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Indirect estimation of black carbon concentration in traffic site based on other pollutants – time variability analysis

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Abstract: Aiming to create more sustainable cities it is necessary to understand and manage different ecological factors which influence human health. One of such factors is black carbon (BC) in atmosphere, which currently is not commonly monitored by environmental monitoring systems. The aim of this research was to estimate by indirect approach the relation between eBC (equivalent of black carbon) concentration and other air pollutants in order to define approximate level of eBC in more efficient approach. The study was conducted in Wrocław (Poland) in October 2021, and combined data on eBC concentration (measured by microaethalometer), air quality (from national environmental monitoring system) and traffic (from municipal traffic management system). Quantile regression was used to assess the relationship between the concentrations of pollutants. The obtained results show that for rise 1 mg·m^{-3} of carbon monoxide, eBC concentration rise between 4.2 and 8.0 μg·m^{-3}, depending on the period of a day. Precision of eBC concentration evaluation is influenced by sun light which results in higher precision of defining a scaling factor for night hours. Outcomes of this study constitute an added value to understanding of interconnections between different factors describing environmental conditions in cities and might be helpful for more effective environmental assessment of human habitats.

Keywords: air pollution, black carbon, carbon monoxides, indirect estimation, traffic

INTRODUCTION

Black carbon (BC) is an important, low-molecular pollutant in the atmosphere. It is produced mainly as a result of incomplete combustion of solid fuel and biofuels used for energy purpose (Bond *et al.*, 2004). It is emitted from the chimneys of furnaces and exhaust pipes of motor vehicles. BC is found throughout the Earth system. It has a unique and important role in the Earth's climate system because it absorbs solar radiation, influences cloud processes, and alters the melting of snow and ice cover (Bond *et al.*, 2013). On a local scale, the emitted BC particles are absorbed by the respiratory system of the inhabitants of the polluted areas. Exposure to BC is associated with cardiovascular and cardiopulmonary premature mortality (Lin *et al.*, 2019; Gu *et al.*, 2020; Tiwari *et al.*, 2021). BC particles are very small – diameter <0.1 μm (Cougo *et al.*, 2018), which allows them to penetrate the body's protective membranes, causing cardiovascular and cardiopulmonary diseases and premature mortality (Lin *et al.*, 2019; Gu *et al.*, 2020). The recent WHO report (WHO, 2021) advises to make systematic measurements of BC, in addition to pollutants for which guidelines currently exist, and to undertake exposure assessments and source apportionment for BC.

Black carbon nomenclature is ambiguous. Usually the names are taken according to the measurement method used. Following the EEA technical report (EEA, 2013) BC is a qualitative description when referring to light-absorbing carbonaceous substances in atmospheric aerosol. Equivalent black carbon (eBC) should be used instead of BC for measurements derived from optical methods. Accordingly, the term eBC will be used hereinafter. Despite the importance of BC, it happens that its concentration is not recorded in air quality national measurement systems (Rovira *et al.*, 2022). It can be caused by additional costs or a need of involving staff to maintain operation of measurement equipment. Such situation can be observed for example in Poland (Gorzelnik and Oleniacz, 2019) which is the country with highest air pollution in the European Union (EEA, 2021). It is therefore necessary to estimate the concentration of BC from other, measured, pollutants. Pan *et al.* (2011) found a strong correlation between eBC and carbon monoxide based on studies in Eastern China. Significant correlations between eBC, carbon monoxide (CO) and ozone (O_3) were shown based on research in India (Latha and Badarinath, 2004). In Poland, very few eBC studies have been conducted – in cities: Warsaw and Racibórz (Maciejewska *et al.*, 2015), Kraków (Samek *et al.*, 2017), Zabrze (Chiliński, Markowicz and Kubicki, 2018; Zioła *et al.*, 2021b), Krynica-Zdrój (Klejnowski, Janoszka and Czaplicka, 2017) and in mountains: vertical structure of eBC in Beskid Mountains (Posyniak *et al.*, 2021). However, just a few of the studies mentioned (Zioła, Błaszczak and Klejnowski, 2021; Zioła *et al.*, 2021) refers to the relationship between the eBC and other variables subject to ongoing environmental monitoring, which is a gap in the current state of knowledge.

The aim of this paper was indirect estimation eBC concentration using other pollutants in the climatic, communication and urban conditions of Central-Eastern Europe. The research area was the city of Wrocław (Poland). For this purpose, measurements of the eBC concentration were carried out in the communication canyon, in the vicinity of the Polish national air quality monitoring system. Then, a comparative analysis of eBC concentrations and pollutants measured at the station was performed, taking into account the traffic intensity. On this basis, a method for estimating the level of eBC concentration has been proposed.

STUDY MATERIALS AND METHODS

STUDY AREA

The research was conducted in Wrocław (GPS coordinates 16.80749–17.17594E; 51.04278–51.20996N). The city is a regional center located close to the border with Germany and the Czech Republic. The city is inhabited by 642.7 thous. people and is the fourth largest city in Poland. The measurement area included the communication canyon in the city of Wrocław running along Hallera St. and Wiśniowa St. (latitudinally) to the east of the intersection with Powstańców Śląskich St. (meridian) – Figure 1.

