

Analysis of Aerosol Spreading in a German Inter City Express (ICE) Train Carriage

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Abstract

This paper focuses on the propagation of aerosols in a rolling stock passenger compartment. Extensive measurements were carried out in our stationary test vehicle DIRK, an ICE 2 rail car, operated in a climate chamber.

It is shown that the propagation of aerosols only occurs for a distance of a few seat rows. Furthermore, the maximum percentage of particles exhaled by a passenger and inhaled by another passenger is less than 0.35%. A mouth-nose-protection (surgical mask) at the aerosol source reduces this value to a maximum of 0.25%. Moreover, the use of a mouth-nose-cover reduced the propagation lengths. Here, only the effect of the mask at the source was considered, a further reduction of inhaled aerosols will be achieved when the receivers also wear masks.

It is concluded that, for this type of passenger coach, the indirect propagation of aerosols, i.e., via the HVAC system, is nearly irrelevant compared to the direct propagation from one passenger to another. However, there is a non-zero aerosol transport via the HVAC system, resulting in local inhaled particles far away from the source of around 0.015-0.026%, which is more than one order of magnitude lower than on the most highly contaminated seats.

Keywords

ICE train carriage, aerosol spreading, tracer gas, artificial saliva, air quality, COVID-19

1. Introduction

At the beginning of the corona virus pandemic (early 2020), there was no proof of viable SARS-CoV-2 in aerosols and so discussions between the World Health Organization (WHO) and leading aerosol-scientists occurred as to whether aerosols are a transport mechanism for the spreading of COVID-19 or not [1] [2]. According to the WHO [3] and the German Robert-Koch Institute (RKI) [4], since summer 2020 it is well accepted that, besides smear infection and large droplets, aerosols that are absorbed through the mucous membranes of the nose, mouth and (possibly) the eye play a major role in the spreading of the virus. A distinction between droplets and aerosols is often applied, where

no strict physical threshold is defined. Typically, one talks of droplets for liquid particle diameters larger than 10 μm , whereas, particles between 0.1 μm and 10 μm are termed 'aerosols' [5].

While coughing and sneezing produce larger respiratory particles (droplets) that will settle to the ground due to gravitational forces more quickly [6], aerosols can also remain suspended in the air for a longer period of time and distribute themselves in rooms, which increases the probability of airborne transmission of the virus [5] [6].

Studies by Morawska et al. [7] and Hartmann et al. [8] evaluated the differently sized particles which humans exhale during different breathing modes, comprising coughing, breathing and talking. During all breathing modes, 80% of the produced particles had a diameter below 1 μm and 99.9% were smaller than 5 μm [8]. Particle number concentrations of up to 1.1 cm^{-3} were reached during talking [7]. Talking and coughing produced higher number concentrations and particle diameters than normal breathing through the nose and mouth respectively. Hartmann et al. identified so called 'super-emitters' that emitted 10-20 times more particles than the average subject of this study [8].

The virological evaluation of outbreak events focuses on many single indoor geometries. Günther et al. [9] analyzed the outbreak of SARS-CoV-2 between employees in a meat processing plant in Germany in early 2020. Temperature, humidity and fresh air rate were identified as the main parameters for the transport and stability of droplets and aerosols. The findings for this particular outbreak suggested that infections occurred between employees of the factory via aerosols over a distance of more than 8 m. One of the first detailed reported and analyzed spreading events in a poorly ventilated restaurant in Guangzhou, China was researched by Li et al. [10]. The outbreak involved 10 persons from 3 different families who were sitting at neighboring tables. During this occasion, a video camera recorded the whole scenario, which allowed a detailed reconstruction of the infection pathways. Between the families, no close contact or fomite contact could be identified so that only airborne infection remained as a possible way of infection.

