Safe to Breathe?

Analyses and Recommendations for Improving Ambient Air Quality Management in Ethiopia

WORLD BANK GROUP

Report No: AUS0002512

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ABBREVIATIONS AND ACRONYMS

AA	Addis Ababa
ADB	Asian Development Bank
AQ	Air Quality
AQM	Air Quality Management
BAM	Beta Attenuation Monitor
BC	Black Carbon
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalent
EF	Emission Factor
EFCCC	Federal Environment, Forest and Climate Change Commission, Ethiopia
EPA	Environmental Protection Agency
EPGDC	AA Environmental Protection and Green Development Commission
ESA	Ethiopian Standard Agency
ESP	Ethiopia State Petro Company
FTA	Federal Transport Authority, Ethiopia
GDP	Gross Domestic Product
GEOHealth	Global Environmental and Occupational Health
GHG	Greenhouse Gas
GIS	Geospatial Information Systems
HDV	Heavy Duty Vehicle
ICS	International Community School
IM	Inspection/Maintenance
IMF	International Monetary Fund
LCS	Low-Cost Sensors
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LMIC	Low- and Middle-Income Countries
MOT	Ministry of Transport
NASA	National Aeronautics and Space Administration
NMA	National Meteorological Agency
NMT	Non-Motorized Transport
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
OECD	Organization for Economic Co-Operation and Development
OSM	Open Streets Maps
PM_{10}	Particulate matter under 10 micro-meter diameter
$PM_{2.5}$	Particulate matter under 2.5 micro-meter diameter
ppm	Parts per million
PWC	Population Weighted Concentration
SCC	Social Cost of Carbon

SO_2	Sulfur Dioxide
SPARTAN	Surface Particulate Matter Network
UNEP	United Nations Environment Program
USDP	United States Diplomatic Post
VOC	Volatile Organic Compounds
WHO	World Health Organization
$\mu g/m^3$	micro-grams per cubic meter

ACKNOWLEDGMENTS

This report summarizes the main findings and recommendations of the World Bank's Advisory Services & Analytics program (ASA) entitled "Ethiopia: Air Quality Management and Urban Mobility." Launched in September 2020, the ASA aimed to assist the Government of Ethiopia in deepening its understanding of ambient air quality management, with a focus on urban transport air pollution control. Specifically, it examined priority issues related to air pollution in Addis Ababa, developed policy recommendations and proposed an action plan for Ethiopia and Addis Ababa to step up AQM efforts.

The ASA was developed under the general guidance of Ousmane Dione (Country Director for Ethiopia), Doina Petrescu (Operations Manager for Ethiopia), Iain Shuker (Practice Manager, Environment, Natural Resources and Blue Economy (ENB) Global Practice), and Maria Marcela Silva (Practice Manager, Transport Global Practice) at the World Bank. It was implemented by a team led by Jian Xie (Sr. Environmental Specialist, World Bank Task Team Leader) and Wenyu Jia (Sr. Urban Transport Specialist, Co-Task Team Leader) and comprised Tamene Tiruneh (Sr. Environmental Specialist), Bereket Belayhun Woldemeskel (Municipal Engineer), Fatima Barry (Health Specialist), Lelia Croitoru (Environmental Economist, Consultant), Sarath Guttikunda (AQM Specialist, Consultant), Jurg Grutter (Transport Specialist, Consultant), Zenebe Tilahun Abayneh (Transport Specialist, Consultant), and Worku Tefera (AQM Specialist, Consultant). In addition, Michelle Anne Winglee (Climate Change Specialist), Caroline Anitha Devadason (Health Specialist, Consultant), Kimberly Worsham (Environmental Specialist, Consultant), and Christopher Arthur Lewis (Environmental Economist, Consultant) participated either in early or late phases of the ASA program.

This report was prepared by Jian Xie, Wenyu Jia, Lelia Croitoru, Sarath Guttikunda, and Jurg Grutter, with input from Tamene Tiruneh (institutional arrangements), Bereket Belayhun Woldemeskel (urban development), Fatima Barry (health), Zenebe Tilahun Abayneh (transport), Worku Tefera (air quality monitoring), Kimberly Worsham (regulatory and policy review), and Christopher Arthur Lewis (financial arrangements).

This report benefits from the participation and support of government officials and experts from various Ethiopian government agencies and institutions, particularly the Federal Environment, Forest and Climate Change Commission (EFCCC), Ministry of Transport (MoT), Federal Transport Authority (FTA), Ministry of Health (MoH), National Meteorology Agency (NMA), Addis Ababa Environmental Protection and Green Development Commission (AAEPGDC), Addis Ababa Transport Bureau (AATB), Addis Ababa Vehicle and Driver Registration and Authorization Authority, Addis Ababa Health Bureau (AAHB), Ethiopia State Petro Company (ESP), and Addis Ababa Institute of Technology (AAIT). It also benefits from regular discussions and consultations with representatives and experts from a group of international organizations actively working on air quality management in Addis Ababa, such as C40 Cities, UNEP, U.S. Embassy and EPA, USAID's Clean Air Catalyst Program (managed through the World Resource Institute and Environmental Defense Fund), Global Environmental and Occupational Health's (GEOHealth's) East Africa Hub, and Surface Particulate Matter Network (SPARTAN).

The authors would like to thank Paul Jonathan Martin, Martin Heger, Fiona Collin, Rodger Gorham, James Robert Markland, Sameer Akbar, and Marius Vismantas for their valuable comments and suggestions. Special thanks also go to the participants of the consultation workshops held virtually in March, April, and June 2021 for their review and discussions on the findings and results of studies and technical reviews of the ASA. Ross Hughes helped coordinate within World Bank's county management unit. Esther Bea and Sofia Said provided administrative and logistic assistance to the program. Demetra Aposporos provided editorial assistance and Guomeng Ni provided infographic design.

EXECUTIVE SUMMARY

1. **Air pollution presents a global problem that undermines health and economic productivity**. Data from the World Health Organization (WHO) shows that 9 out of 10 people breathe air containing high levels of pollutants, with low- and middle-income countries (LMICs) bearing the brunt of poor air quality. Air pollution is the leading environmental risk factor for premature death. In 2019 alone, indoor and outdoor air pollution was estimated to have contributed to 6.67 million deaths worldwide, nearly 12% of the global total. The health impacts of air pollution are also reflected in morbidity levels, loss of income, decreased participation in the workforce, disability, and higher health care costs.

2. **Poor air quality during the COVID-19 pandemic may further jeopardize hard-won gains in public health**. Particulate matter (PM), especially fine particulate matter such as $PM_{2.5}$ (PM with aerodynamic diameter less than 2.5μm), can affect respiratory, cardiovascular, cardiopulmonary, and reproductive systems, and can in some instances lead to cancer. Ongoing research suggests a correlation between poor air quality and the incidence of severe illness and death among people exposed to COVID-19 with pre-existing, non-communicable diseases (NCDs), such as cardiovascular and respiratory diseases.

3. **Air pollution, exacerbated by urbanization and increasing mobility, is a growing concern across Africa**. In Africa, indoor and outdoor air pollution has already become the most significant environmental contributor to premature death, outpacing malaria and HIV. Reports show that ambient air pollution causes 73 premature deaths per 100,000 urban residents in Cairo, 46 in Lagos, and 35 in Abidjan. Growing rural-urban migration, traffic congestion, and increasing industrialization are increasing air pollution and resulting in poorer air quality, aggravating health impacts. Ambient air pollution also affects the quality of soil and water resources, impeding flora development, reducing food production, and contaminating water surfaces.

4. **Rapid economic growth and urbanization in Ethiopia, particularly in its capital Addis Ababa (AA), have resulted in environmental deterioration and health concerns.** Ethiopia is one of the fastest-growing economies in the region, growing at 9.9% annually from 2008 to 2018. Ethiopia's urban population accounted for 21.2% of its total population of 112 million in 2018, and the urbanization rate is projected to increase to 39% in 2050. Growing economic activities, unmanaged urban sprawl, and increasing mobility and transportation in AA have increased pollution emissions, traffic congestion, land and environmental deterioration, and risks to public health. Analysis of visibility data in AA suggests that air quality has been declining since the 1970s, with average air quality now approximately 1.6 times worse than it was in the 1970s. There are increasing incidents of airborne diseases. The impact of air pollution on public health is becoming a growing concern for both governments and the public.

5. **As is the case in many other countries, ambient air pollution in Ethiopia, particularly in AA, includes emissions from multiple pollutants and various sources.** Common drivers of ambient air pollution in a city and its surrounding areas include activities such as transport, cooking and heating, industries, construction sites, bare earth open areas, agricultural activities, and solid waste management (including open waste burning). Unlike many polluted cities in the world, in which power is largely generated by coal-based thermal power plants, AA's predominant power generation source is hydro and other sectors predominantly use biomass, diesel, and coal for fuel. Primary air pollutants that put pressure on airsheds include particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_2), volatile organic compounds (VOC),

and ozone. Among these pollutants, $PM_{2.5}$ is considered the most relevant urban air quality indicator in AA and worldwide. $PM_{2.5}$ is responsible for aggravating respiratory, circulatory system, and heart problems, as well as leading to premature mortality. Moreover, studies also associate air pollution with increases in communicable infections, such as influenza and COVID-19.

6. **Air pollution and AQM involve numerous stakeholders, including households, vehicle owners, manufacturers, government agencies, and so on, across various sectors.** Managing the different stakeholders involved in AQM is complex. Government agencies from different levels and across different sectors must develop and implement policies and regulations that consistently minimize air pollution across their jurisdictions while aligning with national and even international standards. This can be challenging, as agencies need to balance priorities while accommodating objectives from other agencies. Managing the public's behavior in reducing air pollution is also complicated, as the public, such as vehicle divers and households, need awareness programs that encourage their participation and behavioral changes.

7. **Integrated air quality management (IAQM) is necessary to comprehensively address air pollution problems and protect the public from health issues and economic losses from poor AQ.** IAQM involves developing a knowledge base or analytical tools for air pollution emissions and AQ monitoring that can support pollution control planning. Analysis of the interplay between different sources of pollutants, their consequences on health, the environment, and the economy, supports the interpretation of data for different actors. Additionally, key to implementing an IAQM strategy is building institutional and human resource capacity for pollution monitoring and management; institutional coordination between different sectors; national standards, regulations, and policies for pollution; and compliance monitoring and regulatory enforcement.

8. **This study aims to deepen the understanding of ambient air pollution and develop policy recommendations for improving AQM in Ethiopia.** Conducted from September 2020 to June 2021, the study reviewed ambient AQ and institutional arrangements, assessed the impacts of ambient air pollution on health, analyzed emission inventory and source apportionment, and identified and prioritized urban transport air pollution mitigation measures. It focused on AA and the urban transport sector due to limited data available nationwide and limited time and resources. This report summarizes the main findings and recommendations of the study.

9. **Although Ethiopia has environmental policies and regulations that touch on air quality, the country has no specific framework on AQM.** Ethiopian national standards of ambient AQ were issued in 2003. Its standard for annual average ambient $PM_{2.5}$ concentration is set at 15 $\mu g/m^3$, higher than the WHO guideline of 10 $\mu m/m^3$ and standards in many other countries. There are no rules or laws around fuel quality and vehicle emissions standards, which leads to the transportation sector and vehicle owners emitting unnecessarily high levels of air pollution with low-quality fuel.

10. **The government agencies with mandates for AQM are facing weak institutional and financial capacity to enforce AQ standards and implement AQM programs.** In the federal government, the Environment, Forest, and Climate Change Commission (EFCCC) leads air pollution control efforts. Other line agencies support AQM, including the ministries for health and transport and the Ethiopian Standard Agency (ESA). In AA, the AA Environmental Protection and Green Development Agency (AAEPGDA) coordinates the city's AQM planning and oversees air pollution controls. Other city agencies, such as the AA Transport Bureau and Health Bureau, participate in and support AQM. However, there is a lack of functional units in

charge of AQM in AAEPGDA and other agencies, making it difficult to ensure AQM roles and responsibilities. Also, the mandates of some line ministries or agencies for AQM are not clearly defined. Ethiopia's enforcement of environmental regulations and standards has also been inconsistent and weak because of conflicting goals, insufficient data for government coordination, low capacity, and low persistence of enforcement. Other underdeveloped areas include financial arrangements for AQM. Environmental taxation and fees are rare, with little earmarked to fund air pollution control activities. Line ministries/agencies and municipal governments lack a specific budget for AQM. Private sector investments in AQM are few. There have been few investment activities in air pollution reduction, even in key polluting sectors (for example, urban transport and industry) though some investments have gone towards building AQ monitoring networks.

11. **AQ monitoring is relatively new in Ethiopia and AQ data is scarce**. AQ monitoring began in 2014 when three AQ monitoring stations were established by the National Meteorological Administration (NMA): in AA, Adama, and Hawassa. The AQ monitoring network in AA has since gradually expanded and the past two years have seen a boom of installing low-cost sensors. As of March 2021, about 20 AQ monitors have been installed inside AA. Most are low-cost sensors that encounter operational challenges due to power and internet connectivity-related problems. So far, only a few stations release continuous monitoring data to the public.

12. **AQ monitoring data available in recent years shows that AA's annual average $PM_{2.5}$ is 2-3 times higher than WHO guidelines and, as a result, the city's air is unhealthy**. Air pollution concentrations vary by location and time, and some AQ monitoring stations indicate that $PM_{2.5}$ can reach several times above the WHO standards. A short AQ study done by the Eastern Africa Global Environmental and Occupational Health (GEOHealth) Hub in AA's city center from November 2015 to November 2016 shows that the mean (±SD) daily $PM_{2.5}$ concentration was 53.8 (±25.0) µg/m3, with 90% of sampled days exceeding the WHO's guidelines. The World Bank program's review of AQ monitoring data reveals that the annual average $PM_{2.5}$ concentration in AA varies between 30 $\mu g/m^3$ and 36 $\mu g/m^3$ across 2016-2020.

13. **Ambient $PM_{2.5}$ causes health damages estimated at the equivalent of 1.3% of the city's GDP each year.** In Ethiopia, air pollution is the second leading risk factor for premature death, after malnutrition. Ambient $PM_{2.5}$ pollution is a growing public health problem in the country's urban areas, particularly AA. This study estimated the health impacts caused by the ambient $PM_{2.5}$ for a typical non-COVID year. Using ground monitored $PM_{2.5}$ data from a few locations and the population exposed in each, the study estimates the annual average $PM_{2.5}$ concentration at about 34 $\mu g/m^3$ – slightly higher than that of other African capitals, such as Abidjan (Côte d'Ivoire) and Cotonou (Benin). Then, based on the Global Burden of Disease methodology, it showed that long-term exposure to this pollution level causes about **1,600 premature deaths** a year in AA. Stroke, ischemic heart disease, and lower respiratory infections are the leading causes of $PM_{2.5}$-related mortality; the elderly are the most affected. In addition to deaths, exposure to ambient $PM_{2.5}$ causes morbidity (disability), related to a plurality of health outcomes, e.g., chronic bronchitis, hospital admissions, etc. The study estimated that these effects correspond to about **4,100 Years Lived with Disability (YLDs)** annually. Overall, the total health damage due to air pollution in AA is estimated at $78 million, which is equivalent to about 1.3% of the city's GDP. Although the estimate is lower than that in very polluted megacities - 2.1% of Lagos' GDP, 4.5% of Greater Cairo's GDP, 5.5% of New Delhi's GDP – it points to the need to investigate the main pollution sources and hotspots in AA.

14. **An air pollution source apportionment study further shows that source contributions to $PM_{2.5}$ pollution in AA are dominated by vehicle exhaust, residential use, and industrial sources.** The transport

sector–including urban transport and aviation–emits 29% of $PM_{2.5}$, 97% of NO_x, 71% of SO_2, and 96% of CO_2. The transport sector's contribution to ambient $PM_{2.5}$ concentration further reaches 35% because PM from vehicle emissions are fine and stay in the air. The remainder of the ambient $PM_{2.5}$ pollution originates from residential fuel combustion in rural and urban areas using a mix of biomass, coal, and LPG with a share of 28%; industrial sources with a majority using biomass as fuel and quarries using diesel; open waste burning; and some long-range sources outside the city's airshed. A closer look at the spatial distribution of industrial sources found that heavy industrial polluters are scattered along the edge of the city, requiring the attention of a concerted effort in managing $PM_{2.5}$ by the city and surrounding regions.

15. **The AQ issues in the transport sector in AA are characterized by rapid motorization, an aging vehicle fleet, high-sulfur fuels, lack of emission standards, ineffective and unenforceable emission inspections, and increasing emissions.** In the past five years, registered vehicles in the city increased by 40 percent, reaching 630,000 vehicles in 2020 and accounting for nearly 50% of Ethiopia's registered vehicles. Most registered vehicles are over 10 years old. Ethiopia currently imports 500ppm sulfur diesel and 10ppm sulfur gasoline; this high sulfur content in fuels pollutes directly, but also prevents the use of newer vehicles with better pollution control technologies. Emission inspection is ineffective and unenforceable for vehicle emission control. In the next decade, should the current vehicle growth trend continue at 8% a year, AA would expect 1.3 million vehicles. Even a conservative estimate, which assumes vehicle growth at the GDP growth rate, projects 900,000 vehicles in AA by 2030. In these scenarios, the level of vehicle emissions will increase in the range of 50% to over 100%.

16. **Continuing business-as-usual (BAU) will further degrade air quality in AA, threatening the city's livability and ability to grow**. Without changes to transport standards, policies, and technologies, transport air pollution in AA will have profound local and national impacts. Meanwhile, the current approach of accommodating vehicle growth has not effectively improved accessibility, but has exacerbated road fatalities, worsened traffic congestion, increased greenhouse gas emissions and deteriorated air quality locally. It is imperative for transport, a contributing sector, to identify and act on air quality management measures.

17. **The Government has undertaken studies to understand the need for air pollution control measures for the transport sector in AA and in Ethiopia.** The Government of Ethiopia and the City Government of AA have prepared studies and plans to identify and implement measures for reducing vehicle emissions. This study reviewed these documents and looked into ongoing urban transport investments and policy works in AA relating to short-term mitigation of emission and air pollution. Based on the review of government studies and ongoing sector activities, assessment of local context, consultation with relevant government agencies, and international experiences, a list of potential mitigation measures in the transport sector in AA was identified for further assessment. These mitigation options fall into three groups: fuel and emission standards, vehicle measures, and public transport.

18. **Overall, a set of policy recommendations are suggested to improve AQM in Ethiopia.** They cover the following areas.

- **Regulation and Policy Reforms:** Ethiopia needs to strengthen its institutional arrangements for AQM, particularly its current regulatory and policy framework, including AQ standards and governmental organization structure.

- **AQM strategy and plan:** Although AA, with external support, has recently developed its AQM plan, no national strategy or plan exists. It is necessary for the country and other cities to develop their strategy and action plan to guide their AQM activities in the future.
- **Budgeting and capacity building:** Low financial and institutional capacity will make sustainable AQM impossible. The governments should attach a high priority to strengthening financial and implementation capacity of line agencies responsible for AQM.
- **AQ monitoring:** Ethiopia must establish a robust AQ monitoring program and network nationally and strengthen existing AQ monitoring.
- **Data collection and analytics:** Ethiopia needs to deepen its analytical work, including AQ data collection and analysis, air pollution dispersion modeling, emission inventory and source apportions, transport modeling and spatio-temporal analysis of traffic and vehicle air emissions, impact assessment, and economic valuation and analysis of AQM programs to better inform AQM planning and decision making.
- **Awareness raising and behavioral change:** The country should conduct communications and public awareness activities to increase understanding and change behaviors that worsen air pollution.
- **Vehicle emissions control:** It is important to prioritize and implement air pollution control measures from the transport sector because of its significant and growing contributions to ambient air pollution.
- **Point and area sources control:** Although this study focused on transport air pollution reduction, it is necessary to point out that point and area sources from other sectors are also important to ambient AQ. Therefore, it is important to develop and implement air pollution control measures for point- and area-sources including (a) controlling air pollutant emission from industries, (b) improving SW collection and reducing open burning of trash, (c) raising public awareness of the health impacts of burning plastic and hazardous wastes, and (d) implementing best practices for control of construction and road dusts.

Table ES-1 highlights the highest-priority and most actionable recommendations in each area.