MEASUREMENTS DEVICE

Measurements were performed using a microaethalometer (microAeth®, AE51, AethLabs) which is a device that samples ambient air via a teflon-coated borosilicate glass fibre filter ticket. The transmission of 880 nm LED light source through the sampled spot of 3 mm is measured with a photodiode detector. The transmission of light via the filter reduces as the filter becomes loaded with black substance. The quantity of BC is measured based on the reduction in light transmission via the filter. Measurement of eBC on the basis of optical absorption with an aethalometer is outlined in Hansen, Rosen and Novakov (1984) and Dons *et al.* (2012). The flow rate of the microaethalometer was set at 150 $cm^3 \cdot min^{-1}$, and measurements were made at a 5 min temporal resolution.

DATA

The research used data from eBC measurements carried out for this study, data on air pollution from the national air monitoring system and data on the number of vehicles from the city's road traffic management system (Intelligent Transport System). eBC measurements were carried out from October 1 to 29, 2021. October was selected intentionally as on the on hand it excludes holiday period with lower traffic on streets, and on the other hand it does not overlap with a heating season (which could influence analysis with other sources of pollution). The microaethalometer was placed at a height of 4 m on the balcony (Fig. 1) to ensure the safety of the device and easy access to replace the filter. Data from the device was transferred in digital form via a physical connection to the computer.

Fig. 1. Map of Wrocław with research area; yellow circle = meteorological station, yellow rectangle = BC device location, analysed intersection on the western part of the picture; source: own elaboration based on www.google.com/maps

Pollution data, which were used in the research, are collected by the Provincial Environment Protection Inspectorate (Pol. Wojewódzki Inspektorat Ochrony Środowiska), which operates five measurement stations in Wrocław. In this study we focused on the only traffic station located near analysed intersection (GPS coordinates: 51.1050N, 16.9000E; height 120 m a.s.l.) and pollutants related with BC (based on literature review): particulate matter ($PM_{2.5}$) and CO. The eBC measurement was located 260 m away from intersection (Fig. 1). BC is a component of generally understood particulate matters. CO is the only carbon compound measured at the station. All automatically taken measurements are available at hourly intervals.

Due to the hourly frequency of data from the measuring station, the data obtained from the microaethalometer has also been aggregated to hourly values. They are determined as the average of 12 measurements made during an hour, provided that there are at least 10 valid measurements in an hour. Due to the missing data, 135 cases (hourly) were deleted. The data gaps were for two main reasons: they were removed due to incorrect values (extremely high or negative) or the measurements were not made due to the incorrect positioning of the filter. Ultimately, the dataset counted 529 cases.

The traffic data were provided by the Traffic and Public Transport Management Department of the Roads and City Maintenance Board in Wrocław (Pol. Zarząd Dróg i Utrzymania Miasta we Wrocławiu) under Intelligent Transport System (ITS), one of whose elements is the measurement of traffic volume at selected intersections. The system covers the analysed area, more precisely the intersection Hallera–Powstańców Śląskich. The data includes the number of vehicles crossing the intersection per hour. Traffic intensity shows a clear diurnal variability (Fig. 2). On its basis, a day was divided into four parts with respect to traffic conditions: 6–8 morning traffic peak (MTP), 9–14 during the day (DAY), 15–19 afternoon traffic peak (ATP) and 20–5 night (NIGHT).

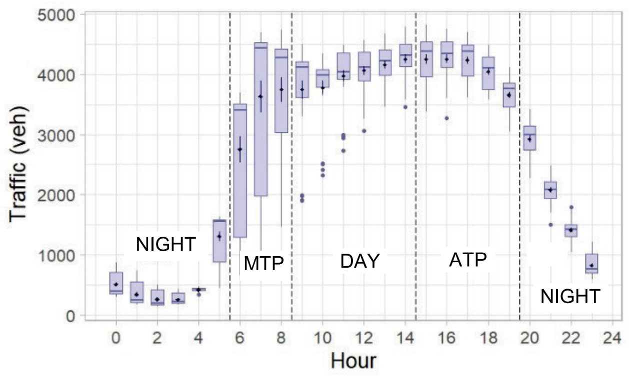


Fig. 2. Traffic flow hourly variation in analysed intersection; boxplot – Q_1, Me (median), Q_3; dot and vertical segments – mean with standard deviation; source: own elaboration

