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Street characteristics and traffic factors determining road users' exposure to black carbon

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HIGHLIGHTS

- ► Aethalometers, an electronic diary and GPS were used to measure exposure in transport
- ► More than 1500 trips with active modes and in motorized transport are studied
- ► Exposure is higher on highways, in urban areas and during traffic peak hours.
- ► Traffic intensity is the major explanatory variable for in-vehicle BC exposure.
- ► Exposure of cyclists is largely independent of road type.

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ABSTRACT

Many studies nowadays make the effort of determining personal exposure rather than estimating exposure at the residential address only. While intra-urban air pollution can be modeled quite easily using interpolation methods, estimating exposure in transport is more challenging. The aim of this study is to investigate which factors determine black carbon (BC) concentrations in transport microenvironments. Therefore personal exposure measurements are carried out using portable aethalometers, trip diaries and GPS devices. More than 1500 trips, both by active modes and by motorized transport, are evaluated in Flanders, Belgium. GPS coordinates are assigned to road segments to allow BC concentrations to be linked with trip and road characteristics (trip duration, degree of urbanization, road type, traffic intensity, travel speed and road speed). Average BC concentrations on highways (10.7 μg/m^3) are comparable to concentrations on urban roads (9.6 μg/m^3), but levels are significantly higher than concentrations on rural roads (6.1 μg/m^3). Highways yield higher BC exposures for motorists compared to exposure on major roads and local roads. Overall BC concentrations are elevated at lower speeds (<30 km/h) and at speeds above 80 km/h, in accordance to vehicle emission functions. Driving on roads with low traffic intensities resulted in lower exposures than driving on roads with higher traffic intensities (from 5.6 μg/m^3 for roads with less than 500 veh/h, up to 12 μg/m^3 for roads with over 2500 veh/h). Traffic intensity proved to be the major explanatory variable for in-vehicle BC exposure, together with timing of the trip and urbanization. For cyclists and pedestrians the range in BC exposure is smaller and models are less predictive; for active modes exposure seems to be influenced by timing and degree of urbanization only.

1. Introduction

Black carbon (BC) is a component of both fine and coarse particulate matter (PM), though because of its small size, it is most strongly associated with the fine particle (PM2.5) fraction (Smith et al., 2009; Viidanoja et al., 2002). Incomplete combustion of wood and diesel engine exhaust are the major environmental sources of BC pollution, respectively in rural and urban areas. Health effects of PM2.5 are well documented (Brook et al., 2010) and BC is suspected to be one of the most harmful fractions responsible for health effects in exposed individuals (U.S. EPA, 2012) and is a suitable indicator for assessing the health risks of traffic related air pollution (Janssen et al., 2011). Health outcomes associated with BC include cardiovascular effects (Adar et al., 2007; McCracken et al., 2010; Wellenius et al., 2012), respiratory effects (Lin et al., 2011; Patel et al., 2010) and mortality (Gan et al., 2011). Some of these effects can be demonstrated at ambient concentrations below 1 μg/m^3 (Adar et al., 2007; McCracken et al., 2010). In addition BC contributes to global warming and has therefore gained more attention in recent years, resulting in its inclusion in several high level policy documents (UNECE, 2010; UNEP, 2011; WHO, 2012). BC is not yet regulated, but many PM2.5 reduction measures, especially in the transportation field, should lead to reductions in BC exposure as well.

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Although short in duration, exposure during transport can be important in integrated daily exposure to BC. In a personal exposure study in Belgium covering different degrees of urbanization and with a fleet dominated by diesel cars, concentrations of BC in transport have been shown to be a factor 2 to 5 higher compared to concentrations at home (Dons et al., 2011, 2012). People spend on average 6% of their time in transport, but this leads to over 20% of daily integrated exposure, and up to 30% of the inhaled dose when taking breathing rates into account (Dons et al., 2012). Travel behavior (Dhondt et al., 2012), exposure in transport (Dons et al., 2012) and factors influencing in-vehicle air pollution (Fruin et al., 2004), are thus relevant factors to consider in integrated exposure assessment.

The mass of BC particles is measured in some stations of the national air quality network using an optical technique: MAAP (multi-angle absorption photometer). This technique is based on the measurement of the absorption and scattering of particles collected on a filter tape (Petzold et al., 2005); it thus relies on the optical properties of particulate matter. Atmospheric elemental carbon (EC) is a product of incomplete combustion. The terms EC and BC are often used interchangeably; however they are defined by the different measurement method applied (Quincey et al., 2009). EC is measured based on its chemical stability using thermal techniques. Fixed measurement stations are required to check compliance with national or international legislation. Many epidemiological studies use fixed site measurements as a surrogate measure of exposure. Unfortunately, fixed stations are a poor marker for personal exposure, especially for pollutants highly variable in time and space like BC (Koutrakis et al., 2005).

