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Passenger exposure to aerosols on intra-European train travel

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Abstract

Knowledge about personal aerosol exposure in different environments is fundamental for individual and common decision-making, shaping the way we build our infrastructure or change our social behaviours. Aerosols are a leading cause of death and well-known vector for infectious diseases. Yet, passenger exposure to aerosols during long-distance train travel is surprisingly underexplored. Two small, light-weight personal monitoring instruments were employed during a train journey across Europe, to measure the fine particle ($PM_{2.5}$) and equivalent black carbon (eBC) passenger exposure, respectively. The journey was divided into three legs, inside three different trains, and two layovers in city environments. Highest mean concentrations of $PM_{2.5}$ and eBC were found within the oldest train type, and revealed $PM_{2.5}$ concentrations of 58.4 ± 12.7 µg m^{-3} and eBC of 5.4 ± 2.9 µg m^{-3}. The more modern the train system was, the lower the measured concentrations were to be found. In the newest tested system, the air quality was considerably better inside the train than outdoor air measured by a monitoring network, or simulated by the Copernicus Atmosphere Monitoring Service (CAMS) model ensemble analysis. The mean $PM_{2.5}$ concentration was roughly 20% lower inside the train than the outdoor air simulated by CAMS. Both the light-weight personal monitoring and the monitoring network indicate that the CAMS ensemble substantially underestimates $PM_{2.5}$ concentrations for the day of the journey. Effective ventilation and air filtration significantly decrease the passenger's aerosol exposure, as compared to a stay in outdoor air, leading to a small statistical increase in life expectancy. If this could also reduce the risk of contagion with an infectious disease remains to be explored.

Keywords Air quality · Fine particles · Black carbon · Passenger exposure

Introduction

High mobility and a carbon footprint in line with the Paris 1.5 °C target remain in conflict with each other. Air and land transport are the number one cause of greenhouse gas (by CO_2 equivalent) emissions among the top 1% EU households, which are defined as having an annual net income of > €40,000 per person (Ivanova and Wood 2020). As long as mobility remains a desire of our society and its most affluent elements, more sustainable ways of transport must be sought. Renewable energy–powered high-speed trains are undoubtedly the most sustainable mode of (mass) transport, currently available. Yet little is known about the quality of air inside intra-European or long-distance trains in general.

This is relevant for two reasons: (1) air pollution from aerosols is a leading cause of death (Lelieveld et al. 2020) and (2) being in close proximity to other humans inside narrow spaces for prolonged periods of time bears additional risks, like the spread of infectious diseases via aerosols (Morawska et al. 2020; Prather et al. 2020). Knowledge about potential exposure to aerosols in train carriages is a factor which passengers will likely consider in their decision-making, if there are alternative means of transport.

In this study, concentrations of particulate matter smaller than 2.5 µm ($PM_{2.5}$) and equivalent black carbon (eBC), particles of incomplete combustion, were observed with two small, light-weight personal monitoring instruments during an ~ 8.5 h journey from Zürich, Switzerland, to Amsterdam, The Netherlands. Similar work has been performed in different micro-environments or commuting environments around the world (Karanasiou et al. 2014; Kaur et al. 2007), but never in long-distance or international trains. Very few

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studies exist with observations during relatively longer (1–2 h) journeys (Abadie et al. 2004; Fridell et al. 2011; Leutwyler et al. 2002), of which two were measured in an era where smoking was still allowed on trains (Abadie et al. 2004; Leutwyler et al. 2002). Studies with passenger carriages are often conducted in local city underground networks (Cheng et al. 2012; Johansson and Johansson 2003; Kam et al. 2011; Li et al. 2007; Smith et al. 2020; Van Ryswyk et al. 2017; Vilcassim et al. 2014) or local overground micro-environments (Dons et al. 2012; Hasenfratz et al. 2014; Morales Betancourt et al. 2017; Ragettli et al. 2013; Yang et al. 2015).

A systematic review of passenger exposure during short-distance micro-environment commute found that, compared to pedestrians and cyclists, the most exposed people are passengers in cars without ventilation settings, followed by busses, motorcycles, cars with ventilation, and finally local train and subway systems (Cepeda et al. 2017). When physical activity was considered, the review authors found that passengers of motorised transport lose, statistically, up to 1 year of life expectancy compared to cyclists. Knowledge about air pollution exposure of long-distance train travelers will be an addition to future assessments of exposure studies, and can guide personal and common decision-making.

Material and methods

Experimental settings

Air quality measurements were conducted on a train commute from Zürich, Switzerland, to Amsterdam, The Netherlands, on Wednesday the 23rd January 2019 (Table 1). Thanks to the German Railways' (DB) high-speed rail system with its Intercity-Express (ICE) trains, the 840 km distance is overcome in about 8.5 h.