Table ES-1. Summary of Recommendations for AQM

Category	Recommendation
Regulation and Policy Reforms	Clearly define or clarify the roles and mandates of key government agencies at the federal and municipal level for AQM through functional review of relevant agencies
	Introduce taxation and pricing policies or other fiscally neutral instruments or incentives to encourage newer and cleaner vehicles such as hybrids and electric vehicles and phase out polluting vehicles
	Upgrade AQ standards (including ambient $PM_{2.5}$ standards)
	Introduce low sulfur fuel standards (start with 50 ppm; progress to 10 ppm) with the Euro 4/IV vehicle emission standards nationwide, along with other transport standards
AQM Strategy and Plan	Develop a national urban AQM strategy and action plan
	Strengthen institutional capacity of responsible agencies for AQM, particularly for regulating and enforcing AQ regulations and standards

Budgeting and Capacity Building	Develop mechanisms for promoting inter-agency and cross-sectoral coordination and collaboration as well as experience sharing and learning on AQM
	Increase government revenue and budgets for AQM by reviewing and revising environmental taxation and fee systems
AQ Monitoring	Develop standardized and unified systems for monitoring and reporting ambient AQ and emission levels at critically polluted source regions in AA and other major cities
	Make verified and standardized AQ data open to public access via the internet and mobile apps
Data Collection and Analytics	Systematically collect and analyze AQ and air emission data
	Adopt the top-down chemical analysis-based approach in AA to further update and verify the results of the bottom-up emissions inventory and source apportionment study
	Improve and extend the economic valuation of air pollution impacts beyond health impacts and develop the guidelines of the cost-benefit analysis or cost-effectiveness analysis of AQM programs, investment projects, and interventions
	Develop an abatement cost curve and a plan to implement AQM interventions to cost-effectively reduce air pollution emissions and incorporate the results of health impact assessment and economic analysis
Vehicle Emissions Control	Introduce low-sulfur (max 50ppm) diesel fuel and Euro 4/IV vehicle emission standards or their equivalent
	Ban importing secondhand diesel passenger cars or light commercial vehicles and restrict imports to new and secondhand imported diesel vehicles weighing more than 3.5t gross (i.e., continue to allow imported heavy diesel vehicles, such as trucks or buses)
	Promote and strengthen public transport and non-motorized transport (NMT) measures, with possible transport demand measures and/or transit-oriented development

20. **There are areas to further improve the analytical results and recommendations.** This rapid assessment has faced some limitations. The first is the lack of reliable and comprehensive AQ data. The study behind the report had to rely mostly on open-source data, literature, and limited access to government data in its analytics including emission inventory and source apportionment and health impact assessment. Secondly, the study was carried out within a short period from October 2020 to June 2021 during the Covid-19 pandemic and, as a result, it was impossible to conduct field trips and in-person discussions with stakeholders for the firsthand and in-depth assessment of the local situation. Thirdly, due to data availability and time and resource constraints, most of the analytical work was done in AA only and air pollution emission control measures focus on the transport sector. Therefore, to enhance its policy analysis and decision-making capacity, Ethiopia should continue conducting in-depth analyses for various aspects of AQ, such as ambient air pollution dispersion modeling, spatial distribution of populations vulnerable to AQ, wider assessment of the health and non-health

impacts of air pollution, and cost-effectiveness or cost-benefit analysis of AQM interventions. While this report used an established bottom-up approach to estimate source contributions, a complimentary program that includes a top-down chemical analysis-based approach at a representative number of locations across the airshed of AA would help strengthen and verify the results and increase confidence in policy applications. From the additional analyses, Ethiopia can develop a more evidence based IAQM action plan that includes recommendations for nationwide action and corresponding investment activities.

1. Introduction

Air pollution is a global problem that undermines health and economic productivity. Air emissions are a risk in tandem with greenhouse gas (GHG) emissions. Data from the World Health Organization (WHO) shows that 9 out of 10 people breathe air containing high levels of pollutants, with low- and middle-income countries (LMICs) bearing the brunt of poor air quality levels.[1] Air pollution is the leading environmental risk factor for premature death. In 2019 alone, air pollution globally caused 6.7 million premature deaths, corresponding to about 19 percent of the total premature deaths (IHME, 2020). The health impacts of air pollution are also reflected in morbidity levels, loss of income, decreased participation in the workforce, disability, and higher health care costs. Air pollution has also been known to impede cognitive development in children, with long-term implications on human capital development.

Poor air quality during the COVID-19 pandemic may further jeopardize hard-won gains in public health. $PM_{2.5}$ can affect respiratory, cardiovascular, cardiopulmonary, and reproductive systems, and in some instances can lead to cancer. Ongoing research suggests a correlation between poor air quality and the incidence of severe cases and death among people exposed to COVID-19 who have pre-existing, non-communicable diseases (NCDs), such as cardiovascular and respiratory diseases (Conticini, E., et al. 2020; Fattorini, D. and Regoli, F. 2020).

Air pollution, exacerbated by urbanization and increasing mobility, is a growing concern across Africa. Growing rural-urban migration, traffic congestion, and increasing industrialization will increase air pollution emissions and may result in poorer air quality, aggravating the health effects. In Africa, indoor and outdoor air pollution have already become the most significant environmental contributors to premature death, outpacing malaria and HIV.[2] Reports indicate the numbers of premature deaths in a year per 100,000 population (urban) due to ambient air pollution was 73 in Cairo, 46 in Lagos, and 35 in Abidjan.[3] Ambient air pollution also impacts the quality of soil and water resources, impeding flora development, reducing food production, and contaminating water surfaces.[4]

Over recent decades, Ethiopia has achieved strong economic growth, accompanied by urbanization and mobility. The country is one of the region's fastest-growing economies, growing 9.9% annually from 2008 to 2018, compared to a regional annual average of 5.4%. Extreme poverty fell markedly, from 55% in 2000 to 26.7% in 2016. Ethiopia's urban population accounted for 21.2% of its total 112 million population in 2019. A UN study on world urbanization prospects estimates Ethiopia's annual average rate of urbanization at 2.0%

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[1] World Health Organization. 2018. "9 out of 10 people worldwide breathe polluted air, but more countries are taking action." Available at: https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action#:~:text=New%20data%20from%20WHO%20shows,containing%20high%20levels%20of%20pollutants.&text=%E2%80%9CAir%20pollution%20threatens%20us%20all,%2C%20Director%2DGeneral%20of%20WHO.

[2] World Health Organization. March 2018a. Ambient (outdoor) air pollution. Available at: https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

World Health Organization. March 2018b. Household air pollution and health. Available at: https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health.

[3] Larsen (2019) for Cairo; Croitoru et al. (2020) for Lagos; Croitoru et al. (2019) for Abidjan.

[4] "Air pollution: effects on soil and water." Government of Canada. Available at: https://www.canada.ca/en/environment-climate-change/services/air-pollution/quality-environment-economy/ecosystem/effects-soil-water.html.

from 2018 to 2050 and the urbanization rate is projected to increase to 39% in 2050.[5] Urban areas—housing only 15% of the national workforce—contribute over 38% of national GDP.[6] Addis Ababa (AA), Ethiopia's capital, is the country's most economically and politically significant city. The city was estimated to have a population of about 4.8 million in 2020,[7] or 4.1% of the national population. Its annual average population growth rate in 2015-2020 is 4.4%. Its GDP has grown on average by over 15% in recent years[8] and is about 8% of the national GDP. As the demographic and economic center of the country and a major regional hub, AA's growth will continue.

Rapid economic growth and urbanization in AA have resulted in environmental deterioration. Urban air pollution is an increasing problem, among others, and threatens public health and local ecosystems. Growing economic activities (e.g., construction and industrial development), unregulated urban sprawl, and increasing mobility and transportation in AA have increased pollution emissions, traffic congestion, land and environmental deterioration, and risks to public health. Transportation-related air pollution due to increasing demands and traffic congestion is emerging as the most important source.

Ethiopia's deteriorating air quality (AQ) undermines its citizens' quality of life, but the country has a limited capacity for AQ monitoring and management. An analysis of AA's visibility data suggests that air quality has been declining since the 1970s, with the average air quality now approximately 1.6 times worse than in the 1970s.[9] Although the capital has the largest air quality monitoring network in the country, it lacks the long-term data required to determine air quality variations temporally and spatially; AQM hardly exists in other cities.

The Ethiopian Constitution protects the right to a clean and healthy environment (Article 44/1). The country's National Environmental Law Development and Enforcement Programme (NELDEP) identifies air pollution as a key area for improvement from 2020-2030 under its vision to integrate environmental laws into Ethiopia's development strategies.[10] The city of AA is also taking steps to develop its first Air Quality Management Plan (AQMP), which has identified a lack of basic information and analytical work on ambient AQ monitoring and source apportionment and a weak institutional capacity.

Ethiopia has few AQM studies, even in AA, especially on ambient/outdoor air pollution. Limited AQ monitoring data are available, although the last two years has seen an installation boom in low-cost sensors in AA. Information on source apportionment and chemical compositions of particulate matter (PM) and other air pollutants is scarce. There are a few reports that cover source apportionment of $PM_{2.5}$ and PM_{10} sources in AA (Etyemezian et al., 2005; Gebre et al., 2010; Tefera et al., 2020), though there are no published sources identifying the PM and other pollutant sources nor CO_2 via receptor modeling or principal component analysis.

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[5] UN, 2019. World Urbanization Prospects: The 2018 Revision. Available at https://worldpopulationreview.com/world-cities/addis-ababa-population".

6 Ethiopia Urbanization Review: Urban Institutions for a Middle-Income Ethiopia. World Bank. 2015. Available at: https://openknowledge.worldbank.org/handle/10986/22979.

[7] World Urbanization Prospects - United Nations population estimates and projections of major Urban Agglomerations. Available at https://worldpopulationreview.com/world-cities/addis-ababa-population.

[8]The State of Addis Ababa. UN Habitat. 2017. Available at: https://www.urbanafrica.net/wp-content/uploads/2017/07/State-of-Addis-Ababa-2017-Report-web-1.pdf.

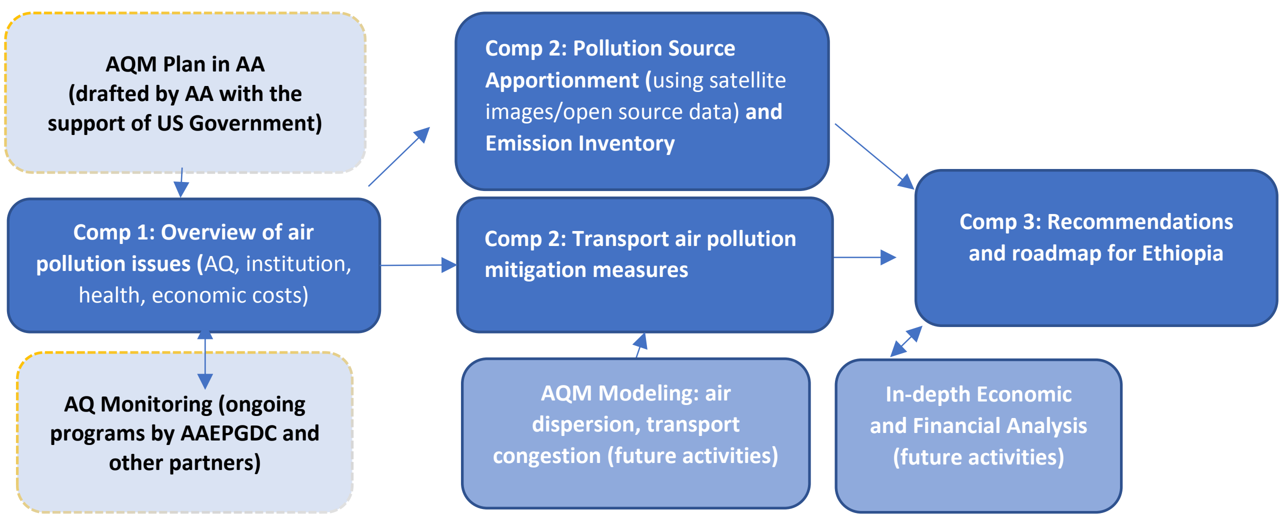
[9] ASAP East Africa, 2019.-Air Quality Briefing Note: Addis Ababa (Ethiopia). https://assets.publishing.service.gov.uk/media/5eb16f4b86650c4353446282/ASAP_-_East_Africa_-_Air_Quality_Briefing_Note_-_Nairobi.pdf.

[10] Ethiopian National Environmental Law Development and Enforcement Programme 2020 – 2030. Ethiopia Environment, Forest and Climate Change Commission. 2020.

Studies on air pollution outside of AA are also hard to find (Kume et al., 2011; Embiale et al., 2019; Amhayesus, 2019; Bulto, 2020). Transport air pollution mitigation measures have not been systematically assessed, despite some efforts to study the causes of transport air pollution and prepare a strategy for transport environmental control in AA.

AQM has been one of the areas that the World Bank has been supporting. The World Bank launched an Advisory Services & Analytics (ASA) program entitled "Ethiopia: Air Quality Management and Urban Mobility" in September 2020. The ASA program aims to assist the Government of Ethiopia in deepening its understanding of ambient AQM through analytical studies and develop policy recommendations and an action plan for institutional strengthening and physical investments. Given the complexity and magnitude of AQM issues and time limitations, the program's scope of work, as shown in Figure 1 below, focus on a few main issues in AA: reviewing ambient AQ and institutional arrangements, assessing health, valuing its economic cost, analyzing emission inventory and source apportionment, and identifying and prioritizing urban transport air pollution mitigation measures. This report summarizes the main findings and recommendation of the studies carried out under the program. It is not feasible for the program to conduct the studies nationwide in a short period and lacking data; the AQM program largely focuses on AA. The Program builds on the ongoing work of AA's AQM planning and AQ monitoring carried out by the City Government of AA, the US Embassy/USEPA, UNEP, and other partners. Due to limited time and resources, the modeling work on air pollution dispersion, spatio-temporal analysis of travel time and vehicular air emissions, and in-depth economic and financial analyses of AQM programs and projects will have to be done in the future.

Figure 1. Relationship of the Components of the World Bank AQM Program



This report is the synthesis of the key findings and recommendations of the studies carried out under the World Bank's Ethiopia AQM ASA program. The rest of the report is organized as follows. Chapter 2 is an overview of air pollution issues, including air pollutants and impacts, the concept of integrated AQM, and the air quality situation in AA. Chapter 3 assesses the health impact of air pollution in AA and valuates its economic costs. Chapter 4 summarizes the study results of emission inventory and source apportionment, while Chapter 5 proposes and prioritizes the mitigation measures for transport air pollution control. The final Chapter provides recommendations and a road map that Ethiopia might take to address emerging air pollution problems and improve AQM nationwide and in AA over the next ten years.

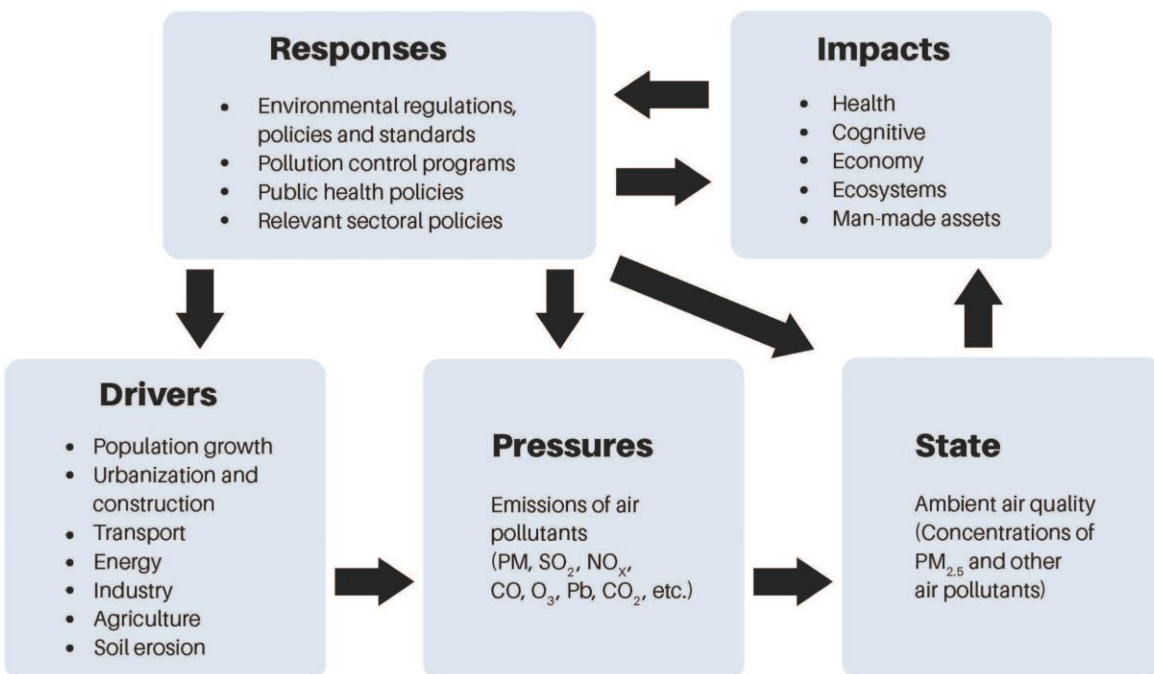
2. Overview of Urban Air Pollution Problems in Ethiopia

This chapter provides a brief overview of air pollution problems and impacts, introduces the IAQM approach, reviews institutional arrangements and gaps for AQM in Ethiopia, and examines AA's AQ monitoring programs and results.

2.1 Introduction to Air Pollution Problems

Ambient air pollution is a complex issue related to emissions from multiple pollutants from various sources involving numerous stakeholders across multiple sectors. These different pollutants create a chain reaction of health and environmental impacts that require addressing. Figure 2 below uses the generic DPSIR diagram to show the drivers (D), pressure (P), state (S), impact (I), and response (R) and their interaction in AQM.

Figure 2. DPSIR Diagram for Air Pollution

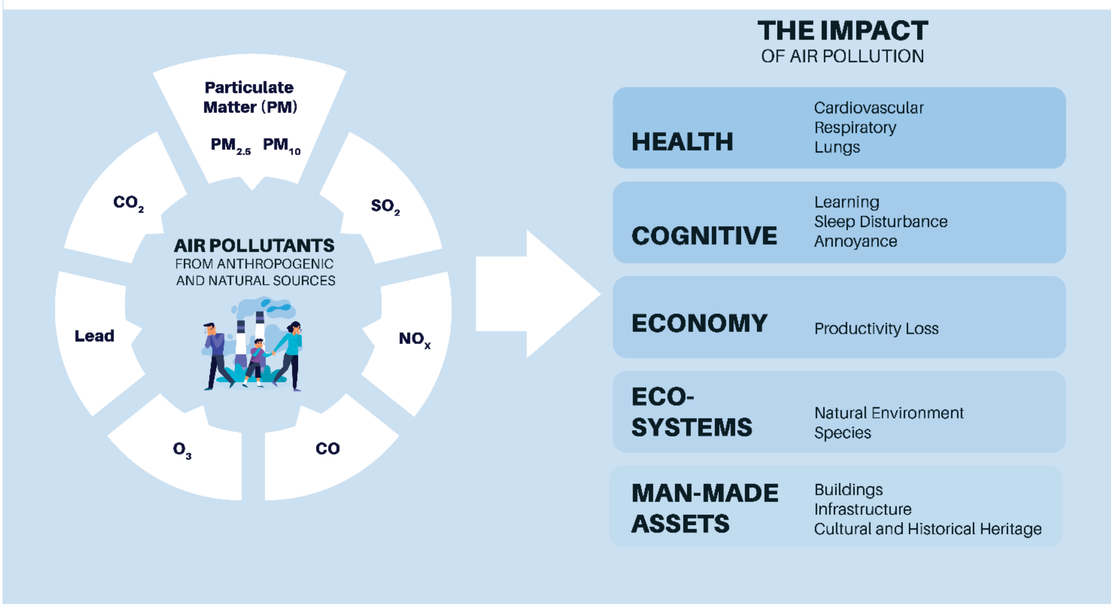


Common drivers of ambient air pollution in a city and its surrounding areas include activities such as cooking and heating; industries, including thermal power plants; construction sites; unpaved roads; and bare earth open areas; agricultural activities (especially the burning of agricultural residuals), and solid waste management, including the open burning of trash. Some studies in other African cities demonstrate that the transport sector is dominant in air pollution emissions. For example, a study in Nairobi, Kenya, shows traffic is responsible for 39% of ambient $PM_{2.5}$ concentrations (Gaita et al., 2014). Air pollution from transport includes emissions from inefficient, aging vehicles, incomplete combustion from diesel vehicles, traffic congestion, and unpaved roads. Limited air pollution emission data exists in Ethiopia, and there are no systematic studies on air pollution source apportionment; this is also true for AA. A lack of information and data of air emissions inventory and source apportionment hinders pollution control planning. Therefore, the World Bank AQM program conducted pollution emission inventory and source apportionment studies, with the results summarized in Chapter 4.

Primary air pollutants that put pressure on airsheds include PM, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_2), and volatile organic compounds (VOC). PM is a complex pollutant and further divided by its aerodynamic diameter in micrometers (µm); most commonly, $PM_{2.5}$ with diameters less than or equal to a nominal 2.5µm and PM_{10} less than or equal to 10µm. $PM_{2.5}$ is considered the most relevant indicator for urban air quality (Cohen et al., 2005) and an important risk factor for premature death worldwide. It can pass the barriers of the lung, enter the bloodstream, and destroy the integrity of the blood-brain barrier, thus causing premature deaths, as well as respiratory, cardiovascular, and neurological diseases (Brook et al., 2010; Bowe et al., 2019; Shou et al., 2019; Peeples, 2020). CO, NO_x, and VOC are mainly from vehicular or industrial activity emissions, and SO_2 is usually the byproduct of coal and burning fuel. These pollutants also cause respiratory, circulatory system, and heart problems, and can be fatal. Moreover, studies recently associated air pollution with increased infections, such as influenza and COVID-19 (Petroni et al., 2020; Zivin et al., 2021).