According to Ott (1982) a person i is exposed to concentration c of a pollutant at a particular instant of time when person i comes into contact with the pollutant at concentration c. This definition can be decomposed into two events occurring at the same time: person i is present at location x,y,z at time *t*, and concentration c is present at location x,y,z at time *t*. Whether an individual is highly exposed, thus depends on the concentration levels the person encounters in the microenvironments visited over a day. Improving exposure estimates has been recognized as an important topic (Int Panis, 2010) and the U.S. EPA has launched several programs to achieve better indoor (SHEDS) and personal (EMI) exposure estimates (Breen et al., 2010). For static microenvironments ('places'), it is fairly straightforward to model outdoor concentrations by using an air quality model, and if desirable supplemented with an indoor air model (Burke et al., 2001). For mobile environments ('in transport') estimating concentrations is much more difficult because the location and conditions are constantly changing. One possible approach is to calculate concentrations on center points of road segments using a land use regression or dispersion model, and to intersect this polyline map of pollution with trips (Mölter et al., 2012). A similar approach uses a concentration grid, e.g. as an output of a dispersion model, and time-weights this grid with trips crossing different grid cells (Marshall et al., 2006). Other studies either ignore exposure in transport (Hatzopoulou and Miller, 2010), or use concentrations modeled (Dhondt et al., 2012) or measured (Beckx et al., 2009) at fixed stations near busy roads. Kaur et al. (2007) stated that four factors can contribute to BC levels in transport: personal factors, mode of transport factors, traffic factors and meteorological factors. The impact of personal factors (time–activity pattern, timing of trips and breathing rates) and transport mode factors are discussed in Dons et al. (2012). The aim of the current analysis is to determine traffic factors influencing exposure to BC in transport and to derive an 'in-transport exposure model'. The analysis is based on measurements of BC in Flanders, Belgium. Road and traffic data associated with a road network were linked in a GIS with geocoded BC-measurements. Relevant factors are identified and discussed. A simple set of models is constructed to estimate average BC exposure during trips based on data that is readily available from most traffic models.

2. Materials and methods

A set of mobile measurements was collected between April 2010 and July 2010, and between December 2010 and February 2011. Sixty-two volunteers measured their personal exposure to BC continuously for 7 days, while also logging GPS positions and reporting detailed time–activity patterns. All participants were living in Flanders, an urbanized region in the north of Belgium (13,521 km^2; 6,251,983 inhabitants). A description of the study set-up is given below; technical specifications of the portable devices used are summarized in Table 1.

2.1. Time–activity diary and GPS logging

A handheld computer or PDA (personal digital assistant) was equipped with the software tool PARROTS (PDA system for Activity Registration and Recording of Travel Scheduling) to facilitate the registration of activities and locations visited (Kochan et al., 2010). The GUI of PARROTS was developed as a continuous timeline, and participants had to build and annotate time blocks in a visually appealing way by using drop-down menus, check boxes, etc. The data provided had to be accurate to within 5 min. Start time and end time of each activity had to be indicated, together with the type of activity choosing from 13 predefined activity categories. PARROTS offers a choice of several transport modes: car driver, car passenger, motorcycle, bike, on foot, bus, train, light rail/metro, taxi, or 'other'. Trips during which participants used multiple modes had to be reported as one trip, but each part of the trip had to be detailed (transport mode, travel time, waiting time). During the week, every diary was repeatedly checked on consistency and completeness: no gaps or overlaps were allowed. Afterwards the time–activity data was automatically processed in SAS 9.2.

A GPS receiver was integrated in the PDA, logging positions on a one second time base. Participants had to initiate the GPS each time they started a trip, and stop it when the trip was finished to prevent unnecessary logging and to conserve the battery. Sporadically volunteers forgot to start or stop the GPS, resulting in loss of information on certain trips. Since the accuracy of the GPS signal is influenced by the number of satellites in view, GPS waypoints were cleaned such that each observation was made with at least 5 satellites: this was the case for 88.6% of all observations in transport. Rail-based modes are not explored further because of regular failure of reception of satellite signals (also observed by Bohte and Maat (2009) and Beekhuizen et al. (in press)). If GPS coordinates indicated a trip, but the diary reported an activity on a fixed location, the observation was omitted because the lack of information on e.g. transport mode.

Table 1
Technical specifications of the portable devices.

	Time base	Tech specs
GPS receiver	1-s	GPS receiver integrated in PDA (personal digital assistant, type MIO 168, weight 147 g, 4 hour run time on single battery charge if in use, 12 GPS channels)
Electronic diary	5-min	Custom designed software installed on PDA
Micro-aethalometer AE51	5-min	Flow rate 100 ml/min, weight 280 g, 24 hour run time on single battery charge, optical measurement of BC