Each of the two light-weight instruments (described in more detail in the following section) was placed inside one of the two stretch-woven pockets on the outside of a backpack. The backpack was stored in the open overhead compartment on each of the three trains connecting Zürich and Amsterdam. In this manner, the instruments were not placed in the direct airflow of the train's air conditioning (aeration) system, yet the inlet faced towards the cabin centre. It is fair to assume enough turbulence within a passenger carriage that aerosol concentrations are evenly distributed. Differences might exist among carriages of the same train composition, due to varying types of deployed carriages and the performance of their aeration system. The Swiss Federal Railways (SBB) and DB feature both 1st and 2nd class seats. The instruments were placed in the 2nd class, which transports more people per train and carriage. All trains were electricity-powered.

Table 1 Train connection details according to the timetable. No major delays or other mutations were experienced

Train stop	Date	Time	Platform	Train ID
Zürich HB	23.01.2019	15:00 (dep.)	16	IC 776
Basel SBB	23.01.2019	15:53 (arr.)	5	(IC)
Basel SBB	23.01.2019	16:13 (dep.)	6	ICE 274
Frankfurt (Main) Hbf	23.01.2019	19:08 (arr.)	9	(ICE 1)
Frankfurt (Main) Hbf	23.01.2019	19:29 (dep.)	19	ICE 120
Amsterdam Centraal	23.01.2019	23:28 (arr.)	5a	(ICE 3)

The first train, Intercity IC 776, was operated and owned by SBB and the instrument was placed inside a relatively old carriage (type Z2, carriage ID 2173), built between 1972 and 1978. These carriages are all one open space with 80 seats, grouped into units of four (two seats facing each other, 'Vis-à-Vis') on each side of the carriage. Within this relatively small volume with noticeable turbulence, it is safe to assume that all passengers are exposed to the same aerosol concentrations.

The second train was an ICE 274 operated and owned by DB, on route Basel-Berlin. This train is a first-generation ICE 1 (five other variants exist today: ICE 2, ICE 3, ICE T, ICE TD, ICE 4), built between 1988 and 1993, with a max. speed of 280 km h^{-1}. The seats inside the chosen carriage are a mixture of compartments with six seats (24 seats total) and open space seating with single seats, rows by two, and 'Vis-à-Vis' (50 seats total). The instruments were placed in the open space seating. The air quality in the compartments of six, which can be closed by sliding door, can be expected to vary significantly and would not be representative of the overall carriage air quality.

The last train was an ICE 120, operated by DB as well, on route Frankfurt-Amsterdam. This third-generation ICE 3 was built between 1997 and 2012, with a maximum speed of 330 km h^{-1} (in operation up to 300 km h^{-1} in Germany, and 320 km h^{-1} in France). Various 2nd class carriages exist, with 52, 54, 64, and 72 seats. The instruments were placed in an open space seating featuring 72 seats total.

The instruments were switched on upon boarding the train in Zürich, and were only switched off for a couple of minutes (inside the connecting train) in Basel, to check if data retrieval was in order. The final minutes of data collection were recorded during a short walk from the Amsterdam central station through the Eastern inner city.

Scattering

A personal aerosol monitor, the TSI SidePak™ AM520 Optical Particle Counter, was used to measure $PM_{2.5}$ particle concentration. The AM520 uses 90° light scattering of a 650-nm laser diode and is factory-calibrated against a gravimetric reference ISO12103-1 (Arizona Road Dust) aerosols with a density of 2.65 mg m^{-3} and a volumetric mean diameter (VMD) of 2.12 µm (Jiang et al. 2011). Measurements were made at a flow of 1.7 L min^{-1} at 10-s intervals, using the default calibration factor for ambient aerosol 0.38 (Dacunto et al. 2013). Given that the right calibration factor is applied, the AM520 delivers reliable results ($R^2 = 0.82$), when compared to reference instruments such as a BAM 1020, Beta Ray Attenuation Monitor 1020, MetOne Instruments (Stauffer et al. 2020). The AM520 was tested during chamber experiments against computed mass concentration from a Scanning Mobility Particle Sizer (SMPS), as described in Vernooij et al. (in prep.) and Vernooij and Winiger (2019). Using the PM_1 particle impactor, a linear R^2 of 0.84 (p-value < 0.001) was found.

Absorption

A light-weight aethalometer (MicroAeth® AE51, AethLabs) was used for the measurement of equivalent black carbon (eBC). The aethalometer measures aerosol absorption at 880 nm on a T60 borosilicate glass-fibre filter with Teflon coating, with a precision of ± 0.1 µg m^{-3} (minute average at 150 mL min^{-1}). Measurements were made at 30-s intervals using a flow of 100 mL min^{-1}.

The fidelity of the aethalometer was tested during chamber experiments against a reference instrument, a multi-wavelength aethalometer (AE33, Magee Scientific), as described in Vernooij et al. (in prep.) and Vernooij and Winiger (2019). Good agreement was found at 880 nm between the two instruments, with a linear R^2 of 0.95 (p-value < 0.001) at concentrations up to 100 µg m^{-3}. A study with several AE51 found mean uncertainty ranges of about 10% when compared to a stationary Multi-Angle Absorption Photometer (MAAP) (Viana et al. 2015). Hence, the AE51 aethalometer is a reliable and suitable instrument for mobile absorption measurements.