Another study, by Swadi et al. [11], which used data from the journeys, disease progression and virus genomics of seven infected travelers during an 18 hour long-haul flight from Dubai to New Zealand, concluded that it is very likely that the infection occurred in-flight. All infected persons were sitting within 5 seat rows of a Boeing 777 during the flight. This finding agrees a study in a ground-based aircraft cabin undertaken by Schmeling et al. [12], where increased inhalation-aerosol concentrations above 0.1 % of the exhaled aerosols are only found in an area restricted to five rows around the source.

In order to estimate the infection risk for SARS-CoV-2 between people inside buildings or vehicles, different risk calculation models were derived and applied, e.g., by Kriegel et al. [13] [14], Rudnick et al. [15] or the Harvard T.H. School of Public Health [16], who based their findings on the COVID-19 outbreak on the Diamond Princess cruise ship in early 2020 [17]. Further studies on the risk of SARS-CoV-2 infection of passengers and railway staff in passenger trains were carried out by Hu et al. [18], Gravert et al. [19] and the UIC [20]. Based on the infection data collected during the year 2020, infections that could be traced back to public transportation were significantly low [19] [20]. Also, operational railway staff, working on trains in Germany during the pandemic, had a lower infection-rate than the average infection-rate in the population as a whole [19].

In order to investigate the distribution and propagation of aerosols and, therefore, infectious viruses such as SARS-CoV-2, in ventilated and air-conditioned means of transportation, the "Air Quality in Rail Vehicles - LUQAS" research project was jointly initiated by Deutsche Bahn AG and the German Aerospace Center (DLR). The project focused on possible propagation paths of aerosols particles in the passenger compartments of rail vehicles.

The project was planned and carried out by DB Systemtechnik (DB ST), Centre of Competence Aerodynamics and HVAC, and the DLR Institute of Aerodynamics and Flow Technology, Ground

Vehicles Department. The investigations included extensive flow and propagation measurements in the (stationary) test vehicle DIRK (an ICE 2 car). Corresponding simulation calculations were also carried out. The project took place from July to October 2020 with an additional measurement campaign in March 2021.

The present study focused on aerosol spreading and distribution and did not provide an analysis regarding infectivity. Nevertheless, the results provide a deeper understanding of the realistic dispersion processes within a train carriage and, furthermore, can serve as a basis and starting point for virologists and medical staff who could evaluate the infection risk based on their knowledge of the infectious doses of the different viruses or different variants.

This report presents the results of the LUQAS project, focusing on (i) the influence of the distance between the infected person and other passengers, i.e., the dispersion lengths in the carriage depending on the source location and other parameters, (ii) mouth-to-nose coverage, and (iii) the fresh air supply of the air-conditioning system, as well as an assessment of the transferability of the obtained results to other vehicle types. The baseline condition was a 'summer-case' (HVAC system in cooling mode), however, ventilation and winter cases were also analyzed.

After a quick overview of the test facility, which includes the train carriage and the climate chamber, our measurement techniques and testing matrix will be explained. This is followed by the presentation of our results, a discussion and, finally, the conclusion of our studies.

2. Test Facility

2.1. ICE Train Carriage

The Demonstrator for Innovations in Passenger Comfort and Air-Conditioning (DIRK) [21], is a redesigned ICE 2 car of the Bpmz 802.9 large-capacity car type, which has 74 seats and was still in regular operation at Deutsche Bahn, until the end of 2019; it was equipped and converted into a new stationary test vehicle in early 2020. Some exterior views of the DIRK are presented in Figure 1. The car is air-conditioned by a split system with R134a as a refrigerant; this has a total heating / cooling capacity of 50.9 kW / 33 kW. The heating takes place in three different systems: the air conditioning unit, electric re-heaters and underfloor heating. The DIRK is located on the site run by DB Systemtechnik in Minden. The seat map of the DIRK is shown in the test matrix in section 3.3.



Figure 1: Exterior views of the DIRK research train facility.

In Figure 2(a) the basic ventilation scheme of the DIRK railway car is described. The air supply (blue), return air (orange), mixed air (light pink) and waste air (dark pink) are shown with the respective flow directions indicated by arrows. Additionally, the emerging flow field for standard operation during summer conditions is determined with computational fluid dynamics (CFD) and presented in Figure 2(b) for a better understanding of the large-scale flow patterns.