Air pollution negatively impacts human health, the economy, and ecosystems. Figure 3 below shows the main air pollutants and their impacts from the corrosion of man-made structures and cultural heritage, impaired health, and cognitive development–particularly in children–to their damage to ecosystems, for example, excess nitrogen in waterways harms aquatic life.

Figure 3. Air Pollution and Its Impacts

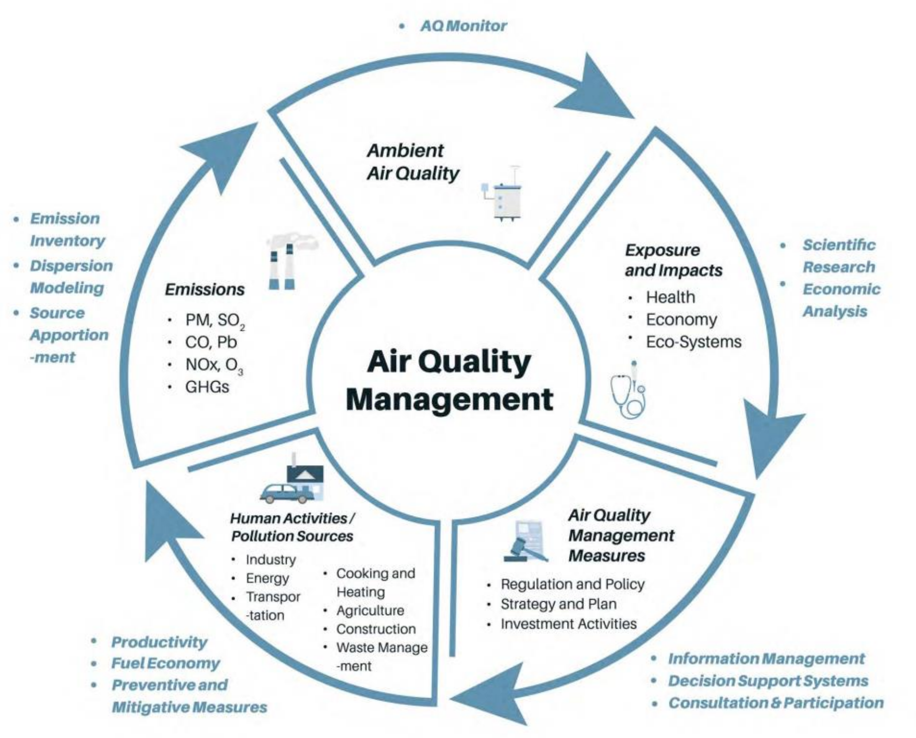


2.2 Need for an Integrated AQM Approach

Air pollution issues involve a complex network of sectors and stakeholders, which creates challenges for aligning policies, regulations, and government structures that address air pollution. An integrated approach to AQM is necessary to address complexities around AQM – including challenges in working across sectors, engaging a diverse set of public and private stakeholders, and other technical and financial constraints.

Figure 4 depicts an Integrated air quality management (IAQM) approach, which involves developing a knowledge base or analytical tools for air pollution emissions and AQ monitoring that can support pollution control planning. An effective AQM plan will require actions from multiple stakeholders, targeting different pathways and pollutants. Analysis of the interplay between different sources of pollutants, their consequences on health, the environment, and the economy, supports the interpretation of data for different actors. Additionally, it is key to implement an AQM strategy by building institutional and human resource capacity for pollution monitoring and management; institutional coordination between different sectors; national standards, regulations, and policies for pollution; and compliance monitoring and regulatory enforcement. Improved public awareness on sources and impacts of pollution can further support successful AQM.

Figure 4. Integrated Air Quality Management



IAQM has been a key approach for countries and cities to comprehensively address air pollution problems and protect the public from health issues and economic losses resulting from poor AQ. International experiences in most developed countries, and progress in some developing countries (e.g., Mexico, China, and Thailand), demonstrate that IAQM has successfully reduced air pollution and GHG emissions and dramatically improved air quality.

2.3 Stakeholder Mapping and Institutional Arrangements for AQM

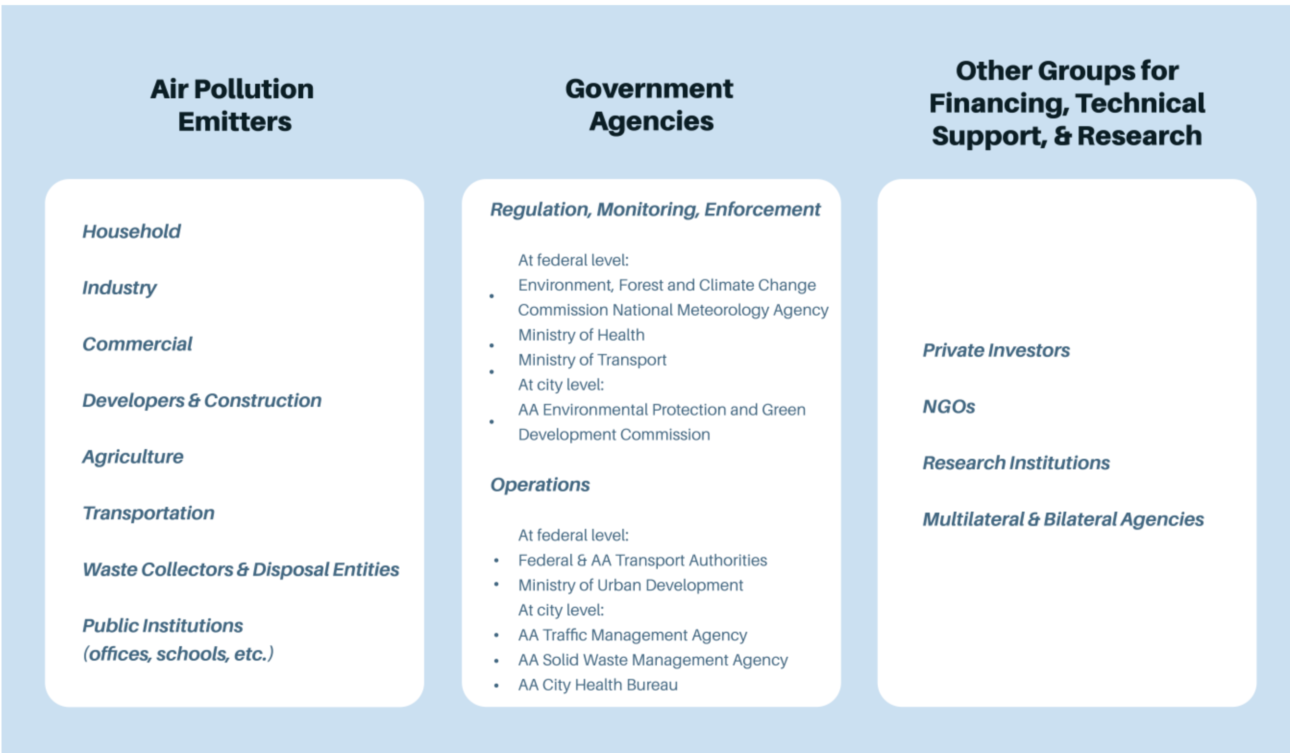
The Government of Ethiopia recognizes that long-term economic growth must incorporate sustainable, climate-aligned development to combat challenges related to urbanization and pollution problems. The City Government of AA has also started to pay attention to its growing air pollution problems and launched its AQM plan in May

2021. To provide an accurate assessment and relevant recommendations for AQM in Ethiopia, this study reviewed the stakeholders and institutional arrangements currently available for air pollution.

Stakeholder Mapping

Air pollution and AQM involve numerous stakeholders, including households, vehicle owners, manufacturers, and so on, across various sectors. Figure 5 maps out key stakeholders with whom AQM needs to interact. They include those that emit air pollution, are affected by air pollution, and are in charge of AQM, such as government agencies, public institutions, households, and business sectors.

Figure 5. Air Quality Stakeholder Mapping



Households cook and openly burn their trash, emitting and inhaling pollution from different sources. The transportation sector has the largest air pollution emissions, and commercial activities, developers, and construction projects emit pollution. Agricultural stakeholders are impacted by air quality because pollution can negatively affect their crop yields. Many government agencies are responsible for parts of AQM. Academic and research institutions and NGOs study air pollution impacts, deepening the understanding of air pollution issues, advocating for improved AQM, and raising public awareness. The public and private sectors as well as bilateral and multilateral organizations, play a role in financing air quality-related initiatives at the national and local levels.

Managing the different stakeholders involved in air quality management is complex. Different layers of participation must happen–from government agencies to institutions and even to households. Government agencies from different levels and across different sectors must develop and implement policies and regulations that consistently minimize air pollution across their jurisdictions while aligning with international standards. This can be challenging, as agencies need to balance priorities while accommodating objectives from other agencies. The public can also be complicated to manage, as they need awareness programs that encourage participation and behavioral changes in reducing air pollution. Strong political will, leadership, and senior officials' commitments are essential to ensure that agencies plan, implement, and enforce air quality measures.

Highlights of Regulatory and Policy Review

Ethiopia has many different environmental policies and regulations at the federal and city levels. These focus on environmental protection and health or address environmental concerns for specific industries, such as the energy and transportation sectors, with the ultimate purpose of protecting citizens' health by providing healthy living environments and balancing economic development with preventing environmental pollution (UNEP & ECI, 2018).

Although these policies and regulations touch on air quality (including vehicle emissions testing) in different ways (UNEP & ECI, 2018; AATB, 2020), the country has no AQM-specific policy as well as no national AQM strategy or plan–aside from its reference in the CRGE Strategy. Ethiopian national standards of ambient AQ were issued in 2003 as guideline values which cover SO_2, NO_2, CO, ozone (O3), lead (Pb), PM_{10}, and $PM_{2.5}$. The guideline value for annual average $PM_{2.5}$ is set at 15 µg/m3, higher than the WHO guideline of 10 µm/m3 as well as standards in many other countries (UNEP & ECI, 2018). There are few rules or laws around fuel quality and vehicle emissions standards. There are only two parameters in Ethiopia around vehicle emissions – smoke and carbon monoxide (CO) and they were however introduced within the Standards for Industrial Pollution Control. AA currently has no vehicle emission standards. The lack of fuel quality and vehicle emission standards leads to the transportation sector and vehicle owners emitting unnecessarily high levels of air pollution through low-quality fuel (EPSE, 2021). To create aggressive economic development, the objectives in different policies conflict with promoting environmental protection, including air quality, and often are not evidence-based (UNEP & ECI, 2018). Furthermore, the country’s regulatory and policy framework lacks explicit AQM measures that intersect different sectors.

In sum, the current regulatory and policy framework provides an insufficient incentive to manage and penalize air pollution activities from any particular stakeholder group (AACPPO, 2017). Ethiopia needs to enhance current ambient air quality standards, introduce air pollution emissions and fuel quality standards, and develop a more comprehensive and integrated policy package specifically addressing and guiding AQM, including providing clear financial incentives and penalties on air pollution activities from the urban transport, industrial and business sectors.

Governmental Organizational Setup for AQM

The Government of Ethiopia has designated a few agencies responsible for different aspects of AQM at the federal and municipal levels. In the federal government, the Environment, Forest, and Climate Change Commission (EFCCC) is the national environmental protection agency (EPA) that leads air quality efforts by coordinating national policies and laws and overseeing AQM (Kumie et al., 2014; UNEP & ECI, 2018). The Ethiopian Standard Agency (ESA) prepares air quality standards in collaboration with the EFCCC. Other agencies support AQM, including the ministries for health and transport. As the city-level EPA, the AA Environmental Protection and Green Development Agency (AAEPGDA) coordinates the city's AQM strategies and oversees air pollution controls (Tariku et al., 2019). Other city agencies support air pollution, such as the bureaus for transport and health, matching the federal level (AATB, 2020). However, there is a lack of functional units in charge of AQM in leading agencies such as EFCCC and EPGDA, making it difficult to ensure AQM roles and responsibilities. Also, the mandates of some line ministries or agencies (e.g., Transport Bureau or Health Bureau in AA) for AQM are not clearly defined, despite the organizational structure of the governments for AQM.

Ethiopia's enforcement of environmental regulations and standards, including those related to AQ, has been inconsistent and weak because of conflicting goals, insufficient data, low capacity for government coordination and implementation, and low persistence of enforcement (UNEP & ECI, 2018). In particular, agencies with AQM roles normally have limited personnel and capacity to develop, plan, and enforce AQM-specific policies and regulations and prepare and implement AQM activities. For example, Federal EFCCC and AA EPGDA have little means to monitor AQ and enforce ambient AQ standards and policies. The AA Transport Bureau supporting vehicle emission control in the city only has two staff members who are without a sufficient budget, equipment, or guidance on their work to manage vehicle emission control (AATB, 2020). As a result, there is limited data for benchmarking standards and existing ambient air quality standards are barely enforced in AA (UNEP & ECI, 2018). The situation is undoubtedly even worse in the country's regional and secondary cities.

Government agencies or units also face limited capacity to coordinate and implement policies, regulations, and plans among themselves and across sectors. Weak coordination, collaboration, and communication among various government agencies and stakeholders are common horizontally and vertically. Government bodies are not used to collaborating on air quality efforts, and existing governmental structure and policy frameworks do not offer guidance. Some ministries that would be effective in the organizational setup–such as the ministries for agriculture, energy, trade, and industry–are not yet involved in AQM, hampering AQM efforts.

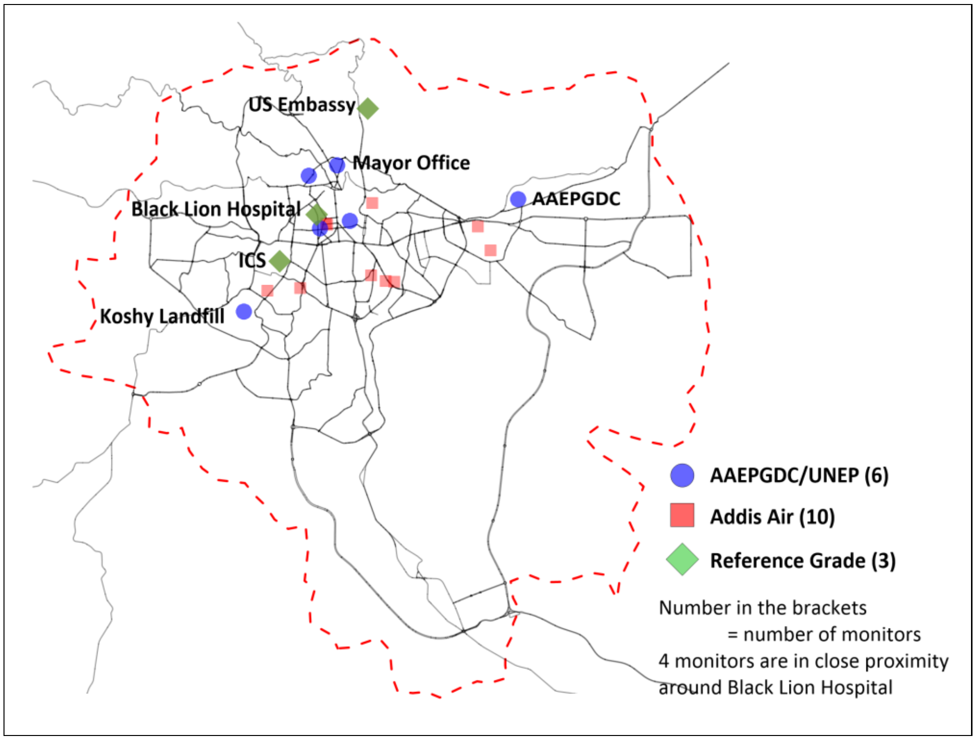
Another underdeveloped area is finance and financing arrangements for AQM. Environmental taxation and fees are rare, with little earmarked to fund air pollution control activities. Line ministries/agencies and municipal governments commonly have no specific budget for AQM. Private sector investments in AQM are minimal, except for in recent years some partnerships of private entities and public or international organizations to finance AQ monitoring programs. Few investment activities have been made in air pollution reduction even in key polluting sectors, for example, urban transport and industry.

2.4 Air Quality in AA: A Review of Existing AQ Monitoring Efforts and Results

AQ monitoring in AA

AQ monitoring in Ethiopia is fairly new. The NMA established the first batch of three AQ monitoring stations in 2014–one at a meteorological station in AA and one each in Adama and Hawassa. NMA's stations only measure the gaseous pollutants CO, NO_2, and O_3, with the AQ monitoring network in AA gradually expanding since then. In 2016, the US Government (through the USDOS and EPA) set up two AQ monitoring stations in AA–one inside the US Embassy and the other at International Community School (ICS). The Eastern Africa GEOHealth Hub also set up a station in 2017. These three reference-grade monitoring stations use Beta Attenuation Monitors (BAM) and monitor $PM_{2.5}$. In 2019, there was a dramatic increase in AQ monitoring stations when AddisAir and AAEPGDC/UNEP installed low-cost sensors. As of March 2021, there have been about 20 AQ monitors installed in AA (Figure 6). C40 Cities, SPARTAN Network, and GIZ are also planning to support AQ monitoring in AA; more AQ monitoring devices–stationary or mobile–should be available in the coming years.

Figure 6. Location of AQ Monitors in Addis Ababa



During the period from 2016 to 2019, only three $PM_{2.5}$ monitoring sites operated in AA, all of which were financed by development partners, i.e., the two installed by the US Diplomatic Post (USDP) at US Embassy and International School, respectively, and one by East Africa GEOHealth Hub at Black Lion Hospital (BLH) on the campus of AA University. Only the two US-operated monitoring stations, which are part of the US DOS's global ambient air quality monitoring network, have since disseminated hourly $PM_{2.5}$ data to the public in near real-time via AirNow.gov since 2016 (Dhammapala, 2019). However, the ICS monitor has had operational challenges for months due to power and internet connectivity-related problems. Starting in late 2019, additional AQM sensors were installed by AAEPGDA with the support of UNEP and by AddisAir, a network of citizens and organizations. These new sensors are low-cost sensors, some of which malfunction for various reasons, and provide limited uncalibrated data.

The GEOHealth Hub's monitoring station at BLH started operating in April 2017. Its monitoring data is not yet available to the public due to the project's research nature; this report only obtained an aggregated average of $PM_{2.5}$. Table 1 presents the coordinates, aggregated $PM_{2.5}$ concentration, and operational period of the three reference grade monitoring stations at the ISC, US Embassy (Central), and BLH. It shows that BLH's $PM_{2.5}$ monitoring results are higher than those from ISC and US Embassy location monitors, likely due to its location in the urban center.

Table 1. Location and $PM_{2.5}$ Monitoring Results in Addis Ababa

	Location		
	ICS	**US Embassy**	**TASH/Black Lion**

			Hospital / AAU
Longitude	38.727623	38.763649	38.7425
Latitude	8.996519	9.058076	9.0154
Average Conc. $PM_{2.5}$ (ug/m3)	30.7	24.3	43
Year reported	2020	2020	2020
Period	--	01/101/20-12/31/20	4/1/17-3/30/20
Total number of days monitored	--	348	--
Land use zoning	Largely residential area	Urban background area	Traffic/Institutions/ residential

AAEPGDC worked on another AQ monitoring effort in AA with the technical support of UNEP as part of the US-funded project. It has installed 6 Kunak-cloud low-cost sensors (LCS) (out of 10 planned) at different locations in AA. The monitors have measured AQ since September 2019, and output data utilizing the AQCSV standard to enable interoperability. However, sensor availability for continuous measurement has been challenging for various reasons including stability of the electrical power supply. Limited monitoring data is accessible through several applications situated on the UNEP WESR platform (https://wesr.unep.org/topic/index/1). The system will be integrated into a heterogeneous data management system under development in collaboration with the US EPA to take advantage of reference instruments within the wider network for quality assurance.

AddisAir launched its AQ monitoring network program in late 2019 to understand AA's AQ and increase citizens' awareness of AQ and its health effects. As of March 2021, It had ten sensors installed at different locations in AA. Their sensors are real-time and low-cost, using a light-scattering method to measure $PM_{2.5}$ and send monitoring data regularly to AddisAir's website (https://airquality.addisabeba.info/). Though AddisAir's sensors have provided some data since late 2019, most of them are not functioning as of April 2021. Table 2 details the features of its ten sensors and shows that the $PM_{2.5}$ average concentrations across the city, from 22.4 $\mu g/m^3$ in Arat-Kilo to 55.5 $\mu g/m^3$ in the EU Delegation to AU location. However, a lack of calibration of the monitoring results raises some concern over the data's reliability.