Model

The hourly $PM_{2.5}$ model data of January 23rd 2019 was downloaded from the open-access platform Atmosphere Data Store of the Copernicus Atmosphere Monitoring Service (CAMS 2020). CAMS is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission. The data was downloaded as ensemble analysis from the available models for that date CHIMERE, EMEP, LOTOS-EUROS, MATCH, MOCAGE, SILAM, and EURAD-IM (DEHM and GEM-AQ data are only available since October 16th 2019). The ensemble has a 0.1° resolution and the values are calculated for each grid from the median of the different model values (Marécal et al. 2015). BC data was not available for January 23rd 2019.

This analysis contains modified Copernicus Atmosphere Monitoring Service information 2020; neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

Reference stations

Daily averaged $PM_{2.5}$ data was downloaded from the open-access platform of the German Environment Agency (UBA 2020b). This database contains air quality data from all official German air quality monitoring stations, belonging to federal and state monitoring networks. Hourly eBC data was kindly provided by the German Environment Agency's Air Quality Assessment unit (II 4.2) upon request. Information on the individual stations can be found on another open-access platform (UBA 2020a). A selection of the available stations is given in Table 2, i.e. a full list of stations that provided eBC data.

Data analysis

All data analysis was conducted in python using Jupyter notebooks (Kluyver et al. 2016) and the following packages:

NumPy 1.18.1 (Oliphant 2006), Pandas 1.0.3 (McKinney et al. 2010), Matplotlib 3.1.3 (Hunter 2007), xarray 0.15.1 (Hoyer and Hamman 2017), SciPy 1.4.1 (SciPy 1.0 Contributors et al. 2020), NetCDF4 1.4.2 (NETCDF4 2020), and CDO 1.9.8 (Schulzweida 2019).

GPS data was generated using the android My Tracks app (v1.1) on a Fairphone 2 mobile device. GPS bounce was fixed by removing physically impossible changes in geographical data, removing the few data points leading to train speeds above 400 km h^{-1} (maximum operational ICE train speed is around 300 km h^{-1}). This GPS dataset was merged with the data from the SidePak™ AM520 and the MicroAeth® AE51. Missing GPS signal led to several smaller gaps, when projecting the data on a map.

Hourly CAMS $PM_{2.5}$ was resampled to daily averages with xarray. The anomaly (divergence) between the daily model average and the scattering data of the reference network or TSI SidePak™ AM520, respectively, was computed using CDO's *remapbil* and *sub* functions (Schulzweida 2019).

Results and discussion

Concentration measurements

Absorption and scattering observations with the two instruments are arranged in five groups, according to the different

Table 2 All stations within the network of the German Environment Agency that produced eBC data for January 23, 2019

Station code	Station name	Classification	$PM_{2.5}$ instrument	eBC instrument
DERP007	Mainz-Mombach	Urban background	Only PM_{10}	MAAP
DERP010	Mainz-Parcusstraße	Urban traffic	Nephelometry and beta attenuation	MAAP
DERP041	Ludwigshafen-Heinigstraße	Urban traffic	"Light scattering"	MAAP
DERP045	Koblenz-Hohenfelder Straße	Urban traffic	Only PM_{10}	MAAP
DERP046	Neuwied-Hermannstraße	Urban traffic	Nephelometry and beta attenuation	MAAP
DERP047	Trier-Pfalzel	Suburban industrial	Nephelometry and beta attenuation	MAAP
DERP060	Pirmasens-Innenstadt	Urban background	Only PM_{10}	MAAP
DEST050	Halle/Nord	Urban background	Nephelometry and beta attenuation	"light absorption"
DEST077	Magdeburg/West	Urban background	Nephelometry and beta attenuation	"light absorption"
DEST089	Zartau/Waldstation	Rural regional background	Only PM10	"light absorption"
DEST102	Halle/Paracelsusstr	Urban traffic	"Light scattering"	"light absorption"
DEST103	Magdeburg Schleinufer	Urban traffic	Low volume sampler (gravimetry)	"light absorption"
DEUB005	Waldhof	Rural background	Nephelometry and beta attenuation	MAAP

stages of the recorded train journey (Fig. 1). The three different trains are categorized by train type (IC, ICE1, and ICE3; according to Table 1). In addition to those longer train legs are the two city environments in Frankfurt (FRA) and Amsterdam (AMS), measured outside of the trains. Observations at FRA consist only of a 5-min change of trains, including a walk through a pedestrian underpass, and are likely not representative of the city or even the main train station of Frankfurt. The 15-min walk in AMS also only gives a glimpse into the inner-city air quality. In Basel, the connecting trains were on the same platform and the changeover was so fast (<30 s) that almost no measured data is available.

The $PM_{2.5}$ measurements revealed that passengers experienced the highest concentrations in the IC (leg 1), with mean concentrations of 58.4 ± 12.7 μg m^{-3} (1 standard deviation; σ). Mean concentrations decreased in the consecutive train ICE1 (leg 2) to 32.6 ± 7.2 μg m^{-3}, and further to 21.5 ± 7.3 μg m^{-3} in the final (leg 3) train. The two cities showed similar values of 55.3 ± 15.3 μg m^{-3} (FRA) and 51.9 ± 9.9 μg m^{-3} (AMS), comparable to the IC train.