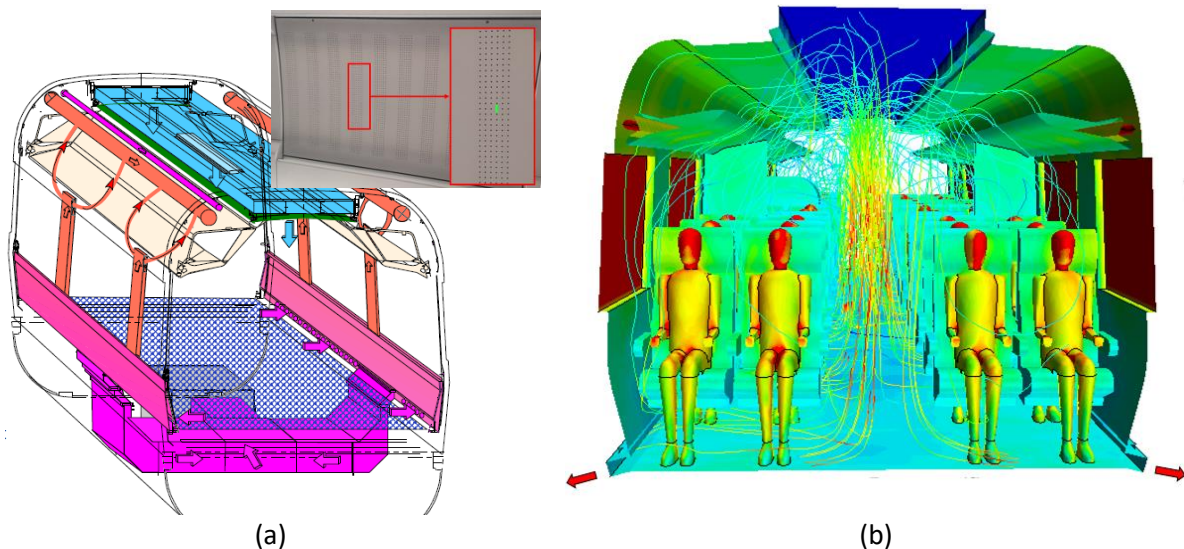


Figure 2: (a) DIRM ventilation scheme, with color coded air supply (blue), return air (orange), mixed air (light pink) and waste air (dark pink) © LUWA reprinted with the friendly permission of Liebherr. The photograph shows one of the ceiling panels (green in the ventilation scheme) with many holes for the air supply into the compartment. (b) Large-scale flow field in the DIRM for summer conditions, determined by CFD.

The fresh air and return air from the interior are mixed in a fixed ratio, depending on the outside temperature: at extreme temperatures above 26°C or below -5°C the fresh air rate is reduced to 15 m³/h per seat, due to energy saving reasons; in normal operations, it should be at least 20 m³/h per seat. This follows the requirements of the current comfort guidelines for trains, i.e., EN13129 [22] for high speed and long-distance trains.

After the mixing chamber, the air is filtered (normally by a coarse G4 filter, following EN779 [23]), heated up or cooled down and then distributed as supply air to the compartment by a supply air duct in the ceiling. Between the ceiling and supply air duct there is a pre-mixing chamber, where the air is throttled and, if required for heat-balancing reasons, additionally heated by electrical heaters, to ensure an even and comfortable temperature distribution in all sectional areas of the passenger compartment. The ceiling consists of 10 sectional panels equipped with 34,800 little holes, to ensure an even and smooth, draft less distribution of the air over the whole interior (see Figure 2). In the passengers' footrest area, the air is sucked out of the interior (light pink in Figure 2(a)). The air partially recirculates as return air through ducts in the ceiling (light red) to the mixing chamber of the HVAC system, whereas, the rest is discharged to the outside as waste air (dark pink) by the waste air fans. Waste air fans and supply air fans work in a special manner, ensuring that there is a permanent slight overpressure in the saloon, this avoids the unwanted infiltration of outside air into the coach, e.g., by leakages.

