Consistency of urban background black carbon concentration measurements by portable AE51 and reference AE22 aethalometers: Effect of corrections for filter loading

Nicola Masey¹,⁴, Eliani Ezani¹,², Jonathan Gillespie¹, Fiona Sutherland¹,
Chun Lin³, Scott Hamilton⁴, Mathew R. Heal³, Iain J. Beverland¹*

¹Department of Civil and Environmental Engineering, University of Strathclyde,
James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, UK
²Department of Environmental and Occupational Health, Faculty of Medicine and Health Science,
Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
³School of Chemistry, Joseph Black Building, University of Edinburgh,
David Brewster Road, Edinburgh, EH9 3FJ, UK
⁴Ricardo Energy and Environment, 18 Blythswood Square,
Glasgow, G2 4BG, UK

*CORRESPONDING AUTHOR:
Dr Iain J. Beverland,
Department of Civil and Environmental Engineering, University of Strathclyde,
James Weir Building, 75 Montrose Street,
Glasgow, G1 1XJ, UK.
Email: iain.beverland@strath.ac.uk; Tel: +44 141 548 3202
Abstract: Measurement of exposure to black carbon with portable monitoring devices is an important part of research on the health impacts of combustion-related air pollutants. We collected 786 hourly-averaged equivalent black carbon (eBC) measurements from co-located duplicate portable AethLab AE51 aethalometers and a UK government reference Magee Scientific AE22 aethalometer (latter adjusted for filter darkening effects using a standard procedure for UK government AE22 aethalometers) at an urban background site in Glasgow, UK. AE51 and reference AE22 aethalometer concentrations were highly correlated ($R^2 \geq 0.87$) over the combined deployment periods. Application of a previously-reported method for correction of underestimation of concentrations by AE51 monitors associated with filter loading generally overestimated [corrected] reference AE22 aethalometer eBC concentrations (e.g. for two AE51 monitors normalised mean bias = +14% and +25% for literature-based correction method cf. -2% and +3% for unadjusted AE51 data across the full range of measurements). We found limited and inconsistent evidence for underestimation of eBC cf. corrected AE22 eBC measurements for the two AE51 instruments evaluated (for AE51 attenuation (ATN) $\leq \sim52$). Our observations suggest that the AE51 monitors we evaluated do not require correction for filter loading, at relatively low ATN values in environments with low eBC concentrations, to achieve close agreement with UK government corrected AE22 eBC measurements.

Keywords: air pollution; equivalent black carbon; aethalometer; micro-aethalometer; attenuation; filter loading
1. Introduction

Black carbon (BC) is a constituent of airborne particulate matter (PM) produced during incomplete combustion of carbon-based fuels. The health effects associated with exposure to PM and BC include respiratory and cardiovascular diseases (WHO, 2005; World Health Organization, 2013), including associations between health outcomes and proximity to roads where BC concentrations are frequently elevated (Grahame et al., 2014; Janssen et al., 2011, 2015). In the UK, BC concentrations are measured continuously at 14 sites in a nationally-coordinated network (https://uk-air.defra.gov.uk/networks/network-info?view=ukbsn) using a mains-powered rack-mounted aethalometer (AE22, Magee Scientific, CA, USA). The number of fixed-site BC measurements is limited because of the high installation, equipment and maintenance costs and because BC does not need to be measured under current UK air quality compliance legislation.

Battery-powered, hand-held aethalometers have also been developed to measure real-time concentrations of BC. The small size and light weight of these monitors make them suitable for use in a variety of applications including static locations in a network (Gillespie et al., 2016; Montagne et al., 2015; Weichenthal et al., 2014), mobile monitoring (Apte et al., 2011; Hankey and Marshall, 2015; Van den Bossche et al., 2015) and/or personal monitoring (Dons et al., 2012, 2013a, 2013b; Williams and Knibbs, 2016). In this study, we evaluated two microAeth AE51 portable BC aethalometers (AethLabs, San Francisco, CA, USA).