Table 2. Location and Results of AddisAir's $PM_{2.5}$ Monitoring Network

	Location									
	Arat-Kilo*	**Churchill Avenue****	**EU Delegation to AU**	**EU Delegation to Ethiopia**	**ICS/ Bisrate Gebriel**	**ILRI/ CCAFS**	**Kirkos**	**Lambert**	**Lycée Francais**	**Peacock Park-Bole Atlas**
Longitude	38.7579	38.7520	38.7411	38.7570	38.7579	38.7520	38.7411	38.7570	38.727623	38.8143
Latitude	9.0351	9.0221	8.999	8.9819	9.0351	9.0221	8.999	8.9819	8.996519	9.0163
Average Conc. $PM_{2.5}$ ($\mu g/m^3$)	22.4	45.5	55.5	24	24.4	23.9	29.2	26	45.3	23.6
Year reported	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
Period		12/3/2019-6/30/2020				12/3/2019-9/3/2020		12/4/19-11/6/2020	12/4/19-12/3/2020	12/4/19-8/1/2020
Number of days		207				200		124	356	239
Land use at the location	Residential area	Traffic/ Commercial/ School area	AU HQ area/ Residential/ Traffic	Green parks background area/Traffic	Residential area	Green area/ Institutions/ Offices	Commercial/ Residential	Residential area (Hilly side)	Traffic/ Commercial/ School area	Parks/ River Kebena/ Urban agriculture

Evaluation of AQ in AA

According to the WHO and US EPA standards, $PM_{2.5}$ concentrations should not exceed 10-12 µg/m3. The Government of Ethiopia's national AQ standard for annual average $PM_{2.5}$ has been 15 µg/m3 since 2003. The available monitoring results indicate the annual average of $PM_{2.5}$ concentrations shows that AA's AQ exceeds the standards. Some AQ monitoring stations indicate that $PM_{2.5}$ can be 4-5 times above the WHO standards.

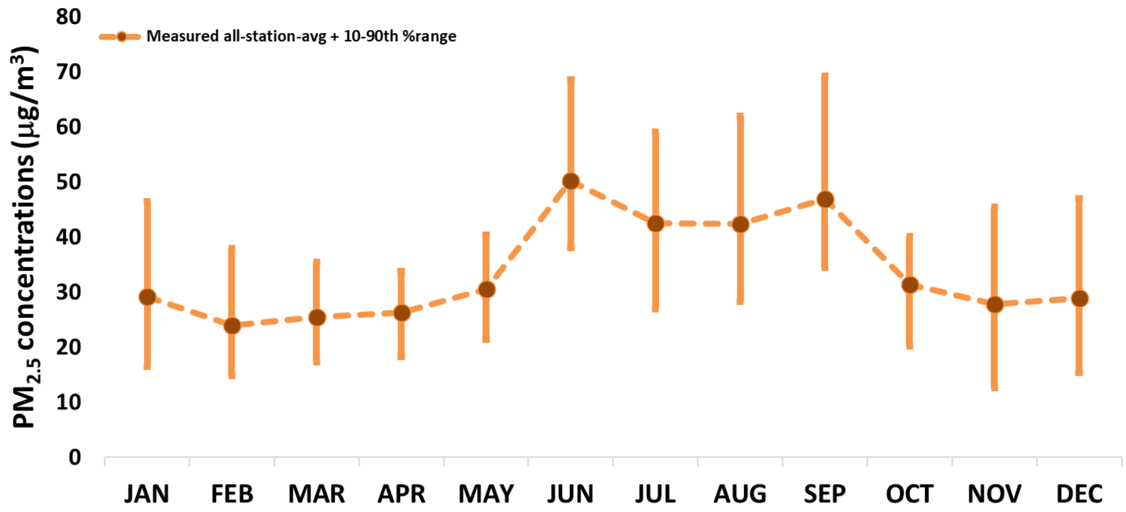
The results from the US-monitored sensors indicate that AA's rainy season AQ is routinely Unhealthy for Sensitive Groups (USG) and unhealthy even during periods of stronger wind. Winds of all speeds, mostly from the southwest quadrant, degrade air to USG levels, while other directions are mostly associated with Good or Moderate Air. Table 3 and Figure 7 below further present monthly average concentrations and their variations. The table considers all the hourly averages within a month available from all the stations to construct the variations.

Table 3. Monthly Average (and Standard Deviation) in the $PM_{2.5}$ Concentrations Data in 2018-19 from All the Stations in Addis Ababa Airshed

Unit: µg/m3

January	29.2 ± 14.2	**July**	42.5 ± 11.9
February	24.0 ± 11.8	**August**	42.4 ± 12.6
March	25.4 ± 9.6	**September**	46.9 ± 13.7
April	26.3 ± 7.4	**October**	31.3 ± 11.3
May	30.5 ± 8.7	**November**	27.8 ± 15.5
June	50.2 ± 12.1	**December**	28.9 ± 14.6

Figure 7. A Summary of All $PM_{2.5}$ Concentrations Data Showing Monthly Averages and the Variation in Hourly Data by Month



Source: Authors' interpretation

Typically, experts do not expect high concentrations of $PM_{2.5}$ during the rainy months (June through August), but the trends in AA appear to deviate from expectations. There was also a short AQ monitoring and research from November 2015 to November 2016, where the research collected 24-

hour $PM_{2.5}$ samples in AA's city center every 6 days. Its results show that the mean (±SD) daily $PM_{2.5}$ concentration was 53.8 (±25.0) μg/m3, with 90% of sampled days exceeding the WHO's guidelines (Tefera et al., 2020). Typically, it is not expected to see highs in $PM_{2.5}$ during the rainy months (Jun-Jul-Aug), but the trend in AA is an aberration which can be linked to lower surface temperatures, lower mixing layer heights and wind speeds under 2 m/s causing limited dispersion of emissions. These observations are consistent with the prevalent amount of anthropogenic air pollution sources characterized by low buoyancy. For example, enhanced biomass burning during the rainy season is one possible explanation for high concentrations of $PM_{2.5}$ (Dhammapala, 2019).

A summary of daily trends and a comparison of monthly average data from reference-grade and low-cost sensors present similar qualitative trends. However, there are differences in absolute values. Low-cost sensor data indicate $PM_{2.5}$ levels average 30% higher than the reference-grade sensor data. However, it must be noted that the locations for these sensors have different characteristics and land use at their location and lack information to calibrate the sensors. Since the overall quantity and quality of sensor data was not good but this collective data is useful in qualitative model verifications. The overall comparison and validation exercise can be replicated in the coming years when more data is available from the expanded AQ monitoring network.

In summary, the air quality of AA is unhealthy and its annual average of $PM_{2.5}$ in recent years exceeds WHO guidelines by 3-4 times. Air pollution concentrations vary by location and time. However, a limited number of functioning and calibrated AQ monitoring stations in AA hinders the thorough assessment of ambient AQ in the city. AA needs to continue to expand its AQ monitoring network and develop a unified and standardized data management system for AQ monitoring.

Epidemiology studies have found consistent association with both mortality and morbidity by exposure to fine particulate matter ($PM_{2.5}$) air pollution. The next chapter will further introduce the population-weighted $PM_{2.5}$ concentrations and assess the health impact of AA's air pollution and economic costs.

2.5 Recommendations

Ethiopia must strengthen its institutional arrangements to support AQM. To start, authorities should review, strengthen, and harmonize existing regulatory and policy frameworks at the national and local levels to address AQM requirements well. Along with reviewing frameworks, the government should conduct a functional review of government agencies to further clarify line ministries and their roles, mandates, and functions for AQM. This could include improving details on which government agencies should have AQM units or staff specifically allocated to manage their mandates. Once government agencies have clear AQM mandates and functions communicated, building institutional capacity in the line ministries about AQM. Building capacity will be particularly important to ensure agencies can properly regulate and enforce AQ standards, monitor air pollution control activities, and manage the daily tasks required to ensure AQM is successful.

Along with this clarification of roles and capacity-strengthening efforts, authorities should introduce a mechanism for inter-agency and cross-sectoral coordination and collaboration on AQM activities that also fosters learning and experience sharing. These mechanisms can also build a coalition to mobilize different stakeholders and incentivize them to change behaviors that emit significant air pollution. These stakeholder groups include the general public (including households and vehicle owners), the private sector, civil society, and other groups that can significantly contribute to the financing and management of air pollution prevention. These institutional reforms will only succeed if key line ministries have adequate budget and support to accomplish these reforms. Budgets can be boosted through examining environmental taxation and fee systems and develop the tax base and sources for AQM's public financing.

For institutional reform, Ethiopia also needs to introduce new standards for ambient air quality and air pollution emissions. This work would need to include increasing national guideline standards of ambient AQ, particularly updating the $PM_{2.5}$ standard to follow WHO guidelines. It would also need to include new fuel quality and emission standards specifically for the transportation sector that is clear and enforceable so that vehicle owners and fuel users can comply with them. Part of this process should also include supporting the government's petroleum authority, the Ethiopian State Petro Company (ESP)'s efforts to import fuel with lower sulfur contents, started with 50 ppm. Apparently, the regulations and standards on ambient air pollution control in other sectors such as industries, solid waste management, and agriculture are under development and more studies are necessary on these areas.

Secondly, Ethiopia must establish a most robust AQ monitoring program and network nationally and strengthen existing AQ monitoring networks. The AQ monitoring network in AA would also require the key line ministries to strengthen information management of AQ data. Authorities can establish better data management by developing standardized and unified systems to report AQ and emission levels. This reporting system should make it easy for the public to access the internet and mobile apps.

In AA, the capital city's ambient AQ monitoring network should have reference-grade systems at multiple representative locations for the analysis of long-term pollution trends and support them with calibrated sensors to increase the overall data density and produce a pollution map. This network can support regulations and validate the baseline emissions and pollution estimates similar to those presented in this report.

3. Health Impacts and Economic Costs of Air Pollution in Addis Ababa

As introduced earlier, air pollution is a threat to public health and environmental quality. Air pollution affects lung function and can trigger asthma, among other health conditions, and can lower productivity. Air pollution also has a distinct impact on vulnerable groups, including women and children, as studies have shown that high exposure to air pollution can affect the ovaries and fertility.[11] In Ethiopia, PM pollution is the second leading risk factor for death after malnutrition (IHME, 2020). Local residents in urban areas, especially in a large city like AA, are at considerable risk of heart and lung diseases and premature death. While household air pollution is the most prominent contributor to mortality,[12] ambient $PM_{2.5}$ pollution is a growing public health problem in urban areas (Berhane et al., 2016), primarily due to vehicle exhaust, resuspended dust on roads, and industrial activities (see Chapter 4 for more details). Several studies have assessed the consequences of ambient air pollution on people's health in Ethiopia (see Tefera et al., 2016 for a review; and IEC, 2019); however, no economic valuation has been done of the health impacts of air pollution.

This chapter addresses this gap by providing a physical and economic assessment of the health impacts caused by ambient $PM_{2.5}$ pollution in AA. It uses the most updated methodology developed by the Institute of Health Metrics and Evaluation (IHME-2020) regarding the Global Burden of Disease (GBD) and the WHO for the health impact assessment, and the World Bank/IHME (2016) guidelines for the economic valuation of the damages to health. The valuation focuses on a typical year,[13] then briefly highlights potential linkages among the current pandemic, air pollution, and health. As the analysis was conducted during a short period (December 2020-March 2021), it is based on secondary information, complemented by some primary $PM_{2.5}$ data reported in the report's overview chapter. The following sections present the main results of the analysis, while Annex 2 provides further details.

3.1 The Health Impacts of Ambient Air Pollution

The health effects of long-term exposure to ambient $PM_{2.5}$ include ischemic heart disease, lung cancer, chronic obstructive pulmonary disease (COPD), lower respiratory infections (such as pneumonia), stroke, type 2 diabetes, and adverse birth outcomes (GBD 2019 Risk Factors Collaborators, 2020). This chapter assesses these impacts based on the four steps presented below.

Estimate the $PM_{2.5}$ exposure

Exposure to $PM_{2.5}$ is commonly estimated using the population-weighted $PM_{2.5}$ concentrations (PWC) for a given year, which are based on the number of people living within a certain area and the $PM_{2.5}$ concentrations they are exposed to. PWC provides better population exposure estimates than other types of averages (e.g., arithmetic mean, median, mode). It gives proportionally greater weight to the air pollution experienced where most people live (HEI/IHME, 2020).

Data derived from ground monitors are often seen as the "gold standard" globally. However, their spatial coverage is usually limited (Zeger et al., 2000); many efforts have focused on measuring $PM_{2.5}$ concentration using other methods (e.g., satellite-based imagery and atmospheric chemical models) to

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[11] European Society of Human Reproduction and Embryology. "Air pollution found to affect marker of female fertility in real-life study: Decline in ovarian reserve related to particulate matter and nitrogen dioxide in atmosphere." June 2019.

[12] In 2019, there were 67,800 deaths due to household air pollution vs. 8,960 deaths due to ambient air pollution in Ethiopia (http://ghdx.healthdata.org/gbd-results-tool, accessed March 2021).

[13] In the context of this chapter, a typical (regular) year is intended as a year without dramatic changes, such as those brought by COVID-19. Assessing the impact of an atypical year would require consideration of additional factors for which current data are not available, e.g., changes in population exposed to ambient $PM_{2.5}$.

overcome this problem. That said, these methods complement surface ground-monitored data rather than fully replacing them (Duncan et al., 2014). Ideally, integrating data from ground-based monitors, satellite imagery, and other models should leverage the benefits of each data source–thus providing $PM_{2.5}$ concentration estimates over a wide geographic scale with better accuracy (Diao et al., 2019). This study did not conduct this type of data fusion[14]–in its absence, the average population-weighted $PM_{2.5}$ concentration was estimated based on available ground-level monitored data and the population exposed to air pollution in the proximity of each station.

Table 4 highlights the results, which indicate that the annual average $PM_{2.5}$ concentration varies between 30 µg/m^3 and 36 µg/m^3 across 2016-2020. These estimates are in the same broad range; the differences among them result from several factors, such as differences in the number of stations from which data were collected and possible changes in seasonal parameters across years (e.g., rainfalls, wind speed, etc.) This analysis aims to estimate $PM_{2.5}$'s impact on health during a typical year by using exposure averages across 2016-2019 as the basis, which corresponds to 34 µg/m^3.

Table 4. Annual Average $PM_{2.5}$ Concentration in Addis Ababa

Year	Observations on monitoring stations	Population-weighted $PM_{2.5}$ concentration (µg/m^3)
2016	2 stations: USDP Central, USDP School	36
2017	3 stations: USDP Central, USDP School and Black Lion	34
2018	3 stations: USDP Central, USDP School and Black Lion	35
2019	2 stations: USDP Central and Black Lion	30
2020	14 stations: USDP central, USDP school, Black Lion, NMA Geo Health, and 10 Addis Air stations.	33

Quantify the impacts of ambient $PM_{2.5}$ on premature mortality

Several epidemiological studies revealed strong correlations between long-term exposure to $PM_{2.5}$ and premature mortality (Apte et al., 2015; Cohen et al., 2017; Wu et al., 2020). Recent research associated $PM_{2.5}$ exposure with mortality related to several other health outcomes: lower respiratory infections; tracheal, bronchus, and lung cancer; ischemic heart disease; stroke; chronic obstructive pulmonary disease; type 2 diabetes mellitus; and adverse birth outcomes (IHME GBD 2019 Risk Factor Collaborators, 2020).

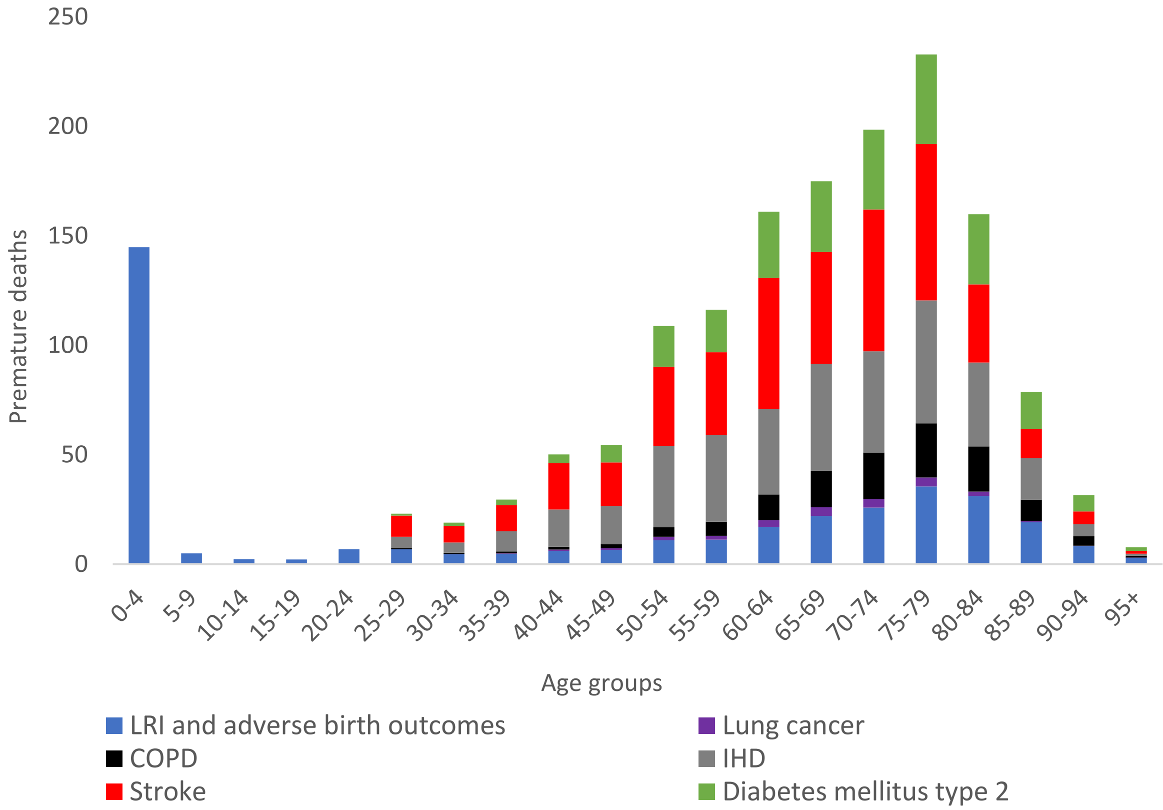
The number of premature deaths attributable to ambient $PM_{2.5}$ pollution in Addis Ababa is estimated for each of the above outcomes using data on (i) mortality by disease and age group at the national level, based on IHME (2020); (ii) adjustment for AA, considering the differences in population distribution by age group between the city and the national level (projections from CSA, 2013); (iii) proportion of deaths attributable to $PM_{2.5}$, calculated based on specific relative risk factors for the $PM_{2.5}$ concentration of AA (34 µg/m^3), which differ by the outcome. It is important to note that the most recent relative risk factors developed by the IHME GBD 2019 Risk Factors Collaborators (2020) differ considerably from those used in the previous GBD methodology.[15]

The results show that exposure to ambient $PM_{2.5}$ causes about 1,600 premature deaths per year, on average. While the estimate provides a good indication of the magnitude of the air pollution problem, it should not be interpreted as a precise quantification of the impact of air pollution in the city. To reflect this uncertainty, a range of 1,200 to 2,100 premature deaths has been estimated, based on the lower and

[14] IEC (2019) used air quality data from ground monitors and satellite sources for ground-truthing the $PM_{2.5}$ information for 2016. However, as the present analysis refers to a more recent period (2016-2019), it did not use the IEC information.
[15] This is because the most updated risk curves for ischemic heart disease, stroke, chronic obstructive pulmonary disease, lower respiratory infections, and type II diabetes do not include studies of active smoking data. For more details, see supplementary appendix 1 to GBD Risk Factors Collaborators (2020).

upper bounds of mortality provided by the GBD 2019 in Ethiopia. Stroke, ischemic heart disease, and lower respiratory infections are the leading causes of $PM_{2.5}$-related mortality. The elderly (people between 60 and 84 years of age) are most affected by $PM_{2.5}$, accounting for about 58% of premature deaths (Figure 8). The same group accounts for a relatively large share of the total premature deaths due to ambient $PM_{2.5}$ at the national level, according to the IHME GBD 2019 study (Annex 2).

Figure 8. Estimated Number of Premature Deaths Due to $PM_{2.5}$ Exposure, by Age Group



Source: Authors, based on data from IHME (2020) and GBD 2019 Risk factors collaborators (2020).
Notes: IHD = ischemic heart disease; LRI = lower respiratory infections; COPD = chronic obstructive pulmonary diseases; the adverse birth outcomes include neonatal disorders due to low birth weight and short gestational age.

Quantify the impacts of ambient $PM_{2.5}$ on morbidity

In addition to mortality, exposure to $PM_{2.5}$ causes disability related to a plurality of health outcomes (e.g., chronic bronchitis, respiratory and cardiovascular hospital admissions, lost workdays), suffered by various agents (e.g., patient, family, co-workers) (World Bank/IHME, 2016). Based on recent guidelines on quantifying non-fatal outcomes (Robinson and Hammitt, 2018), this study estimates the morbidity due to exposure to ambient $PM_{2.5}$ based on the number of Years Lived with Disability (YLDs). The YLD is defined as the equivalent of one full year of healthy life lost due to disability or ill health (WHO, 2021). It measures the burden of living with a disease or disability.