The absorption measurements showed a similar pattern to the scattering observations. The highest mean eBC was observed in the IC with 5.4 ± 2.9 μg m^{-3} (1 σ), with consecutively decreasing concentrations in the following ICE1 (1.4 ± 0.7 μg m^{-3}) and ICE3 (0.5 ± 0.2 μg m^{-3}) trains. eBC mass concentrations in FRA were again slightly higher (3.4 ± 0.3 μg m^{-3}) compared to AMS (2.5 ± 1.7 μg m^{-3}).

The eBC and $PM_{2.5}$ concentration show relatively good linear correlations of $R^2 = 0.73$ (p-value < 0.001). The respective concentration changes show a very similar pattern over the entire travel distance (Fig. 2). During the first leg from Zürich to Basel, some of the highest values of the entire campaign were frequently recorded for both eBC and $PM_{2.5}$. Resulting eBC and $PM_{2.5}$ exposure levels in the IC train were comparable to busy roadsides in an urban European environment (Karanasiou et al. 2014). At times, a metallic smell could be sensed as a result of braking. It is likely that most of the highest spikes in both eBC and $PM_{2.5}$ were created through abrasion and other processes during deceleration. There is strong evidence that this was mostly iron oxide (e.g. Fe_2O_3) (Bukowiecki et al. 2007; Burkhardt et al. 2008). It is also likely that eBC measurements have been particularly influenced by iron and other metal oxides, leading to overestimated eBC readings. The influence of metal oxides could be quantified, if absorption had been measured at more than one wavelength, as metal oxides absorb stronger at lower wavelengths (Alfaro 2004). On the other hand, it has been shown that our particular type of instrument is underestimated by up to 70%, depending on the specific treatment of the filter loading effect (Good et al. 2017). The here presented data are therefore from the direct reading of the instrument, without any corrections. Corrections would only be possible if the measured aerosol would have been monitored with e.g. a multi-wavelength or multi-spot aethalometer (Drinovec et al. 2015). These sources of uncertainty present a major limitation of the one-wavelength micro-aethalometer measurements. However, the relatively old train type in question is less and less in operation. Most commuters in Switzerland sit in newer carriages nowadays, presumably with better air filtration systems. The metallic smell of the brakes is at least mostly a thing of the past.

No peculiar patterns emerged from the measurements of the second leg in the ICE1. The 5-min change of trains at the end of the second leg at the FRA main station led to increased particle exposure, for both eBC and $PM_{2.5}$. Observed mean concentrations of $PM_{2.5}$ were higher than what was found in a comparable study with 30-min measurements during summer in and around FRA main station (Gerber et al. 2014). The difference in observation could be

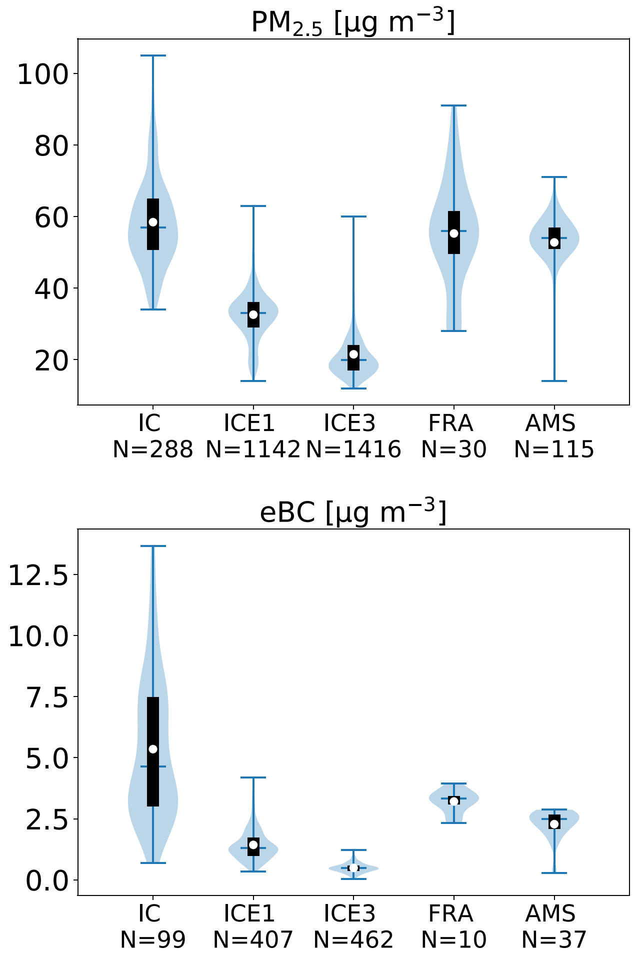

Fig. 1 Violin plots showing the distribution of measurements made for particulate matter $PM_{2.5}$ (top) and equivalent black carbon eBC (bottom). The top and bottom whiskers show the range of the data. The black box extends from the lower to upper quartile values of the data, with a line at the median. The white point indicates the mean. IC, ICE1, and ICE3 stand for the three different train types of the journey (according to Table 1). FRA and AMS are the cities of Frankfurt and Amsterdam, respectively. Sample size (*N*) is indicated below the label

