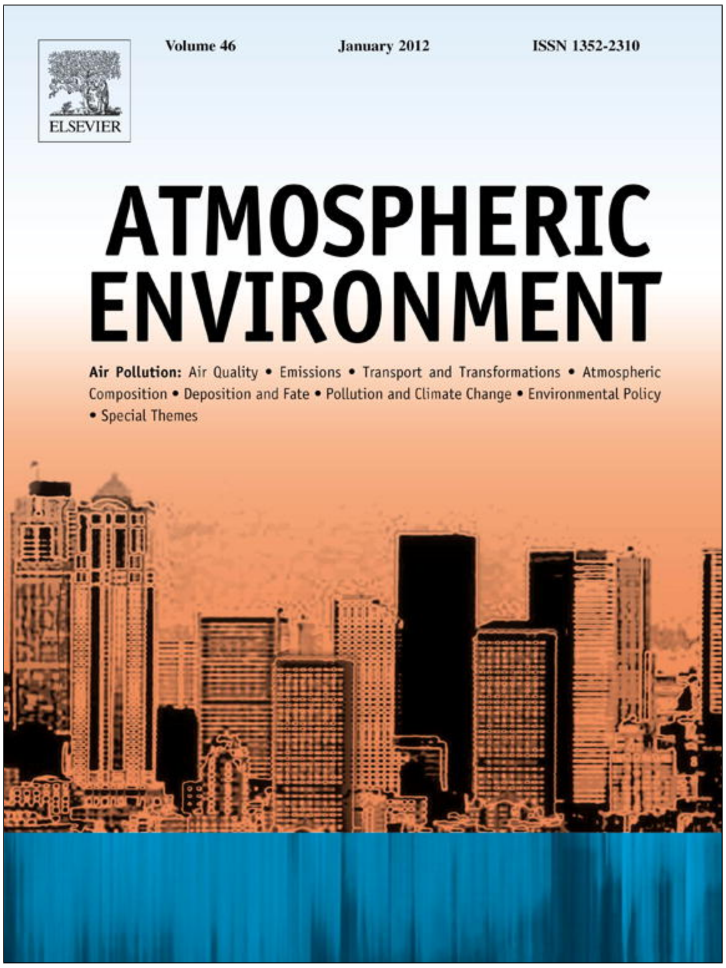

(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

Atmospheric Environment 61 (2012) 1–8

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Elemental carbon as an indicator for evaluating the impact of traffic measures on air quality and health

M.P. Keuken [a,*], S. Jonkers [a], P. Zandveld [a], M. Voogt [a], S. Elshout van den [b]

[a] *Netherlands Organisation for Applied Scientific Research, TNO, The Netherlands*
[b] *Rijnmond Environmental Agency, DCMR, The Netherlands*

HIGHLIGHTS

► EC more appropriate indicator to evaluate traffic measures than $PM_{2.5}$ and PM_{10}.
► Speed management effective measure to improve air quality and health near a motorway.
► Low emission zone for heavy duty trucks is hardly effective at inner-urban roads.

ARTICLE INFO

Article history:
Received 24 April 2012
Received in revised form
2 July 2012
Accepted 6 July 2012

Keywords:
Air quality
Traffic measures
Health impact
Elemental carbon

ABSTRACT

From 2005 to 2009 there was a 40% decrease in the number of days on which the European daily limit value of PM_{10} was exceeded at traffic locations in European cities. Yet, in many of these cities, air quality is still not in compliance with the European Air Quality Directive and additional traffic measures are planned. Our study shows that elemental carbon (EC) is a more appropriate indicator than $PM_{2.5}$ and PM_{10} for evaluating the impact of traffic measures on air quality and health. The modelled improvement in EC concentration was translated in life years gained as a result of a traffic measure. This was investigated for a speed management zone on a motorway in the city of Rotterdam. Eighty-five per cent of those living within 400 m of the motorway gained 0–1 months of life expectancy and another 15% gained 1–3 months, depending on their distance from the motorway. In addition, EC was used to evaluate a low emission zone in Amsterdam, specifically for those living along inner-urban roads with intense traffic levels. The zone only restricts heavy duty vehicles with Euro emission class 0 to 2, Euro 3 older than eight years or more recent Euro 3 without diesel particulate filter. The results indicate a population-weighted, average gain of 0.2 months in life expectancy as compared with a maximum potential gain of 2.9 months. It is concluded that on motorways speed management is an effective measure, while a low emission zone as implemented in our case study, is less effective to reduce health effects of road traffic emissions. For inner-urban roads reduction of traffic volume seems the most effective traffic measure for improving air quality and health.

1. Introduction

Exposure to elevated levels of particulate matter (PM) has been associated with health effects and loss of life expectancy (e.g. Pope III and Dockery, 2006). Many countries have responded by introducing air quality policies intended to achieve compliance with the mass-based air quality standards. An increasing number of studies show that traffic emissions are particularly associated with short-term and long-term health effects (Künzli et al., 2000; Hoek et al., 2002; WHO, 2005; Bayer-Oglesby et al., 2006; Brunekreef et al., 2009). This is especially of concern in urban areas, where large numbers of people live in the immediate vicinity of substantial road traffic emissions. Traffic-related primary PM emissions involve exhaust emissions of elemental carbon (EC) and organic compounds (OC), and non-exhaust emissions of re-suspended road dust and heavy metals from wear and braking processes (Harrison et al., 2004; Weijers et al., 2011; Keuken et al., 2012). Some studies suggest that certain specific components and size fractions of these PM emissions (rather than the mass of the PM alone) play a significant part in generating specific health effects such as cardiovascular, respiratory and neurological diseases (Atkinson et al., 2010; Cahill et al., 2011; Weuve et al., 2012). In addition, the relative risk of elemental carbon (per mass unit) has been estimated to be around ten times higher than that of $PM_{2.5}$. This

* Corresponding author.
E-mail address: menno.keuken@tno.nl (M.P. Keuken).

1352-2310/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.atmosenv.2012.07.009

represents a 6% increase in mortality per μg m^{-3} EC against 0.7% per μg m^{-3} $PM_{2.5}$ (Janssen et al., 2011). Aside from the health issues involved, EC may also be a more sensitive indicator than PM mass for evaluating the impact of traffic measures on air quality (Cyrys et al., 2003; Schauer, 2003; Jones and Harrison, 2005; Invernizzi et al., 2011; Keuken et al., 2011; Lefebvre et al., 2011). The main reason is the relatively low urban background of EC concentrations (Putaud et al., 2010), as compared with the mass of EC from road traffic exhaust emissions (Ntziachristos and Samaras, 2009). As a result, the ratios of traffic-related EC emissions and EC concentrations in urban areas are much larger than those of $PM_{2.5}$ and PM_{10}. In our study, we investigated EC as an indicator for evaluating the impact of traffic measures on air quality and health.