Following recommendations made by Petzold et al. (Petzold et al., 2013) in the remainder of this paper we use the term equivalent black carbon (eBC) to describe BC concentrations quantified by optical absorption technique used in aethalometer instruments. In this technique air is sampled through a filter and the concentration of BC is estimated by comparing the attenuation (ATN) of light passing through the particles deposited on the filter to that passing through an unloaded reference point on the same filter. An important consideration is that the relationship between ATN and BC loading is not linear at higher attenuation values. Different methods to correct aethalometer data to account for these filter loading effects have been proposed (Kirchstetter and Novakov, 2007; Virkkula et al., 2007) but few studies have compared the correction algorithms to determine if they are always necessary, and which provides the most accurate correction (Good et al., 2017).
The aim of our study was to compare methods commonly used to correct BC measurements from AE51 aethalometers and to establish how consistent the measurements from these portable systems are with a static aethalometer used in the UK Government black carbon network. We build on the study of Good et al. (2017), who evaluated correction algorithms for filter darkening, by evaluating some of these correction methods during repeated AE51 aethalometer field deployments. Good et al. (2017) used an online photoacoustic extinctiometer (PAX Droplet Measurement Technologies, Boulder, CO, USA) as a reference instrument under controlled laboratory conditions. In contrast, we deployed duplicate AE51 aethalometers close to the inlet of an AE22 ‘reference’ aethalometer at an urban background site in the city of Glasgow, UK, for 786 hours of co-located measurements interspersed between April and August 2016. The static outdoor deployment of the AE51 aethalometers avoided the potential introduction of large spurious readings due to mechanical shocks that has been observed during mobile monitoring (Apte et al., 2011). The static deployment also minimised another potential source of error sometimes experienced during personal monitoring: the condensation of water on the AE51 monitor filters or optics arising from rapid changes in temperature and/or relative humidity (Cai et al., 2013). Since these two sources of potential error were reduced in our study, we were able to focus our field-based assessment of filter loading effects directly on the agreement between measurements from portable and reference aethalometer instruments.
2. Methods

2.1. Site description; AE22 aethalometer operation

Measurements were made at the Glasgow Townhead monitoring site, an urban background location in central Glasgow (55.866 °N, 4.244 °W) that is part of the UK black carbon monitoring network. Hourly-averaged reference eBC measurements made at this site using a Magee Scientific AE22 aethalometer are publicly available (https://uk-air.defra.gov.uk/data/data_selector). AE22 instrument operation and data ratification are subject to national QA/QC protocols (Butterfield et al., 2015). Prior to publication, the AE22 hourly-averaged reference concentration data are corrected for filter darkening effects estimated from changes in quantified concentrations at the time of automatic filter advances using a standard correction procedure (Butterfield et al., 2015; Virkkula et al., 2007).

2.2. AE51 aethalometer set up and operation

Two microAeth AE51 aethalometers (https://aethlabs.com/), subsequently referred to as ‘BC_1204’ and ‘BC_1303’, were deployed in waterproof boxes on the roof of the monitoring station and sampled ambient air through a 1 m length of tubing supplied by the manufacturer. A conductive asbestos sampling inlet (SKC Ltd, UK) was connected to the inlet of the tubing as a rain hood to prevent water ingress. The flow rate of the AE51 aethalometers was set to 50 mL/min and data were recorded each minute.

The AE51 aethalometers were co-located at the monitoring station on 8 occasions in 2016 (Table 1). During each deployment the site was visited approximately every 5 days to download the AE51 data and to change filters. The AE51 filter attenuation did not exceed 52.01 during any deployment period.

The 1-min data collected by the AE51 aethalometers were averaged to hourly concentrations for comparison with reference AE22 eBC concentrations.
2.3. Correction of AE51 equivalent black carbon data

Prior to filter darkening correction procedures we smoothed the AE51 data to minimise the number of negative values using Optimized Noise-reduction Algorithm (ONA) software from the AethLabs website (https://aethlabs.com/dashboard) (Hagler et al., 2011). We set the change in attenuation value used to average eBC concentration data in this ONA method to 0.05.