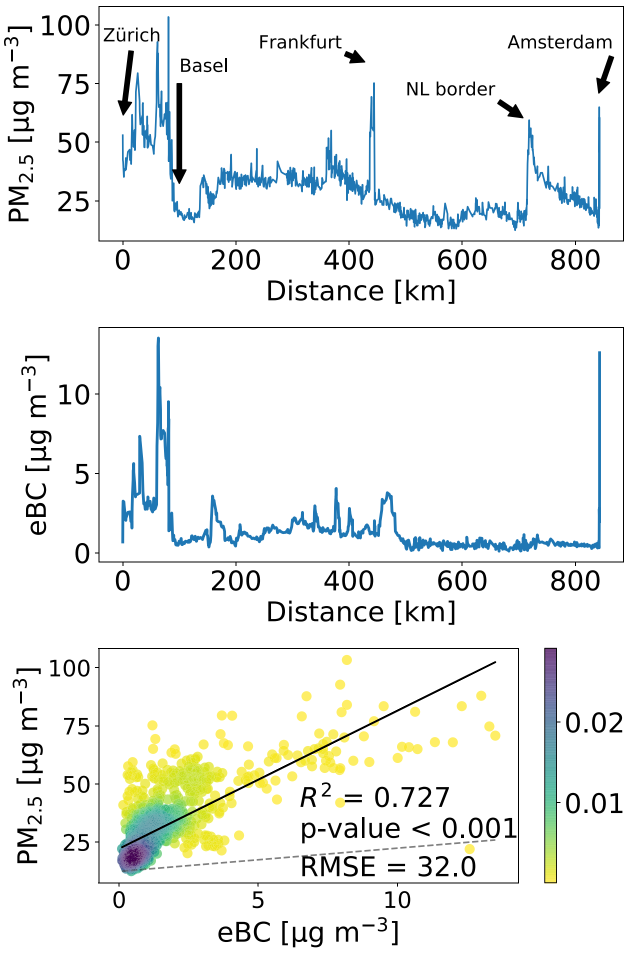

Fig. 2 Particulate matter $PM_{2.5}$ (top) and equivalent black carbon eBC (middle) concentrations during the entire journey from Zürich to Amsterdam. Note that eBC is slightly off compared to $PM_{2.5}$, because of the different sampling interval, short interruptions in measurements, and resulting fit to GPS measurements. Correlation of $PM_{2.5}$ and eBC (bottom) shows linear R^2 (black line), *p*-value, and root mean square error (RMSE). The colour code shows observation density fraction and the 1:1 ratio (dashed line)

due to differences in daily and seasonal particle load (i.e. relatively higher winter vs lower summer concentrations).

On the journey from FRA to AMS, concentration measurements of eBC concentration remained stable. Concentrations of $PM_{2.5}$, on the other hand, spike right at the Dutch-German border and thereafter slowly decrease to pre-border values (Fig. 3). It is very likely that this is caused by the change of the electric traction system at the border from Germany's 15 kV_{AC} to the Dutch 1.5 kV_{DC} (new high-speed lines use 25 kV_{AC}). The system change happens via rolling transition, whereby the ICE3 train (previous generations are single voltage only) is detached from the German grid and reconnected to the Dutch grid without ever stopping. The pantograph of the 15 kV_{AC} transformer retracts from the overhead wire before the 15 kV_{AC} pantograph extends on the other side of the border. In-between this process, there is no current on the train. Active air filtration stops and outside air intrudes unfiltered into the passenger carriage. This border can be classified as rural background, with a strong influence of agriculture, as indicated by the relatively high (hourly) ammonia concentrations simulated by the CAMS model ensemble (for the day of the journey). The CAMS model ensemble showed increased $PM_{2.5}$ values at the border for 22:00 CET (roughly the time when the train was crossing), from a westward-moving plume over northern Germany (Figure S2). The peak of the plume was upwind of the train tracks. No information on black carbon is available from CAMS, but carbon monoxide concentrations (a proxy for incomplete combustion) were relatively low, showing