Similar to the valuation of premature deaths, the number of YLDs is valued using data on (i) the total number of YLDs by disease and age group, based on the IHME (2020); (ii) adjustment for AA, considering the differences in population distribution by age group between the city and the national levels (projections by CSA, 2013); (iii) proportion attributable to $PM_{2.5}$, calculated based on specific relative risk factors for the $PM_{2.5}$ concentration of AA. The results indicate that exposure to ambient

$PM_{2.5}$ is responsible for about 4,100 YLDs annually,[16] on average (with a range between 2,800 YLDs and 5,700 YLDs). Middle-aged people (40–69 years of age) are most affected by illnesses due to $PM_{2.5}$, accounting for about 58% of the total morbidity related to $PM_{2.5}$. This result is consistent with the 2019 IHME GBD study at the national level, which found that the same age group accounts for a similar proportion in the total ambient $PM_{2.5}$-related morbidity cases (Annex 2).

To put the health assessment results into a regional context, Table 5 illustrates the ambient $PM_{2.5}$ concentrations and their impact in selected African cities. It shows that the $PM_{2.5}$ concentration and its effects on health in AA are slightly higher than those in other African capitals, namely Cotonou (Benin), Lomé (Togo), and Abidjan (Côte d'Ivoire). At the same time, it is lower than that in very polluted megacities, such as Lagos (Nigeria) and Cairo (Egypt).

Table 5. Impact of Air Pollution in Selected African Cities

Cities	Ambient $PM_{2.5}$ concentration (μg/m^3)	Deaths due to air pollution	Deaths/100,000 people
Dakar	21	270	25
Cotonou	32	200	32
Lomé	32	490	31
Abidjan	32	1,500	35
Addis Ababa	**34**	**1,600**	**35**
Lagos	68	11,200	46
Cairo	76	12,570	73

Sources: Authors for Addis Ababa; Croitoru et al. (2020) for Lagos; Croitoru et al. (2019) for Abidjan, Cotonou, Dakar, Lomé; Larsen (2019) for Cairo. Note: A portion of these estimates represents deaths due to the joint effect of exposure to ambient and household air pollution. Adjusting the estimates to capture only the impact of ambient air pollution would require the quantification of the number of people exposed to both household and ambient air pollution; in-depth knowledge about the causes of household air pollution; and data on household PM2.5 concentration in the affected areas. As this chapter did not focus on household air pollution, it does not incorporate this adjustment.

The average estimate obtained–about 1,600 premature deaths–should be considered conservative because it is much lower than the estimate for AA AQM planning from US EPA and C40 Cities (2020) of 2,700 premature deaths. However, the US EPA estimate is related to different years, methodologies (Burnett et al., 2018), and tools (BenMap), and thus is difficult to directly compare with the result of this study.

Finally, it is important to highlight that this section did not address the links between COVID-19, air pollution and health. This relationship is quite complex. First, COVID-19 affected air pollution in different ways: in many cities, the lockdown triggered lower vehicular traffic and industrial emissions (He et al., 2020); after the transition to partial relaxation, these concentrations often returned to pre-pandemic levels (Rybarczyk and Zalakeviciute, 2021). The situation is different in AA, where available research suggests that $PM_{2.5}$ concentration was higher during the pandemic (March-July 2020) compared to prior months (October 2019–March 2020), primarily due to the lack of lockdown measures (Bulto et al., 2020). Second, it is important to note that long-term exposure to air pollution affected COVID-19 related mortality: for example, a study from Harvard Chan School of Public Health found that a 1 μg/m^3 increase in air pollution was associated with an 11 percent increase in mortality from COVID-19 infection in the United States (Wu et al., 2020). Moreover, other studies found significant relationships between short-term exposure to air pollution and COVID-19 morbidity, for example in China (Zhu et al., 2020).

[16] Considering a population of 4.6 million in 2019 of Addis Ababa (https://worldpopulationreview.com/world-cities/addis-ababa-population), this is equivalent to about 0.3 days lived with disability per person per year, on average.

3.2 Economic Cost of Health Impacts due to Exposure to $PM_{2.5}$

The economic valuation of the health impacts estimated in the previous section refers to both mortality and morbidity, as follows.

Cost of mortality. This is estimated based on the number of premature deaths caused by the exposure to ambient $PM_{2.5}$ and the Value of Statistical Life (VSL), based on the World Bank/IHME (2016) guidelines. The VSL reflects the society's willingness to pay to reduce the risk of death, or rather, the local trade-off rate between fatality risk and money (Viscusi and Masterman, 2017; Kniesner and Viscusi, 2019). The valuation of the VSL for Ethiopia is based on the benefits transfer method, following the World Bank/IHME (2016) guidelines. Accordingly, the VSL for Ethiopia is estimated at $43,600 for 2019. It should be noted that the VSL result is a conservative estimate, which does not capture the full value of life.[17] Using the number of premature deaths estimated in the previous section (1,600 deaths), the economic cost of premature mortality reaches $70 million.

Cost of morbidity. This is estimated based on the number of YLDs due to exposure to ambient $PM_{2.5}$ and the Value of Statistical Life Years (VSLY). The VSLY is derived by dividing the VSL by the discounted expected life years remaining for an individual at the mean age of the population studied (Robinson and Hammitt, 2018). Accordingly, the VSLY for Ethiopia was estimated at $1,800 for 2019. Using the number of YLDs estimated in section 3.1 (4,100), the cost of morbidity is valued at about $8 million.

Economic value of health impacts. Adding up the values obtained above, the total health cost is estimated at $78 million. This is equivalent to 0.1% of the country's GDP in 2019, or about 1.3% of AA's GDP.[18] The estimate is lower than that obtained in very polluted megacities, such as Lagos (2.1% of the state's GDP), Greater Cairo (4.5% of its GDP), and New Delhi (5.5% of its GDP).[19] The estimate for AA points to the need to further investigate the main pollution sources and particularly, the pollution hotspots in the city. For example, Kumar et al. (2021) examined the health risks caused by in-car open-window exposure to $PM_{2.5}$ pollution in several hotspots of ten world cities. The authors found that in AA, the annual deaths caused by in-car exposure to $PM_{2.5}$ pollution represents more than 10 percent of the total ambient $PM_{2.5}$-related deaths among car commuting population; this is a very high share compared to that found for other polluted cities – such as Dhaka (Bangladesh), Chennai (India), and São Paolo (Brazil) – which is less than 3 percent.

Considerable effort was made to calculate meaningful estimates of the impact of air pollution based on reliable information. Nonetheless, the analysis remains subject to several limitations. These relate to the use of (i) population-weighted $PM_{2.5}$ concentrations based on data collected from monitoring stations with different–sometimes low–coverage across the period 2016-2019; (ii) relative risk factors that, while reflecting the newest development in the field (IHME, 2020), are not specifically adjusted to Ethiopian conditions; (iii) VSL and VSLY concepts, which are based on benefits transfer from other countries, due to lack of primary studies in Ethiopia.

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[17] The concept of the VSL is very different from and should not be compared with the notion of "salary" or "wage."

[18] Ethiopia's GDP was $95.9 billion in 2019 (https://data.worldbank.org/, accessed March 2021). Addis Ababa's GDP was estimated at 6.4% of Ethiopia's GDP by the World Bank (2018).

[19] For Lagos, the estimate refers to 2018, based on Croitoru et al. (2020); for Greater Cairo, it refers to 2017, based on the health cost of 1.35% of Egypt's GDP, estimated by Larsen (2019); and the contribution of Greater Cairo to the country's GDP of 30% (UN-Habitat et al., 2019); for New Delhi, it is based on https://energyandcleanair.org/revealing-the-cost-of-air-pollution-in-real-time/, and excludes the cost related to NO_2. The estimate for New Delhi refers to the first half of 2020.

3.3 Recommendations

Overall, this analysis estimates the health damage due to exposure to ambient $PM_{2.5}$ at about $78 million, or 1.3% of AA's GDP in 2019. Air pollution causes about 1,600 premature deaths a year, on average. Stroke, ischemic heart disease, and lower respiratory infections are the leading causes of $PM_{2.5}$-related mortality. People between 60-84 years of age are most affected by $PM_{2.5}$, accounting for about 58% of the total premature deaths. The results point to the need to:

- improve the assessment of health and other environmental impacts (e.g., visibility, changes in property prices) of ambient air pollution. To do so, it is important to strengthen the collection of data related to air pollution, e.g., $PM_{2.5}$ concentrations at other representative locations; carry out epidemiological studies in Ethiopia using local hospital information, to adapt current concentration-response functions to the country conditions; conduct primary studies that assess the Value of Statistical Life and the willingness to pay to avoid morbidity, based on local information.

- conduct new studies that apply modelling to estimate the relationship between urban mobility and air quality. This would involve data on traffic measurements (volumes and vehicle mix) along principal corridors as input to vehicle emissions models (like MOVES or COPERT), followed by a linear dispersion model to estimate street-level concentrations, matched to daytime population estimations.

- identify the AQM interventions that reduce ambient air pollution, focusing on the most contributing sectors; and conduct economic analysis (e.g., cost-effectiveness or cost-benefit analysis) of these interventions - with the aim of reducing ambient air pollution to specific targets, such as those identified by the annual ambient air quality guidelines of Ethiopia (15 $\mu g/m^3$) and of WHO (10 $\mu g/m^3$) (UN, 2018; WHO, 2005).

4. Emission Inventory and Source Apportionment

A prerequisite to creating an AQM plan is to have an idea of the main sources of pollution and their potential for controlling emissions. This would help in prioritizing both local and regional efforts for effective management. Therefore, the World Bank AQM program conducted studies on air emission inventory and source apportionment. This Chapter presents the emissions inventory results and quantifies the source contributions to $PM_{2.5}$ pollution in AA.

4.1 Data resources

In addition to the published reports on air quality in AA and Ethiopia, to support the background information on energy consumption and sectoral activities, the study also accessed a number of open-source databases listed below.

- OpenAQ website to access ambient $PM_{2.5}$ concentrations data measured at 2 reference grade monitoring stations (https://openaq.org)
- AddisAir website to access ambient $PM_{2.5}$ concentrations data (from November 2019 to November 2020) at 10 low-cost sensor stations (https://airquality.addisabeba.info)
- EthioInfo dashboard of the Statistical Office of Ethiopia, for information on population, gross domestic product, fuel usage, and vehicle registrations (http://www.dataforalldemo.org/dashboard/v1/ethioinfo/ethioinfo#/)
- FTA Ethiopia via staff communications for information on vehicle registrations by vehicle type and age
- STATISTA is a commercial data service site, which provides limited information on vehicle sales, registration by vehicle type and year, population, and GDP (https://www.statista.com)
- Open Street Maps (OSM) database for information on road network covering highways, arterial, and feeder roads; and commercial activity points such as hotels, hospitals, apartment complexes, industries, parking lots, fuel stations, malls, markets, office and commercial complexes, banks, cafes, restaurants, and convenience stores (http://overpass-turbo.eu)
- European Space Agency (ESA)'s global human settlements (GHS) program for information on the built-up urban area in the airshed for the years of 1975, 1990, 2000, and 2014 (https://ghsl.jrc.ec.europa.eu/datasets.php)
- LANDSCAN program for information on gridded population at 30 sec resolution for the entire city airshed (https://landscan.ornl.gov/landscan-datasets). This database uses official estimates from the respective governments at district and ward level, which is further segregated to finer grids using information on commercial, land use, and night light data fields. We also received the ward-level population totals from the Ethiopian office
- FlightStats is a commercial data service, which provides information on domestic and international flight schedules for airports in the airshed (https://www.flightstats.com)
- VIIRS satellite retrievals for information on open biomass-burning fires spotted daily. The satellite resolution is 375m and capable of detecting fires during daytime and nighttime (http://viirsfire.geog.umd.edu)
- Google Earth, for information on interesting features for which GIS fields are not readily available
- All meteorological data was processed through the Weather Research Forecasting (WRF) modeling system (https://www.mmm.ucar.edu/weather-research-and-forecasting-model). All the data necessary for emissions and the pollution modeling system is available at a spatial resolution of 0.01° and one-hour temporal resolution

- The Washington University in St. Louis program for long-term $PM_{2.5}$ concentration data based on a global chemical transport model coupled with satellite retrievals (https://sites.wustl.edu/acag/datasets/surface-pm2-5)
- For baseline emissions inventory development, an emission factors database was extracted from the GAINS modeling system (https://gains.iiasa.ac.at/models).

For reference, a summary of material extracted from these reports is presented in Table 6. Source information is detailed in the following sections. All the extracted data files are available upon request, including the meteorological fields.

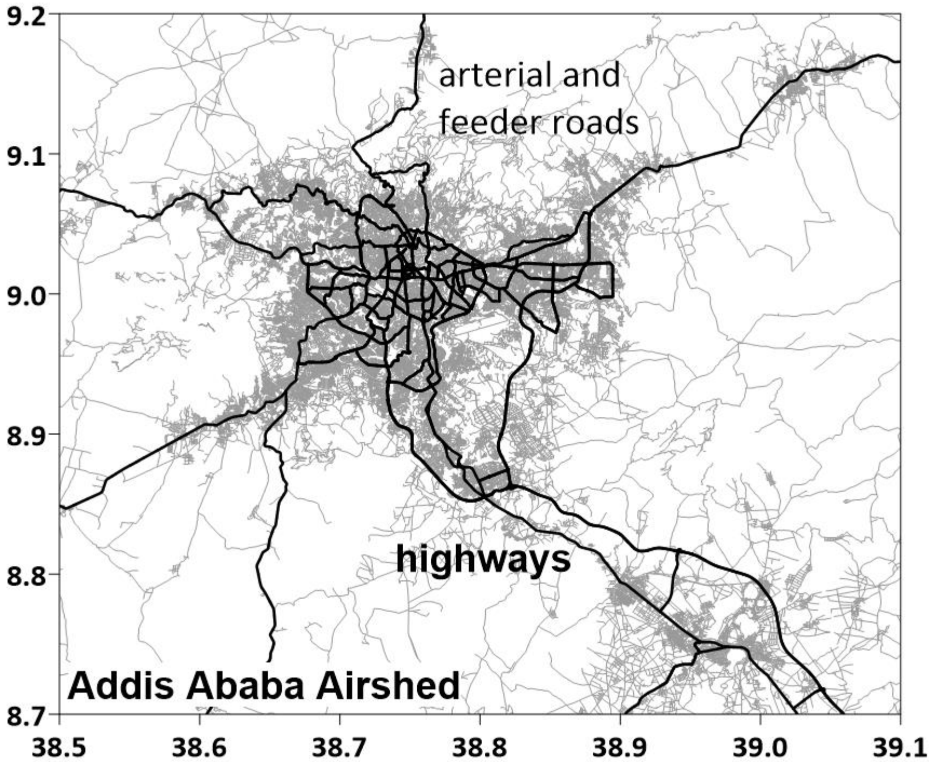
Table 6: Summary of Ethiopia and Addis Ababa geographical, economic, and environmental characteristics

Category	Remarks
Ethiopia	
National GDP per capita	$974 (nominal, 2020 est.)
Ethiopia national population (2018)	10.9 million
Total registered vehicle fleet (2020)	1.2 million
Estimated premature mortality from $PM_{2.5}$	1,060-10,700 in 1990 and 4,180-16,200 in 2019
Predominant fuel source	All biomass
Predominant electricity source	Hydro
Addis Ababa	
District population (2020)	2.8 million
District land area	527 km^2
Airshed size	60 x 50 grids (~1 km^2 each at 0.01° resolution)
Airshed area	3,646 km^2
No. of sub-cities	10
Urban share of the airshed land mass	18%
Airshed population (2018)	4.9 million
Urban share of airshed population (2018)	87%
No. of grids with pop > 30,000	56
% increase in built-up area (1990-2014)	190%
Total registered vehicle fleet (2020)	0.7 million
Total mapped highways length	1,350 km
Total mapped roads length	17,600 km
Total mapped landfill area	0.5 km^2
Total mapped quarries area	9.9 km^2
Total mapped commercial activity points	10,700
Predominant wind direction	Westerly for Jun-Jul-Aug and easterly for the rest
Predominant rainy months	Jun-Jul-Aug
No. of official AQ monitoring stations	2
Max. $PM_{2.5}$ monthly average (in 2018-19)	50.2 ± 12.1 mg/m3 in June
Min. $PM_{2.5}$ monthly average (in 2018-19)	24.1 ± 11.8 mg/m3 in February
Annual average (in 2018-19)	24.9 ± 21.2 mg/m3
Long-term $PM_{2.5}$ trend (1998 and 2018)	15.4 and 21.8 mg/m3
No. of airport landings & take-offs per day	450 (2018 average)

4.2 The Airshed

For the analysis of AA's AQ, an airshed spanning 60 x 50 grids between 38.5°E to 39.1°E in longitudes and 8.7°N and 9.2°N in latitudes was selected (Figure 9). This covers the main city area and the neighboring satellite cities, industrial estates, landfills, and quarries. The spatial grid resolution is 0.01°; each grid is equivalent to 1 km^2. All the collated information and analyzed results from the study are maintained in standard GIS-ready formats at this grid resolution.

Figure 9. Addis Ababa City Airshed with Road Density



This report used 2018 as the base year for all the meteorology, emissions, and pollution analyses and then projected forward using business-as-usual conditions. While some basic information is available for 2020, the COVID-19 lockdown caused limited activity for multiple months for most sectors, so it was not used as a representative baseline year. For example, while total vehicle registration numbers were available for the beginning of 2020, they were affected by lockdown conditions. With little or no information available on the change in usage, a 2020 baseline cannot be normalized to support long-term planning.

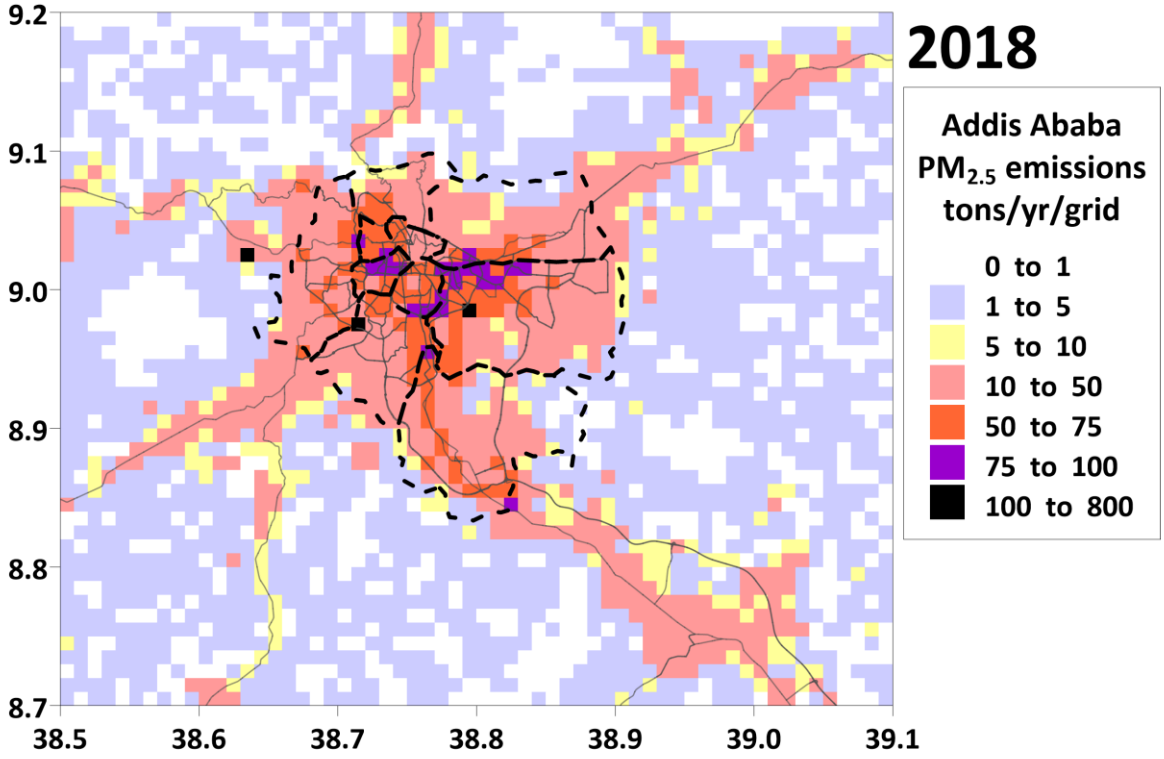
In AA's airshed, the prevalent wind direction is westerly for the rainy months of June through August and easterly for the rest of the year. Wind speed variation is consistent over all months, with a brief reduction in averages for June through August. The nighttime surface temperatures are under 10°C during winter months and consistently under 15°C in all others, indicating some need for space heating. In AA, space heating is an integral part of cooking and baking, often by burning wood, crop residue, coal, and cow dung. Air mixing heights are lowest between June and August, which restricts the movement of emissions. In general, the nighttime mixing layer height is half that of daytime. Figure 7 in Section 2.4 presents monthly average $PM_{2.5}$ pollution and its variation within a month, which will be used in this chapter to verify the emissions results.