METHODS

Preliminary analysis of the data described above indicates non-normality distribution of hourly concentrations, for all three considered contaminants. The transformation of data by logarithm did not result in the distribution of the transformed variables being consistent with the normal distribution. Due to the expected interpretative possibilities of the relationship between eBC and other pollutants, no other transformations were tested. Due to impossibility ordinary least squares (OLS) method application as an alternative quantile regression model was applied (Koenker, 2005) using original (untransformed data). The main difference between quantile regression (QR) and OLS is the estimation of conditional medians (QR) instead of conditional mean (OLS). Thus, the classic minimisation of the mean square error (OLS) has been replaced by the minimisation of median absolute deviation with loss function giving asymmetric weights to the error depending on the quantile and overall sign of the error (QR). The median in QR could be replaced by any quantile. The value for the 25th quantile estimated on the basis of the QR model means that the explained variable, with a probability of 25%, will be lower than it, at the same time with 75% chance, above predicted value. The calculations at the papier were made using the open-source R (https://www.r-project.org) and *quantreg* package (Koenker *et al.*, no date). QR method was successfully used for modelling connected with air pollution e.g.: Vasseur and Aznarte (2021) for probabilistic forecasting of NO_2 pollution levels, Munir, Chen and Ropkins (2014) for characterising the relationship of ground-level ozone temporal variations to traffic-related air pollutants. Quantile regression is widely use in different air pollution connections with: health e.g. (Peralta *et al.*, 2022), economy (Fitzenberger *et al.*, 2022), ecology (Bandyopadhyay *et al.*, 2022) or socioeconomic (Yan *et al.*, 2020).

RESULTS

BASICS STATISTICS

According to the division the day into parts presented in section DATA, the basic statistics for the considered variables: traffic flow, eBC, CO and $PM_{2.5}$ concentration were determined (Tab. 1). The lowest traffic intensity was noticed at NIGHT: in average 1038 veh·h^{-1} and median 661 veh·h^{-1}. The difference between the given average measures results from the existence of high values for 20 o'clock when traffic is systematically decreasing. For the rest parts of the day such differences were not recorded, which indicates the homogeneity of the subsets. Morning traffic peak (MTP) is characterised by average values exceeding 3300 veh·h^{-1}. The highest values of traffic intensity occur during the day – DAY and afternoon traffic peak hours (ATP) in both cases, on average around 4000 and median around 4140 veh·h^{-1}. Similar values of the statistical measures for the DAY and ATP indicate similar traffic conditions. However, the concentrations of pollutants during these periods are noticeably different.

Both median and mean concentration of eBC for ATP is about 0.6 μg·m^{-3} (33 and 28% respectively) higher than for DAY. The same applies to CO: 21 and 20% respectively and $PM_{2.5}$: 7.5 and 20.5% respectively. This means that despite the comparable traffic intensity during the DAY and ATP, there are higher concentrations of pollutants in the afternoon, and therefore different conditions prevail in the atmosphere that residents breathe.

Based on the above observations, it was decided to analyse separately the relationships between the concentrations of the pollutants for each of the four indicated times of the day.

Table 1. Descriptive statistics

Variable	N	Min.	Q_1	Me	Mean	Q_3	Max.	*SD*
Traffic flow (veh·h^{-1})	**669**	**150**	**852**	**3420**	**3697**	**4190**	**4805**	**1631**
MTP	84	661	2844	3618	3374	4424	4738	1281
DAY	165	1905	3874	4136	3991	4332	4790	548
ATP	140	3041	3769	4142	4084	4452	4805	408
NIGHT	280	150	366	661	1038	1575	3418	879
eBC (μg·m^{-3})	**529**	**0.188**	**1.511**	**2.317**	**2.691**	**3.241**	**12.168**	**1.751**
MTP	78	0.501	1.942	2.886	3.479	4.334	11.986	2.448
DAY	80	0.351	1.180	1.780	2.069	2.669	9.500	1.460
ATP	121	0.986	1.749	2.370	2.685	3.125	8.766	1.362
NIGHT	250	0.188	1.480	2.412	2.637	3.341	8.531	1.607
CO (μg·m^{-3})	**666**	**377**	**560**	**656**	**704**	**783**	**1970**	**217**
MTP	84	443	692	784	835	945	1970	306
DAY	165	458	562	596	632	683	1110	110
ATP	139	476	625	723	759	833	1525	194
NIGHT	278	377	506	624	674	761	1439	216
$PM_{2.5}$ (μg·m^{-3})	**666**	**3.86**	**12.02**	**17.46**	**19.56**	**25.14**	**64.32**	**10.04**
MTP	83	3.97	14.29	20.61	23.06	29.12	64.32	12.06
DAY	163	4.56	9.87	14.41	15.63	18.49	45.52	7.42
ATP	140	5.49	11.93	15.49	17.93	22.23	45.02	7.98
NIGHT	280	3.86	13.14	20.61	21.61	28.50	59.49	10.75

Explanations: *N* = number of cases, *SD* = standard deviation, MTP = morning traffic peak, ATP = afternoon traffic peak, eBC = equivalent of black carbon, $PM_{2.5}$ = fine particulate matter, bold – statistics for all dataset.
Source: own study.

Analyses were performed for 521 cases from all three pollutants concentration values (eBC, CO and $PM_{2.5}$). A high, statistically significant, at the level of α = 0.05, correlation between the concentrations of eBC and CO was identified and lower but still statistically significant correlation eBC with $PM_{2.5}$ (Fig. 3). Due to the lack of conformity empirical eBC, CO and $PM_{2.5}$ distributions to normal distribution the Spearman's rank correlation coefficient was used.