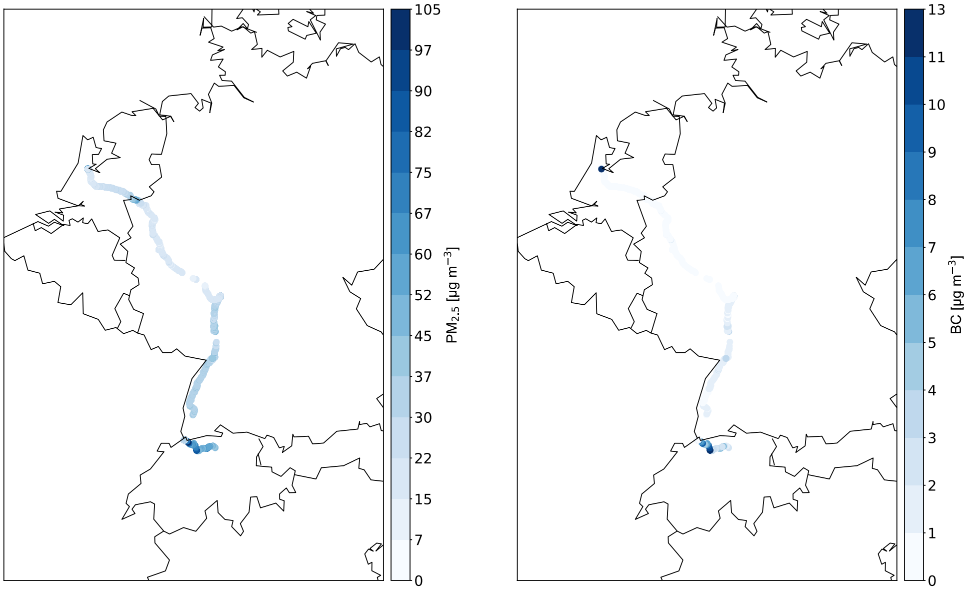

Fig. 3 Geographical view of the particulate matter $PM_{2.5}$ (left) and equivalent black carbon eBC (right) concentrations during the entire journey from Zürich to Amsterdam. Note the missing data points resulting from the GPS fit

only one big point source further away and downwind of the train tracks.

After disembarking the train in AMS, the observations were continued by foot, walking through a pedestrian underpass and exiting the station on the Eastside. The walk led along a canal towards the East of the inner city, through an area which is largely closed off to taxi traffic (a main source of traffic emissions) after 22 o'clock, walking further eastward. The instruments were switched off right beyond the edge of the low-emission zone (Figure S1). Measurements in city environments show high variations over short distances (Alas et al. 2019; Van den Bossche et al. 2015). The herein presented data is not representative of the general air quality in Amsterdam and functions only as a contrast to the in-train observations.

Analysis of model $PM_{2.5}$ vs personal aerosol monitor

As a first reference, the $PM_{2.5}$ observations made inside the train were compared to the CAMS ensemble analysis (Fig. 4). Therefore, the observations were subtracted from the mean of all hourly model values (i.e. the daily model mean), to give the divergence, hereafter referred to as anomaly. Negative values mean that the model concentrations are lower than the observations. The overall anomaly of the entire journey was − 4.06 ± 14.4 μg m^{-3}

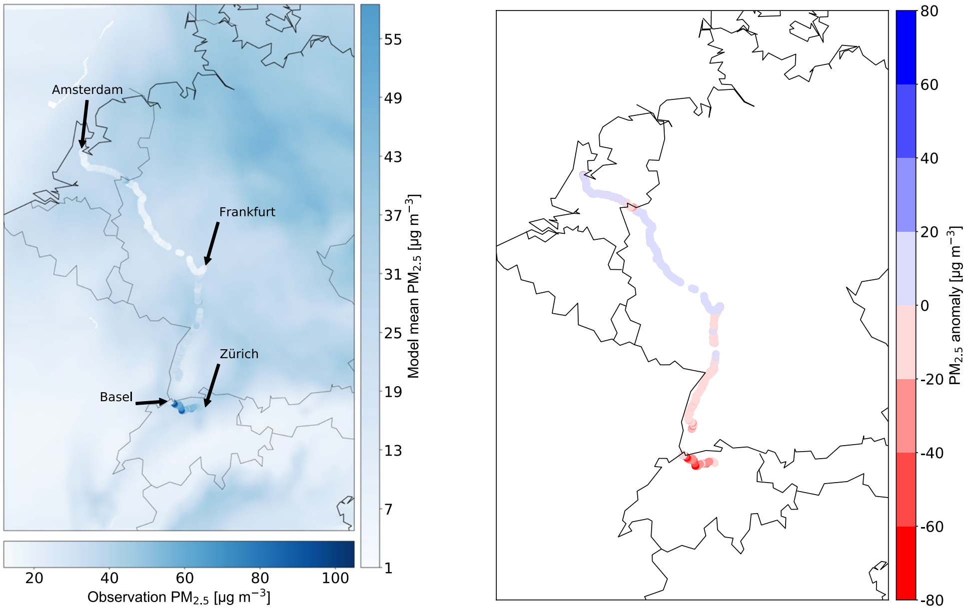

Fig. 4 Comparison of observed to modelled $PM_{2.5}$. Daily mean model $PM_{2.5}$ for January 23rd compared to high-resolution $PM_{2.5}$ observation (left). The same colour scale applies to both data. Anomaly of observation and model data (right), i.e. divergence of model from observation. Negative values (red) indicate where observations are higher than the model, and vice versa

