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# Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya

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## Abstract

Air quality is a serious and worsening problem in the rapidly growing cities of sub-Saharan Africa (SSA). However, the lack of ambient monitoring data, and particularly urban roadside concentrations for particulate matter in SSA cities severely hinders our ability to describe temporal and spatial patterns of concentrations, characterize exposure–response relationships for key health outcomes, estimate disease burdens, and promote policy initiatives to address air quality. As part of a collaborative transportation planning exercise between Columbia University and the University of Nairobi, air monitoring was carried out in February 2006 in Nairobi, Kenya. The objective of the monitoring was to collect pilot data on air concentrations (PM<sub>2.5</sub> and black carbon) encountered while driving in the Nairobi metropolitan area, and to compare those data to simultaneous ‘urban background’ concentrations measured in Nairobi but away from roadways. For both the background and roadway monitoring, we used portable air sampling systems that collect integrated filter samples. Results from this pilot study found that roadway concentrations of PM<sub>2.5</sub> were approximately 20-fold higher than those from the urban background site, whereas black carbon concentrations differed by 10-fold. If confirmed by more extensive sampling, these data would underscore the need for air quality and transportation planning and management directed at mitigating roadway pollution.

**Keywords:** particulate matter, fine particles, Nairobi, outdoor air pollution, traffic, urban, black carbon, sub-Saharan Africa

## 1. Introduction

Air quality is a serious and worsening problem in the rapidly growing cities of sub-Saharan Africa (SSA), due in part to growing vehicle fleets, limited road infrastructure, road congestion, and high per-vehicle emissions. In Kenya, car imports increased 50% between 1992 and 1999 (Maina 2004), most of which were second-hand cars with poor fuel efficiency imported from Japan and United Arab Emirates (UNEP

2006). Until 2006, leaded gasoline was the predominant fuel used throughout most of SSA, rendering catalytic converters inoperable and promoting the practice of stripping catalytic converters from cars upon importation. Other urban sources of air pollution in many SSA cities include domestic charcoal and wood fires used for cooking, uncontrolled burning of waste and refuse, and a range of industrial facilities.

The World Health Organization recently released updated global air quality guidelines for particulate matter less than 10 and 2.5  $\mu\text{m}$  in diameter (PM<sub>10</sub> and PM<sub>2.5</sub> respectively) as well

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as interim target concentrations for use by developing countries in measuring progress towards the guideline concentrations (WHO 2006). For  $PM_{10}$ , the interim targets for annual average concentrations start at  $70 \mu\text{g m}^{-3}$  and extend down to the  $20 \mu\text{g m}^{-3}$  guideline. For  $PM_{2.5}$ , the first annual target is  $35 \mu\text{g m}^{-3}$ , and the guideline is  $10 \mu\text{g m}^{-3}$ . It is reasonable to ask how current ambient particulate matter concentrations in SSA cities compare with these values. Unfortunately, very little monitoring data exist upon which to base even a preliminary answer. A recent analysis of the global environmental burden of disease due to ambient PM uncovered useful air monitoring data from only three sites in all of SSA (Cohen *et al* 2005). Disease burdens for unmeasured SSA cities had to be estimated using  $PM_{10}$  concentrations derived from a regression model that was fit with data from several hundred world monitoring sites, the vast majority of which were in the developed world.

The lack of ambient monitoring data for particulate matter in SSA cities severely hinders our ability to describe temporal and spatial patterns of concentrations, to characterize exposure–response relationships for key health outcomes, to estimate disease burdens, and to promote policy initiatives to address air quality. For example, we are aware of no routine  $PM_{10}$  or  $PM_{2.5}$  monitoring anywhere in SSA other than South Africa prior to 2005. Starting in 2005, a collaboration between the US Environmental Protection Agency (EPA) and the United Nations Environment Program (UNEP) has led to the development of air monitoring networks in two SSA cities: Accra, Ghana and Dar Es Salaam, Tanzania. Emerging data from the new monitoring network in Accra suggest that annual average  $PM_{10}$  concentrations may typically be considerably higher than WHO targets and guidelines, and that exposure and disease burdens may be especially great for persons driving, working, or living near congested roadways (Nerquaye-Tetteh 2006). However, it remains unclear to what extent the increased concentrations observed near roadways were due to tailpipe emissions (mainly fine particles) versus re-suspended road dust (mainly coarse particles).

Because of the growing influence of motor vehicles in SSA cities, it is of particular interest to assess the role that roadway emissions play in causing high PM concentrations. Though previous studies have addressed regional aerosols in SSA (Maenhaut *et al* 2002, Swap *et al* 2002), little work has been aimed at measuring urban roadside particulate matter concentrations. PM concentrations on and near roadways are especially important in SSA because much transport, commerce, and other pedestrian activity takes place there. Heavy-traffic roadways may create pollution hotspots where health risks exceed those encountered more generally throughout a city, and where risks are borne mainly by the poor (Kinney and O'Neill 2006).