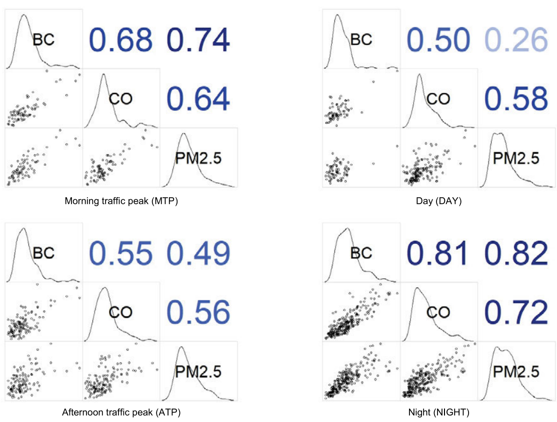


Fig. 3. Correlogram for analysed variables (Spearman's coefficient); BC = black carbon, CO = carbon monoxide, $PM_{2.5}$ = fine particulate matter; source: own study

Morning traffic peak hours are characterised by the highest concentrations of eBC (Mean = 3.479, Me = 2.886 μg·m^{-3}) from the four considered parts of the day, with the greatest deviation (*SD* = 2.448 μg·m^{-3}). CO and $PM_{2.5}$ concentrations for MTP morning hours show similar features. In this period, almost the greatest (except at night) is also the strength of the linear relationship between the concentrations of eBC and CO, and $PM_{2.5}$ (0.81 and 0.82 respectively). During the day (DAY), when the traffic intensity is relatively high throughout the entire period, the lowest values of both quartiles were observed (Q_1 = 0.012, Me = 1.780, Q_3 = 2.669 μg·m^{-3}) as well as the mean concentration of BC (2.069 μg·m^{-3}). Similar properties have been shown by the position measures for middle of the day hours (DAY) for CO and $PM_{2.5}$. High traffic during the day indicate high emissions with exhaust gases. However, along with the increase of the sunlight incidence angle, the processes of chemical transformations catalysed by photons intensify. As a result, carbon molecules react with nitrogen oxides, CH_4 and other gasses like volatile organic compounds, which significantly affects the modification of the amount of pollutants compared to the emission (Westberg, Cohen and Wilson, 1971). The lowest concentrations of eBC occur around noon when the sun is at its zenith (Fig. 4). Dynamic chemical changes and different reactivity of eBC and CO results in the lowest correlation coefficient equal to 0.50 for this part of the day (DAY).

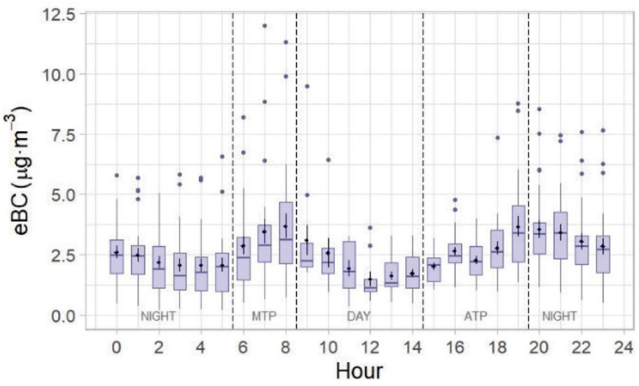


Fig. 4. Hourly variation of equivalent of black carbon (eBC) concentration in analysed intersection; boxplot – Q_1, Me, Q_3; dot and vertical segments – mean with standard deviation; source: own study

Completely different pollutant characteristics (Fig. 5b): eBC and quantitative $PM_{2.5}$ concentrating all particles solely due to their diameter, results in a low 0.26, statistically insignificant ($\alpha = 0.05$) correlation value in this part of the day (DAY). During afternoon traffic peak hours (ATP) when traffic flow is the most intense (Me = 4142, $\bar{x}$ = 4084 veh), the observed average eBC concentration measures are comparable with the daily averages (Me = 2.370, $\bar{x}$ = 2.685 µg·m^{-3} and Me = 2.317, $\bar{x}$ = 2.691 µg·m^{-3} respectivelly). During this part of the day, CO concentrations are relatively high: lower than for MTP, but higher than the average daily measures. On the other hand, $PM_{2.5}$ concentrations are slightly higher than the values for the DAY periods and lower than the daily average values. Between 15 and 19 (ATP) in Wrocław, the sun is sinking over the horizon. On October 1, 2021, sunset occurred at 18:24 and on October 29 at 17:25. Therefore, in this period, the influence of photons on chemical reactions taking place in the atmosphere is much lower than for DAY part (Fig. 4). The correlation coefficient between eBC and CO is equal 0.55, eBC with $PM_{2.5}$ 0.49. At NIGHT traffic flow is the lowest being on average 1/6 of the intensity observed during the day. Whereas the concentrations of eBC and CO are comparable to the average daily values with relatively high variability (Figs. 4 and 5a). Due to the lack of intense chemical changes in the atmosphere, the linear relationship between eBC and CO concentrations at night is the strongest in the entire day (correlation coefficient equal to 0.81). The relationship between eBC and $PM_{2.5}$ at night is also strong, with a correlation coefficient of 0.82.