4.3 Air Pollution Emissions

This study established a first-of-its-kind emissions inventory at a spatial resolution of 1 km^2 by using the data collected from Ethiopia's environmental and statistical offices and open resources (Figure 10). These data sources included (i) satellite retrieval feeds on urban and rural built-up areas, land use and land cover classification, road networks, commercial activities, and population; (ii) other resources such as high-resolution gridded population and energy demand measures, and consumption statistics; and (iii) published literature by academic and non-governmental organizations on air pollution in AA.

As described above, all the calculations were conducted with 2018 as the base year and projected forward using business-as-usual conditions.

Figure 10. Estimated Gridded Annual $PM_{2.5}$ Emissions for Addis Ababa's Airshed in 2018

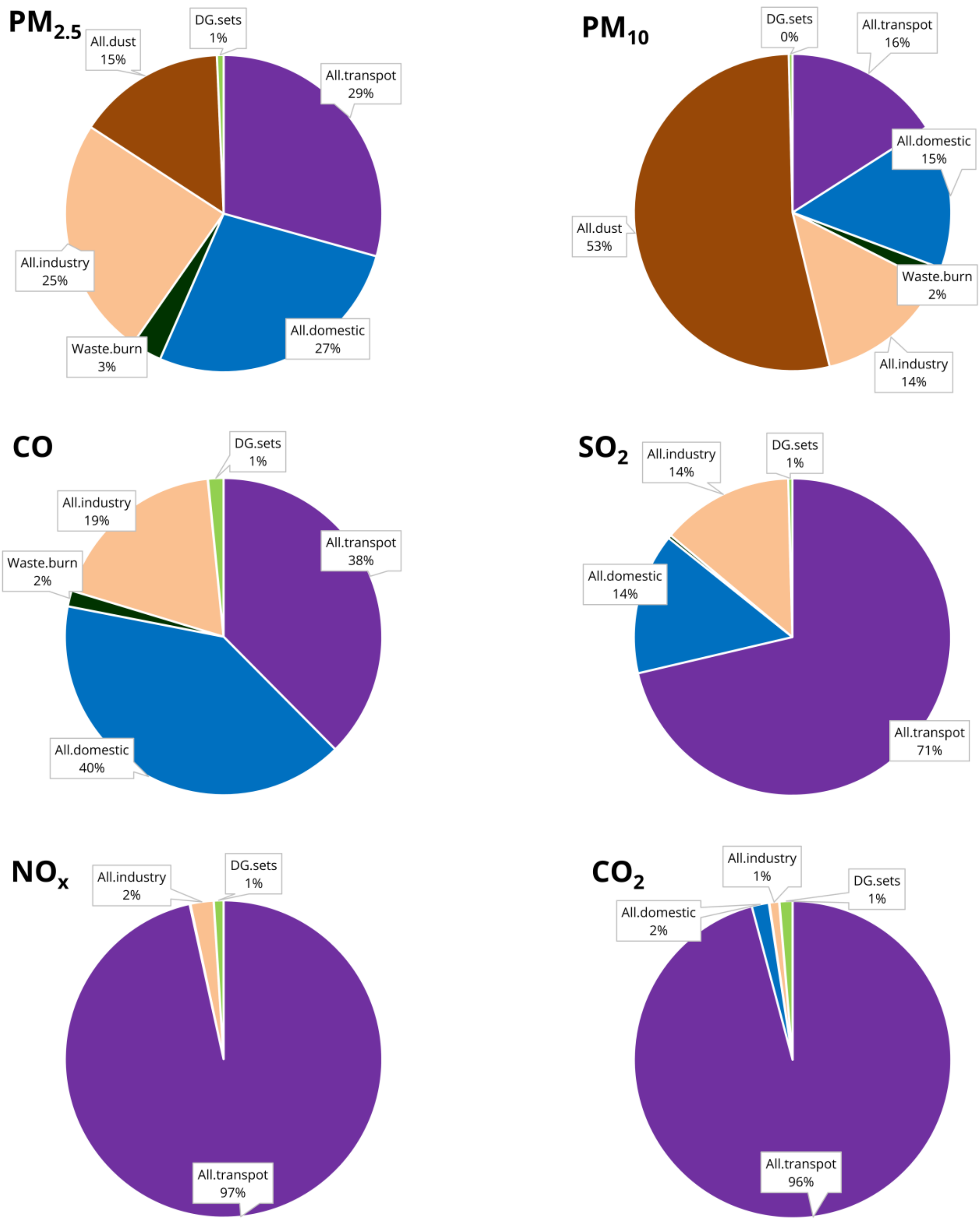


The emissions inventory includes PM in two bins (PM_{10} and $PM_{2.5}$), SO_2, NO_x, CO, non-methane VOCs, and CO_2. Major sources of emissions are road transport; residential activities like cooking and lighting; resuspended dust from roads, construction, and erosion; open waste burning; and industrial activities. Particularly, transportation contributes 29% of $PM_{2.5}$, 16% of PM_{10}, 97% of NO_x, 71% of SO_2 and 96% of CO_2. A summary of estimated total emissions is presented in Table 7, and percent shares are presented in Figure 11 below.

Table 7. Estimated Total Emissions for AA's Airshed for Base Year 2018

tons/year	$PM_{2.5}$	PM_{10}	NO_x	CO	VOC	SO_2	CO_2
All transport	7,850	8,050	120,100	94,200	10,750	4,550	8,683,250
Residential	7,300	7,450	100	101,500	15,100	900	157,800
All industries	6,650	7,700	2,950	47,000	13,700	850	92,250
All dust	3,950	26,100	-	-	-	-	-
Open waste burning	850	900	-	4,050	800	-	5,400
Diesel generator sets	200	200	1,250	3,950	1,750	50	120,000
Total	**26,800**	**50,400**	**124,400**	**250,700**	**42,100**	**6,350**	**9,058,700**

Figure 11. Estimated Sector Shares to Addis Ababa Airshed's Total Emissions in 2018 for (a) $PM_{2.5}$, (b) PM_{10}, (c) CO, (d) SO_2, (e) NO_x, and (f) CO_2



For $PM_{2.5}$ and PM_{10}, the major sources of emissions are biomass burning in domestic and industrial sectors, vehicle exhaust, and resuspended dust from roads and construction activities. Freight vehicles and old passenger buses contribute to 80% of the total $PM_{2.5}$ emissions by clubbed vehicle types. On a fuel basis, more than 95% of the emissions are associated with diesel-based vehicles. A comprehensive summary of emission factors by fuel and by vehicle type is included in the annex material. The emissions inventory also includes contributions from open waste burning and diesel generator sets. These emission shares, while small at the airshed level, are mostly concentrated in the core urban parts of the city. Due to the coarse nature of crustal elements in dust, dust contributes primarily to PM_{10} emissions. Since the country's overall energy needs are dominated by biomass burning in the domestic and industrial sectors, this is also reflected in the total CO emissions, along with the transport sector, which remains a key contributor to all the pollutants. VOC emission rates follow the same trend as CO emissions. SO_2, NO_x and CO_2 emissions are mostly from the transport sector.

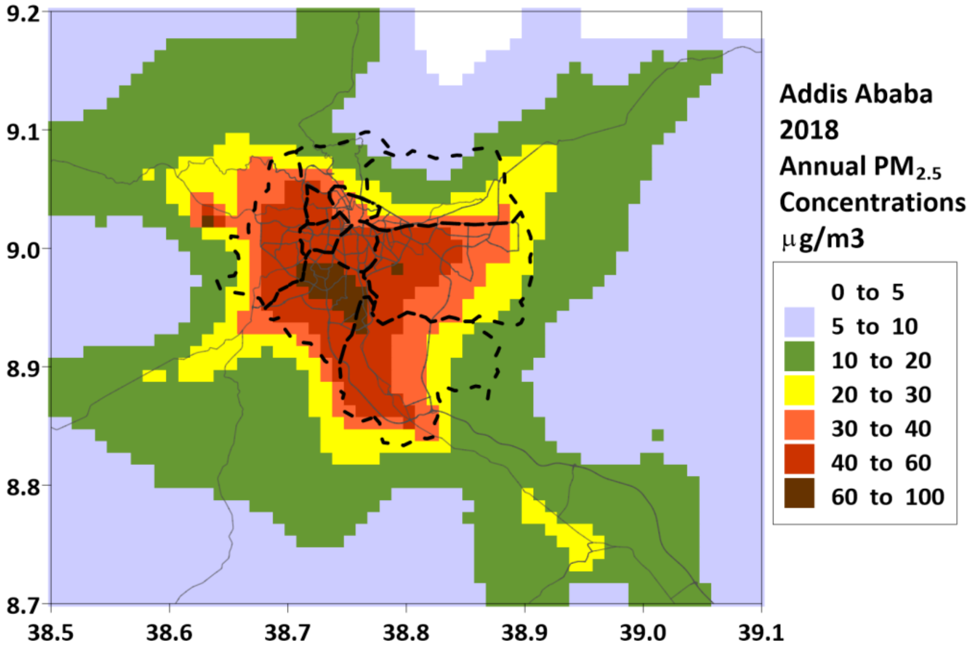
Using satellite observations, open biomass fires were detected over Western Ethiopia, Northern Uganda, and Eastern South Sudan. While these fires are an important emission source in Ethiopia, fire instances were limited in AA's airshed.

All the calculations and databases are maintained in chemical transport model-ready formats at the grid level. The spatial distribution of the emissions combines total emission calculations, and multiple layers of GIS feeds for various sectors. There is no published official or unofficial gridded emissions inventory to represent AA's AQ at this spatial resolution. Therefore, no direct or indirect comparisons can be made with any studies discussing emissions and pollution levels in the city.

4.4 Source Apportionment

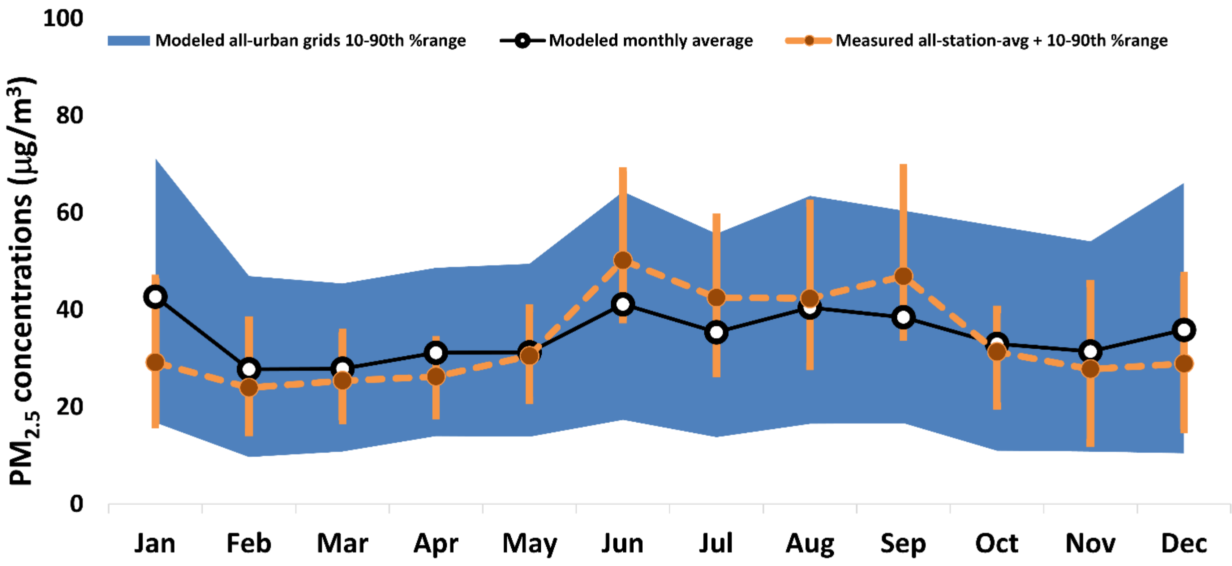
For this study, the open-source Comprehensive AQ Model with extensions (CAMx) (http://www.camx.com), coupled with the meteorological data processed through the Weather Research Forecasting (WRF) model, was utilized to transform emissions into concentrations for further analysis (Figure 12). The maximum annual average concentration appears in the most populated area of the city, with most emissions originating from transport and residential activities. In the month-by-month maps, the winter months (Dec-Jan) and rainy months (Jun-Jul-Aug) stand out, which also represent the months with the highest fraction of hours with temperatures under 15°C, slow moving winds, and lower mixing layer heights limiting the overall dispersion of emissions.

Figure 12. Modeled Annual $PM_{2.5}$ Concentrations for Addis Ababa's Airshed in 2018



The pollution modeling exercise replicated the spatial and temporal variations in the available ambient monitoring data, thus providing baseline confidence in the estimated emissions inventory for AA's airshed (Figure 13). The blue band represents the 10^{th} to 90^{th} percentile range over all urban grids within each month (approximately 600 grid points). The solid black line represents modeled monthly average concentration, and the dashed orange line represents the measured monthly average concentration and its variation within the month. Going forward, this emissions inventory can be used for the analysis of possible emission control mechanisms and likely benefits of a reduction in ambient concentrations, health impacts, and environmental degradation.

Figure 13. Modeled Annual Average $PM_{2.5}$ Concentrations in Addis Ababa's Airshed in 2018



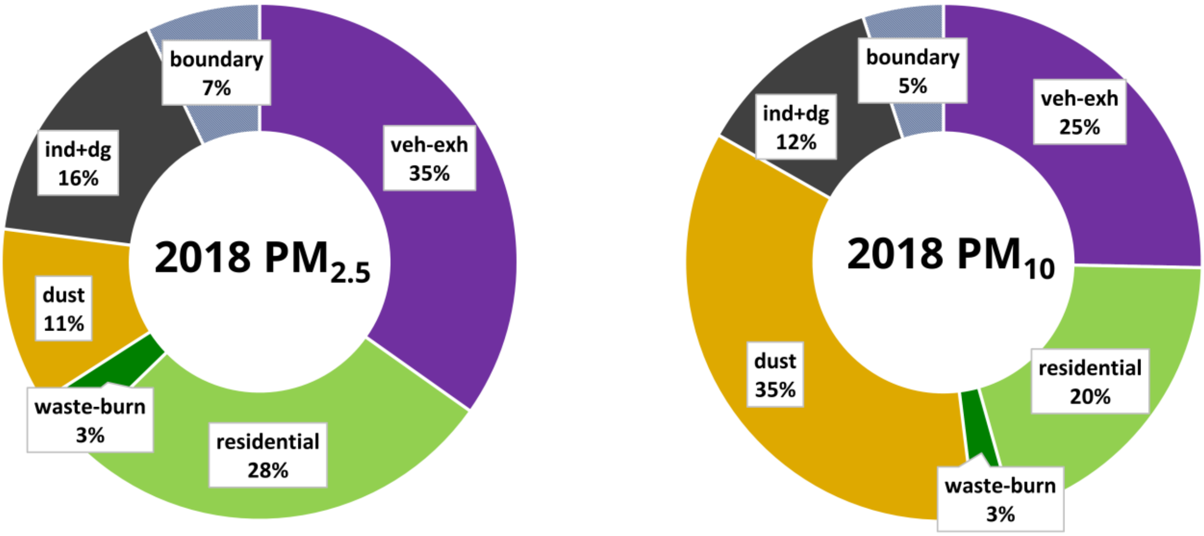
In addition to annual and monthly average concentrations, the modeling system also allows for source apportionment. The term "source apportionment" refers to the estimation of source contributions to ambient pollution levels and is important to differentiate from an emissions inventory, which also provides information at the source level. Pollution source apportionment data is critical for policy discussions.

The modeled source contributions for AA (Figure 14) highlight various key findings:

- On an annual basis, source contributions to $PM_{2.5}$ pollution are dominated by vehicle exhaust, residential activities, resuspended dust, and industries. Without exception, vehicle exhaust remains the main source, and a constant one, of pollution in all months.
- On an annual basis, dust is a major contributor to PM_{10}. Resuspended dust on roads due to the constant movement of vehicles is substantial in both $PM_{2.5}$ and PM_{10} fractions. It will increase with an increasing number of vehicles (irrespective of the engine/fuel technology) if dust control programs like paving, watering, and greening the roads are not introduced.
- The use of biofuels dominates all non-transport sources. Biomass in the form of wood, crop residue, cow dung, and charcoal is the dominant fuel source for all residential activities like cooking and baking, and some space heating in the outlying parts of the city.
- Open waste burning and diesel generator sets are not significant contributors but are not negligible.
- The term "boundary" represents the contribution of sources outside the modeling airshed and is an indicator of regionally transported pollution. Overall boundary contribution is under 10% for all months, indicating a limited influence of sources outside the city airshed. This contribution is higher during the months of easterly winds.

- With limited variation in the monthly weather patterns, the variation in the sectoral contributions is also limited.

Figure 14. Modeled Source Contributions to Annual Average $PM_{2.5}$ Pollution in Addis Ababa



Similar concentration trends were observed in a chemical analysis-based source apportionment study with samples collected at one station (Tefera et al., 2020). Since that paper discusses results from only one location, it is not possible to generalize the results for the city airshed, but the presence of higher organic and black carbon components supports the conclusion of higher contributions from biomass and diesel combustion, followed by dust from the presence of crustal elements in the collected samples.[20] The fraction of secondary components such as sulfates, nitrates, and ammonium are small, indicating limited contributions from regional sources.

4.5 Recommendations

As emission inventories and source apportionments are fundamental to planning and prioritizing emission reduction activities, AA and other cities need to develop and/or update them. This exercise would build confidence in the modeling platform. For example, data in the road transport emissions analysis relies on various reports and the basic registrations database which can be further improved. This exercise could include conducting surveys at fuel stations to understand in-use vehicle characteristics like age mix, vehicle distance traveled, and fuel efficiency. Similarly, a survey to understand fuel mixes and usage in the domestic sector will help in bettering the emission estimates.

A source apportionment exercise is a technically and financially taxing project. While this report used an established bottom-up approach to estimate source contributions, a complimentary program that includes a top-down chemical analysis-based approach at a representative number of locations across the AA airshed would strengthen and validate the results and increase confidence in adopting policy applications. Besides using this analysis for long-term policy “what-if” scenarios, the modeling system can be extended to conduct short-term air quality forecasting. The platform simulates weather and

[20] The findings of this chemical analysis-based study and the bottom-up analysis presented in this study are comparable to studies conducted in cities with a similar mix of urban-rural classification and similar mix of emission sources (like transport, industries, residential, etc.). For example, a study conducted in six cities by India’s Central Pollution Control Board (https://cpcb.nic.in/source-apportionment-studies, 2011), concluded that the transport sector is responsible for 20-40% of the pollution in the cities, with the remaining contributions spread between industrial, residential, open waste burning, and dust.

pollution patterns every day for the following 3 to 5 consecutive days and uses the results to alert the public on air quality.

5. Zooming in Urban Transport: Vehicle Emission Control in Addis Ababa

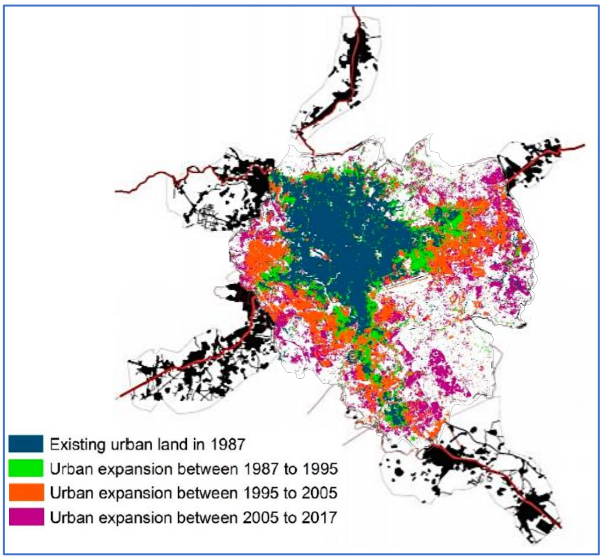
Prior to this study, there was limited transport air pollution data and few systematic studies on vehicle emission inventory in AA, even though urban transport is widely recognized as a key contributor to ambient air pollution. The emission inventory analysis of this study estimated the transport sector contributed 29% of $PM_{2.5}$ emissions and more than 90% of NO_x and CO_2. The health impact analysis provided data-driven evidence that air pollution in AA has become a public health crisis, with a societal cost equivalent to $78 million or 1.3% of AA's GDP in 2019.