We then applied one of the following two alternative filter darkening correction procedures to the ONA-adjusted eBC data from the portable AE51 aethalometers to account for potential underestimation of eBC as the darkness of the filter increased.

(a) The correction procedure published by Kirchstetter and Novakov (2007) (subsequently referred to as K&N):

\[
eBC_{\text{corrected}} = eBC_{\text{ONA}}((0.88 \times \exp^{-\text{ATN}/100}) + 0.12)^{-1}
\]

Equation (1)

where \(eBC_{\text{ONA}}\) is the AE51 concentration after ONA correction (outlined above) and ATN is the attenuation of the AE51 filter. We used the ATN values directly from the AE51 monitors as clean filters were used on each occasion, in contrast to Good et al. (Good et al., 2017) who used the percent change in attenuation between the start and end of the study to account for the use of preloaded filters.

(b) The correction procedure developed by Virkkula et al. (2007), which is based on the concept that increasing ATN results in a linear underestimation of the correct eBC concentration.

\[
eBC_{\text{corrected}} = (1 + k \times \text{ATN})eBC_{\text{ONA}}
\]

Equation (2)

We estimated values of \(k\) from the linear regression slope between the ratio of AE22 aethalometer concentrations divided by AE51 \(eBC_{\text{ONA}}\) concentrations vs. corresponding AE51 ATN values with a fixed intercept value of 1 (Cheng and Lin, 2013).

In an equivalent way as was described for uncorrected 1-min A51 data in the preceding section, corrected 1-min AE51 aethalometer data were averaged to hourly concentrations for comparison with reference AE22 eBC concentrations.
3. Results

3.1. Precision and accuracy of AE51 Aethalometers

Unadjusted concentrations measured by the two duplicate AE51 aethalometers tracked each other closely over extended time periods (regression analyses of AE51_1303 vs. AE51_1204: slope = 1.06, intercept = 0.00, n = 786, \( R^2 = 0.97 \)) (Figure 1) with both instruments recording similar overall average values (0.66 and 0.69 µg/m³ for AE51_1204 and AE51_1303 respectively, Table 2). The mean absolute percentage error and normalised mean absolute error for duplicate measurements (Fig 1) were both 5% (following normalisation of observations from individual instruments by the average of duplicate measurements). Similarly high correlations between duplicate AE51 aethalometers have been reported in other studies, e.g. \( R^2 \) values > 0.95 between 13 co-located monitors (Dons et al., 2012).

Time series of hourly-average unadjusted concentrations from the duplicate AE51 Aethalometers and the reference AE22 aethalometer also showed very similar temporal patterns (Figure 2a-d) with \( R^2 \) values between AE51_1204 vs. AE22 and AE51_1303 vs. AE22 of 0.88 and 0.87 respectively (Fig 2e,f). A previous study at a BC network monitoring site in Birmingham, UK (Delgado-Saborit, 2012) reported high correlation (\( R^2 = 0.90 \)) between AE51 and reference AE22 aethalometer concentrations over a similar range of reference analyser BC concentrations (0 – 5 µg/m³) to the BC concentrations observed during our deployments.

3.2. Effect of filter loading corrections

Examination of scatterplots of AE51-AE22 vs. AE51_ATN provided no obvious indication of reduction in measured BC by AE51 instruments cf. AE22 instruments as the ATN of the former increased between 0 – 50 (Fig 2g-h). The correlation between the difference between AE51 and AE22 concentrations, and AE51_ATN, was very low (\( R^2 < 1\% \) for both AE51 instruments), with no evidence of a slightly negative slope that might be expected from relative underestimation by AE51 as AE51_ATN increased. Almost identical findings were noted for hourly averaged ONA adjusted AE51 observations (Fig 3) consistent with the ONA adjustment mainly affecting short-term fluctuations that were removed by averaging over hourly periods.
In contrast ONA and K&N adjusted AE51 observations substantially overestimated AE22 observations (e.g. AE51 vs. AE22 regression lines of $1.04AE22 + 0.6$ and $1.16AE22 + 0.05$ [Fig 4a-f]), with clear indication that the K&N adjusted AE51 overestimation increased with increasing AE51_ATN (Fig 4g-h).