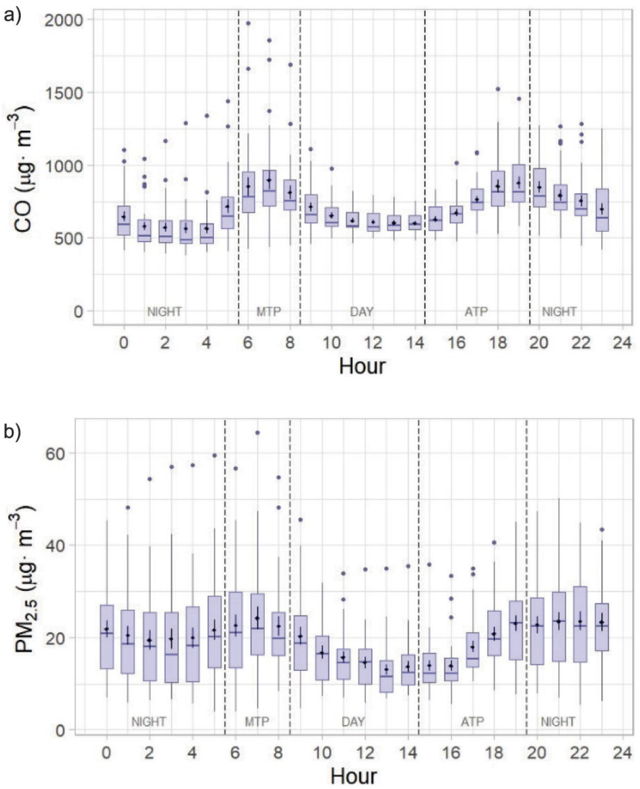


Fig. 5. Hourly variation of concentration in analysed intersection: a) carbon monoxide (CO), b) fine particulate matter ($PM_{2.5}$); boxplot – Q_1, Me, Q_3; dot and vertical segments – mean with standard deviation; source: own study

High correlation coefficients between eBC and CO was presented by Pan *et al.* (2011) based on diurnal concentrations. The correlations range from 0.87 to 0.94 depending on trajectory air mass pathways in China. One should remember that the average daily concentrations are similar to the normal distribution and mentioned authors determined the Pearson correlation coefficient, which may be the reason for the observed differences.

Due to the lack of statistical significance of the relationship between eBC and $PM_{2.5}$ during the day (DAY), only the eBC-CO reactions were quantified later.

QUANTILE REGRESSION

Quantile regression (QR) method (Koenker, 2005), unlike linear regression which uses ordinary last square method (OLS) to determine conditional mean, estimates the conditional median. Quantile regression could be extend to any quantile for a particular value in the feature variable. Additionally, QR has no assumptions about normality, homoscedasticity etc. like OLS.

The strong correlation between BC and CO concentrations indicates the existence of a relationship between the variables. Due to the lack of conformity variables to normal distribution, quantile regression analysis was performed using the *quantreg* (R-package). Quantile regression equation was estimated three quantiles: 0.1, 0.5 = Me and 0.9. The analysis results has been presented in Table 2 and Figure 6.

Table 2. Quantile regression equation equivalent of black carbon (eBC, in µg·m^{-3}), carbon monoxide (CO, in µg·m^{-3})

Part of the day	0.5 quantile regression	R^2	*MAPE*	*RMSE*
Morning traffic peak	eBC = –0.001537 + 0.007611CO	0.67	0.55	1856
Day	eBC = –0.003202 + 0.008043CO	0.46	0.60	1338
Afternoon traffic peak	eBC = –0.000634 + 0.004179CO	0.48	0.43	1359
Night	eBC = –0.001793 + 0.006419CO	0.72	0.48	1158

Explanations: R^2 = determination coefficient, *MAPE* = mean absolute percentage error, *RMSE* = root-mean-squared-error.
Source: own study.

