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Mobile assessment of on-road air pollution and its sources along the East–West Highway in Bhutan

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HIGHLIGHTS

- There is no information regarding on- and near-road pollution levels in Bhutan.
- We did six measurement trips along a major roadway (570 km) in Bhutan.
- We measured PM_{10}, PNC and CO during all trips.
- Major sources were vehicles, unpaved roads, roadworks and roadside combustion.
- Further studies to assess health impacts of roadway pollution are required.

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ABSTRACT

Human exposures in transportation microenvironments are poorly represented by ambient stationary monitoring. A number of on-road studies using vehicle-based mobile monitoring have been conducted to address this. Most previous studies were conducted on urban roads in developed countries where the primary emission source was vehicles. Few studies have examined on-road pollution in developing countries in urban settings. Currently, no study has been conducted for roadways in rural environments where a substantial proportion of the population live. This study aimed to characterize on-road air quality on the East–West Highway (EWH) in Bhutan and identify its principal sources. We conducted six mobile measurements of PM_{10}, particle number (PN) count and CO along the entire 570 km length of the EWH. We divided the EWH into five segments, R1–R5, taking the road length between two district towns as a single road segment. The pollutant concentrations varied widely along the different road segments, with the highest concentrations for R5 compared with other road segments (PM_{10} = 149 μg/m^3, PN = 5.74×10^4 particles/cm^{-3}, CO = 0.19 ppm), which is the final segment of the road to the capital. Apart from vehicle emissions, the dominant sources were road works, unpaved roads and roadside combustion activities. Overall, the highest contributions above the background levels were made by unpaved roads for PM_{10} (6 times background), and vehicle emissions for PN and CO (5 and 15 times background, respectively). Notwithstanding the differences in instrumentation used and particle size range measured, the current study showed lower PN concentrations compared with similar on-road studies. However, concentrations were still high enough that commuters, road maintenance workers and residents living along the EWH, were potentially exposed to elevated pollutant concentrations from combustion and non-combustion sources. Future studies should focus on assessing the dispersion patterns of roadway pollutants and defining the short- and long-term health impacts of exposure in Bhutan, as well as in other developing countries with similar characteristics.

1. Introduction

Several studies have reported that air pollution levels in transportation microenvironments, such as on or near roadways and

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inside vehicles and tunnels, were higher than ambient concentrations (Hitchins et al., 2000; Zhu et al., 2002; Bae et al., 2007; Knibbs et al., 2009; Canagaratna et al., 2010; Li et al., 2013). For example, Kittelson et al. (2004) measured PN concentrations at different distances from the highway in Minnesota. They observed high on-road PN concentrations, ranging from 10^4–10^6 particles/cm^3. The concentrations were much lower at 10–20 m, and significantly lower in areas 500–700 m from the highway. Inside the tunnel, average CO, NO_x and $PM_{2.5}$ concentrations were found to be 17, 25 and 8 times higher than the background concentration in San Francisco (Kirchstetter et al., 1999). In Jakarta, CO concentrations during commuting for various transport modes were 180–700% higher than other microenvironments (Both et al., 2013). Similarly, in Lahore, Pakistan, roadside PM_{10} and $PM_{2.5}$ concentrations were 3 and 2 times higher than urban background levels (Colbeck et al., 2011). Therefore, fixed-site air quality monitoring does not adequately represent the pollution levels on and near roadways, and leads to an underestimation of exposure in these environments (Kaur et al., 2007; Apte et al., 2011).

Although time-activity surveys conducted in the United States have found that people spend only 6% of the day inside enclosed vehicles (Klepeis et al., 2001), this can account for a disproportionate fraction of exposure to air pollutants like ultrafine (<100 nm) particles (e.g. Fruin et al., 2008; Wallace and Ott, 2011). Characterizing air pollution in transport microenvironments is therefore important for understanding human exposure.

Characterization of on-road air quality is challenging, since a spatially dense network of fixed monitoring sites would be required to capture the spatial and temporal distribution of pollutant concentrations on and near the roads. This has led to the development of vehicle-based mobile sampling methods specifically aimed at quantifying on-road pollution during real-world driving (Gouriou et al., 2004; Knibbs et al., 2009). In recent years, several studies have reported using mobile platforms to quantify on-road pollution. Around the world, on-road mobile measurements have been used for both tunnel (Gouriou et al., 2004; Yao et al., 2007; Knibbs et al., 2009) and above-ground urban road studies (Kittelson et al., 2004; Westerdahl et al., 2005; Pirjola et al., 2006; Zavala et al., 2006; Yao et al., 2007; Fruin et al., 2008; Wang et al., 2009; Westerdahl et al., 2009; Guo et al., 2014). The focus of these studies ranged from the estimation of emission factors (Kittelson et al., 2004; Westerdahl et al., 2009; Guo et al., 2014) to in-vehicle exposure assessment (Gouriou et al., 2004; Zhu et al., 2008; Apte et al., 2011; Colbeck et al., 2011), quantification of non-exhaust vehicle emissions (Hussein et al., 2008; Kwak et al., 2014) and evaluation of air quality control measures (Wang et al., 2009; Westerdahl et al., 2009).