We examined ratios of AE22/AE51 for possible underestimation of eBC by AE51 instruments as AE51_ATN increased (Fig 5). When all available data were included in the regression analyses of AE22/AE51 vs. AE51_ATN the values of $k$ calculated were 0.0017 and -0.000009 for 1 h average data for BC1204 and BC1303 monitors respectively (Fig 6, Table 1). $k$ values calculated for the 8 individual measurement periods (Fig S1) had overall averages (and relative standard deviations) of 0.0051 (RSD = 112%) and 0.0007 (RSD = 346%) (Table 1, Fig S2). Negative $k$ values suggest that non-corrected eBC concentrations overestimate the ‘true’ eBC concentrations and have been suggested to occur in summer months when the ratio of black carbon to aerosol volume concentrations are lower (Virkkula et al., 2007). The range of $k$ values that we calculated was not inconsistent with widely ranging calculations in other studies (e.g. $k = -0.0039$ (Cheng and Lin, 2013); $k = 0.0033$ (Cheng et al., 2014); $k = 0.01$ (Morales Betancourt et al., 2017)).

We then corrected $BC_{ONA}$ values, using Equation (2) with both: the $k$ values calculated for the complete dataset (i.e. all 8 periods grouped together); and the average $k$ values calculated for the 8 individual measurement periods. Data adjusted in this way using average and complete-dataset $k$ values were only marginally different from the unadjusted data with only minor changes in statistics comparing the adjusted data against reference AE22 observations – with the average $k$ value cases resulting in minor deterioration in the closeness of fit been adjusted and observed data (Table 2).

The increased regression slopes for K&N corrected AE51 data was reflected in prediction model statistics that illustrated the scale of overestimation (e.g. NMB statistics of 14 and 25% [Table 2]). The K&N corrected hourly AE51 aethalometer concentrations had the largest NRMSE statistics (NRMSE = 34% and 44% for BC1204 and BC1303 respectively, Table 2). Hence the K&N equation overcorrected the AE51 aethalometer concentrations for filter loading effects, with lower correlation against the reference aethalometer concentrations than the unadjusted AE51 data (Table 1).
4. Discussion

Portable AE51 aethalometers are widely used in mobile and personal monitoring. However, there have been limited field evaluations comparing AE51 monitors to ‘reference’ eBC monitoring instruments. In our studies the coefficient of determination between two AE51 monitors and an AE22 reference aethalometer were 87% and 88% when hourly averaging was used. These values are higher than the $R^2$ values > 0.75 reported for 10-min average concentrations between AE51 monitors and a Thermo Multi-Angle Absorption Photometer (MAAP) BC concentrations for a dataset with minimum concentration of 1.5 µg/m$^3$ (Viana et al., 2015).

After K&N correction for filter darkening, AE51 concentrations overestimated the reference AE22 concentrations and had larger errors than the unadjusted eBC concentrations (Fig 4, Table 1). In contrast, underestimation of eBC has been reported previously in a chamber experiment comparing unadjusted AE51 eBC concentrations measured using unloaded filters to a photoacoustic extinctiometer (Good et al., 2017). However, in that chamber experiment study it was also noted that K&N correction overcompensated filter loading effects when pre-loaded filters were used (Good et al., 2017). We concluded that in the relatively low concentration and low filter loading conditions (no measurements with ATN values > 53) in our study the K&N correction overcompensated AE51 eBC estimates in comparison to AE22 eBC concentrations corrected by the Virkkula et al. method (Virkkula et al., 2007).

Our study has several important limitations including being specific to one geographical location over a relatively short time period. Also we did not have access to the uncorrected measurements from the reference AE22 aethalometer instrument – these are not available on the government internet site where the corrected AE22 data are published. Further analyses of the extent of agreement between AE22 and AE51 eBC measurements, at locations where more detailed data may be available, could potentially examine the effects of: composition of the black carbon particles, meteorological conditions, and the numerical extent of filter loading corrections on measurements from the AE22 instrument.