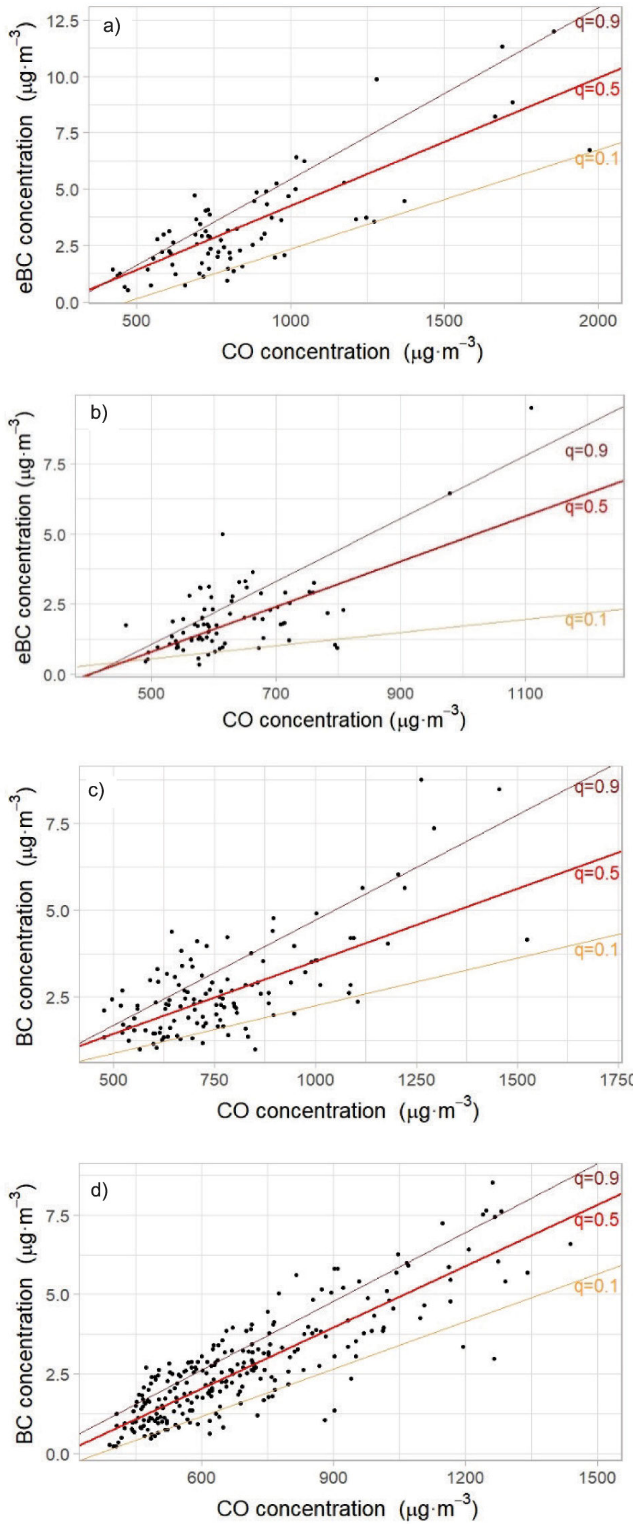
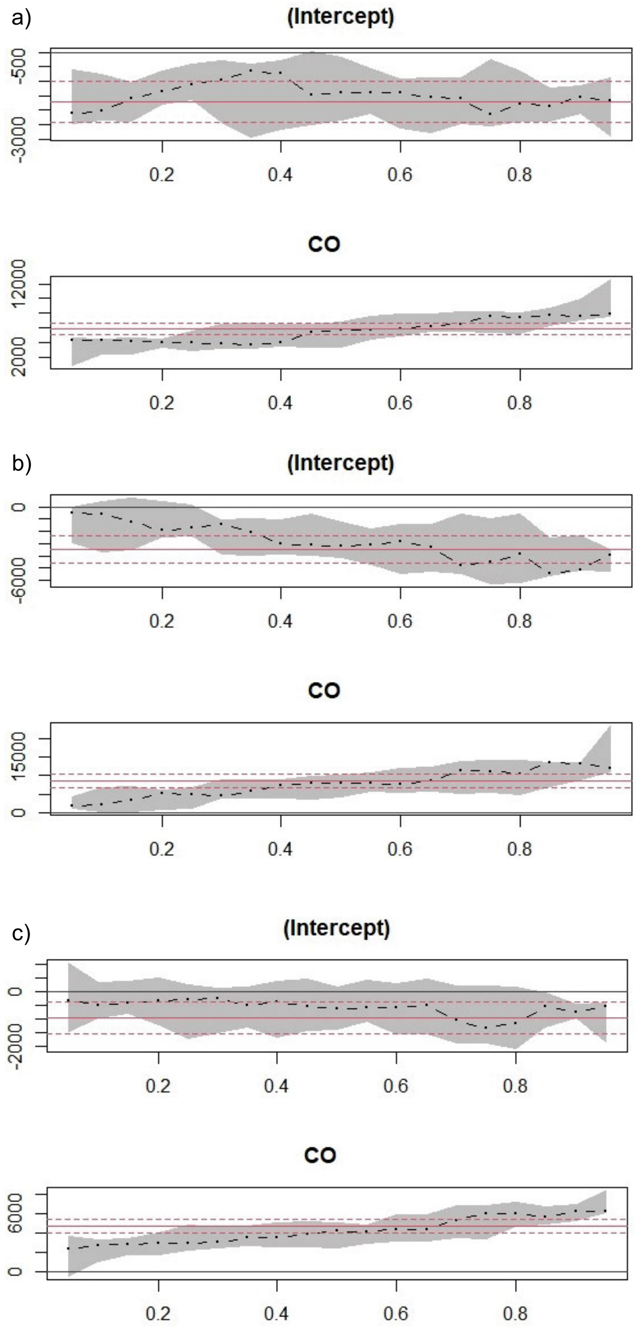


Fig. 6. Quantile regression lines for 0.1, 0.5 and 0.9 quantiles during the different parts of the day: a) morning traffic peak, b) day, c) afternoon traffic peak, d) night; BC = black carbon, CO = carbon monoxide; source: own study

In each case, the increase in CO concentration is related to the increase in BC, while for middle day hours (DAY) the increase in CO concentration is related to the highest increase in concentration BC – 8.043 μg·m^{-3} for each 1 mg·m^{-3} CO. For this part of the day, the lowest correlation and the weakest model fit were observed (Tab. 2). For night hours, the median quantile regression model was the best fit for empirical data (the highest R^2 = 0.72, the lowest *RMSE* = 1158 and *MAPE* = 0.48). Regression equations are different for each quantile (Figs. 5–6). The regression line for the 0.1 quantile should be interpreted as follows: there is a 10% chance the BC concentration is below the prediction.