This chapter focuses on transport air pollution control in AA. Building upon the overview of the urban transport sector context, documents from the government and development partners, and ongoing interventions, the chapter identifies mitigation options for transport emissions in consideration of global practices in the local context, assesses their effectiveness and applicability and recommends priority measures for short- and mid-term action, and presents key findings and recommendations on transport air quality mitigation.[21]

5.1 Urban Transport Development and Air Pollution

AA is at the forefront of urbanization and motorization. The city expanded spatially three-fold in the past two decades, from 99 km^2 to 284.9 km^2. This increase decreased urban density in AA from 17,000 (people/km^2 built-up area) in 1987 to 13,000 in 2017 (see Figure 15). As described above, the urbanization and motorization trend in AA has also come at a price of environmental degradation, with significant loss of green space and farmland and increasing vulnerability to climate change.

Figure 15. Spatial Expansion of Addis Ababa



Source: WB multi-sector ASA

This rapid expansion has drastically increased the demand for motorization and increased needs to move both people and freight. The number of registered vehicles in the city has increased by 40% in the past

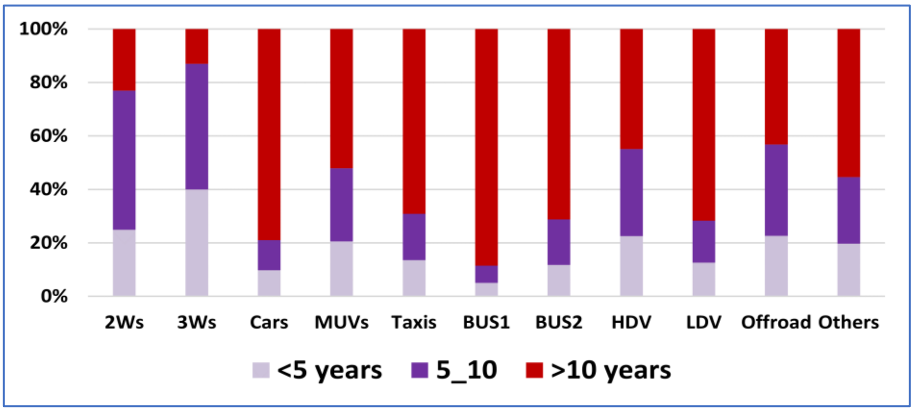
[21] The details of the study on the transport mitigation can be found in a separate report titled "Steering Towards Cleaner Air: Measures to Mitigate Transport Air Pollution in Addis Ababa" (Grutter, J., W. Jia and J. Xie, 2021).

five years. The city's registered vehicle stock reached 630,000 in 2020, accounting for nearly 50% of all registered vehicles in Ethiopia. Motorization is posing huge challenges for AA in all dimensions.

The previous approach to addressing motorization through expanding main roads and accommodating vehicle growth has not effectively improved accessibility but has nonetheless generated negative externalities. In AA, 54% of the population walks and 31% rides on public transit, yet the city has low accessibility; only 17% jobs can be reached via public transport within one hour, and only 15% on foot. Walking can be dangerous, too, as studies by the World Health Organization (WHO) and the government show the city has disproportionately high pedestrian fatalities for the country and for Africa. In addition to the exacerbation of road fatalities, rapid motorization also worsens traffic congestion, increases greenhouse gas emissions, deteriorates air quality locally, and results in health impacts and economic costs. This calls for integrated, comprehensive management of motorization and air quality.

Air pollution problems from the transport sector in AA are characterized by high-sulfur fuels, lack of emission standards, ineffective and unenforceable emission inspections, and an aging vehicle fleet. Ethiopia currently imports 500ppm sulfur diesel and 10ppm sulfur gasoline, allowing for operation of Euro 3/III vehicles. Emission inspection, while mandatory, only detects smoke and carbon monoxide and does not set any threshold for acceptance. Therefore, it does not influence the pass/fail decision for an inspection and is not enforceable. Most registered vehicles are over 10 years old, including buses, passenger cars and light duty vehicles, many of which are not subject to emission control under the current practice. Mini- and midi-buses are predominantly old and lack vehicle emission controls (Figure 16).

Figure 16. Type and Age of Registered Vehicles in Addis Ababa in 2020



Note: MUV – Multipurpose vehicle; Bus1 – mini/midi bus; Bus2 – standard bus, HDV/LDV – heavy/light duty vehicle

Continuing business-as-usual (BAU) management of motorization and air quality will further degrade air quality in AA, threatening the city's livability and ability to grow. As discussed in previous chapters, in AA, the transport sector – including urban transport, aviation, and roads – currently contributes 29% of $PM_{2.5}$ emissions, 71% SO_2, 97% NO_x, and 96% of CO_2. In the next decade, should the current vehicle growth trend continue at 8% a year, AA would expect 1.3 million vehicles. Even a conservative estimate, which assumes vehicle growth at the GDP growth rate, projects 900,000 vehicles in AA by 2030. In these scenarios, the level of vehicle emission would exponentially increase in proportion to vehicle growth, increasing at least 50% and possibly over 100%. Without a change of course, transport air pollution in AA will create profound local and national impacts. Furthermore, there exist co-benefits between local pollution control and climate change at a global level, as increased particle emissions damage air quality and increase Black Carbon (BC) emissions. Scientific assessments of BC emissions and impacts have found that they are the second most important emission that drives climate change, second to CO_2.

Managing motorization and controlling vehicle emissions will help AA to reduce air pollution, improve public health and boost quality of life while providing climate co-benefits through the reduction of GHG emissions. They are a pathway to the city's livability, competitiveness, and growth.

5.2 Identification and Assessment of Potential Mitigation Options

The Government of Ethiopia and the City Government of AA have conducted studies on air pollution problems to identify measures for reducing vehicle emissions. The documents, reviewed during this study, include but are not limited to: the Air Quality Management Plan (AQMP) prepared by the city government in 2021 (through its AAEPGDC with the support from the US Government); the 2016 Greenhouse Gas Emissions Inventory Report by C40 Cities in 2020; Motorization Management in Ethiopia, prepared by the World Bank in 2017; an Air Quality Policy and Regulatory Situational Analysis (UNEP, 2018); an Electric Bus Study by World Resource Institute and Lucy Partners; and multiple urban transport studies by AA City.

Ongoing urban transport investment and policy work in AA will come to fruition in the short-term and contribute to the mitigation of emissions and air pollution. The city of AA is working with the World Bank to modernize its public transport and traffic management systems, and with the French Development Agency to develop its first Bus Rapid Transit Line, all of which will be operationalized in 2-3 years. The city also built its first dedicated bike lane in 2020. Meanwhile several key studies covering comprehensive transport development, paratransit transformation, and other strategic areas will inform AA's policies and priorities for the management of motorization and air pollution.

Based on the review of government studies and sector interventions, assessment of local context, consultation with relevant government agencies, and learning from international experience, nine potential mitigation measures were identified for AA's transport sector (Table 8). The identification also aligns with the urban transport policy framework "Enable, Avoid, Shift and Improve" (EASI),[22] recommended by the Sub-Saharan Africa Transport Policy Program (SSATP). The potential measures are further categorized into three clusters or groups: (i) standards, (ii) vehicle measures, (iii) public transport.

Table 8. List of Potential Transport Air Pollution Mitigation Options

Category	Option Group No.	Proposed Options with Abbreviated Name
Fuel and vehicle emission standards	1	Low-sulfur fuels
	2	Vehicle emission standards for newly registered vehicles
	3	Maximum emission levels for in-use vehicles (I/M)
	4	Fuel economy or CO_2 emission standards
Vehicle measures	5	Vehicle retrofits with emission control equipment
	6	Maximum vehicle age for imports and in-use vehicles
	7	Ban on import and new registration of light diesel vehicles
	8	Promote low-carbon vehicles (electric and hybrid vehicles)

[22] https://www.ssatp.org/topics/urban-mobility

Public transport measures	9	Improve public transport/non-motorized transport (NMT)/transport demand management (TDM)

Under each option group, there are varied, inter-connected measures. Among them, most were identified in the studies done by the government and development partners. Only two options – vehicle retrofits with emission control equipment and restricting sales of diesel vehicles – are proposed as new measures in this study, as they have been implemented in other countries with success and have potential applicability for Ethiopia. Various reports also included biofuels, though they alone will not significantly impact air quality because they do not affect vehicle emission standards. The impact on GHG emissions depends on the type of biofuel used and requires a life-cycle assessment, including direct and indirect impact on land-use change, which this study does not provide.

Potential mitigation options were assessed based on the following criteria: (i) efficacy and environmental impact on local air pollutants and GHG emissions in AA; (ii) efficiency expressed in terms of economic cost-benefit and social impact; (iii) technical feasibility for AA in consideration of implementation capacity; and (iv) effort and time required to implement the measure in a sustainable manner in the local context.

For the study's economic analysis, the economic benefits of emission reduction from each mitigation measure are estimated based on the cost of air pollutants in Ethiopia presented in an International Monetary Fund (IMF) publication (IMF, 2014). The IMF study calculated the cost of a few main pollutants, namely, $PM_{2.5}$, SO_2, and NO_x, based on local pollution at the ground level and cost and health impact of each pollution type in Ethiopia. By taking the cost values for Ethiopia from the IMF publication, the study further updated unit costs to their US$ equivalent as of 2019 according to the GDP per capita of Ethiopia. The following costs per ton of air pollutant are used in the study: US$4,014 per ton of $PM_{2.5}$ emitted, US$132 per ton of SO_2 emitted, and US$28 per ton of NO_x emitted.[23]

The economic analysis also included global warming externality costs through the social costs of carbon (SCC), which estimate the economic damages associated with increases in CO_2 emissions. Valuating the economic damage of CO_2 emissions is complex and depends on discount rates. The Asian Development Bank (ADB) reported an SCC unit value of US$36 per ton of CO_2e in 2016 prices for emissions, which increases by 2% annually in real terms to reflect the potential of increasing marginal damage of global warming over time. Updated to 2019 real US$ and including the annual increase results in around US$40 per ton CO_2e for 2019.

Table 9 highlights key aspects of the assessment outcomes.

[23] Please note that the cost of $4,014 per ton of $PM_{2.5}$ used in the assessment of transport emission mitigation measures is different from what one may derive from calculations of economic cost of the health impact of $PM_{2.5}$ presented in the previous chapters of this report. The economic cost presented in Chapter 3 aims to demonstrate the scale of economic cost of mortality and morbidity due to ambient $PM_{2.5}$ and represents a fraction of total costs. Therefore, the assessment in this chapter adopts the more complete cost data from an IMF study (IMF, 2014).

Table 9. Summary of the Assessment of Mitigation Measures

Category	Option Groups	Air pollution impact	GHG impact	Cost-Benefit	Implementation complexity	Overall assessment and recommendation
Fuel and vehicle emission standards	1. Low-sulfur fuels: Introduction of 50ppm sulfur (stage 1) and 10ppm sulfur (stage 2) diesel.	• Direct: strong SO_2 reduction; small $PM_{2.5}$ reduction; no NO_x impact • Indirect combined with vehicle emission regulations: see below	No impact	• Stand-alone: significantly higher costs than benefits • Combined with vehicle emission regulations: see below	• Technically simple as fuels are imported • Fuel sur-cost is 1-2 US$ cents per liter which is not considered a huge barrier	• Current level: 500ppm • A pre-condition for most other measures • Euro 4 fuel (50ppm) recommended; Euro 5 fuel (10ppm) not recommended yet due to costs • Low-sulfur fuels without subsequent issuance of tighter vehicle emission standards will only have a limited impact
	2. Emission standards for newly registered vehicles (used or new units): Euro 4 (stage 1) and Euro 6 (stage 2)	• Direct: large reduction of all pollutants • Measure requires low-sulfur fuels as pre-condition	No impact	• Euro 4 together with 50ppm sulfur fuels cost-neutral • Euro 6 together with 10ppm sulfur fuels has significantly higher costs than benefits	• Technically simple as vehicles are imported and certificates of conformity can be used • No investment in national vehicle testing center is required	• Current level: none but primarily Euro 2 vehicles • Euro 4 emission standard for new or used vehicles is recommended once 50ppm sulfur fuel is available • Euro 6 level not recommended yet due to higher costs than benefits • Euro 3/5 standards not recommended due to marginal benefits compared to Euro 2/4 • This measure can only be implemented together with low-sulfur fuels • Vehicle emission standards cannot be replaced with in-use vehicle emission controls as the latter are only to identify faulty vehicles with excessive emissions
	3. Maximum emission levels for in-use vehicles (I/M); emissions testing is already performed together with the roadworthiness test and the government is in the process of	Low impact due to limited vehicle degradation in emission (i.e., increasing emissions over time due to aging of vehicles) and complexity of effective implementation & enforcement	No impact	In theory more benefits than costs but in practice many systems only incur costs due to lack of adequate implementation and enforcement	Highly complex to enforce and control	• Support the government in the establishment of maximum levels for in-use vehicle emission controls including measurement procedures and equipment standards • Strengthen the process of integration of emission testing in road-worthiness tests with appropriate quality control and enforcement measures • In-use vehicle inspection cannot be used to determine the vehicle emission standard or the compliance of a vehicle with a given vehicle emission standard, but only to identify gross

	determining maximum pass levels for in-use vehicle emission controls					polluters significantly in excess of prescribed limits.
	4. Fuel efficiency or CO_2 emission standards	• Small impact if no fuel switch • Highly negative if this results in dieselization • Positive impact if switch towards electric vehicles (EVs)	Moderate impact	No general statement possible	• Fuel efficiency labels are complex to design • Implementation is complex for second-hand vehicles • Simple if focused on hybrids and EVs	Fiscal measures to promote low-emission vehicles should be designed to be fiscally neutral.
Vehicle measures	5. Vehicle retrofits with emission control equipment	Significant reduction of $PM_{2.5}$	Small increase in fuel consumption but reduction of Black Carbon: total small reduction	Significantly higher costs than benefits	• Requires Euro 4 fuels • Technically complex • On-road enforcement and controls required	Not recommended due to highly negative cost-benefit relation and high implementation complexity
	6. Maximum vehicle age for imports and in-use vehicles eventually combined with scrapping programs	Vehicle age is not an adequate proxy for vehicle emissions and as a stand-alone measure could increase emissions, as vehicle deterioration rates are lower than changes in emission standards (a 10- or even 20-year-old Euro 4 vehicle has lower emissions than a brand-new Euro 2 unit)	• GHG emissions of HDVs are not related to age • Small age deterioration • Car GHG emissions more related to CO2 standards	Vehicle scrapping programs have significantly higher costs than benefits	• Pure age limitations are simple to regulate but for in-use vehicles seldomly enforced (e.g., multiple countries have maximum ages for buses which are never enforced) • Scrapping programs are	• Age is not an adequate proxy and is not correlated well with emissions • Emission standards are the appropriate parameter to limit vehicle emissions • Scrapping programs are not recommended due to very high costs with limited benefits

			than to vehicle age		complex to design	
	7. Ban on import and new registration of diesel passenger cars and light commercial vehicles	High reduction of $PM_{2.5}$ and NO_x	Marginal increase to neutral	Neutral for country but slightly higher cost for private diesel car users due to diesel being subsidized and petrol not	Simple measure	• Highly recommended due to simplicity and immediate impact • Petrol cars are a cost-effective alternative to diesel units
	8. Promote low-carbon vehicles (hybrids and EVs)	High reduction per vehicle but low impact due to low levels of vehicle renovation and low vehicle numbers	High impact due to low carbon grid factor of Ethiopia	Higher upfront costs and in general still higher total lifetime financial costs	Simple measure but requires new business models to be commercially viable	• Recommended for urban buses but requires more in-depth evaluation first • Develop an e-mobility strategy across multiple sectors, which could include designing and/or implementing a demonstration project
Public transport measures	9. Improve public transport, NMT and TDM	All measures result in mode shift and have a high potential for reducing local pollutants	All measures potentially result in high GHG emission reductions due to modal shift	Dependent on concrete measure but in general highly positive in economic terms due to congestion reduction, time savings, reduced vehicle operating costs and reduced health costs	• Often requires high initial investment • TOD and TDM measures are highly complex to design and implement • Benefits often only accrue in the long-term due to requiring behavioral change	• Recommended measures to ensure a sustainable low-emission transportation system • Priority on implementing ongoing interventions and key policy recommendations: (i) Sidewalks and bike lanes, (ii) Anbessa and BRT projects under DP financing, (iii) Public transport network optimization including paratransit minibus reform, (iv) Parking management pilot project, and (v) Completing BRT and TOD studies.

5.3 Conclusions and Recommendations

Based on the results of the assessment shown in Table 9, the potential mitigation options are screened and prioritized in Table 10.

Table 10. Prioritization of Mitigation Measures

Priority	Measure	Rationale
High-priority measures	Low-sulfur diesel (50ppm; at a later stage 10ppm) (option no. 1)	This measure is a pre-condition for many other measures including stricter vehicle emission standards or import of low-emission vehicles. This measure should be linked with vehicle emission standards as otherwise its impact will be limited.
	Vehicle emission standards: once 50ppm sulfur fuels are available introduce Euro 4/IV; long-term Euro 6/VI (option no. 2)	This measure directly results in lower emissions and is also a good criterion for selecting which vehicles to import. This measure is dependent on low-sulfur fuels.
	Improve public transport and NMT, if possible combined with TDM measures (option no. 9)	This is important for achieving sustainable low-emission transportation systems and the economic benefits in general outweigh the costs by far.
	Establish maximum levels for in-use vehicle emissions, measurement procedures, equipment standards, and strengthen its integration into the roadworthiness test (part of option no. 3)	Maximum in-use vehicle emission levels are under development by Addis Ababa; adequate measurement procedures, standards and a high-quality supervision and enforcement system including on-road spot checks can reduce the potential to circumvent the system.
	Ban on import and new registration of diesel passenger cars, and light commercial vehicles less than 3.5t (option no. 7)	The measure has a significant impact on reducing pollutants with a positive cost-benefit ratio and is very simple to implement
Medium-priority measures	Foster electric and hybrid vehicles (option no. 8)	In the long-run carbon neutrality in transportation will only be achieved with EVs. The measures could start with electric buses and then be expanded to other commercial vehicles used in urban settings
	Age limitation for in-use urban fossil public transport buses (part of option no. 6)	This option allows for periodic renovation of the bus fleet and thereby also improves the attractiveness of public transport and gives an incentive to usage of electric units. However, the cost-benefit of the measure is negative and it will only have significant positive impact if the vehicles meet higher emission standards
	Integrate emission testing including data access and sharing in roadworthiness test control centers (part of option no. 3)	This measure will depend on the establishment of minimum emission standards, and effectiveness and soundness of emission inspections. Introducing this measure faces weak capacity, high complexity, and lower cost-benefit.
Low priority, not recommended	Fuel efficiency standards (option no. 4)	High complexity with a low impact for Ethiopia plus the potential to result in a further dieselization with resultant worsening of air quality

	Vehicle scrapping programs (part of option no. 6)	High cost, negative cost-benefit, high complexity and limited impact
	Vehicle retrofit programs with diesel particle filters (option no. 5)	High technical complexity and highly negative cost-benefit
	Age limitations for import of new or in-use vehicles (part of option no. 6)	This is not an adequate proxy for vehicle performance

The recommended priorities from this study are further screened by their magnitude and rapidity of impacts and categorized into short-term, medium-term and long-term measures. Sometimes, high priority does not necessarily translate into quick implementation. Short-term refers to implementation with impact within 1-2 years, medium-term for impact within 3-5 years, and long-term beyond 5 years. Proposed short- and mid-term measures are:

Short-term measures include the following:

(i) Introducing 50 ppm-sulfur diesel fuel, combined with Euro 4/IV vehicle emission standards or equivalent, which is a high priority for the government.
(ii) Fostering public transport and NMT measures, if possible, combined with transport demand measures and transit-oriented development. This is also consistent with government priorities, as AA city administration recently announced an initiative to add 3,000 buses. Public transport, at today's 31% mode share, carries high passenger volume and results in significantly lower GHG emissions per passenger-kilometer than private means of transport. However, due to usage of diesel buses public transport is also a major source of local pollutants. Moreover, without increasing the efficiency of public transport, fostering of public transport alone will not result in air quality improvements. Measures such as operational improvements and restructuring to allow for replacement of minibuses with larger units on heavy demand routes are the most relevant in terms of air quality improvement.
(iii) Establishing maximum in-use vehicle emission levels and measurement procedures and strengthening the integration of emission testing in road-worthiness tests with quality control and enforcement measures, which are being developed by the Federal Transport Authority.
(iv) Introducing a ban on importing all diesel vehicles with less than 3.5t gross vehicle weight, including both new and second-hand vehicles. At present, 36% of registered vehicles in Ethiopia are diesel vehicles. Even with the best available diesel technologies, the real-world performance of diesel engines results in high PM and NO_2 emissions.

Among these measures, (i), (iii) and (iv) are identified as high priority by the government.

Medium–term measures:

(i) Promote hybrids and EVs with fiscally neutral instruments and other policies (short term can start with developing multi-sector e-mobility strategy and understanding power infrastructure investment to support e-mobility).
(ii) Integrate emission inspection including data access and sharing for vehicle roadworthiness test centers.
(iii) Limit the age of in-use fossil buses for urban public transport to speed up public transport renovations and incentivize switching to electric units.

