is a large share of diesel fleets [6,64,92]. However, for Kenya in 2010, we found motorcycles were a key source of PM, followed by heavy duty vehicles and urban buses (Fig. 3). Heavy duty vehicles make the largest contribution to BC, NO_X and SO_2 emissions, with scenario SC1_FEVES having the largest emission reductions. In Kenya, heavy duty vehicles and urban buses were considered to be uncontrolled using basic injection technology [93]. Kenya's fuel quality sulphur content in diesel (500 parts per million) improved ten-fold from 2010 to 2015, (specifications are shown in the supplementary section, Table A.1) [50,51], therefore there is a SO_2 reduction over this historical period in all scenarios. Diesel vehicles are responsible for the majority of the NO_X emissions which are key secondary $PM_{2.5}$ and O_3 precursors [5], therefore heavy duty vehicles with 100% diesel share in Kenya, have the highest contribution of NO_X. Urban buses (matatus) in Kenya in 2010, comprised 46% diesel, a lower than expected proportion as there is a high importation of petrol-driven smaller vans, pickups and station wagon [44] converted to matatus [36,62], mostly circulating in rural areas. Even with this relatively low diesel proportion, urban buses were the second highest contributors of NO_X, BC and SO_2 after heavy-duty vehicles. In addition to the scenario SC1_FEVES for maximum emission reduction, SC2_CNG shows significant reductions for BC and SC4_BRT had modest reductions for urban buses.

We did not include other forms of transport in the mitigation scenarios even though it is probable emissions from other forms of transport increase in importance into the future. We had limited data especially on rail transport even though rail emissions will most likely increase because as part of Kenya's vision 2030 there is rapid expansion of current rail infrastructure to include light rail transport in the NMR and expand passenger and freight transport country wide [46]. This could potentially reduce the demand for heavy duty vehicles to transport freight across Kenya, but this element of the future transport landscape in Kenya has not been evaluated in this study.

4.2. Comparison of emissions with previous estimates

The emission dataset developed for this study was compared to a global inventory compiled using ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) dataset [94] created using GAINS (Greenhouse-Air Pollution Interaction and Synergies) model [3], for Kenya. See Fig. 2 for this study and Figure C.1 in the supplementary for the ECLIPSE study. The residential sector in ECLIPSE accounts for the majority of emissions for almost all pollutants except CH_4 (agriculture) and NH_3 (agriculture) and SO_2 (industry). This study's total emissions for Kenya, for all sectors for each species were higher than ECLIPSE emissions, except for BC (27% lower). VOCs and PM_{10} were over 50% higher, SO_2 and NO_x emissions were 40% higher in this study, $PM_{2.5}$ and CO over 30% higher, CH_4 over 20% higher, NH_3 over 10% higher. Differences in transport emissions explained much of the differences in total emission estimates. In this study, PM_{10} and $PM_{2.5}$ emission included re-suspended dust from unpaved roads in addition to tail-pipe emissions, and it was estimated that road dust accounts for 96% of $PM_{2.5}$ and 100% of PM_{10} emissions across the transport sector in 2010. This is due to the high fraction of unpaved roads in Kenya [33,52,67]. ECLIPSE datasets did not estimate unpaved road dust [6], or other sectors such as savannah and grassland burning, which may account for lower emissions of OC, CO, PM_{10} and $PM_{2.5}$ in the ECLIPSE inventory.

The dominant contribution of road transport to transport emission in Kenya is consistent with previous studies where road transport in Kenya (when compared to rail and water) was identified as contributing 99% of transport GHG emissions in Kenya [46]. In an inventory for Africa, over 90% of CO and NO_X emissions from total transport was from road transport. In previous inventories for Kenya, OC emissions from the transport sector represented 13% of total OC emissions [15]. In this study and the ECLIPSE estimation, OC emissions were both ~2%, and therefore the Lacey et al [15], estimation of OC from transport was greater than this study's estimate.

The ECLIPSE data set made three assumptions for high emitting vehicles that differ from those assumptions applied in this study. The first is the assumption that high emitters comprise 20% of the fleet in Kenya [6]. Even though few vehicle exhaust emission tests have been conducted, a previous study found 70% of vehicles failed emission standards for Kenya [46]. In this study, it was assumed that all vehicles were effectively pre-euro, even if manufactured originally to higher Euro standard. The second assumption is that durability of emission controls increased. In this work it is assumed that this is not the case for fleets that do not have the emission control or they are often removed or tampered with, as is the case in Kenya, in addition to the absence of I/M. The latter was found to be produce pollution rates significantly deviating from certification for new vehicles [80], thus we can infer emissions for older vehicles this would be more substantial. Although there is limited information on the fraction of emission controls removed or tampered with in Kenya. The third assumption is amplification of emissions for high emitting vehicles (presumably with malfunctioning technology) to be a factor of 3–10 for all vehicle technologies. Real-world emissions testing has proven vehicles with up to Euro V tested on the road instead of a laboratory have sometimes up to 300% higher emissions [95–97]. For Kenya, the discrepancy between real-world and laboratory emissions may be even greater than in developed countries due to the older, imported second-hand fleet with poor I/M. The DICE-Africa model from which Lacey et al [15], based their estimation for Kenya's transport inventory to be 49 motorcycles per 1000 people from a prior study [11]. This estimate is greater than the 18 motorcycles per 1000 people registered in Kenya in 2013 [40], and may in part explain the higher OC transport emissions for Kenya in Lacey et al. [15], compared to this study.