The waste air duct integrated at floor level into the side wall consists of a rectangular flow channel with holes and slots and ranges over the whole length of the coach, on both sides. This ensures a direct air flow through the interior, from the ceiling to the bottom in the cooling and ventilation mode (see Figure 2). In the heating mode, additional surface heaters in the floor overlay the heating by the supply air, coming from the ceiling, as it is realized in the cooling mode.

2.2. Climate Chamber

MEiKE is the 'Minden facility for HVAC testing of railway vehicles' run by DB AG and located in Minden. This test facility is a climatic chamber for railway vehicles and it is able to ensure stable and reproducible boundary conditions to simulate all climatic weather conditions, as they occur in reality [24]. The main parameters are as follows:

- Temperature range in test chamber, from -20°C to +45°C

- Snow and ice, sunlight in driver's cab
- Controlled chamber air humidification at temperatures in excess of +10°C
- Test chamber size up to 75 m x 5 m x 5 m (L x W x H), can be divided into sections measuring 35 m, 10 m, and 30 m in length

As the climatic chamber is usually used for climatic testing for railway vehicles under test conditions, in accordance with the relevant standards and for the optimization of thermal comfort, air quality and energy consumption, it was recognized as an ideal environment for the provision of all relevant boundary conditions to be of interest in the LUQAS research project.

3. Measurement Techniques and Test Matrix

3.1. Tracer Gas Measurements

To evaluate the performance of the HVAC, regarding contaminant transport and removing efficiency, tracer gas measurements were part of the investigations presented. Here, the latest studies prove that tracer gas is a suitable surrogate for analyzing the dispersion and transport mechanism of the smallest particles, like aerosols, in a closed environment [25]. Hence, a corresponding measurement system was installed in the train's passenger compartment, which uses CO₂ as a tracer gas.

The gas was emitted at head level for the previously defined seats within the passenger compartment (see Table 1). The resulting gas concentrations were measured and monitored simultaneously using a sensor system which comprised 30 CO₂ detectors in total, see measurement area shown in the test matrix section. The accuracy of the SCD30 (Sensirion) CO₂ sensors used is given as $\pm (30 \text{ ppm} + 3\% \text{ MV})$ [26], the repeatability is as good as 10 ppm and the response time is 20 s.

3.1.1. CO₂ Supply

The gas supply system was installed in a luggage area of the train. It comprised a CO₂ bottle, combined with a pressure monitoring system and a volume flow measurement unit, see Figure 3(a).

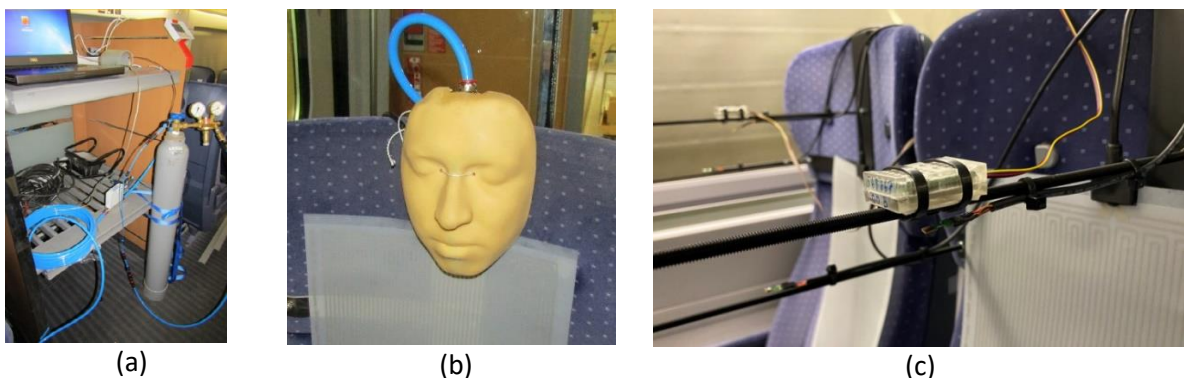


Figure 3: (a) CO₂ supply system installed in a luggage area of the ICE 2 train. (b) 3D-printed face with nose exhalation and CO₂ supply pipe. (c) CO₂ sensors installed in the breathing zone of surrounding seats.