While a few of the above listed on-road studies were conducted in Asian countries, they were based on measurements along busy metropolitan roads, where traffic volume was an important factor for determining road selection (Yao et al., 2007; Wang et al., 2009; Westerdahl et al., 2009; Apte et al., 2011; Colbeck et al., 2011; Guo et al., 2014; Kwak et al., 2014). On-road studies have not been extended to major roads traversing rural areas or to include a range of geographical settings. This is important because, in addition to traffic contributions, rural areas can be affected by the long-range transport of urban pollutants, as well as local combustion sources, such as agricultural and residential wood burning in developing countries. Also, substantial numbers of people may live and work in the vicinity of both vehicle and non-vehicle sources of pollution near roads. Therefore, the contributions of both traffic and non-traffic activities to on-road pollution, as well as commuter and roadside exposure outside urban and metropolitan areas is not known.

The aim of the present study was to quantify and characterize on-road air quality for the East–West Highway (EWH) in Bhutan using a mobile platform method, in order to identify its principal sources. The primary objectives were to: (i) quantify PM_{10}, particle number (PN) count and CO, and relate these to activities along the road; and (ii) assess the contribution of different on-road and proximate sources to pollution levels.

2. Methods

2.1. Study location

Bhutan (population ~700,000) is a small eastern Himalayan nation bordered by India and China, with an area of 38,394 square kilometres. In general, the environmental conditions, as well as social characteristics, are largely comparable with the rest of the Himalayan region. In recent years, the road network in Bhutan has increased significantly, as more roads have been constructed, penetrating deeper into remote settlements, in order to enhance the local economy and the delivery of services. However, the road conditions are generally poor, with long unpaved stretches, sharp bends and steep slopes, even on the major road networks connecting different districts. As of 2013, Bhutan had a total of 67,926 registered vehicles (NSB, 2014).

The road under investigation, the EWH, is an economic lifeline for all of the eastern districts and some of the districts in central and western Bhutan. The present study covered the entire 570 km length of the EWH between Kanglung (X) in the east and Semtokha (Y), on the outskirts of the capital, Thimphu, in the west (Fig. 1). For the purposes of this study, the entire EWH was divided into five segments, R1–R5, with the road length between two district towns considered a single road segment (Fig. 1). The distance of each segment varied from 68 km (R3) to 193 km (R2). Because the road is narrow, with lots of sharp turns, a one-way journey along the EWH requires two days of travel (approximately 18 h), at an average speed of 30–40 km/h. Except for R5, which had two lanes (one lane in both directions), the rest of the EWH has only one lane, with vehicles from both directions using the same lane. The road transverses diverse geographical features: deep valleys, mountaintops, wilderness areas, rugged terrain, and village and urban settlements (SI Fig. S.1). The altitude along the EWH ranges from 600 to over 3700 m.

The four district towns (T1–T4, Fig. 1) connected by the EWH, where the road runs through the heart of the towns, vary in terms of area, degree of urbanization and resident population. Geographically, T1 is in the east, T2 and T3 are in the central and T4 in the west of the country. In terms of area and urbanization, T1 is the second largest town in eastern Bhutan and it is a gateway for commuters from the eastern districts travelling to central and western Bhutan. T2 and T3 are the largest and the smallest district towns in central Bhutan, respectively, while T4 is the second largest town in Western Bhutan. The 2005 Population and Housing Census of Bhutan showed a population of 6714 for T4, 4203 for T2, 3502 for T1 and 2695 for T3 (RGoB, 2006). While the road was wider through the towns, vehicle speed was much slower than between the towns, due to a higher traffic volume and pedestrians using the same road. There are no town specific statistics of traffic composition and flow rate, other than the total number of registered vehicles in each region, which stands at 53% in the western region, 36% in the southern region, 6% in the central region and 5% in the eastern region (NSB, 2014). Since the residents are mostly public servants and business people, most families own a car. In addition, T2 and T3 are important tourist destinations, and therefore, experience a transient increase in the number of vehicles and population, depending on the season. Also, most commuters travelling between Thimphu and eastern districts spend the night at T3.