This study SC5_Electric scenario assumed a small percentage (10%) fleet of electric motorcycles in Kenya, but because by 2050 in the BAU, motorcycles will be 13.5 million representing 63% of the Kenyan vehicle fleet, this scenario showed significant emission reductions for SO_2, NO_X, CO_2, CH_4, CO and NH_3. Motorcycles were assumed to have no emission controls in the BAU, and to adhere to Bharat III (Indian vehicle standards in SC1_FEVES), as India and China are the main countries where motorcycles in Kenya are imported from. By 2050, the results show that the motorcycles are responsible for the bulk of vehicle exhaust emissions for all species except NO_X. This is comparable to results from a previous study in Ho Chi Minh City, Vietnam where motorcycles comprised 87% of the vehicle fleet in 2015, were then responsible for the majority of vehicle emissions contributing 94% of CO, 68% of NMVOC, 61% [98]. China is the largest manufacturer of electric motorcycles [99] and they have opened various motorcycle plants in Africa, thus this offers a viable scenario whereby Kenya could reduce emissions from motorcycles. This study therefore emphasises that to control emissions into the future, motorcycles need to be considered in any mitigation strategy.

4.3. Uncertainties and limitations

We considered uncertainties in vehicle usage, vehicle kilometres travelled (VKT) and fuel economy (FE) and emission factors per vehicle category and per emission species. In the projections we assume the percentage uncertainties in the base year emissions estimates will propagate over subsequent years [100]. Furthermore, emission factors that over or under estimate emissions in the base year will probably do so in the subsequent years.

Uncertainty in predicting vehicle growth from increase in income per capita results from there being a saturation point [81,101–104]. The Gompertz function [101,102] has been used to model this relation and accounts for saturation levels and parameters which determine the model curvature calculated from historic data. However this equation and parameters have been derived for developed countries with high income ($19,000-$46,0000) GDP per capita, and countries with middle income ($4000-$9,6000) per GDP capita. Motorization rates in these countries are well above Kenya's 44 vehicles per 1000 people and GDP per capita $1400. Therefore, we considered that Kenya is unlikely to reach saturation levels in the time scale concidered and assumed a linear relationship between the GDP per capita and the number of vehicles based on historical Kenyan data. We also did not consider the rate at which a vehicle is scrapped [81], as a function of the vehicle age being the probability of the vehicle remaining operational. With limited data for Kenya, we could not determine the parameters needed to either calculate the scrappage rate or determine the decay of mileage both of which would affect road transport emissions estimation for the fleet.

Dry days were defined as those with less than or equal to 0.1 mm rainfall per day, this is a lower threshold than that assumed in Gillies et al. [68], 0.25 mm. Hence, the PM estimates from road dust in the present study are conservative. However, in the estimate of the proportion travelled on paved or unpaved roads, it was assumed that the VKT travelled on the paved/unpaved roads was a function of the road length. This is likely an over-estimate, as more vehicles will travel on the bigger paved roads. Thus in our estimation, these two factors would tend to balance out the uncertainty associated with the estimation of PM from road dust.

The activity data for vehicle VKT and FE was based on a previous study conducted in NMR which was assumed in this study to be representative of the whole country [49]. While 67% of all vehicles in Kenya circulate in NMR [33], the vehicles outside of Nairobi may circulate for longer distances (higher VKT of intra-country buses and trucks), and may have better FE per km. Further work is required to establish the activity for vehicles outside of NMR.

5. Conclusions

Current and projected future estimates of air pollutant and GHG emissions from Kenya's road transport sector were estimated between 2010 and 2050. An inventory was compiled of all major source sectors so that transport emissions could be set within the context of total national emissions. Five potential mitigation scenarios were evaluated where the methodology, data sources and policy scenario analysis may be applied to other African and developing countries with similar geographic and social-economic profiles.

In 2010, the transport sector emitted an estimated 15.95 Mt of CO_2, 115 kt of NO_X and 249 kt of NMVOC with road transport contributing nearly 97% of these emissions. Emissions for different species from Kenya's road transport sector up to 2050, in the BAU, were projected to increase 9-fold for NO_X, 11-fold for CO_2, 31-fold for NMVOC, 19-fold for PM, 11-fold for BC, and 28-fold for OC. The projected increases in vehicle emissions highlighted that projected increase in motorcycle ownership will result in a large increase in estimated emissions, and therefore motorcycles should be considered as part of any mitigation strategy for Kenya. The mitigation scenario combining better fuel economy with improved emissions standards (SC1_FEVES) was the most effective reduction scenario for almost all pollutants.

These results suggest comprehensive implementation of improvements in both fuel economy and vehicle standards in Kenya will have the most benefits for improving air quality and reducing Kenya's contribution to short and long-term climate warming, although a fuel shift to CNG or electric-powered vehicles, as well as investment in public transport, would also contribute to emission reductions.

Credit author statement

We certify that all persons listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

Declaration of competing interest

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101120.

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