By using this set-up, a constant volume flow rate of $2.5 \text{ l/min} \pm 0.2 \text{ l/min}$ was provided during a measurement run. With the start of the data acquisition, each measurement run was divided into a first phase, where the gas was emitted for 20 minutes, followed by a second phase, where the gas injection was stopped and the data acquisition was run for another 20 minutes. The described schedule is illustrated in Figure 4, where Figure 4(a) shows raw data of the volume flow rate of the CO₂ supply and Figure 4(b) depicts raw data of the resulting concentration curve at an example seat.

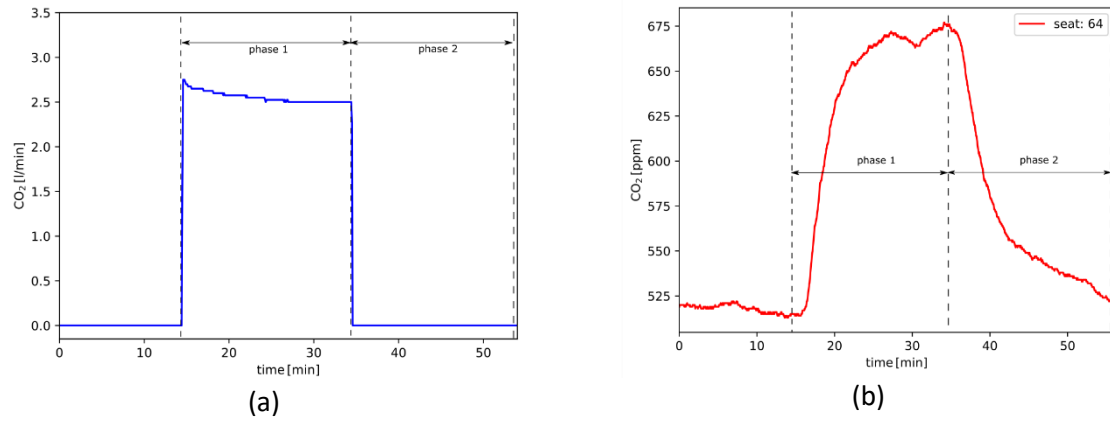


Figure 4: Illustration of the schedule for tracer gas measurements comprising the injection phase (1) and the decay phase (2). (a) represents the CO₂ supply curve, and (b) a selected measurement curve at an exemplary seat.

The CO₂ gas was emitted through a self-developed 3-D printed face (see Figure 3(b)), in order to simulate realistic flow characteristics for the exhalation process through the nose. The face was placed on the head rest of the seat, at a height of 120 cm above the floor.

The sensor system, based on several SCD30 CO₂ detectors, was installed at head level on each seat within the measurement area, see Figure 3(c). The exact positions of the sensors were 115 cm above the floor and 20 cm in front of the head rest, which represented the breathing zone of a typical seated passenger. Detailed information regarding the sensors and the comprehensive measurement system is given in the following section.

3.1.2. Data Acquisition - Measurement System

An in-house data acquisition system was used to record sensor data and to monitor the experiment. The system was designed to read values from over 100 sensors with frequencies up to 20 Hz. Robustness is guaranteed via the usage of easy-to-replace and well-tested off-the-shelf parts. It operates with cost-efficient measurement devices and supports various sensor types, to assess carbon dioxide concentrations in air, fluid temperatures and both mass and number densities of particles on the μm scale. Typically, a measurement device consists of two units. The first measures the physical quantity of interest, while the second is responsible for the analog to digital conversion (ADC). The digital signal is then transmitted to the central host device using a serial protocol (e.g. UART, SPI or I2C), which records and visualizes measurement data for the entire experiment. The on-site ADC rules out possible measurement errors due to losses inside the signal line. The measurements of CO₂ concentrations and particle distributions were executed using this data acquisition system.

