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Estimating emissions from the Indian transport sector with on-road fleet composition and traffic volume

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HIGHLIGHTS

- Emissions of $PM_{2.5}$ and its constituents estimated from transport in India.
- Transport emissions from India in 2010, estimated as $PM_{2.5}$ – 276, BC – 144, OC – 99 Gg/y.
- Contribution to emissions of all species was primarily from on-road vehicles.
- Pre-2005 vehicles account for <50% of the fleet, but most of the emissions.
- Largest emitters are diesel ($PM_{2.5}$ and BC) and two-stroke (OC) vehicles.

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ABSTRACT

Urbanization and rising household incomes in India have led to growing transport demand, particularly during 1990–2010. Emissions from transportation have been implicated in air quality and climate effects. In this work, emissions of particulate matter ($PM_{2.5}$ or mass concentration of particles smaller than 2.5 um diameter), black carbon (BC) and organic carbon (OC), were estimated from the transport sector in India, using detailed technology divisions and regionally measured emission factors. Modes of transport addressed in this work include road transport, railways, shipping and aviation, but exclude off-road equipment like diesel machinery and tractors. For road transport, a vehicle fleet model was used, with parameters derived from vehicle sales, registration data, and surveyed age-profile. The fraction of extremely high emitting vehicles, or superemitters, which is highly uncertain, was assumed as 20%. Annual vehicle utilization estimates were based on regional surveys and user population. For railways, shipping and aviation, a top-down approach was applied, using nationally reported fuel consumption. Fuel use and emissions from on-road vehicles were disaggregated at the state level, with separate estimates for 30 cities in India. The on-road fleet was dominated by two-wheelers, followed by four-and three-wheelers, with new vehicles comprising the majority of the fleet for each vehicle type. A total of 276 (−156, 270) Gg/y $PM_{2.5}$, 144 (−99, 207) Gg/y BC, and 95 (−64, 130) Gg/y OC emissions were estimated, with over 97% contribution from on-road transport. Largest emitters were identified as heavy duty diesel vehicles for $PM_{2.5}$ and BC, but two-stroke vehicles and superemitters for OC. Old vehicles (pre-2005) contributed significantly more (~70%) emissions, while their share in the vehicle fleet was smaller (~45%). Emission estimates were sensitive to assumed superemitter fraction. Improvement of emission estimates requires on-road emission factor measurements for all vehicle types and a better understanding of vehicle utilization and superemitter fraction.

1. Introduction

Energy use in India's transport sector has increased significantly over the last few decades, with the national consumption of diesel and gasoline increasing by factors of 3.5 and 4.6, respectively, from 1996 to 2011 (MOPNG, 2012). On-road vehicles are the dominant modes of transport for both passengers (80% of passenger-km) and

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freight (60% of ton-km), with freight showing a steady increase in its share of road traffic (MOF, 2000). Emissions from transportation constitute a severe air-quality problem in developing countries, especially in urban areas (Badami, 2005; Reynolds et al., 2011). Emissions of $PM_{2.5}$ (particles less than 2.5 μm in diameter) are of particular relevance, as they are linked to several adverse effects on human health, including cardiovascular and pulmonary effects. The recent "Global Burden of Diseases, Injuries, and Risk Factors Study" (IHME, 2013) found that outdoor PM pollution is the seventh largest contributor to disease in India. Vehicular emissions lead to significantly higher-than-background $PM_{2.5}$ concentrations in transportation microenvironments, i.e., inside vehicles and on roadways (Apte et al., 2011). Urban areas in Asian countries face a higher risk of morbidity and mortality related to higher $PM_{2.5}$ intake fractions; in cities like New Delhi, Kolkata and Dhaka, they are approximately double those found in developed countries (Apte et al., 2012). Mitigating $PM_{2.5}$ emissions can also benefit the climate, as its constituents, black carbon (BC) and organic carbon (OC), affect the atmospheric-radiation balance (Grieshop et al., 2009).

In 2005, PM-emission estimates from road transport in India ranged from 201 to 274 Gg/y (Baidya and Borken-Kleefeld, 2009, and in previous estimates reviewed therein), with the spread in values attributable to differences in estimates of the activity (annual vehicle-km traveled) and in the emission factors used. Baidya and Borken-Kleefeld (2009) provided a methodology that used technology-vintage divisions by employing a fleet model, and reduced uncertainties by calibrating the annual vehicle utilization to the national fuel consumption. More recently, Yan et al. (2011) developed a framework for estimating the parameters of a fleet model using vehicle registration and age-distribution data. Regional surveys (MoUD, 2008; NSSO, 2012) allowing estimation of the annual vehicle use state-by-state and measurement of regionally-appropriate emission factors for regular and super-emitter vehicles (ARAI, 2007; Subramanian et al., 2009), were recently published.