In summary, we compared field measurements of eBC concentrations at an urban background site using two portable AE51 aethalometers vs. reference AE22 aethalometer. Uncorrected AE51 eBC observations were in close agreement with AE22 eBC concentrations corrected by the
Virkkula et al. method with slight overall underestimation by one AE51 aethalometer (NMB = -2%) and slight overall overestimation by the second AE51 aethalometer (NMB = +3%). After correction for filter loading, data from both AE51 aethalometers generally overestimated reference AE22 aethalometer concentrations (NMB = +15% and +25% respectively). Our observations suggest that AE51 aethalometer measurements may not require correction for filter loading to maintain consistency with reference [Virkkula et al. corrected] AE22 concentrations when AE51 ATN values are less than 52.
Acknowledgements

Nicola Masey was funded through a UK Natural Environment Research Council (NERC) CASE PhD studentship (NE/K007319/1), with support from Ricardo Energy and Environment. Eliani Ezani was funded by the Ministry of Higher Education Malaysia (KPT(BS)860126295394). Jonathan Gillespie was funded through an Engineering and Physical Sciences Research Council Doctoral Training Grant (EPSRC DTG EP/L505080/1 and EP/K503174/1) studentship, with support from the University of Strathclyde and Ricardo Energy and Environment. Chun Lin was funded through NERC/Innovate UK grant NE/N007352/1. We acknowledge access to the reference black carbon measurement data, which were obtained from uk-air.defra.gov.uk and are subject to Crown 2014 copyright, Defra, licenced under the Open Government Licence (OGL). We thank Kings College London for providing access to the 5-min temporal resolution black carbon concentrations. The research data associated with this paper are available at: http://dx.doi.org/XXXXX (doi to be provided at time of publishing).

The authors declare no conflict of interest
References


Figure 1: (a) Time series of unadjusted hourly-average eBC concentrations measured by two AE51 micro-aethalometers (BC_1204 & BC_1303) between 29/04/16 and 26/05/16. (a) Time series of unadjusted hourly-average eBC concentrations measured by BC_1204 & BC_1303 between 08/08/16 and 22/08/16. Gaps in plot separate non-consecutive time series. (b) Scatter plot with linear regression of hourly-average unadjusted concentrations measured during both of the above periods by duplicate AE51 aethalometers. The dashed line represents 1:1 correspondence.
Figure 2: (a)-(d) Time series of adjusted hourly-average eBC concentrations from reference AE22 aethalometer and unadjusted concentrations measured by two AE51 micro-aethalometers for 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16. (e)-(f) Scatter plots of unadjusted eBC concentrations from AE51 micro-aethalometers vs. adjusted eBC concentrations measured by the AE22 aethalometer. Dashed lines represent 1:1 correspondence. (g)-(h) Scatter plots of difference between AE51_eBC - AE22_eBC vs. AE51_ATN. Panels (a)-(h) in this figure are arranged from left to right, top to bottom.
Figure 3: (a)-(d) Time series of adjusted hourly-average eBC concentrations from reference AE22 aethalometer and ONA adjusted concentrations from two AE51 micro-aethalometers for 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16. (e)-(f) Scatter plots of ONA adjusted eBC concentrations from AE51 BC micro-aethalometers vs. adjusted eBC concentrations measured by the AE22 aethalometer. Dashed lines represent 1:1 correspondence. (g)-(h) Scatter plots of difference between ONA adjusted AE51_BC - AE22_eBC vs. AE51_ATN. Panels (a)-(h) in this figure are arranged from left to right, top to bottom.
Figure 4: (a)-(d) Time series of adjusted hourly-average eBC from reference AE22 aethalometer and consecutive ONA and K&N adjusted concentrations from two AE51 micro-aethalometers for 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16. (e)-(f) Scatter plots of consecutive K&N & ONA adjusted eBC concentrations from AE51 eBC vs. adjusted eBC concentrations measured by the AE22 Aethalometer. Dashed lines represent 1:1 correspondence. (g)-(h) Scatter plots of difference between K&N and ONA adjusted AE51_eBC - AE22_eBC vs. AE51_ATN. Panels (a)-(h) in this figure are arranged from left to right, top to bottom.
Figure 5: Time series of ATN from two AE51 micro-aethalometers and ratio of adjusted hourly-average eBC concentrations from reference AE22 aethalometer and AE51 micro-aethalometers for 29/04/16 - 26/05/16 ((a) & (b)) and 08/08/16 - 22/08/16 ((c) & (d)).
Figure 6: Scatter plots of hourly-average eBC concentration ratios for reference AE22 aethalometer (adjusted) / AE51 micro-aethalometers (non-adjusted and adjusted) for 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16. Panels (a)-(h) in this figure are arranged from left to right, top to bottom.
Table 1: Dates and descriptive statistics for co-located AE51 and reference AE22 aethalometer deployments at the Glasgow Townhead network monitoring site. Data are based on hourly averages. $k$ values represent the slope of the ratio of $AE22/AE51$ vs. $AE51$ ATN as outlined in Methods section.