The median in quantile regression corresponds to the mean in OLS. A comparison of the coefficients for each QR models determined for quantiles from 0.05 to 0.95 with a step of 0.05 with OLS coefficient (which is independent of quantiles – red horizontal lines on Fig. 7) shows consistent results. In all cases, the coefficients determined for q = 0.5 (median) were within the OLS regression coefficient interval. This means that with a 95% probability, the coefficients of the equations obtained by the QR method for the median and OLS do not differ from each other.



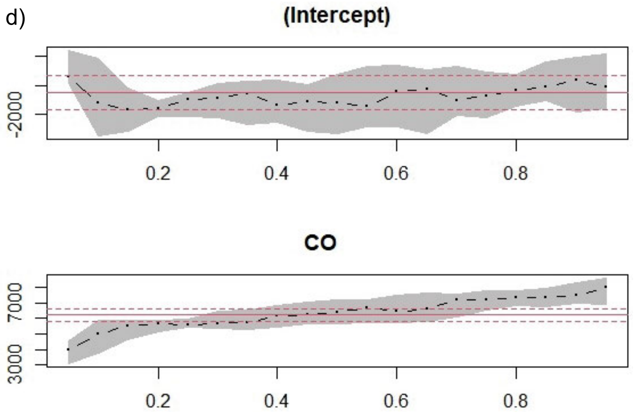


Fig. 7. Quantile regression coefficients for different quantiles (form 0.05 to 0.95) for different parts of the day: a) morning traffic peak, b) day, c) afternoon traffic peak, d) night; red line – ordinary least squares' coefficient with 0.95 confidence interval, CO carbon monoxide; source: own study

On the basis of the presented analyses, it can be concluded that it is possible to estimate the concentration of eBC on the basis of the recorded CO concentrations in the communication canyon. It should be remembered that the results of eBC estimation may be affected by different errors, depending on the time of day (the lowest errors for the afternoon traffic peak – ATP and the highest errors for DAY). The use of quantile regression also allows the estimation of BC concentrations on the basis of CO concentrations with a given probability of exceeding. Therefore, it can be concluded that during the morning traffic peak hours when the CO concentration is equal to 1500 μg·m^{-3}, with a probability of 90% BC concentration do not exceed 9.880 μg·m^{-3}. Such information can be a valuable material for analysing the exposure of residents and, consequently, the impact of BC on health.

DISCUSSION

Studies on BC are currently conducted around Europe and present different geographical contexts. The analysis of eBC concentrations at the fix station was also performed in Madrid and Jaén in Spain (Becerril-Valle *et al.*, 2017), where a BC equivalent mean (±*SD*) were 3.70 ±3.73 μg·m^{-3} at the traffic urban site, 2.33 ±2.96 μg·m^{-3} at the urban background location, and 2.61 ±5.04 μg·m^{-3} in the rural area. In presented measurements the means varies from 2.07 ±1.46 to 3.48 ±2.45 μg·m^{-3} depending on a part of the day and 2.69 ±1.75 μg·m^{-3} for full days datasets. Therefore, it can be concluded that the observed mean concentrations are comparable, but the concentration of eBC in Poland is characterised by a lower variability. There can be two reasons: a different climate and the size of the city. Wrocław has 0.6 mln inhabitants and Madrid – more than 3 mln. In Madrid with Mediterranean continental climate significant high air pollution episodes happen during the autumn under atmospheric anticyclonic stagnation conditions (Artíñano *et al.*, 2003). In two large cities – Sofia and Burgas in Bulgaria the monthly BC concentrations ranged from 0.37 to 3.6 μg·m^{-3} (Hristova *et al.*, 2022).

The BC measurements on 15 locations in Helsinki (Finland) shows the largest annual mean eBC concentrations at the traffic sites (from 0.67 to 2.64 μg·m^{-3}) and the lowest at the regional background sites (from 0.16 to 0.48 μg·m^{-3}) (Luoma *et al.*, 2021), therefore much less than in Wrocław. It should be noticed the much lower traffic in Helsinki. The highest intensity was indicated in the location Kehä I 69,200 veh per weekday thus 2883 veh·h^{-1}. In our study, the average traffic flow during the research period (including weekends) was equal to 3697 veh·h^{-1}.