2. Outline of the research

In Section 3.1, we analysed increases in the number of days on which the daily limit value in the EU Air Quality Directive for PM_{10} was exceeded at traffic locations, compared to the urban background. $PM_{2.5}$, PM_{10} and EC were investigated as indicators for traffic-related PM emissions in Section 3.2. EC emission factors for road traffic in the Netherlands in 2010 are presented in Section 3.3. Based on these emission factors, the spatial distribution of annual EC concentrations in 2010 for the Dutch city of Rotterdam is modelled in Section 3.4. Section 3.5 describes a study into the effect of traffic volume, composition and congestion on EC concentrations along an inner-urban road and near a motorway. In Sections 3.6 and 3.7, EC is used in two case studies to evaluate its impact on air quality and health. The former section deals with speed management on a motorway in the Dutch city of Rotterdam, while Section 3.7 concerns a low emission zone in the city of Amsterdam. Finally, the results are discussed in Section 4.

3. Methodology and results

3.1. Increase in daily PM_{10} concentrations on urban streets in European cities in 2005–2009

The European Air Quality Directive 2008/EC/50 (EC, 2008) includes the requirement that the daily average PM_{10} concentration of 50 μg m^{-3} should not be exceeded on more than 35 days each year. In cities which have a relatively high urban background concentration of PM_{10}, it is particularly difficult to comply with this requirement in the vicinity of intense traffic (EEA, 2011). In many cities, measures have been implemented to reduce PM emissions by road traffic (http://sootfreecities.eu/). This primarily involves measures to reduce:

i. traffic volume (e.g. stimulating public transport)
ii. traffic emissions (e.g. low emission zones; speed management)
iii. the population's exposure (e.g. road tunnels in urban areas)

We analysed the effectiveness of these measures by comparing exceedances of the daily PM_{10} limit values at traffic locations and urban background in various European cities in 2005 and 2009. The results are presented in Fig. 1.

The linear regression coefficient of 0.6 in Fig. 1 indicates that, for most cities, the *increment* in number of days exceeding 50 μg PM_{10} per m^3 at traffic locations as compared to the urban background was almost half in 2009 as compared to 2005. This suggests that traffic measures (at least in the streets with monitoring stations) for most cities have been effective to reduce PM_{10} emissions by road traffic. The cities of Graz, Paris, London, and Milan deviate from the general trend. In Graz, Paris, and Milan the increases in 2009 were larger than those seen in 2005, while in London the increase has fallen below the overall European trend. This suggests that in the former cities, traffic measures were less effective, while in London these measures were more effective in controlling PM_{10} levels. However, more detailed studies are required to assess the causes for the deviation by these cities.

Despite a generally declining trend in the number of days on which PM_{10} concentrations exceeded 50 μg m^{-3}, many cities are still not in compliance with the European Air Quality Directive in particular at traffic locations (EEA, 2011). In addition to measures addressing residential and industrial emissions to reduce the urban background, further traffic measures would therefore seem to be required. PM_{10} is the statutory indicator for evaluating the effectiveness of such measures. In view of the elevated health effects near intense traffic in particular (see: Section 1) it might be relevant to include other PM characteristics in this evaluation. Potential candidates in this regard are particle number concentration, $PM_{2.5}$

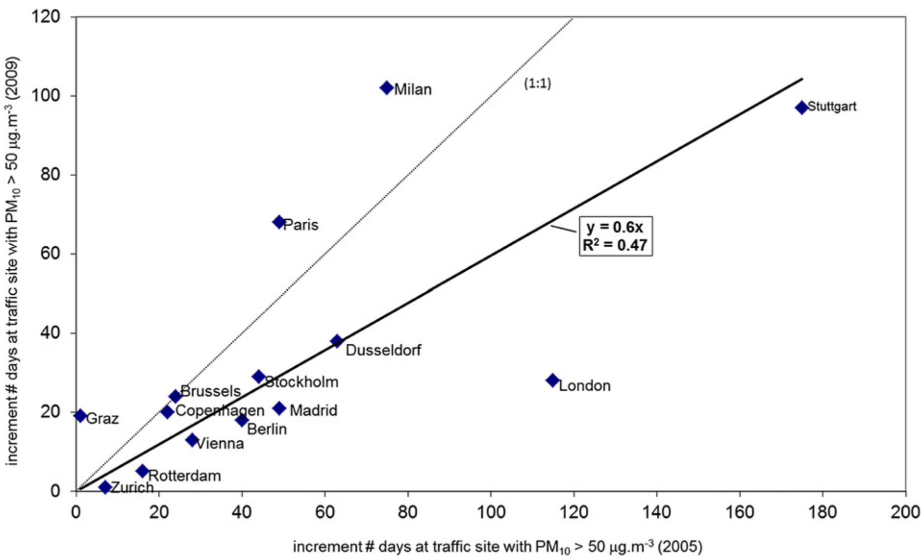

Fig. 1. Increase in the number of days withPM$_{10}$ concentrations exceeding the daily PM$_{10}$ limit value at a street location as compared to the urban background in various European cities in the years 2005 and 2009. (source: http://www.eea.europa.eu/themes/air/airbase).

and the mass of EC/OC as indicators of exhaust emissions (Keuken et al., 2012), or heavy metals as indicators of brake-wear emissions (Gietl et al., 2010). Our study focuses on the use of EC to assess the impact of traffic measures on air quality.

3.2. Urban-rural and street-urban increases in EC, $PM_{2.5}$ and PM_{10} in Europe

In this section, EC, $PM_{2.5}$ and PM_{10} are compared as indicators of PM emissions by road traffic. This comparison is based on results from a study by Putaud et al. (2010) into the chemical composition of PM across Europe. The data for EC has been expanded by measurements taken in the context of "TRANSPHORM" (www.transphorm.eu) a current European research project into transport-related PM. The additional data relate to average annual EC concentrations in the cities of Barcelona (Spain), Munich (Germany), Oslo (Norway) and Rotterdam/Amsterdam (the Netherlands). Based on these data, the increases of average annual concentrations for EC, $PM_{2.5}$ and PM_{10} have been determined for urban versus rural sites and for street versus urban sites. The results for central and eastern Europe, north-western Europe and southern Europe are presented in Fig. 2.