<table>
<thead>
<tr>
<th>Period</th>
<th>$N$</th>
<th>Min BC (AE22)</th>
<th>Max BC (AE22)</th>
<th>Min ATN (AE51)</th>
<th>Max ATN (AE51)</th>
<th>$R^2$</th>
<th>$k$</th>
<th>Min ATN (AE51)</th>
<th>Max ATN (AE51)</th>
<th>$R^2$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29/04 - 04/05/16</td>
<td>114</td>
<td>0.1</td>
<td>2.1</td>
<td>-1.12</td>
<td>24.07</td>
<td>0.90</td>
<td>0.0028</td>
<td>3.20</td>
<td>27.97</td>
<td>0.85</td>
<td>0.0054</td>
</tr>
<tr>
<td>04/05 - 09/05/16</td>
<td>117</td>
<td>0.1</td>
<td>3.9</td>
<td>-1.50</td>
<td>44.87</td>
<td>0.93</td>
<td>-0.0012</td>
<td>-0.54</td>
<td>48.64</td>
<td>0.92</td>
<td>-0.0027</td>
</tr>
<tr>
<td>09/05 - 13/05/16</td>
<td>94</td>
<td>0.2</td>
<td>1.7</td>
<td>2.64</td>
<td>37.93</td>
<td>0.83</td>
<td>0.0004</td>
<td>3.18</td>
<td>39.54</td>
<td>0.81</td>
<td>-0.0003</td>
</tr>
<tr>
<td>18/05 - 22/05/16</td>
<td>95</td>
<td>0.1</td>
<td>1.9</td>
<td>-6.17</td>
<td>20.28</td>
<td>0.94</td>
<td>0.0107</td>
<td>0.99</td>
<td>30.05</td>
<td>0.93</td>
<td>0.0032</td>
</tr>
<tr>
<td>23/05 - 26/05/16</td>
<td>68</td>
<td>0.1</td>
<td>1.2</td>
<td>-4.36</td>
<td>14.59</td>
<td>0.85</td>
<td>0.0157</td>
<td>0.58</td>
<td>19.11</td>
<td>0.80</td>
<td>0.0017</td>
</tr>
<tr>
<td>08/08 - 12/08/16</td>
<td>88</td>
<td>0.1</td>
<td>3.5</td>
<td>-3.08</td>
<td>21.92</td>
<td>0.98</td>
<td>0.0065</td>
<td>6.18</td>
<td>33.85</td>
<td>0.98</td>
<td>-0.0003</td>
</tr>
<tr>
<td>12/08 - 17/08/16</td>
<td>117</td>
<td>0.1</td>
<td>2.4</td>
<td>-1.07</td>
<td>37.64</td>
<td>0.95</td>
<td>0.0049</td>
<td>2.02</td>
<td>43.51</td>
<td>0.96</td>
<td>-0.00005</td>
</tr>
<tr>
<td>17/08 - 22/08/16</td>
<td>93</td>
<td>0.2</td>
<td>3.6</td>
<td>-0.33</td>
<td>43.97</td>
<td>0.96</td>
<td>0.0010</td>
<td>0.24</td>
<td>52.01</td>
<td>0.94</td>
<td>-0.0010</td>
</tr>
</tbody>
</table>