To begin addressing identified gaps in air quality data in SSA cities and lay a foundation for future work, a small air monitoring study focusing on  $PM_{2.5}$  concentrations was carried out in Nairobi, Kenya in February 2006. We compared  $PM_{2.5}$  concentrations on a heavy-traffic corridor with those from an urban background site less impacted by roadway emissions. We hypothesized that tailpipe emissions would

**Table 1.** Means and ranges of  $PM_{2.5}$  and black carbon concentrations at urban background and roadway sites in Nairobi, Kenya.

	Urban background	Roadway
$PM_{2.5}$ ( $\mu\text{g m}^{-3}$ )	19.9 (15.0–27.8)	414.0 (396.8–431.3)
Black carbon ( $10^5 \text{ m}^{-1}$ )	5.7 (4.4–6.7)	60.3 (53.5–67.0)
Sample size (N)	4	2

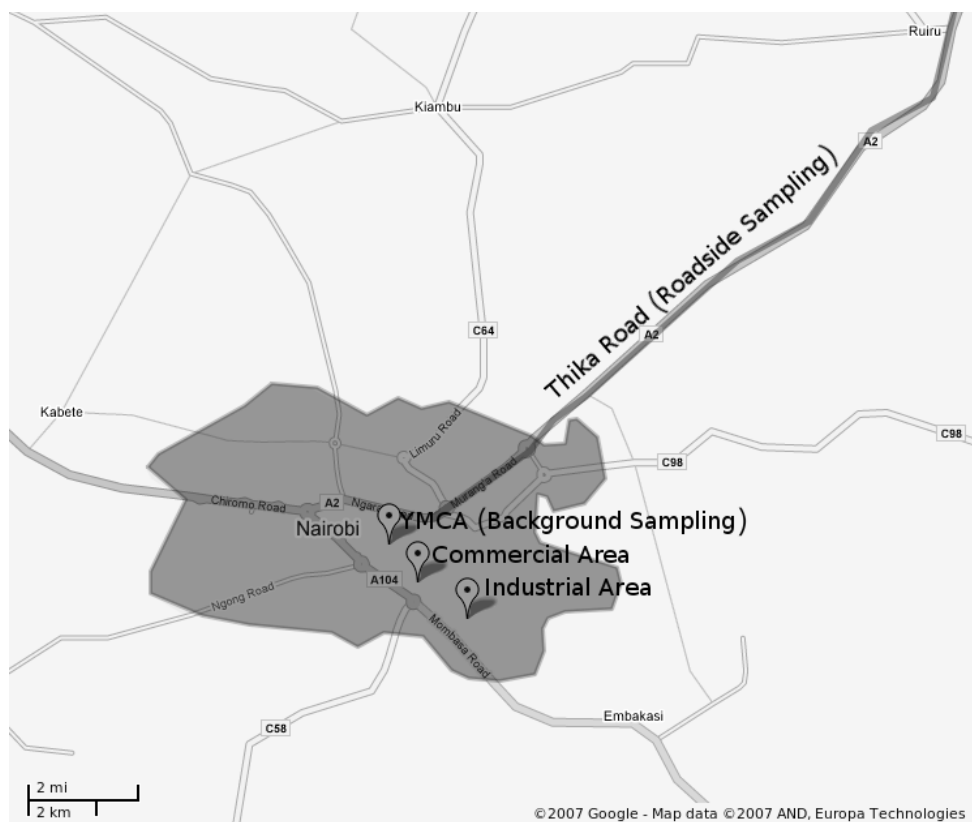
lead to substantially elevated  $PM_{2.5}$  concentrations on or near roadways.

## 2. Methods

Nairobi is the capital city of Kenya, with a population over two million people and growing. The climate in Nairobi is tropical, and meteorological conditions are reasonably stable throughout the year. However, as in much of SSA, seasonal changes in Kenya are measured by changes in precipitation rather than by changes in temperature. Rain comes mainly in two seasons, with heavy rains from March to May and lighter rains from October through November. Average temperatures in the month of February, when monitoring took place, typically range from 13 to  $28^\circ\text{C}$ .