The results in Fig. 2 show that the ratios of average annual EC concentrations across Europe are between 1.5 and 2.7, for $PM_{2.5}$ they range from 1.1 to 1.3, while the PM_{10} ratios are between 1.2 and 1.5. In addition, the EC ratios for street-urban locations are larger than these ratios for urban-rural locations. It is concluded from these findings that across Europe, EC is a more sensitive indicator of the mass of exhaust emissions by road traffic than either $PM_{2.5}$ or PM_{10}. In the next section, EC emissions by road traffic are quantified using emissions factors for road traffic in the Netherlands.

3.3. Emission factors of EC for road traffic in the Netherlands

Since 1992, exhaust emissions in Europe have been regulated by emission limit values in accordance to "Euro classes": Euro 1 (1992), Euro 2 (1996), Euro 3 (2000), Euro 4 (2005), Euro 5 (2009–11) and Euro 6 (2014) (EC, 2007). The exhaust emissions of new vehicles must comply with particular Euro class emission limits for the year in which these vehicles entered the European car fleet. A vehicle's actual exhaust emissions (in mass per km, for a given pollutant) are determined by a combination of on-road measurements and dynamometer driving cycles that simulate urban, non-urban, and motorway traffic (Ntziachristos and Samaras, 2009). In the Netherlands, emission data are collected annually for a limited number of vehicles to derive *annual* updates of road traffic emission factors in the Netherlands (PBL, 2008). These emission factors take into account the various Euro classes present in the car fleet in the Netherlands in a particular year. This concerns four vehicle categories (L1–L4), namely passenger cars (L1), light duty vehicles with a weight under 3.5 ton (L2), heavy duty vehicles with a weight over 3.5 ton (L3) and buses (L4).

There are no emission limits for EC relating to the various Euro classes and consequently no EC emission factors are routinely determined in the annual update in the Netherlands. However, the fraction of EC in exhaust PM has been derived from dynamometer testing (Ntziachristos and Samaras, 2009). The data show that the EC fraction in exhaust PM is relatively constant for different vehicle categories and fuel types: 20% for petrol-fuelled L1, 80% for diesel-fuelled L1 and L2, and 70% for L3 and L4. EC emission factors for road traffic in the Netherlands have been estimated from exhaust-PM emission factors on the basis of these fractions. The results for 2010 are presented in Table 1.

Speed management in the Netherlands means that the maximum speed limit on a motorway is enforced by surveillance cameras and automatic fining in case of exceedances (Keuken et al., 2010). Strict enforcement of the maximum speed results in less stop-and-go traffic and improves free flowing traffic, which results in lower exhaust emissions (Zhang et al., 2011). This is further elaborated in Section 3.6. The emission factors in Table 1 are applied in Sections 3.4–3.7 to evaluate the impact on air quality of various traffic measures in the Netherlands.

3.4. EC and $PM_{2.5}$ as indicators for road traffic emissions in the city of Rotterdam

The spatial distribution of the average annual concentrations of EC and $PM_{2.5}$ in 2010 in the city of Rotterdam has been modelled by the URBIS model (Beelen et al., 2010). This model combines a linear source model for dispersion of traffic emissions near motorways and a street canyon model for dispersion of traffic emissions along

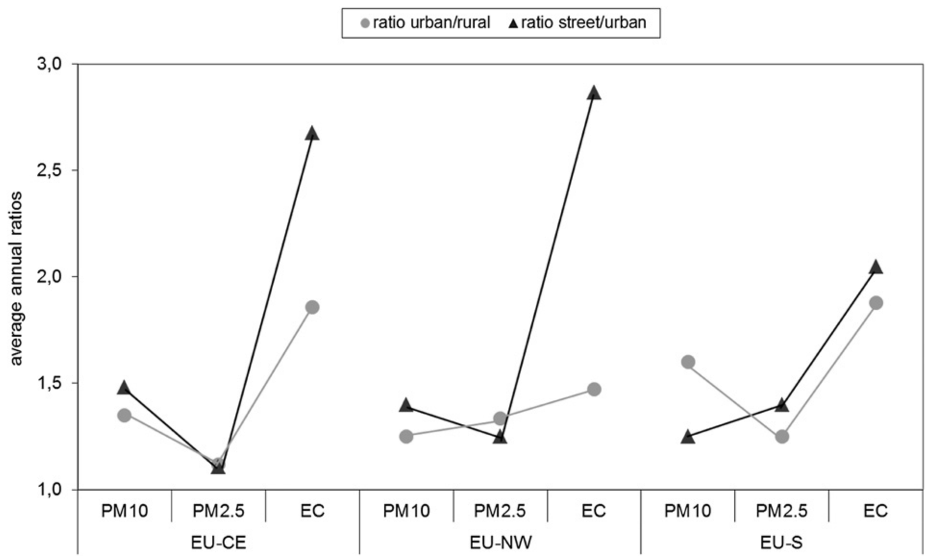

Fig. 2. Ratios of average annual concentrations at urban/rural locations and at street/urban locations for PM_{10}, $PM_{2.5}$ and EC in central-eastern Europe ("EU-CE"), north-western Europe ("EU-NW") and southern Europe ("EU-S") (source: Putaud et al., 2010 and www.transphorm.eu).

Table 1
EC emission factors (mg km^{-1}) in exhaust emissions of road traffic (L1: passenger cars, L2: light duty vehicles, L3: heavy duty vehicles and L4: buses) on urban roads and motorways in the Netherlands in 2010.

	EC emission factors (mg km^{-1})			
	L1	L2	L3	L4
Congested[a] urban road	21	141 (70)[d]	220 (108)[d]	63
Normal[b] urban road	15.3	78 (39)[d]	120 (60)[d]	40
Free-flowing[c] urban road	14.8	48 (24)[d]	80 (37)[d]	28
Congested motorway	16.9	107	181	
80 km h^{-1} (speed management)	12.3	35	46	
80 km h^{-1} (speed limit)	15.1	35	46	
100 km h^{-1} (speed limit)	17.8	35	46	
120 km h^{-1} (speed limit)	19.5	35	46	

[a] Average speed less than 15 km h^{-1}.
[b] Average speed 15–20 km h^{-1}.
[c] Average speed 30–45 km h^{-1}.
[d] Low emission zone (see: Section 3.7).

inner-urban roads. The urban background levels of EC and $PM_{2.5}$ have been established on a 1*1 km^2 spatial grid, on the basis of modelling and measurements in the Regional and National Air Quality Monitoring Network (Velders et al., 2011). Actual traffic data (traffic volume, composition, speed and congestion), meteorological parameters (wind speed and direction) and emission factors were used as input for the URBIS model. The spatial resolution of the output from the model is a 10*10 m^2 grid up to 300 m from the housing façade along inner-urban roads *and* up to 500 m near motorways. Cross-sections of the spatial distribution of the average annual concentrations of $PM_{2.5}$ and EC in the city of Rotterdam in the year 2010 are shown in Fig. 3A and B.