Other measures are considered low priority and not recommended at this stage. Some non-recommended options are parts or sub-components of other options: (i) fuel efficiency standards, due to high complexity and potential dieselization of the vehicle fleet and a subsequent increase in air pollution; (ii) vehicle scrapping programs, due to their highly negative cost-benefit; (iii) vehicle retrofit programs with diesel particle filters, due to their considerable technical complexity and highly negative cost-benefit ratio; and (iv) age limitations for the import of new or second-hand vehicles, due to them not being an adequate proxy for vehicle performance. The correlation between vehicle age and vehicle emissions only exists in countries with advanced vehicle emission regulations. In Ethiopia, used as well as new vehicles arrive from different parts of the world. Second-hand vehicles made in Europe since 2006 comply with Euro 4/IV and with Euro 6/VI for vehicles since 2015, while new heavy-duty vehicles assembled locally in Ethiopia may only meet emission standards of Euro 0. Therefore, introducing an age limitation for importing vehicles may not be effective in Ethiopia at this time.

6. Proposed Action Plan and Concluding Remarks

Ethiopia needs a clear set of action steps to move forward towards IAQM. This final chapter summarizes the policy recommendations already discussed in previous chapters in an action plan. It also points out the limitations of the study and areas for improvement.

To help the governments set priorities and timeframe to take actions, Table 10 below groups policy recommendations in eight categories and suggests the responsible agencies and implementation period for each recommended action.

Table 11. Action Plan for Promoting Integrated AQM in Ethiopia

Table 1	**Responsible agency**	**Short-term (0-2 years)**	**Medium-term (3-5 years)**	**Long-term (6-10 years)**
Regulation and Policy Reforms				
• Review, strengthen, and harmonize existing regulatory and policy frameworks for AQM	EFCCC	**X**		
• Clearly define or clarify the roles and mandates of key government agencies at the federal and municipal level for AQM through functional review of relevant agencies	EFCCC and Municipal EPB in consultation with other line agencies	**X**		
• Introduce taxation and pricing policies or other fiscally-neutral instruments or incentives to encourage newer and cleaner vehicles such as hybrids and electric vehicles and phase out polluting vehicles	MoF, EFCCC		**X**	
• Upgrade AQ standards (including ambient $PM_{2.5}$ standards)	ESA, EFCCC	**X**		
• Introduce low sulfur fuel standards (start with 50 ppm; progress to 10 ppm) with the Euro 4/IV vehicle emission standards nationwide	ESA with the support of ESP	**X**		
• Introduce other fuel quality and emission standards for the transport sector	ESA, EFCCC	**X**	**X**	
AQM Strategy and Plan				
• Develop urban ambient air quality monitoring strategy and implementation plan	Municipal EPA with the support of EFCCC	**X**		

• Develop urban ambient AQM strategy and plan	Municipal EPA with the support of line agency and EFCCC	X	X	
Budgeting and Capacity Building				
• Strengthen institutional capacity of responsible agencies for AQM, particularly for regulating and enforcing AQ regulations and standards.	Relevant agencies	X	X	
• Develop mechanisms for promoting inter-agency and cross-sectoral coordination and collaboration as well as experience sharing and learnings on AQM.	EFCCC and relevant agencies at federal and municipal levels	X	X	
• Increase government revenue and budgets for AQM by reviewing and revising environmental taxation and fee systems.	MoF and Municipal governments	X	X	
AQ Monitoring				
• Develop standardized and unified systems for ambient AQ monitoring and reporting in AA and other polluted cities in Ethiopia	EFCCC and local EPA	X	X	
• Develop a spatially and temporally representative emissions inventory and reporting system in AA	AAEPGDC		X	
• Strengthen the capacity of key line agencies in AQ information management	Relevant agencies	X	X	
• Make verified and standardized AQ data open to public access via the internet and mobile apps	EFCCC and local EPA	X	X	
Data collection, Research & Modeling				
• Systematically collect and analyze AQ and air emission data for better informing AQM planning and decision-making in AA and in Ethiopia	EFCCC and local EPA and relevant agencies	X	X	
• Collect data to update emissions inventory	EFCCC and local EPA	X	X	
• Conduct surveys to understand in-use vehicle characteristics and domestic fuel mixes and usage	MoT and local TB	X	X	
• Adopt the top-down chemical analysis-based approach in AA to further update and verify the	Local EPA	X	X	

results of the bottom-up emissions inventory and source apportionment study				
• Strengthen the collection and analysis of air pollution related health data and establish the empirical relationship between airborne diseases and air pollution in Ethiopia	MoH, EFCCC and local HB and EPA	**X**	**X**	
• Improve and extend the economic valuation of air pollution impacts beyond health impacts develop the guidelines of the cost-benefit analysis or cost-effectiveness analysis of AQM programs, investment projects, and interventions	EFCCC and relevant agencies	**X**		
• Develop an abatement cost curve and a plan to implement AQM interventions to cost-effectively reduce air pollution emissions	EFCCC with the participation of other relevant agencies	**X**		
Awareness Raising and Behavioral Change				
• Develop and implement AQM education and outreaching activities, including communications and dissemination of AQM policies, plans and programs	EFCCC and local EPA	**X**	**X**	**X**
• Engage and mobilize private sector, general public and other stakeholders to change behaviors that emit air pollution	EFCCC and relevant agencies	**X**	**X**	**X**
Vehicle Emissions Control				
• Introduce low sulfur (max 50ppm) diesel fuel and Euro 4/IV vehicle emission standards or their equivalent	ESA	**X**		
• Support efforts to import cleaner fuels with lower sulfur contents	ESP	**X**		
• Ban importing secondhand diesel passenger cars or light commercial vehicles and restrict imports to new and secondhand imported diesel vehicles weighing more than 3.5t gross (i.e., continue to allow imported diesel vehicles, such as trucks or buses)	MoT and local EPA and TB	**X**	**X**	
• Establish maximum emission levels for in-use vehicles, measurement procedures and standards, quality control & enforcement system of emission inspection performance	EFCCC, MoT, local TB and EPA	**X**	**X**	

• Limit the age of in-use fossil buses for urban public transport to speed up public transport renovations and incentivize switching to hybrids and electric vehicles with fiscally-neutral instruments and other policies	Local TB and EPA	**X**	**X**	
• Promote and strengthen public transport and NMT measures, with possible transport demand measures and/or transit-oriented development	Local TB	**X**	**X**	**X**
Point and Area Sources Control				
• Enhance the capacity of cities to point-source monitor facilities, enforcement of city-level regulations for industrial sources, including boilers and oil generator sets	Local EPA	**X**	**X**	
• Develop and implement area source control measures, including (a) controlling air pollutant emission from industries, (b) improving SW collection and reducing open burning of trash, (c) raising public awareness of health impact of burning plastic and hazardous wastes, and (d) implementing best practice for control of construction and road dusts	EFCCC and Local EPA with support of other relevant agencies	**X**	**X**	

As already discussed in the report, the study faced a few limitations. The first is the lack of AQ data, a common phenomenon in many developing countries including Ethiopia. The study behind the report had to rely mostly on open-source data, literature, and limited access to government data in its analytics including emission inventory and source apportionment and health impact assessment. The health impact assessment adopted the methodology developed for GBD and estimate the health impact of annual average $PM_{2.5}$ concentrations available from a few AQ monitoring stations. The economic costs of health impacts were valued by the benefit transfer approach and the Value of Statistical Life (VSL) available from literature. The cost-benefit assessment of transport mitigation options only intends to give an indication or first approximation and its results are insufficient to derive an abatement cost curve that would benefit AQM planning and decision making.

Secondly, the study was entirely carried out within a short period from October 2020 to June 2021 during the Covid-19 pandemic and, as a result, it was impossible to conduct field trips and in-person discussions with stakeholders for the firsthand and in-depth assessment of the local situation. Thirdly, due to data availability and time and resource constraints, most of the analytical work was done on AA only and air pollution emission control measures focus on the transport sector.

Therefore, to enhance its policy analysis and decision-making capacity, Ethiopia should continue conducting in-depth analyses for various aspects of AQ, such as ambient air pollution dispersion modeling, spatial distribution of populations vulnerable to AQ, wider assessment of health and non-health impact of air pollution, and cost-effectiveness or cost-benefit analysis of AQM intervention. While this report used an established bottom-up approach to estimate source contributions, a complimentary program that includes a top-down chemical analysis-based approach at a representative number of locations across the airshed of

AA would help strengthen and verify the results and gain confidence in policy applications. For the urban transport sector, additional analyses could include the spatial-temporal distribution of traffic congestion and travel time to localize pollution hotspots. Lastly, the future study could also include data from the impacts of changes during the COVID-19 pandemic to provide a better benchmark for scenarios when countries and cities reduce emissions under certain circumstances. From the additional analyses, Ethiopia can develop a more evidence-based IAQM plan that includes recommendations for nationwide action and corresponding investment activities.

This report highlights that rapid urbanization and mobility and inadequate environmental management increase air pollution in AA and other major urban areas in Ethiopia. As discussed, Ethiopia faces several challenges in its urban AQM, which threatens its public health, economies, and ecosystems. This report endeavored to assess these challenges and recommend initial actions for Ethiopia and the City of AA to improve AQM. Fortunately, the Government of Ethiopia and the general public are increasingly aware of air pollution problems and are willing to change. With further research and strategic planning, the country can choose a path to balance economic growth and environmental protection and enhance AQM.

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Annex 1. List of Background Paper to this Report

No.1: An Overview of Ambient Air Quality Monitoring and Air Quality in Addis Ababa

No.2: An Overview of Institutional and Financial Arrangements for Air Quality Management in Ethiopia

No.3: Addis Ababa: Air Quality & Source Apportionment

No.4: Steering Towards Cleaner Air: Measures to Mitigate Transport Air Pollution in Addis Ababa

Annex 2. Supporting Information for the Estimation of the Health Impact of Ambient $PM_{2.5}$

The methodology and estimation of the impact of ambient $PM_{2.5}$ on health

This annex provides a description of the main methodological approaches and sources of data used to assess the health impact of ambient $PM_{2.5}$ in Addis Ababa.

(1) **Estimate the $PM_{2.5}$ exposure.** This is calculated based on the following formula:

$$\text{Population-weighted PM}_{2.5} = \frac{\sum_1^n population_i * \text{PM}_{2.5}\ concentration_i}{\sum_1^n population_i}$$

where i = number of monitoring stations; population $_i$ = population located in the proximity of the monitoring station at location i; $PM_{2.5}$ concentration $_i$ = annual average $PM_{2.5}$ concentration measured in location i; and n = number of monitoring stations.

(2) **Quantify the impacts of ambient $PM_{2.5}$ on premature mortality.** This quantification uses the following information:

- Baseline mortality data at the national level, by cause and age group:

Table A2-1. Baseline mortality data at the national level, by cause and age group

Age groups	Deaths LRI	Deaths lung	Deaths COPD	Deaths IHD	Deaths stroke	Deaths diabetes type
0-4	18,591	0	3	0	5	3
5-9	622	0	0	0	1	0
10-14	351	0	0	0	2	0
15-19	347	0	2	1	10	25
20-24	356	0	4	28	84	36
25-29	377	3	25	165	204	30
30-34	355	7	37	280	276	70
35-39	393	14	50	436	391	123
40-44	492	31	78	672	723	193
45-49	563	51	127	960	900	416
50-54	702	80	205	1.289	1.326	704
55-59	889	115	382	1.721	1.649	921
60-64	1.296	173	656	2.351	2.428	1.353
65-69	1.635	230	925	2.970	3.088	1.426
70-74	2.202	268	1.343	3.660	3.541	1.844
75-79	2.773	250	1.427	3.696	4.085	1.893
80-84	2.564	131	1.253	3.351	3.125	1.562
85-89	1.569	45	593	1.998	1.548	822
90-94	681	11	266	773	706	357
95+	249	2	53	219	195	79
All ages	**37,006**	**1,411**	**7,429**	**24,570**	**24,289**	**11,857**

Source: GBD 2019 (http://www.healthdata.org, accessed February/March 2021)

- Adjustment of the above data for Addis Ababa, based on the following: (i) the national crude death rate reported by the World Bank for Ethiopia (6.55 per 1000 people, https://data.worldbank.org/, using national statistics and other sources) compared to that used in the GBD (2019) (5.2 per 1000 people); (ii) differences in population distribution by age group in Addis Ababa compared to the population distribution at the national level, based on projections provided by the CSA (2013);[24] (iii) share of Addis Ababa's population (4.6 million in 2019, https://worldpopulationreview.com/world-cities/addis-ababa-population) in the total country's population (112.1 million in 2019, data.worldbank.org).

According to various studies, large cities often have higher mortality rates compared to those at the national level, partly due to the high demand for the higher quality of health services available in these areas (e.g., Baseera/NPC/UNFPA, 2016). Thus, many rural people travel to these cities for treatment when they have serious health conditions. When deaths occur, they are registered in these cities, resulting in higher recorded crude mortality rates. Thus, we did not adjust the baseline mortality data to reflect the crude death rate in the capital.

- Estimate the proportion of deaths attributable to $PM_{2.5}$, calculated based on specific relative risk factors which depend on the outcome, age and $PM_{2.5}$ concentration. The relative risk factors used are related to the $PM_{2.5}$ concentration of 34 $\mu g/m^3$ and can be found at http://ghdx.healthdata.org/record/ihme-data/gbd-2019-relative-risks. In addition, deaths related to low birth rate and short gestation (LBWSG) attributable to the $PM_{2.5}$ were estimated based on baseline mortality data related to LBWSG (0-27 days) and the attributable fraction specific for Addis Ababa, provided by the IHME (communication with IHME, February 2021).

(3) Quantify the impacts of ambient $PM_{2.5}$ on morbidity. This quantification uses similar steps and input sources as reported above, with reference to YLDs.

(4) Estimate the economic value of health impacts due to exposure to $PM_{2.5}$. Estimating the economic value of premature deaths is based on the VSL. To estimate the VSL for Ethiopia, we use the formula and input data suggested by the World Bank/IHME (2016).

$$VSL_{c,n} = VSL_{OECD} * \left(\frac{Y_{c,n}}{Y_{OECD}}\right)^e$$

Where: $VSL_{c,n}$ is the estimated VSL for country c in year n, VSL_{OECD} is the average base VSL in the sample of OECD countries with VSL studies (US$3.83 million), $Y_{c,n}$ is GDP per capita in country c in year n (adjusted for price inflation and converted to 2011 US dollars at PPP rates); Y_{OECD} is the average GDP per capita for the sample of OECD countries (US$37,000), and e is the income elasticity of the VSL (with a central value of 1.2 for low- and middle-income countries). This approach provides a VSL for Ethiopia in the amount of US$43,600 (2019, current prices) based on a GDP per capita of US$856 (2019, current prices).

Estimating the economic value of premature morbidity is based on the VSLY. It is derived by dividing that VSL by the expected (discounted) life years remaining for an individual at the mean age of the population studied (Robinson and Hammitt, 2018). For Ethiopia, this was estimated at US$1,800, based on an average life expectancy of 66 years (World Bank, data.worldbank.org), an average age of 24 years (estimated based on CSA data), and a discount rate of 3 percent.

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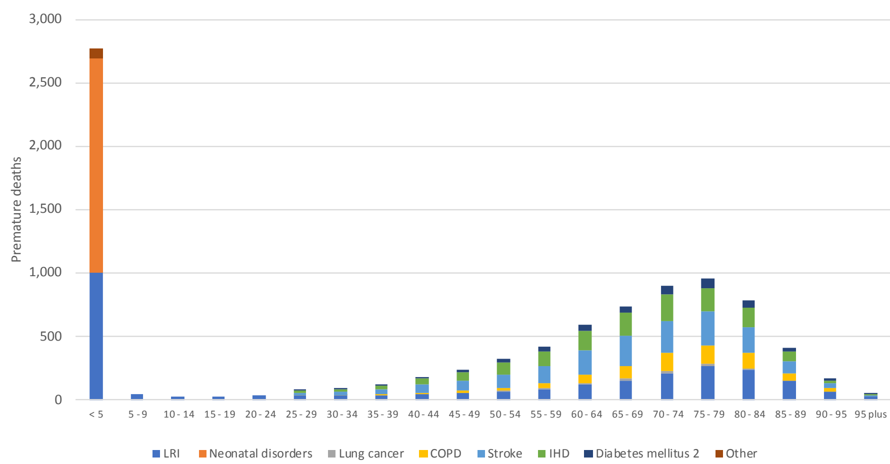
[24] For Ethiopia, the distribution of population by group age was estimated as: 14% (0-5 years), 13% (5-9 years), 12% (10-14), 11% (15-19), 10% (20-24), 9% (25-29), 7% (30-34), 6% (35-39), 5% (40-44), 4% (45-49), 3% (50-54), 2% (55-59), 2% (60-64), 1% (65-69), 1% (70-74), 1% (75-79) and 0% (80+). For Addis Ababa, the distribution of population by group age was: 10% (0-5 years), 10% (5-9 years), 7% (10-14), 6% (15-19), 8% (20-24), 10% (25-29), 12% (30-34), 11% (35-39), 8% (40-44), 6% (45-49), 4% (50-54), 3% (55-59), 2% (60-64), 2% (65-69), 1% (70-74), 1% (75-79) and 0% (80+). (CSA, 2013 – based on projections for 2017 and 2022).

Results of the Global Burden of Disease Study 2019 for Ethiopia

The GBD 2019 study estimated that ambient $PM_{2.5}$ was responsible for about 8,960 premature deaths in in Ethiopia in 2019. Overall, the study showed that the main causes of premature deaths related to ambient $PM_{2.5}$ were lower respiratory infections (30 percent of total deaths), stroke (20 percent), neonatal disorders (19 percent), ischemic heart disease (16 percent)– followed by COPD (8 percent), diabetes mellitus (5 percent), lung cancer (1 percent) and other. Two groups of age were particularly affected: elder people of 60-84 years old (44 percent), due to stroke, lower respiratory infections, and ischemic heart disease; and children under five years old (30 percent of total premature deaths), due to lower respiratory infections and neonatal disorders (Figure 2).

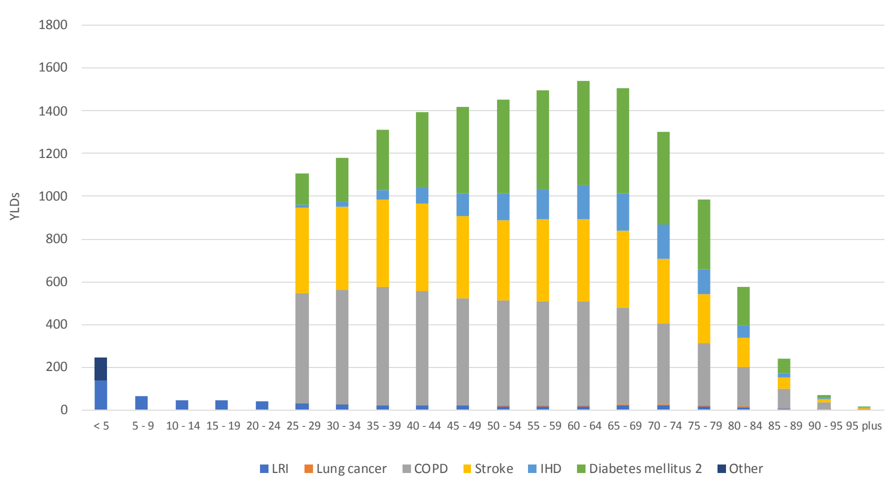
Figure A2-1. Premature deaths due to ambient $PM_{2.5}$ pollution in Ethiopia (2019)



Source: IHME (2020), http://ghdx.healthdata.org/gbd-results-tool

In addition, ambient $PM_{2.5}$ was responsible for about 16,036 YLDs in the same year. The group of 40 – 69 years was most affected by disability, concentrating about 55 percent of the total YLDs due to ambient $PM_{2.5}$ (Figure 3).

Figure A2-2. Years Lived with Disability due to ambient $PM_{2.5}$ pollution in Ethiopia



Source: IHME (2020), http://ghdx.healthdata.org/gbd-results-tool

This report is the synthesis of the key findings and recommendations of the studies carried out in FY21 under the World Bank's Advisory Services & Analytics (ASA) program "Ethiopia: Air Quality Management and Urban Mobility." The ASA aimed to assist the Government of Ethiopia in deepening the understanding of ambient AQM through analytical studies and in developing policy recommendations and an action plan for institutional strengthening and investments.

After an overview of institutional arrangements for AQM in Ethiopia and air quality monitoring in Addis Ababa, the report assesses the health impact of air pollution, valuates its economic costs, and presents the results of emission inventory and source apportionment studies in Addis Ababa. It further identifies, assesses, and prioritizes air pollution mitigation measures for the city's urban transport sector. A set of recommendations and an action plan for AQM in Ethiopia are presented at the end of the report.

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