As part of collaborative transportation planning exercise between urban planning programs at Columbia University and the University of Nairobi, a  $PM_{2.5}$  air monitoring project was carried out on four days between February 4–11, 2006. The objective of the monitoring was to collect pilot data on air concentrations encountered while driving in the Nairobi metropolitan area, and to compare those data to simultaneous ‘urban background’ concentrations measured in Nairobi but away from roadways. We were interested in developing a preliminary assessment of the range (i.e., lower and upper bounds) of concentrations that might exist in comparing transportation hot spots with other urban locations. To assess urban background concentrations, daytime 12 h integrated  $PM_{2.5}$  samples were collected from a window of the downtown YMCA. This location, more than 100 m from any roadway, was not directly influenced by local traffic. On two of the days when the background monitoring was carried out, ‘roadway’  $PM_{2.5}$  concentrations were monitored from the window of a van traveling at slow speeds between Nairobi center and the suburb of Ruiru along Thika Road, the main artery between Nairobi and Ruiru. Roadway monitoring was carried out during both the morning and afternoon commute to Ruiru, for a total of approximately 90 min each day. The geographic relationships between these monitoring locations are shown in figure 1.

For both the background and roadway monitoring, we used portable air sampling systems that collect integrated filter samples. A stainless steel cyclone (BGI Inc., Waltham, MA) was used to remove particles larger than  $2.5 \mu\text{m}$ . After the cyclone, fine particles were collected at a flow rate of  $4 \text{ l min}^{-1}$  onto a Teflon filter held in a plastic cassette, with air being drawn by a BGI personal sampling pump. The pump was powered by a rechargeable battery-pack. Flow rates were checked and recorded before and after each sampling event



**Figure 1.** Location of roadside and urban  $PM_{2.5}$  sampling monitors, Nairobi, Kenya.

using a rotameter (SKC Inc.); sample durations were recorded by a timer on the pumps.

Filters were transported to Columbia University where they were analyzed for mass ( $PM_{2.5}$ ) and black carbon (BC). Filters were pre- and post-weighed under controlled conditions to determine  $PM_{2.5}$  mass, and were then analyzed inside a class-100 flow bench for black carbon using a smoke stain reflectometer (model 43D; Diffusion Systems Ltd, London, UK). Reflectance measurements are expressed as the absorption coefficient in reciprocal meters times 100 000. Black carbon has been shown to closely correlate with elemental carbon, which is emitted in large quantities by diesel and poorly tuned petrol vehicles (Kinney *et al* 2000, Lena *et al* 2002).

### 3. Results

Urban background  $PM_{2.5}$  concentrations in Nairobi ranged between 15 and 28  $\mu g m^{-3}$ , with a mean of 20  $\mu g m^{-3}$  (table 1). Much higher levels of  $PM_{2.5}$  were found on the roadway between Nairobi and Ruiru, where concentrations ranged from 397 to 431  $\mu g m^{-3}$  (mean 414  $\mu g m^{-3}$ ). BC levels at the background site averaged  $5.7 \times 10^5 m^{-1}$  (table 1), whereas BC concentrations on the roadway were about 10-fold higher, averaging  $60 \times 10^5 m^{-1}$ . These data indicate that levels of both  $PM_{2.5}$  and BC measured in-transit far exceed

those encountered at an urban background site, with higher differentials observed for  $PM_{2.5}$  than for BC.

Because we measured  $PM_{2.5}$  concentrations in-transit, these data are most appropriately viewed as indicating possible vehicle occupant exposures during commuting. We did not measure  $PM_{2.5}$  concentrations adjacent to the roadway; however, it may be reasonable to view our in-transit data as an upper bound on such concentrations. We note that the roadway samples were collected for a total of approximately 90 min in a moving vehicle during morning and afternoon commuting, and thus covered only a portion of the 12 h daytime monitoring period at the background site, and only for two of the four background sampling days.

### 4. Discussion

Results of this pilot study suggest that concentrations of  $PM_{2.5}$  are highly elevated on roadways in Nairobi as compared with an urban background site located within Nairobi but away from roadways. Except during dust storm events,  $PM_{2.5}$  is likely to mainly reflect emissions from combustion of fossil fuels (e.g., petrol and diesel), biomass, and other organic matter. Given the pattern of concentrations we observed, it is likely that motor vehicle emissions were the dominant influence on roadway  $PM_{2.5}$ . Regionally elevated  $PM_{2.5}$  would have been captured by the urban background monitoring if present.

We were unable to locate published  $\text{PM}_{2.5}$  data in SSA cities to which our data can be compared. Also, because we used sampling durations shorter than 24 h, it is not possible to directly compare our data against air quality standards or guidelines that are defined on the basis of 24 h or annual average concentrations. However, if we assume that our data are representative of typical background and roadway exposures, we can compute a time-weighted mean 24 h average 'exposure' for a typical commuter who spends 90 min each day on the road (at  $414 \mu\text{g m}^{-3}$ ) and the rest of each day at background levels (at  $20 \mu\text{g m}^{-3}$ ), for a time-weighted average of  $44.6 \mu\text{g m}^{-3}$ . Individuals who live, work, or travel for longer periods on roadways would be expected to have higher exposure levels. This compares with  $25 \mu\text{g m}^{-3}$  and  $50 \mu\text{g m}^{-3}$  for the 24 h WHO guideline and US standard concentrations for  $\text{PM}_{2.5}$ . Further monitoring will be needed before definitive statements can be made however.