The specific objective of this work was to develop a data-based methodology for estimating emissions from on-road, rail, air transport and shipping in India, using suitable technology divisions and regionally-appropriate emission factors, to harmonize studies with the calculation methodologies used in previous global (Borken et al., 2007; Fulton and Eads, 2004; Yan et al., 2011), national (Baidya and Borken-Kleefeld, 2009; Guttikunda and Mohan, 2014; Ramachandra and Swetmala, 2009) and urban (Guttikunda and Calori, 2013) studies. This work includes estimation of $PM_{2.5}$ emissions, as well as its constituents, BC and OC, from on-road vehicles, railways, aviation and shipping. A bottom-up method, involving the on-road vehicle populations, utilization, fuel efficiency and emission factors, was used to estimate the state-by-state emissions from road transport. A top-down method, using nationally-reported fuel consumption, served for calculating emissions from railways, aviation and shipping.

2. Methodology

2.1. General approach

The emission estimates from various transport modes used an overall framework (Eq. (1)) that considers the fuel use in the different modes, distributed among technology types, along with their corresponding emission factors.

$$E_m = \sum_{f,t} F_{m,f,t} \times EF_{m,f,t}, \quad (1)$$

where, E_m are the total emissions in Gg/y from mode m, and $F_{m,f,t}$ and $EF_{m,f,t}$ are the fuel consumption in MT/y, and emission factor in g/kg fuel burned, for fuel type f and combustion technology t within that mode. TableSI1 details the modes, fuels and technologies used in this work.

The approaches used for estimating fuel use among the transport modes are both top-down and bottom-up methods, based either on national reported fuel use in a mode or on detailed user surveys, which address the technology divisions within transport modes. The level of detail chosen was based upon the magnitude of fuel use in a given mode. Road transport, being the largest fuel user, was treated with a bottom-up method based on user surveys that addressed various technology divisions (Ramachandra and Swetmala, 2009). As railways, shipping and aviation are minor fuel users (MOPNG, 2012; Ramachandra and Swetmala, 2009) a top-down approach works well. The following sections discuss the methods used for estimating fuel use.

2.2. On-road vehicles

Recent detailed road-transport inventories (Baidya and Borken-Kleefeld, 2009; He et al., 2005; Yan et al., 2011) applied methodologies that include treatment of (a) engine-performance deterioration with vehicle age and (b) changes in vehicle technology, i.e., efficiency improvements or compliance with new regulations. A Tier-3 methodology (IPCC, 2006) was used to estimate vehicular emissions. This involved the disaggregation of fuel use into vehicle categories and vintages (Table SI1), and the use of corresponding emission factors (Table 3).

$$F_f = \sum_{c} \sum_{c} \sum_{c,v} V_{c,v} \times A_c \times M_{c,f} \quad (2)$$

where F_f is the consumption in MT/y of fuel type f, $V_{c,v}$ is the population in billions, of the vehicle category c and vintage v, A_c is the annual vehicle activity in '000 km/y, by technology division c, and $M_{c,f}$ is the mileage or fuel efficiency in g/km for a given vehicle category and fuel type.

2.2.1. Fleet model

The registered-vehicle populations differ from the number of vehicles actually on-road, since retired vehicles are not de-registered and those sold or transferred between states are re-registered (Baidya and Borken-Kleefled, 2009). Age-distributed, on-road vehicle population was estimated using a fleet model that follows recent studies (Baidya and Borken-Kleefeld, 2009; Yan et al., 2011; Zacharidis et al., 1995), using Eq. (3).

$$V_{c,a}\left(t\right) = V_{c,0}\left(t-a\right) \times Suf_{c,a} \quad (3)$$

where, $V_{c,a}(t)$ is the vehicle population in year t, of vehicle category c and age a, $V_{c,0}(t-a)$ is the population of new vehicles sold (i.e., age 0) in year $t-a$ and $Suf_{c,a}$ is the survival fraction applicable to the given vehicle category and age. For a given vehicle type, survival fraction Suf for age 'a' is calculated as the ratio of survival rate Su for age 'a' to that for age 0.

Vehicle survival was modeled with a logistic function (Eq. (4)). A data driven approach involving long-term vehicle-registration data, vehicle sales and age distribution of vehicles at a specific point in time (2004) was used to determine survival function parameters.