3.2. Saliva Aerosol Measurements

3.2.1. Saliva Aerosol Generation

The aerosol generator in Figure 5(a) consists of an airbrush pistol (AFC-101A, nozzle diameter 0.35 mm) pressurized at 2 bars. It is used to disperse artificial saliva (mixed according to NRF 7.5¹). It can be connected to an artificial face (Figure 5(b)) to simulate realistic mouth-nose exhalation, and also, the application of face masks (Figure 5(c)). The generator is connected to a high-pressure air supply for mixing. Two high precision flow meters were used to measure the volume flow from the generator and the fresh air individually, allowing the control of mixing and outlet volume flow using valves. A pipe system with an internally installed SPS30 sensor measured the aerosol concentration. With the summed volume flows, this allowed for continuous monitoring of the aerosol generation rates. The generated artificial saliva aerosol particle distribution was in a range below 2.5 μm in

¹ According to NRF 7.5: 0.12 g KCl; 0.085 g NaCl; 0.25 g Na₂HPO₄ · 12H₂O; 0.015 g CaCl₂ · 2H₂O; 0.005 g MgCl₂ · 6H₂O; 0.1 g sorbic acid; 0.5 g carmellose sodium 400; 4.3 g sorbitol solution 70%; 1 g ad 100.0 mL H₂O purify [33]

diameter and with a peak at $0.8\ \mu\text{m}$. Thus, the particle size distribution corresponded to a normal breathing scenario.

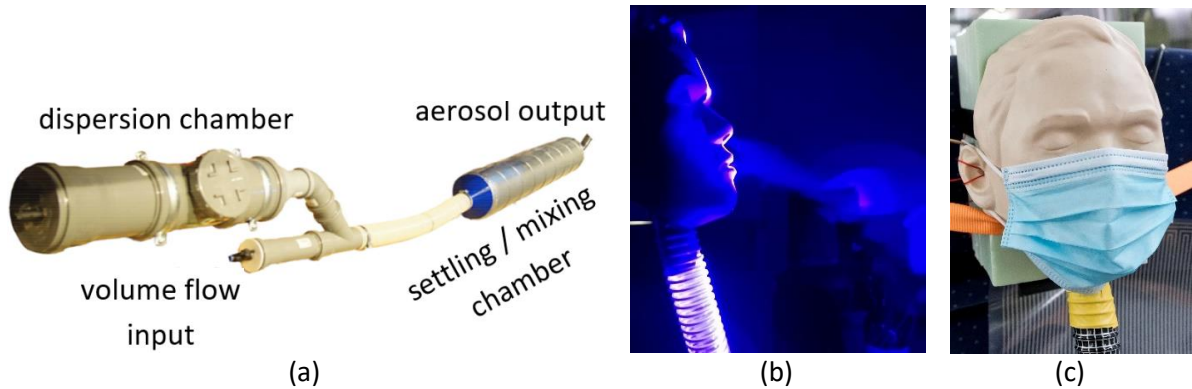


Figure 5: Saliva aerosol generation. (a) generator with saliva reservoir, atomization nozzle, volume flow input and settling/mixing chamber. (b) Artificial facial mask for simulation of combined mouth-nose exhalation and the possibility of using face masks, as shown in (c).