Fig. 3B shows elevated EC concentrations up to around 400 m on both sides of the motorway and on a number of inner-urban roads, while $PM_{2.5}$ concentrations are hardly increased above the urban background. The results for PM_{10} are not shown, but are similar to those for $PM_{2.5}$. As discussed in Section 3.2, Fig. 3B shows that EC is a more sensitive indicator of traffic emissions than $PM_{2.5}$ (and PM_{10}).

EC is used in the following sections as an indicator of the effect of traffic measures on air quality and health, in particular for reduction of the traffic volume on an inner-urban road and a motorway (section 3.5), the introduction of an 80 km h^{-1} speed management zone on a motorway (Section 3.6) and establishment of a low emission zone (Section 3.7).

3.5. EC as indicator of the effect of measures to reduce the traffic volume on an inner-urban road and a motorway

The most effective way of limiting traffic emissions is to reduce the volume of road traffic. This measure is difficult to implement in urban areas, for various reasons. However, traffic volumes are lower on Saturdays and Sundays when compared with average working days, and this difference can be used to estimate the effect of reduced traffic volume on air quality. At the urban motorway A15 (see: Fig. 3A) in 2010, the average traffic volume (# of vehicles per 24-h) on an average working day, Saturday and Sunday was 115 000 (±7%), 72 000 (±4%) and 60 000 (±6%), respectively. At the inner-urban road Pleinweg (see: Fig. 3A), the traffic volume on these days was 31 000 (±4%), 24 000 (±10%) and 21 000 (±9%), respectively. Pleinweg is a typical street canyon with a width of 20 m and buildings at both sides with a height of 15 m. In addition, the traffic composition on Sundays is different from that on other days: in particular, there are fewer heavy duty trucks. The traffic volume and composition on Saturdays, Sundays and working days have been used to evaluate the *potential* effect of measures to reduce the traffic volume. This evaluation has been performed for an inner-urban road ("Pleinweg" in Fig. 3A) and a motorway ("A15" in Fig. 3A) in the city of Rotterdam. The average annual EC emissions were calculated from the traffic data and the EC emission factors given in Table 1, and compared with the EC concentrations in 2010 at these locations.

Average daily EC concentrations in 2010 were measured in Rotterdam at an urban background location ("Zwartewaalsestraat" in Fig. 3A), at the inner-urban road Pleinweg and near the A15 motorway (www.dcmr.nl). These measurements were performed with multi-angle absorption photometers, the MAAP model 5012 (Thermoscience). The MAAP overestimates EC concentrations by the order of 25% (Chow et al., 2009) and consequently the results have been corrected for this.

The differences in daily EC concentrations between the traffic locations and the urban background provide daily *increases* of EC for both traffic locations. These data have been used to determine average annual increases of EC on an average working day, a Saturday and a Sunday for both traffic locations. The results are shown in Fig. 4.

Fig. 4 indicates a linear relation between traffic emissions and the increase of EC concentrations at both traffic locations. The lower emissions at the weekend correspond to lower increases of EC concentrations. Although EC emissions on the motorway are higher by a factor 3–5, the EC increases at both locations are quite similar on Sunday, Saturday and an average working day. This is due to the limited dispersion and dilution of traffic emissions at the Pleinweg which is a street canyon when compared with the motorway A15 with three driving lanes in both directions and no high buildings near the motorway. The different slopes of the linear regression curves of Fig. 4 reflect these differences in dilution and dispersion of traffic emissions at both traffic locations. The variability in the increase of the EC concentrations shown in Fig. 4 is quite high. This is attributed to the variability of meteorological parameters such as wind speed and wind direction, which directly affects the dispersion and dilution of traffic emissions and hence the increase in EC concentrations near road traffic locations. On the other hand, the variability in EC emissions is quite low; this reflects the limited variability in traffic volume, composition and congestion on a particular day.

Apart from traffic volume, traffic composition and congestion are important factors controlling EC emissions. For example in Table 1, the emission factors for light duty (L2) and heavy duty (L3) vehicles are a factor five and a factor ten higher respectively than for passenger cars (L1). Furthermore, emission factors for free-flowing L2 and L3 traffic are a factor two to three lower than for congested traffic, while the traffic flow hardly affects EC emissions from L1 traffic. The contribution of the vehicle categories L1, L2 and L3 to the total number of vehicles and the corresponding emissions of EC on the inner-urban road and the A15 motorway are presented in Table 2.

Table 2 shows that EC emissions are dominated by passenger cars (L1) both on the inner-urban road and the motorway, with the exception of working days on the motorway when heavy duty vehicles (L3) contribute up to 34% of the EC emissions. The differences in emission factors for L1, L2 and L3 vehicles given in Table 1 mean that the effectiveness of measures in reducing EC emissions is different on inner-urban roads and motorways. On inner-urban roads, emission control of *passenger cars* are likely to be most effective. The effect of the introduction of a low-emission zone in Amsterdam will be discussed in Section 3.7. Speed management with strict enforcement which actually results in less congested traffic is more effective on motorways, in particular due to lower emissions from heavy duty trucks (see: emission factor L3 "congested motorway" versus "motorway with 80 km h^{-1} speed