(1 σ). For the different train legs, the highest anomaly was found for leg 1 (IC) − 15.0 ± 19.6 μg m^{-3}, followed by leg 2 (ICE1) − 8.6 ± 7.0 μg m^{-3}, and leg 3 (ICE3) + 4.9 ± 7.2 μg m^{-3}. The number of measurements in the two different city environments was relatively low; therefore, no anomaly is given. However, these results suggest that at least for half of the journey, specifically inside the ICE3, the air was cleaner than the outside air, whereas during the first leg, inside the old IC, the air was considerably worse than the outside air. The roughly 20% lower $PM_{2.5}$ concentration inside the ICE3, compared to CAMS outdoor air, was a result of the air filtration system of this train. According to the French National Railway Company (Société nationale des chemins de fer français, SNCF), in modern trains, the entire air volume inside the carriage is replaced with filtered air from outdoors within a few minutes (SNCF 2020). Compared to staying outdoors, the lower aerosol exposure inside the ICE3 should clearly be beneficial to respiratory health. However, proving statistical relevance is difficult. Especially for this study, which only measured one train journey, and offers a limited snapshot only. Using the method by Burnett et al. (2018) to calculate excess mortality due to $PM_{2.5}$ exposure, it shows that the air inside the most modern train has an attributable mortality fraction that is roughly half as high as that in the oldest train carriage (or the two city environments). The excess mortality due to $PM_{2.5}$ exposure can be calculated as the product of a country-specific baseline mortality rate and population-attributable mortality fraction. For Western Europe, Burnett et al. (2018) calculate that a 100% decrease in air pollution would save about 400,000 lives per year. The following calculation makes the big assumption that the concentrations we measured during 1 day would be stable and valid for an entire year, which is of course unrealistic, as indoor and outdoor concentrations likely change substantially over time and space. However, it goes to show what kind of statistical calculations could be performed with all these numbers and underlying assumptions. When applying Burnett et al.'s (2018) method to the train air and normalizing it per German passenger and per hour of train journey, the oldest train carriage leads to a decrease of statistical life expectancy of ~ 1 min per hour spent in the old train (or equivalent air quality), compared to the newest studied train system. Although the statistical significance of such a number is questionable, it would be tempting to say that sitting inside a (potentially delayed) ICE3 (and newer generations) would actually extend your life expectancy compared to being outdoors. Whether the decreased aerosol exposure has any influence of potential contagion with infectious diseases would be another very interesting hypothesis to follow up on.

$PM_{2.5}$ analysis of the model, reference network, and personal aerosol monitor

The observations and the CAMS ensemble analysis were compared to the monitoring network managed by the German Environment Agency. This network of reference stations spatially spans a large part of the entire journey (Fig. 5). Several stations lie more or less in the vicinity of the passing trains. Without even a quantitative analysis, it is apparent that the air inside of the 3rd leg (ICE3) was much cleaner than the outside air, confirming the first comparison of observations and model ensemble.

Daily averages of both the reference stations and the CAMS ensemble analysis can be subtracted from each other in the same fashion as has been done for the analysis of model $PM_{2.5}$ and the personal aerosol monitor. This gives an overall anomaly of − 12.2 ± 7.7 μg m^{-3} (1 σ). Anomalies were especially high in German regions where the annual average $PM_{2.5}$ air pollution is the highest (Lelieveld et al. 2020). This could mean that the air inside the ICE3 train carriage was effectively > 20% cleaner than outdoors.

eBC reference network vs micro-aethalometer

Only a few stations monitored eBC data for the day of the journey (Fig. 5). The mean of each station and the comparison of the closest 5 measurements of leg 2 and leg 3, respectively, can be found in Table 3. DERP007, an urban background site, had similar values to the eBC of the 2nd leg. The remaining stations are urban traffic sites, which monitored considerably higher values than observed inside the 2nd leg train. For the 3rd leg, all reference stations had considerably higher values than the micro-aethalometer. Reference measurements were all monitored using MAAP instruments, to which the micro-aethalometer measurements show an uncertainty of only 7 to 12% (Viana et al. 2015). The differences in measurements are therefore due to other reasons. If we would assume that both observations are conducted in the same open environment, a large part would surely be due to the geographical distance. However, the biggest influence stems from the air filtration system used in the two different generations of ICE trains.

Conclusion

This limited study shows that the primary factor for the aerosol concentrations and therefore passenger exposure was the type of train carriage, i.e. the applied aerosol filtration system. The newer a train model was, the better its air filtration system compared to the older model. The newest type had even considerably better air quality values than one would expect from outdoor air, whether the outdoor air is measured