3.2.2. Fine-Particle Aerosol Sensor System

For the spatial measurement of particle densities inside the passenger compartment, 41 SPS30 particulate matter sensors by Sensirion were used. Particles suspended in the air scattered light originating from a laser inside the SPS30. The signal of a photo diode, which measures the light intensity, was then internally converted to mass and number densities. A continuous air flow through the device transported fresh air into the measured volume. Values of mass concentrations were binned for particle diameters ranging from $0.3\text{--}1.0\ \mu\text{m}$ ($\text{PM}_{1.0}$), $0.3\text{--}2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$), $0.3\text{--}4.0\ \mu\text{m}$ ($\text{PM}_{4.0}$) and $0.3\text{--}10.0\ \mu\text{m}$ ($\text{PM}_{10.0}$), where the number concentrations were also given for the range $0.3\text{--}0.5\ \mu\text{m}$ ($\text{PM}_{0.5}$), in addition. While $\text{PM}_{0.5}\text{--}\text{PM}_{2.5}$ were retrieved directly from the signals of the photo diode, values for $\text{PM}_{4.0}$ and $\text{PM}_{10.0}$ were calculated based on the distribution profile of all measured particles [27] and, hence, were based on an assumption of the particle distribution. The measurement transducers employed count particles and matched their intensity against an internal calibration curve. The reference aerosol for the optical particle counter was potassium chloride with a refractive index of 1.49. The refractive index of saliva is very close to that of water (1.33) [28]. This results in a decrease of scattered intensity by 30% and an underestimation of the particle diameter by 11%. Since the optical particle sizer covers an order of magnitude of particle diameters, deviations due to a changed refractive index, compared to the reference setup, can be neglected. An automatic self-cleaning mode ensures consistent measurement results in the long-term. The accuracy of this measurement device has been investigated by Tryner et al. [29]. They compared the results of low-cost particle matter sensors with the results of a larger direct mass transducer. With five different aerosol types, they found the SPS30 to be stable against changes in relative humidity and over long measurement periods; the SPS30 outperformed the other sensors addressed in their study.

3.2.3. Laser-Based Particle Image Analysis

Based on the principle of particle image velocimetry, laser-based Particle Image Analysis (PIA) was performed. This typically allows the acquiring of particles with a diameter of $1\ \mu\text{m}$ and larger and yet, no reliable size information could be gathered from the particle images. The particles were illuminated using Litron Nano PIV 200 with a pulse energy of 200 mJ. The scattered light was recorded by a PCO1600 b/w camera at a recording rate of 5Hz. Using a 100 mm Nikon macro-lens with an additional macro adapter, a field of view (FOV) of $L_{\text{PIA}} \times H_{\text{PIA}} = 18 \times 13\ \text{mm}^2$ and a light sheet width of 4 mm was realized. The particles within the FOV were counted using an imaging process consisting of a sliding minimum image subtraction (calculated over 9 frames), an image-normalization (91×91 pixels) and a noise level threshold at 6000. Starting at the highest intensity values, a 3×3 pixel peak detection was performed to determine the particle position, to avoid overlapping particles and determine the particle number on the image.

A typical ceiling panel of the DIRK is shown as a small photo in Figure 2(a), with a close up view of the air outlets on the right-hand side and the highlighted PIA FOV in green. A single row features $N_{H,R}=58$ holes spanning $L = 900$ mm, corresponding to a hole density $r_H = N_{H,R}/L$. The rows are grouped in blocks consisting of six rows, while each panel exhibits ten blocks. A compartment is made of 10 panels, amounting to a total number of holes of $N_{H,Total} = 34,800$. With the light sheet of the PIA aligned with one row of holes, a comparison of particles generated by the source compared to the particles coming from the whole ceiling was possible. The total output from the source $N_{Source,Total}$ was measured using PIA. The fraction of holes within the PIA FOV was $N_{H,PIA} = r_H * L_{PIA}$. The normalization N of the measurement data was obtained as $N = N_{H,Total} / N_{H,PIA} / N_{Source,Total}$.

3.3. Test Matrix

Measurements were carried out under three different climate boundary conditions, adjusted and controlled by means of the climate chamber MEiKE, operated by the DB Systemtechnik in Minden (Germany). Reflecting the typical HVAC requirements arising in daily use, the boundary conditions for cooling (i.e., summer scenario, $T = 28^{\circ}\text{C}$, $rh \approx 45\%$), heating (i.e., winter scenario, $T = -10^{\circ}\text{C}$, $rh \approx 65\%$) and a ventilation scenario ($T = 10^{\circ}\text{C}$, $rh \approx 70\text{-}80\%$) were defined. The impact of solar radiation was neglected for all cases.