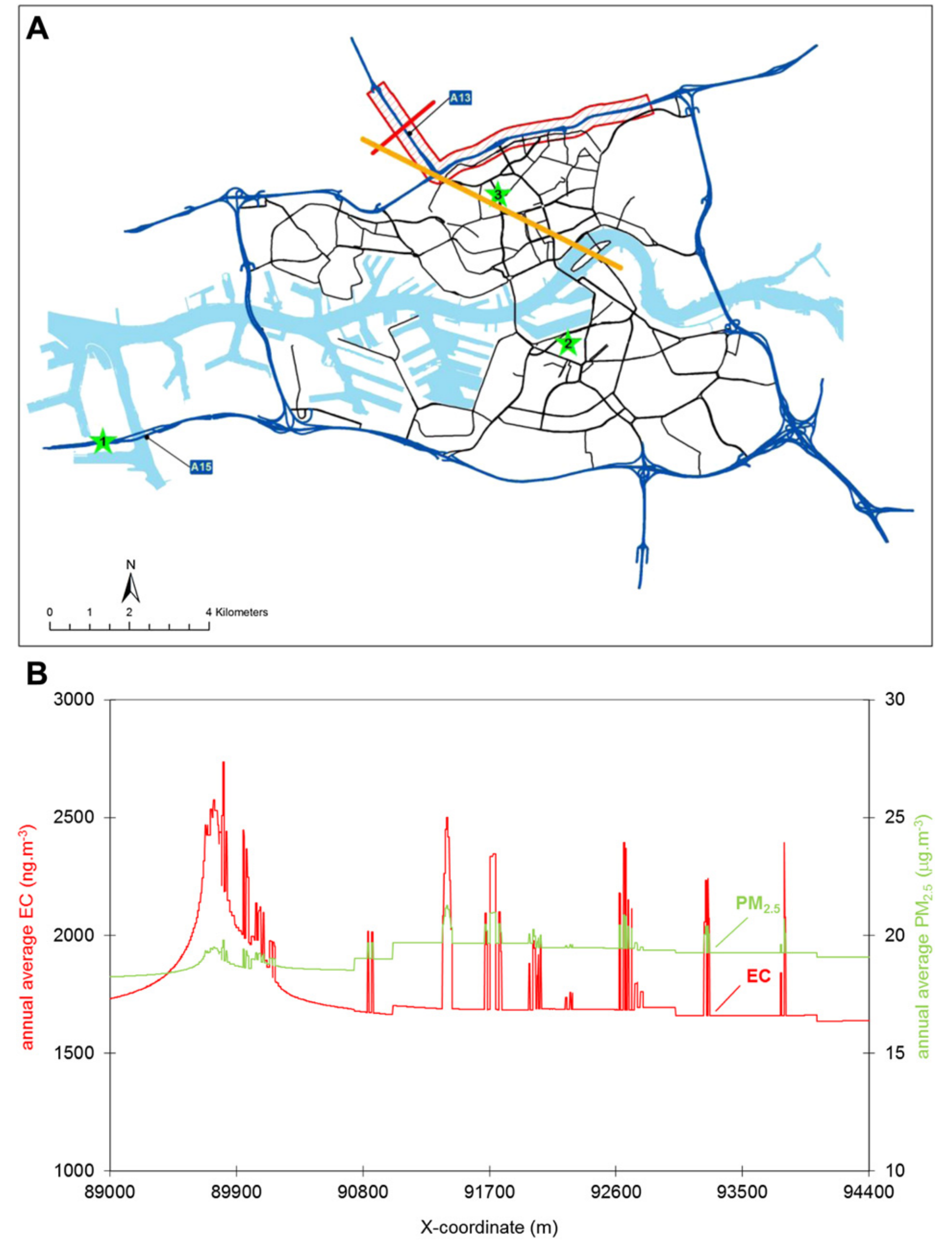

Fig. 3. A: A cross-section in yellow from northwest to southeast over the road network in the city of Rotterdam with motorways in dark blue around the city centre and inner-urban roads with more than 7500 vehicles per 24 h in black. Also indicated is the "80 km h^{-1} speed management zone" with a cross-section over the A13 motorway in red and three monitoring locations in green: "A15" (1: motorway), "Zwartewaalsestraat" (2: urban background) and "Pleinweg" (3: inner-urban road). In addition, the river "Nieuwe Maas" and the harbour area are shown in light blue. B: Annual average EC (on the left *Y*-axis in ng m^{-3}) and $PM_{2.5}$ (on the right *Y*-axis in µg m^{-3}) along the cross-section in yellow in Fig. 3A over the road network in the city of Rotterdam.

management" in Table 1). This will be discussed in greater detail in the next section 3.6.

3.6. The impact of speed management on the A13 motorway in Rotterdam on EC-related air quality and health

Road authorities in various countries such as Spain, Switzerland, the Netherlands and Belgium have used speed management to improve air quality near motorways (Keller et al., 2008; Gonçalves et al., 2008; Dijkema et al., 2008; Lefebvre et al., 2011). Speed management enhances the free flow of traffic, leading to lower exhaust emissions than in congested traffic (Zhang et al., 2011). An 80 km h^{-1} speed limit with trajectory control was introduced on the A13 motorway in Rotterdam (see Fig. 2A) in 2005. This motorway carries on average 130 000 vehicles per day, about 10% of which are heavy duty traffic. Speed management reduced the traffic emissions on the A13 by 30% for NO_x and 8% for PM_{10} (Keuken et al., 2010). As a result, the average annual PM_{10} concentration within 50 m of the motorway fell by 0.5 µg PM_{10} per m^3. This effect is regarded as negligible, however, in view of the average annual background concentration of 30 µg PM_{10} per m^3 in Rotterdam.

We therefore investigated EC as a more suitable indicator of the impact of speed management on air quality. The dispersion of EC emissions was modelled near the motorway A13 in 2010 with a line-source model (see Section 3.4). The input data were the actual meteorology, an average annual urban background concentration of 1600 ng EC per m^3, the actual road traffic volume and