Interestingly, it appeared that roadway concentrations of  $\text{PM}_{2.5}$  were approximately 20-fold higher than those from the urban background site, whereas BC concentrations differed by 10-fold. This implies that there are other particle components such as organic carbon species that contribute significantly to elevated  $\text{PM}_{2.5}$ , or that re-suspended fine particles play a role in roadway  $\text{PM}_{2.5}$  concentrations, above and beyond the impacts of tailpipe emissions. Another Nairobi air monitoring study found sulfur, mainly emitted from vehicular emissions, as the dominant element in fine particles collected at a stationary rooftop monitoring site (Gatari *et al* 2005). With more extensive analysis of elemental species present on the filters, the relative impacts of combustion versus re-suspended dust could be assessed in future work.

With respect to the mix of vehicles in Nairobi, traffic census results obtained from the Kenya Institute for Public Policy Research and Analysis (KIPPRA) reveal that while private cars transport only 22% of Nairobi's passengers, the second-hand private vehicle fleet constitute 64% of total vehicular volume, while public vehicles (mainly small, high-emitting minivans or 'mutatus') transport 78% of Nairobi's passengers and constitute 36% of traffic volume. Specifically on Thika Road, where the monitoring was conducted, private and public vehicles each comprise approximately half (49% private and 51% public) of the total vehicular volume, yet 86% of the vehicular passengers are transported by public vehicles (KIPPRA 2006).

With respect to roadway impacts, emerging data from new  $\text{PM}_{10}$  monitoring networks in Ghana and Tanzania provide useful insights. Preliminary  $\text{PM}_{10}$  data for Accra, Ghana and Dar es Salaam, Tanzania were presented at the Better Air Quality in sub-Saharan Africa conference in Nairobi in July 2006. In Dar, all sixth-day 24 h  $\text{PM}_{10}$  concentrations from August through December 2005 at two residential sites and one commercial site were relatively consistent across sites and stable over time, ranging generally between 70 and  $120 \mu\text{g m}^{-3}$ . In contrast, concentrations at two roadside monitoring sites exhibited considerably greater temporal variability, and a much wider range of concentrations, with most days falling in the range between 100 and  $600 \mu\text{g m}^{-3}$ . In the absence of  $\text{PM}_{2.5}$  data, it is unclear to what extent the

high roadside concentrations represent vehicle fuel combustion emissions (primarily  $\text{PM}_{2.5}$ ) and what proportion represents re-suspended crustal material (primarily coarse PM). However, in light of our observations, it would be reasonable to assume that there is a mixture of the two. Similar findings were reported from the monitoring program in Accra, where concentrations at roadside monitors were considerably higher ( $100\text{--}200 \mu\text{g m}^{-3}$ ) than at the residential and commercial sites ( $30\text{--}130 \mu\text{g m}^{-3}$ ). There were several days when roadside concentrations reached as high as  $600\text{--}1200 \mu\text{g m}^{-3}$  (Nerquaye-Tetteh 2006).

Though our work and others reviewed above point to the importance of vehicular emissions in SSA cities, no studies have yet been reported that comprehensively assess the full range of important PM sources, and there is little or no descriptive data on patterns of  $\text{PM}_{2.5}$  mass concentrations across time and space. Previous literature suggests that in addition to vehicular emissions, biomass and waste burning are among the important sources of air pollution in Nairobi (Gatari *et al* 2005). Nairobi's urbanization trend will only exacerbate the concentrations of pollutants due to an increase in number of motor vehicles, amount of industrial activity and burning of wood, charcoal and refuse.

The findings of this air monitoring study support the conclusion that motor vehicles are an important source of respirable particulate matter in Nairobi. Our data imply that people who spend substantial time on or near roadways are of particular concern regarding potential human health impacts. In addition to the motorists traveling on the roadways exposed to traffic emissions, pedestrians and informal business employees are likely to be exposed to high concentrations of  $\text{PM}_{2.5}$  and black carbon pollution, due to the lack of clean transportation modes and high density of informal business along the roadways. Data from the Nairobi Urban Public Transport Survey shows that walking constitutes the most utilized mode of transport (49%) while public transportation constitutes 40% of transportation. Only 7% reported using a private vehicle for transportation (KIPPRA 2006). If confirmed by more extensive sampling, these data would underscore the need for air quality and transportation planning and management directed at mitigating roadway pollution. Policy options could include use of low-sulfur diesel fuel, catalytic emission controls, and improvements in mass transit options. Reducing PM emissions from motor vehicles would have direct health benefits for residents of Nairobi and other SSA cities, and in addition, would reduce emissions of BC, an important greenhouse pollutant (Highwood and Kinnarsley 2006).

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