Based on on-year from 1 April 2019 to 31 March 2020 measurements in Zabrze (Poland) measured mean eBC concentration for non-heating season (April–September) was 0.75 ±1.26 (range 0.39–8.02) and for heating season 4.70 ±3.13 (range 0.88–20.48 μg·m^{-3}) (Zioła *et al.*, 2021a). Thus, the values recorded in Wrocław are higher than those in Zabrze, despite similar climatic conditions. As shown above, the concentration of BC depends not only on solid sources (e.g. heating) but also on exhaust emissions from road transport. The measuring point in Wrocław was located right next to one of the main arteries of the city. The station in Zabrze was also located in the city center, but not directly on the street with heavy traffic. Presented in section 3 results correspond with other researchers conclusions from around the world. In one of the first paper on the correlation between black carbon aerosols and carbon monoxide over a urban site issue in India (Latha and Badarinath, 2004) the authors point to a strong positive correlation (R^2 = 0.74) with regression coefficient $6,4 \cdot 10^{-3} \frac{g\,BC}{g\,CO}$ which means an increase in BC concentration by 6.4 μg·m^{-3} with increase a CO concentration by 1 mg·m^{-3}. In our research, this coefficient, depending on the time of day, is equal from 4.3 to 8.0 μg·m^{-3} eBC with increase a CO concentration by 1 mg·m^{-3}.

Based on BC and CO measurements at the UNAM Atmospheric Observatory, located within the main campus of the National Autonomous University of Mexico during the period from November 2014 to July 2016, developed slope for BC CO model range from 3.36 to 4.04 depends on season with correlation from 0.54 to 0.71 respectively (Peralta *et al.*, 2019). The data do not include weekends. Urban sites had an average black carbon concentration of above 2.5 μg·m^{-3}, the suburban site 0.75 μg·m^{-3}, and the high-altitude site 0.27 μg·m^{-3}. The correlation may indicates that emissions are associated with a primary source – gasses emitted by vehicles.

BC data are not available from EU reference air quality monitoring networks (Rovira *et al.*, 2022) and there is a limited policy attention to black carbon emissions (Yamineva and Liu, 2019). At the same time, explaining the relationship between BC and other variables that are measured in environmental monitoring systems may contribute to a better understanding of the state of the environment in which people function. The introduction of BC monitoring, as postulated by the WHO, is a task that may pose both financial and organisational challenges for many countries, however, promising tests of low-cost BC sensors are under current research (Wai *et al.*, 2022). Before it will be possible to implement direct measurements of BC on a larger scale, it is worth looking for alternative solutions that will enable faster estimation of the level of eBC in the air in cities. Being aware of the errors in assessing one variable on the basis of others, such an approach is part of the indirect estimation trend (Ke, Khanna and Zhou, 2022), which is carried out not only in the case of air (Barandica *et al.*, 2014; Suganuma *et al.*, 2019), but also other components of the environment (McRoberts *et al.*, 2015;

Matos *et al.*, 2019; Chrobak *et al.*, 2021; Sahu, Mohanta and Kumar, 2022).

Findings of this research may support local governments while designing local mobility policies in the process of selection more suitable paths for non-motorised modes of transport. Promoting walking or cycling should go hand in hand with ensuring safe and healthy conditions for people (Kamińska, Turek and Kazak, 2022). Knowing the values of the level of carbon monoxide, which is often measured by the existing air quality measurement stations, it is possible to estimate the level of black carbon to which users may be exposed. The existing air quality monitoring can therefore be helpful in determining alternative routes to main streets where more sustainable ways of movement will be supported. Apart from transport channels determination, the obtained results may also be useful in creating clean air zones in cities. Such solutions have been introduced in many cities around Europe. With limited mobility of combustion vehicles and measurement of the concentration of carbon monoxide, it will be possible to estimate the change in the concentration of black carbon. As a result it will enable to assess the effectiveness of the introduced changes and their impact on the living conditions of residents. Similarly to assessment of clean air zones, such evaluation can help to distinguish which areas in urban structure have got the best conditions to be used to create public spaces and to guarantee the best environmental conditions for citizens.

CONCLUSIONS

Based on the conducted research it was possible to formulate a few conclusions.

1. Despite of the fact that air quality monitoring systems might not include measurement of equivalent of black carbon (eBC), it is possible to assess possible level of eBC concentration based on more commonly evaluated factor which is carbon monoxide (CO). The use of quantile regression makes it possible to correctly estimate the eBC concentration that will not be exceeded with a given probability based on the known CO concentration.
2. For the case of measurement point in Wrocław it was estimated that for 1 mg·m^{-3} of CO, concentration of eBC rise by:61 μg·m^{-3} during morning traffic peak hours, 8.04 μg·m^{-3} during middle day hours, 4.18 μg·m^{-3} during afternoon traffic peak hours, and 6.42 μg·m^{-3} during night hours.
3. The accuracy of eBC concentration estimation by CO concentration is influenced by sunlight, which results in better estimation accuracy for night hours.
4. Considering different geographic characteristics of cities and variety of their air pollution level, defining scaling factors between eBC and other variables requires local measurement and customised approach.

The research has some limitations which have to be highlighted. Firstly, eBC data collection period last one month. However, future studies could cover longer period presenting seasonal patterns of eBC concentration. Additional limitation is the fact of analysing one air quality measurement station. Selected station was the only one located close to traffic management system which allowed to combine air quality measurement together with data on car congestion. Studies conducted in more remote locations could give less data for multivariable analysis, however, it could present spatial diversification of eBC concentration around a city.

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