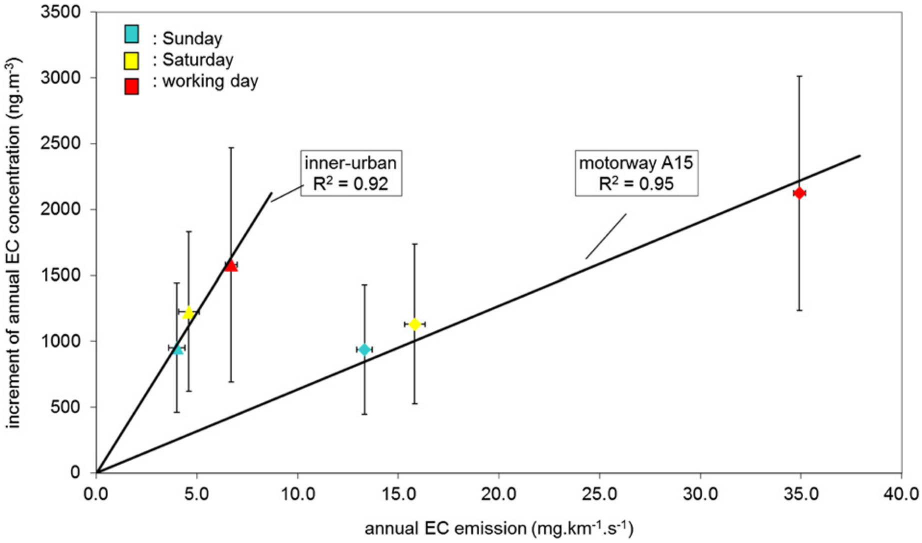

Fig. 4. Average annual road traffic emissions of EC (mg km^{-1} s^{-1}) and average annual increases of EC concentrations (ng m^{-3}), including standard deviation on Saturday, Sunday and an average working day at an inner-urban road (Pleinweg) and a motorway (A15) in the city of Rotterdam (2010). The locations are indicated on Fig. 3A.

composition and the EC emission factors given in Table 1. The current situation (80 km h^{-1} speed management) was compared with the previous situation (100 km h^{-1} speed limit with 25% congestion) but with current traffic volume and composition. The congestion in the current speed management zone was varied between 0% (corresponding to “maximum” effect of speed management) and 25% (“minimum” effect of speed management). The average annual EC concentration as a function of the distance from the road axis was calculated for these three situations. The location of the cross-section for these concentration profiles is indicated in Fig. 3A as a red line in the speed management zone perpendicular to the A13 motorway. The resulting three concentration profiles are presented in Fig. 5.

Fig. 5 shows that both lowering the speed limit from 100 to 80 km h^{-1} and lowering the congestion from 25% to 0% lead to a drop in annual EC concentrations on both sides of the motorway. A health impact assessment (HIA) has been performed for the population (8500) living up to 400 m from the speed management zone on the A13. We applied a mortality impact of 3.5 months of life expectancy gained (or lost) due to a decrease (or increase) in lifetime exposure to EC of 500 ng EC per m^3 (Janssen et al., 2011; Keuken et al., 2010). Depending on the distance from the motorway, the effect of the speed management zone on the annual EC concentrations was in the range 50–100 ng EC per m^3 (“minimum” effect) and 100–200 ng EC per m^3 (“maximum” effect) (see Fig. 5). The related gain in life expectancy due to speed management varied from 0–1 month for 8500 people (assuming the minimum effect) to 0–1 month for 7000 people and 1–3 months for 1500 people (assuming the maximum effect).

Table 2
Traffic composition (%) and contribution to EC emissions (%) for vehicle categories L1, L2 and L3 at an inner-urban road and the A15 motorway in Rotterdam (2010).

	Traffic composition (%)/ EC emissions (%)		
	L1	L2	L3
Inner-urban road			
Working day	93/75	6/20	1/5
Saturday	96/85	4/15	0/0
Sunday	97/89	3/11	0/0
A15 Motorway			
Working day	82/55	6/11	12/34
Saturday	94/87	4/7	2/6
Sunday	96/93	3/5	1/2

3.7. The impact of a low EC emission zone on air quality and health in Amsterdam

Low emission zones have been established in seventy cities across eight European countries in order to improve the air quality in urban areas (EEA, 2009). The volume of highly polluting traffic in these zones is reduced to improve air quality. A study in Milan demonstrated that a car-free zone hardly reduced PM_{10} levels but had a significant effect on EC concentrations (Invernizzi et al., 2011).

A low emission zone with an area of around 20 km^2 and a population of around 250 000 has been in operation in Amsterdam since 2008. No heavy duty vehicles (L3) with Euro emission class 0 to 2, Euro 3 older than eight years or more recent Euro 3 without diesel particulate filter are allowed in this zone. The zone is surveyed by cameras to ensure strict enforcement. As a result, the annual average PM_{10} in streets with more than 7500 vehicles per 24 h in the zone has been reduced by 0.02–0.08 μg m^{-3} (Agentschap NL, 2010).

We modelled the effect of the low emission zone in Amsterdam on EC concentrations and health effects with specific EC emission factors determined for L3 in low emission zones in the Netherlands (www.rivm.nl). Actual traffic and meteorological data were used as input for a street-canyon model (Beelen et al., 2010). The model was run once with the regular emission factors and once with the specific EC emission factors for L3 vehicles (see: Table 1), for streets with more than 7500 vehicles per 24 h. This covers more than 80% of the traffic volume and about 5% of the population living in the low emission zone. The increase in EC concentrations due to road traffic in these streets was in the range from 50 to 1450 ng m^3. The introduction of the low emission zone led to a reduction in the average population-weighted EC concentration of 25 ng EC per m^3.

A health impact assessment was performed, assuming a decrease in life expectancy of 3.5 months due to lifetime exposure to each 500 ng EC per m^3 (see Section 3.6). For the population living along inner-urban roads with intense traffic, this results in a population-weighted average decrease in life expectancy due to traffic-related EC emissions of 2.9 months, with a range of 0.3–10 months. It follows that a car-free zone potentially may lead to

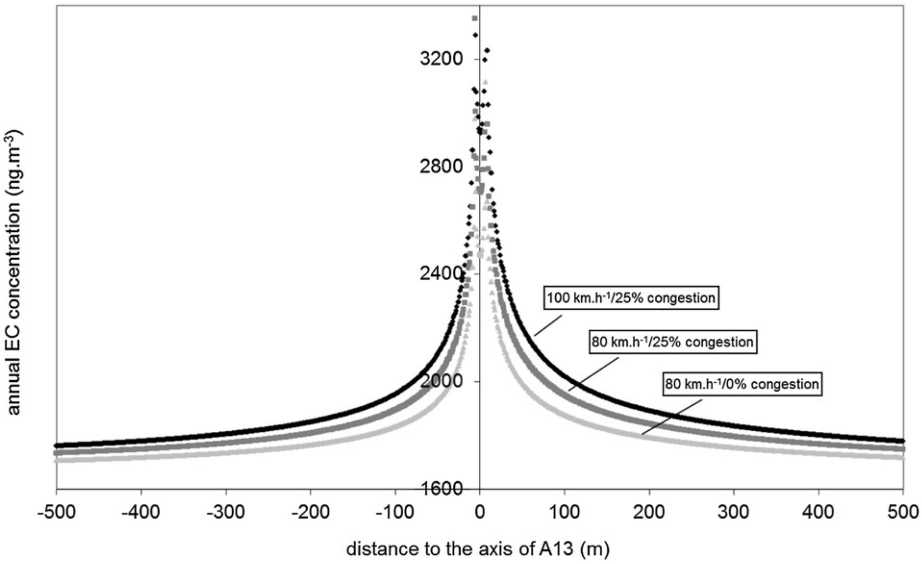

Fig. 5. Average annual EC concentration (ng m^{-3}) as function of the distance from the axis of the A13 motorway in Rotterdam (2010) for "speed limit of 100 km h^{-1} with 25% congestion" "speed management at 80 km h^{-1} with 25% congestion" and "speed management at 80 km h^{-1} with 0% congestion".