Mean $k$ for above 8 periods: **0.0051**

Std dev $k$ for above 8 periods: 0.0057

Relative standard deviation $k$ (%): 112

$k$ for complete dataset: 0.0017 -0.000009
Table 2. Agreement between co-located AE51 and reference AE22 BC aethalometer instruments at the Glasgow Townhead network monitoring site.
Units of Average (Ave); Mean Bias (MB); Mean Absolute Error (MAE); Root Mean Square Error (RMSE) and Intercept are µg m\(^{-3}\). Normalised Mean Bias (NMB); Normalised Mean Absolute Error (NMAE); Normalised Root Mean Square Error (NMRSE); Slope; and \(R^2\) are dimensionless. Statistics were normalised by arithmetic mean of hourly reference AE22 instrument measurements (0.67 µg m\(^{-3}\)). \(BC1024\_Corr(ave)\) & \(BC1303\_Corr(ave)\) represent eBC corrected using average \(k\) values from 8 individual measurement periods. \(BC1024\_Corr(comp)\) & \(BC1303\_Corr(comp)\) represent eBC corrected using \(k\) values from complete dataset (i.e. all 8 measurement periods grouped together).

<table>
<thead>
<tr>
<th></th>
<th>Ave</th>
<th>MB</th>
<th>NMB</th>
<th>MAE</th>
<th>NMAE</th>
<th>RMSE</th>
<th>NMRMSE</th>
<th>Slope</th>
<th>Intercept</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1024</td>
<td>0.66</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.10</td>
<td>0.16</td>
<td>0.15</td>
<td>0.23</td>
<td>0.89</td>
<td>0.06</td>
<td>0.88</td>
</tr>
<tr>
<td>BC1024 ONA</td>
<td>0.66</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.10</td>
<td>0.16</td>
<td>0.15</td>
<td>0.23</td>
<td>0.89</td>
<td>0.06</td>
<td>0.89</td>
</tr>
<tr>
<td>BC1024 K &amp; N</td>
<td>0.76</td>
<td>0.09</td>
<td>0.14</td>
<td>0.15</td>
<td>0.23</td>
<td>0.22</td>
<td>0.34</td>
<td>1.04</td>
<td>0.06</td>
<td>0.84</td>
</tr>
<tr>
<td>BC1024_Corr(ave)</td>
<td>0.71</td>
<td>0.04</td>
<td>0.06</td>
<td>0.12</td>
<td>0.18</td>
<td>0.17</td>
<td>0.26</td>
<td>0.97</td>
<td>0.06</td>
<td>0.87</td>
</tr>
<tr>
<td>BC1024_Corr(comp)</td>
<td>0.67</td>
<td>0.00</td>
<td>0.01</td>
<td>0.10</td>
<td>0.16</td>
<td>0.15</td>
<td>0.23</td>
<td>0.92</td>
<td>0.06</td>
<td>0.87</td>
</tr>
<tr>
<td>BC1303</td>
<td>0.69</td>
<td>0.02</td>
<td>0.03</td>
<td>0.11</td>
<td>0.17</td>
<td>0.16</td>
<td>0.25</td>
<td>0.95</td>
<td>0.05</td>
<td>0.87</td>
</tr>
<tr>
<td>BC1303 ONA</td>
<td>0.69</td>
<td>0.02</td>
<td>0.03</td>
<td>0.11</td>
<td>0.17</td>
<td>0.16</td>
<td>0.25</td>
<td>0.95</td>
<td>0.05</td>
<td>0.87</td>
</tr>
<tr>
<td>BC1303 K &amp; N</td>
<td>0.83</td>
<td>0.16</td>
<td>0.25</td>
<td>0.15</td>
<td>0.23</td>
<td>0.28</td>
<td>0.44</td>
<td>1.16</td>
<td>0.05</td>
<td>0.84</td>
</tr>
<tr>
<td>BC1303_Corr(ave)</td>
<td>0.70</td>
<td>0.03</td>
<td>0.05</td>
<td>0.11</td>
<td>0.18</td>
<td>0.18</td>
<td>0.28</td>
<td>0.97</td>
<td>0.05</td>
<td>0.87</td>
</tr>
<tr>
<td>BC1303_Corr(comp)</td>
<td>0.69</td>
<td>0.02</td>
<td>0.03</td>
<td>0.11</td>
<td>0.17</td>
<td>0.16</td>
<td>0.25</td>
<td>0.95</td>
<td>0.05</td>
<td>0.87</td>
</tr>
</tbody>
</table>