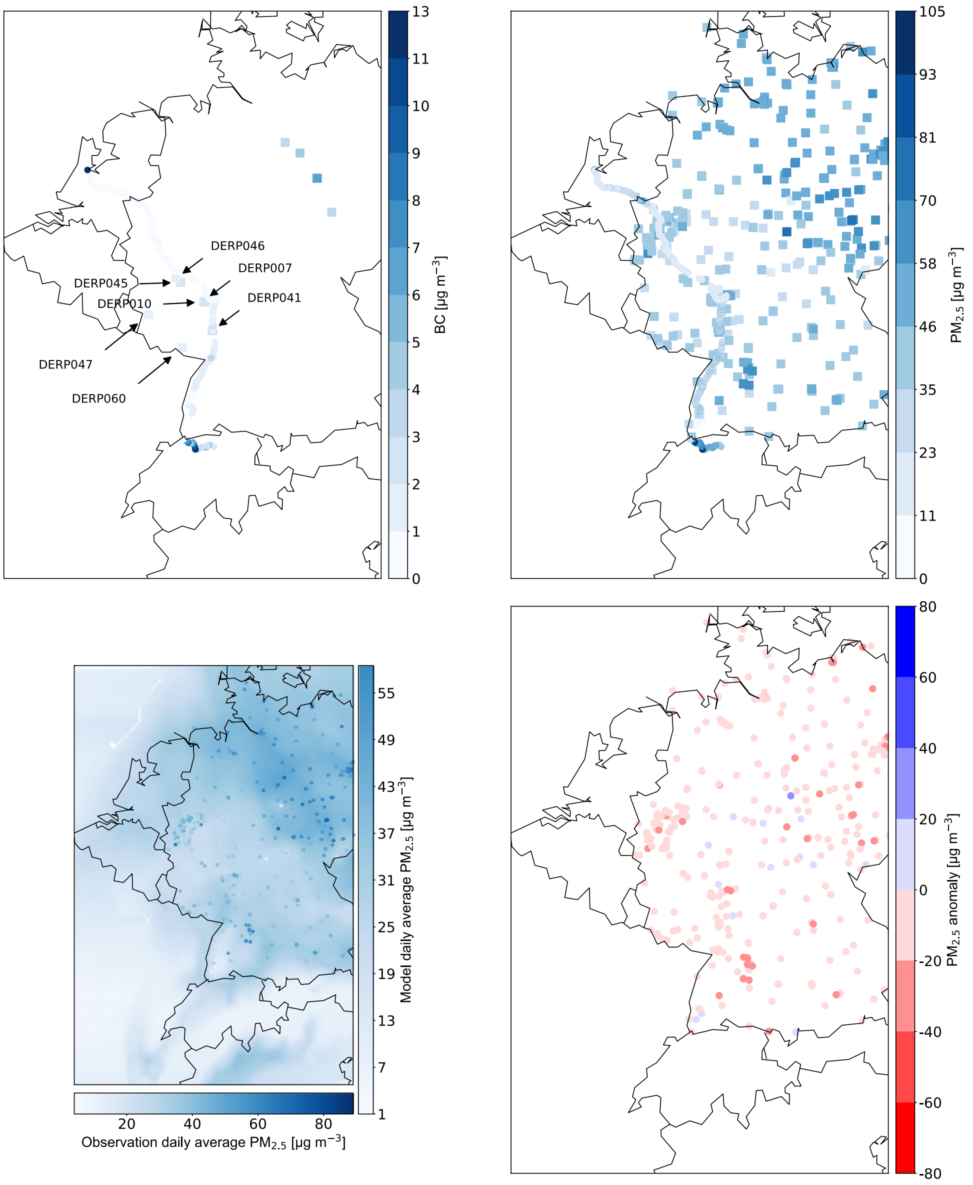

Fig. 5 Comparison of train observation and model data to reference network (all data for same day, 23rd January 2019). The few reference stations with (daily average) eBC data (upper left) are marked with their station code (according to Table 2). Daily average PM$_{2.5}$ data from all German reference stations (upper right). Observed reference station compared to model data, both daily averages (lower left). The same colour scale applies to both data. Anomaly of reference station and model data (lower right), i.e. divergence of model from observation (both daily averages). Negative values (red) indicate where observations are higher than the model, and vice versa

Table 3 eBC values [µg m^{-3}] from closest 5 train samples to the reference station (2 min average ± 1σ)

Station	Station daily mean eBC	Station hourly eBC leg 2 (time)	Station hourly eBC leg 3 (time)	Train eBC leg 2 (time)	Train eBC leg 3 (time)
DERP007	1.74	1.52 (18:00)	1.51 (19:00)	1.17 ± 0.14 (~ 18:00)	0.72 ± 0.24 (~ 18:55)
DERP010	2.35	2.32 (18:00)	2.53 (19:00)	1.30 ± 0.07 (~ 18:00)	0.57 ± 0.14 (~ 18:50)
DERP041	2.64	3.43 (18:00)	-	1.17 ± 0.08 (~ 17:40)	-
DERP045	2.63	-	3.21 (19:00)	-	0.55 ± 0.30 (~ 19:15)
DERP046	2.14	-	2.45 (19:00)	-	0.61 ± 0.20 (~ 19:15)

by a reference network or simulated by ensemble analysis, and despite that the model analysis showed considerably lower PM$_{2.5}$ mass concentration than the reference network.

Mass transit with a high-quality air filtration system and personal protection measures (e.g. masks) could substantially lower the risk of getting exposed to aerosol concentrations. Refitting older trains with active air filtration has the highest potential of reducing aerosol exposure. Reducing aerosol concentrations in general could even lower the risk of getting infected by diseases that use aerosols as a vector to spread through a population. Careful monitoring of cabin air could have additional benefits. This could be by direct aerosol measurements, or by CO_2 concentration as a proxy. Absent reporting of infection hotspots from train travel and a preliminary study showing train conductors not being more frequently affected than control groups (Charité 2020) are positive reinforcements for this suggestion. A safer and healthier mass transit would also have additional implications in changing mass mobility, towards a society in line with temperature limits set out by the Paris Agreement.

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Declarations

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