a gain in life expectancy of 2.9 months (and even more if the impact of noise on life expectancy is considered). The actual population-weighted average gain in life expectancy due to introduction of the low emission zone in Amsterdam was 0.2 months. This is almost negligible compared to the potential gain of 2.9 months. This might have been expected since L3 vehicles in the low emission zone only account in the order of 1% of the traffic volume and 5% of the EC emissions (see: Table 2).

4. Discussion and conclusion

As indicated in Section 3.1, the increase in the number of days at which the daily limiting value of PM_{10} at traffic locations in European cities has been exceeded as compared with the urban background, decreased by 40% between 2005 and 2009. It was suggested that the deviations from this general trend in Graz, Paris, Milan and London provide evidence for the effectiveness of traffic measures. It was noted, however, that the data in Fig. 1 were based on only two monitoring stations per city. Hence, the monitoring results at the limited number of monitoring points may not representative for the city as a whole. While the data in Fig. 1 may thus reflect a general trend in air quality near intense traffic in European cities, more detailed research is needed to draw conclusions on the effectiveness of traffic measures in specific cities.

It was concluded from the ratios of average annual concentrations of EC, $PM_{2.5}$ and PM_{10} in traffic and at urban and regional locations across Europe that EC is a sensitive indicator of the effect of exhaust emissions by road traffic. In addition, the mortality impact of lifelong exposure is a factor ten higher per unit mass of EC than for PM. This makes EC a more sensitive indicator of the health impact of traffic measures than $PM_{2.5}$ or PM_{10}. It is noted that the health effects attributed to EC and PM should not be added in order to avoid double counting. It has further been noted that the health impact of EC is likely to be indirect, as EC particles act as carriers for toxic organic compounds (OC) causing health effects (WHO, 2012). EC is therefore regarded a proxy for the mass of exhaust emissions and associated health effects.

The modelled and measured contribution of traffic emissions to EC concentrations have a linear relation on different weekdays in a street canyon and near a motorway. This shows that the derived EC emission factors provide an adequate basis for modelling the impact of traffic measures on air quality. The residual mass in exhaust emissions is represented by organic compounds (OC), which are less appropriate as indicator than EC due their relatively high background concentrations compared with EC (Keuken et al., 2012).

Traffic volume, composition and congestion are important factors controlling EC emissions. It was concluded from the study in Rotterdam that speed management is particularly effective at reducing EC emissions on working days on a motorway. The higher the proportion of heavy duty vehicles and the higher the ratio of free-flowing to congested traffic after speed management compared to before, the more effective speed management is at improving the air quality near a motorway. It was concluded from the study in Amsterdam that the low emission zone for heavy duty vehicles makes an almost negligible contribution to reducing EC emission. The main reason for this is the low proportion of highly polluting L3 vehicles, which contribute less than 5% of the total EC emission from traffic. Reducing the overall traffic volume is likely to be the only effective measure available at present for reducing the health impact on the population living along inner-urban roads with intense traffic.

Acknowledgements

This work was supported by the Netherlands Ministry of Infrastructure and Environment and the 7th European Framework project TRANSPHORM (ENV.2009.1.2.2.1 – Transport related air pollution and health impacts).

References

Agentschap NL, 2010. Effect Study of Low Emission Zones in the Netherlands (In Dutch). www.milieuzones.nl/publicaties/Effectstudie_2010.pdf.

Atkinson, R.W., Fuller, G.W., Anderson, H.R., Harrison, R.M., Armstrong, B., 2010. Urban ambient particle metrics and health: a time-series analysis. Epidemiology 21 (4), 501–511.

Bayer-Oglesby, L., Schindler, C., Hazenkamp-von Arx, M.E., Braun-Fahrlander, C., Keidel, D., Rapp, R., 2006. Living near main streets and respiratory symptoms in adults; the Schwiss Cohort study on air pollution and lung diseases in adults. American Journal of Epidemiology 164, 1190–1198.

Beelen, R., Voogt, M., Duyzer, J., Zandveld, P., Hoek, G., 2010. Comparison of the performance of land use regression modelling and dispersion modelling in estimating small-scale variations in long-term air pollution concentrations in a Dutch urban area. Atmospheric Environment 44, 4614–4621.

Brunekreef, B., Beelen, R., Hoek, G., Schouten, L., Bausch-Goldbohm, S., Fischer, P., Armstrong, B., Hughes, E., Jerrett, M., van den Brandt, P., 2009. Effects of Long-term Exposure to Traffic-related Air Pollution on Respiratory and Cardiovascular Mortality in the Netherlands: the NLCS-AIR Study. In: HEI Research Report 139. Health Effects Institute, Boston, MA (USA).

Cahill, T.A., Barnes, D.E., Spada, N.J., Lawton, J.A., Cahill, T.M., 2011. Very fine and ultrafine metals and ischemic heart disease in the California Central Valley 1: 2003–2007. Aerosol Science and Technology 45, 1123–1134.

Chow, J.C., Watson, J.G., Doraiswamy, P., Chen, L.-W., Sodeman, D.A., Lowenthal, D.H., Park, K., Arnott, W.P., Motallebi, N., 2009. Aerosol light absorption, black carbon and elemental carbon at the Fresno, Supersite, California. Atmospheric Environment 93, 874–887.

Cyrys, J., Heinrich, J., Hoek, G., Meliefste, K., Lewné, M., Gehring, U., Bellander, T., Fischer, P., van Vliet, P., Brauer, M., Wichmann-Erich, H., Brunekreef, B., 2003. Comparison between different traffic-related particle indicators: elemental carbon (EC), $PM_{2.5}$ mass and absorbance. Journal of Exposure Analysis and Environmental Epidemiology, 134–143.