AE22: Ave: Min: Max: 0.67 0.10 3.90
Supplementary information:

Consistency of urban background black carbon concentration measurements by portable AE51 and reference AE22 Aethalometers: Effect of corrections for filter loading.

Nicola Masey\textsuperscript{1,4}, Eliani Ezani\textsuperscript{1,2}, Jonathan Gillespie\textsuperscript{1}, Fiona Sutherland\textsuperscript{1}, Chun Lin\textsuperscript{3}, Scott Hamilton\textsuperscript{4}, Mathew R. Heal\textsuperscript{3}, Iain J. Beverland\textsuperscript{1*}

\textsuperscript{1}Department of Civil and Environmental Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, UK
\textsuperscript{2}Department of Environmental and Occupational Health, Faculty of Medicine and Health Science, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
\textsuperscript{3}School of Chemistry, Joseph Black Building, University of Edinburgh, David Brewster Road, Edinburgh, EH9 3FJ, UK
\textsuperscript{4}Ricardo Energy and Environment, 18 Blythswood Square, Glasgow, G2 4BG, UK

*CORRESPONDING AUTHOR: Dr Iain J. Beverland, Department of Civil and Environmental Engineering, University of Strathclyde, 505F James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, UK; Email: iain.beverland@strath.ac.uk; Tel: +44 141 548 3202
Figure S1: Time series of adjusted hourly-average eBC concentrations from reference AE22 aethalometer and unadjusted concentrations measured by two AE51 micro-aethalometers for individual deployment periods between 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16.
Figure S1 (continued): Time series of adjusted hourly-average eBC concentrations from reference AE22 aethalometer and unadjusted concentrations measured by two AE51 micro-aethalometers for individual deployment periods between 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16.
Figure S2: Scatter plots of eBC concentrations ratios of hourly-average eBC concentrations from reference AE22 aethalometer (adjusted) / AE51 micro-aethalometers (non-adjusted and adjusted) for individual periods between 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16.
Figure S2 (continued): Scatter plots of eBC concentrations ratios of hourly-average eBC concentrations from reference AE22 aethalometer (adjusted) / AE51 micro-aethalometers (non-adjusted and adjusted) for individual periods between 29/04/16 - 26/05/16 and 08/08/16 - 22/08/16.

BC_1024 (23-26 May 2016):

\[ y = 0.0157x + 1 \]
\[ R^2 = -0.084 \]

BC_1303 (23-26 May 2016):

\[ y = 0.0017x + 1 \]
\[ R^2 = -0.046 \]

BC_1024 (8-12 Aug 2016):

\[ y = 0.0065x + 1 \]
\[ R^2 = 0.0095 \]

BC_1303 (8-12 Aug 2016):

\[ y = -0.0003x + 1 \]
\[ R^2 = 1E-04 \]

BC_1024 (12-17 Aug 2016):

\[ y = -5E-05x + 1 \]
\[ R^2 = -2E-05 \]

BC_1303 (12-17 Aug 2016):

\[ y = 0.001x + 1 \]
\[ R^2 = -0.041 \]

BC_1024 (17-21 Aug 2016):

\[ y = -0.001x + 1 \]
\[ R^2 = -0.005 \]

BC_1303 (17-21 Aug 2016):

\[ y = 0.002x + 1 \]
\[ R^2 = -0.005 \]