Dijkema, M.B.A., van der Zee, S.C., Brunekreef, B., Strien, R.T., 2008. Air quality effects of an urban highway speed limit reduction. Atmospheric Environment 42, 9098–9105.

EC, 2007. Regulation (EC) No 715/2007 of the European Parliament and the Council of 20 June 2007 on Type Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6). European Commission, Brussels, Belgium.

EC, 2008. Directive 2008/50/EC of the European Parliament and the Council of 21 May June 2008 on Ambient Air Quality and Cleaner Air for Europe. European Commission, Brussels, Belgium.

EEA, 2009. Transport at a Crossroads. European Environmental Agency, Copenhagen. Technical Report No. 3/2009.

EEA, 2011. Air Quality in Europe – 2011. European Environmental Agency, Copenhagen. Technical Report No. 12/2011.

Gietl, J.K., Lawrence, R., Thorpe, A.J., Harrison, R.M., 2010. Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road. Atmospheric Environment 44, 141–146.

Gonçalves, M., Jiménez-Guerrero, P., López, E., Baldasano, J.M., 2008. Air quality models sensitivity to on-road traffic speed representation: effects on air quality of 80 km h^{-1} speed limit in the Barcelona Metropolitan area. Atmospheric Environment 42, 8389–8402.

Harrison, R.M., Jones, A.M., Lawrence, R.G., 2004. Major component composition of PM_{10} and $PM_{2.5}$ from roadside and urban background sites. Atmospheric Environment 38, 4531–4538.

Hoek, G., Brunekreef, B., Goldbohm, S., Fischer, P., van den Brandt, P.A., 2002. Association between mortality and indicators of traffic-related air pollution in the Netherlands. Lancet 360, 1203–1209.

Invernizzi, G., Ruprecht, A., Mazza, R., De Marco, C., Močnik, G., Sioutas, C., Westerdahl, D., 2011. Measurement of black carbon concentration as an indicator of air quality benefits of traffic restriction policies within the ecopass zone in Milan, Italy. Atmospheric Environment 45, 3522–3527.

Janssen, N.A.H., Hoek, G., Lawson-Simic, M., Fischer, P., Bree van, L., Brink van, H., Keuken, M., Atkinson, R., Anderson, H.R., Brunekreef, B., Cassee, F., 2011. Black carbon as an additional indicator of the adverse health effects of airborne particles compared to PM_{10} and $PM_{2.5}$. Environmental Health Perspective 119, 1691–1699.

Jones, A.M., Harrison, R.M., 2005. Interpretation of particulate elemental and organic carbon concentrations at rural, urban and kerbside locations. Atmospheric Environment 39, 7114–7126.

Keller, S., Andreani-Aksoyoglu, S., Tinguely, M., Flemming, J., Heldstab, J., Keller, M., 2008. The impact of reducing the maximum speed limit on motorways in Switzerland to 80 km/h on emissions and peak ozone. Environmental Modelling & Software 23, 322–332.

Keuken, M.P., Jonkers, S., Wilmink, I.R., Wesseling, J., 2010. Reduced NO_x and PM_{10} emissions on urban motorways in the Netherlands by 80 km/h speed management. Science of the Total Environment 408, 2517–2526.

Keuken, M.P., Zandveld, P., van den Elshout, S., Janssen, N.A.H., Hoek, G., 2011. Air quality and health impact of PM_{10} and EC in the period 1985–2008 in the city of Rotterdam, the Netherlands. Atmospheric Environment 45, 5294–5301.

Keuken, M.P., Henzing, J.S., Zandveld, P., van den Elshout, S., Karl, M., 2012. Dispersion of particle numbers and EC from road traffic, a harbour and an airstrip in the Netherlands. Atmospheric Environment 54, 320–327.

Künzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. Lancet 356, 795–801.

Lefebvre, W., Fierens, F., Trimpeneers, E., Janssen, S., Van de Vel, K., Deutsch, F., Viaene, P., Vankerkom, J., Dumont, G., Vanpoucke, C., Mensink, C., Peelaerts, W., Vlieger, J., 2011. Modelling the effects of a speed limit reduction on traffic-related elemental carbon (EC) concentrations and population exposure to EC. Atmospheric Environment 45, 197–207.

Ntziachristos, L., Samaras, Z., 2009. EMEP/EEA Emission Inventory Guidebook – COPERT4. www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport.pdf.

PBL, 2008. Netherlands Emission Factor Database and Annual Background Concentrations (In Dutch) (Table H.1, p. 109). http://www.mnp.nl/bibliotheek/rapporten/500088002.pdf.

Pope III, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association 56, 709–742.

Putaud, J.-P., van Dingenen, R., Alatuey, A., et al., 2010. A European aerosol phenomenology – 3: physical and chemical characteristics of particulate matter from 60 rural, urban and kerbside sites across Europe. Atmospheric Environment 44, 1308–1320.

Schauer, J., 2003. Evaluation of elemental carbon as a marker for diesel particulate matter. Journal of Exposure Analysis and Environmental Epidemiology 13, 443–453.

Velders, G.J.M., Aben, J.M.M., Jimmink, B.A., van der Swaluw, E., de Vries, W.J., Geilenkirchen, G.P., Matthijsen, J., 2011. Large Scale Air Quality and Deposition Maps for the Netherlands, Report of 2011. In: RIVM Report 680362001, 2011. National Institute for Public Health and the Environment, Bilthoven, the Netherlands. www.rivm.nl/gcn.

Weijers, E.P., Schaap, M., Nguyen, L., Matthijsen, J., Denier van der Gon, H.A.C., ten Brink, H.M., Hoogerbrugge, R., 2011. Anthropogenic and natural constituents in particulate matter in the Netherlands. Atmospheric Chemistry and Physics 11, 2281–2294.

Weuve, J., Puett, R.C., Schwartz, J., Yanosky, J.D., Laden, F., Grodstein, F., 2012. Exposure to particulate air pollution and cognitive decline in older women. Archives of Internal Medicine 172, 219–277.

WHO, 2005. Health Effects of Transport-related Air Pollution. World Health Organization, Regional Office for Europe, Copenhagen. www.euro.who.int/pubrequest.

WHO, 2012. Health Effects of Black Carbon. World Health Organization, Regional Office for Europe, Copenhagen. www.euro.who.int/pubrequest.

Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: comparison of work zone, rush hour and free-flow conditions. Atmospheric Environment 45, 1929–1939.