The passenger compartment was seated to 100% (simulated by heating blankets) and the interior lighting was switched on. If not stated otherwise, the HVAC was operated in automatic mode, using a nominal volume flow of fresh air of $870 \text{ m}^3/\text{h}$. The target temperature in the interior T_{ic} was 25°C for the cooling case and 22°C for the ventilation and the heating cases, according to EN13129 [22].

The investigated cases regarding the aerosol and tracer gas dispersion within the passenger compartment are summarized in Table 1 and the cases regarding the HVAC dilution are summarized in Table 2. The respective measurement areas for the different measurement systems are highlighted in Figure 6. The abbreviations in the comment column represent: ‘vav’ – vis-à-vis, i.e., two passengers facing each other (occurring for seats at the tables), ‘F2B’ – front-to-back, i.e., ‘normal’ seating arrangement where the passengers look in the same direction, ‘B2B’ – back-to-back, i.e., seats where two backrests are next to each other and the passengers are looking away from each other, and ‘wind.’ – window.

*Table 1: Investigated cases for aerosol / tracer gas dispersion within the passenger compartment. The given seat number in the source columns correspond to the seat layout of the DIRK, shown in Figure 6. *Mask only considered at source, not at receivers: a three-layer surgical mask was used.*

ID #	HVAC mode	T _{chamber} MEiKE	$\dot{V}_{fresh\ air}$ [m ³ /h]	HVAC Filter	Mask*	Comment	Source CO ₂	Source aerosol
01	cooling	+28°C	870	G4	no	vav, aisle	63	24
02	cooling	+28°C	870	G4	no	vav, wind.	61	---
03	cooling	+28°C	870	G4	no	F2B, aisle	64	---
04	cooling	+28°C	870	G4	no	B2B, aisle	93	---
05	cooling	+28°C	870	G4	yes	vav, aisle	63	24
06	cooling	+28°C	870	G4	no	vav, aisle, no table	63	---
07	cooling	+28°C	610	G4	yes	vav, aisle	---	24
08	cooling	+28°C	1110	G4	yes	vav, aisle	---	24
10	heating	-10°C	870	G4	no	vav, aisle	63	---
11	heating	-10°C	870	G4	no	vav, wind.	61	---
12	heating	-10°C	870	G4	no	F2B, aisle	64	---
13	heating	-10°C	870	G4	no	B2B, aisle	93	---
14	heating	-10°C	870	G4	no	vav, aisle, no table	63	---

Table 2: Investigated cases for HVAC dilution analysis. The seat number given in the ‘source PIA’ column, i.e., during the particle image analysis measurements (see section 3.2.3), corresponds to the seat layout of the DIRK, shown in Figure 6. In contrast to the spreading analysis on the seats, the source was mounted in the legroom during the HVAC dilution analysis and not in the face region.

ID #	HVAC mode	T _{chamber} MEiKE	$\dot{V}_{fresh\ air}$ [m ³ /h]	HVAC Filter	Source PIA
15	cooling	+28°C	870	no	Legroom 31
16	cooling	+28°C	870	G4	Legroom 31
17	cooling	+28°C	870	G4n	Legroom 31
18	cooling	+28°C	870	M5	Legroom 31
19	ventilation	+10°C	870	no	Legroom 31
20	ventilation	+10°C	870	G4	Legroom 31
21	heating	-10°C	870	No	Legroom 31
22	heating	-10°C	870	G4	Legroom 31
23	cooling	+28°C	870	no	Legroom 111
24	cooling	+28°C	870	G4	Legroom 111
25	cooling	+28°C	870	G4n	Legroom 111
26	cooling	+28°C	870	M5	Legroom 111

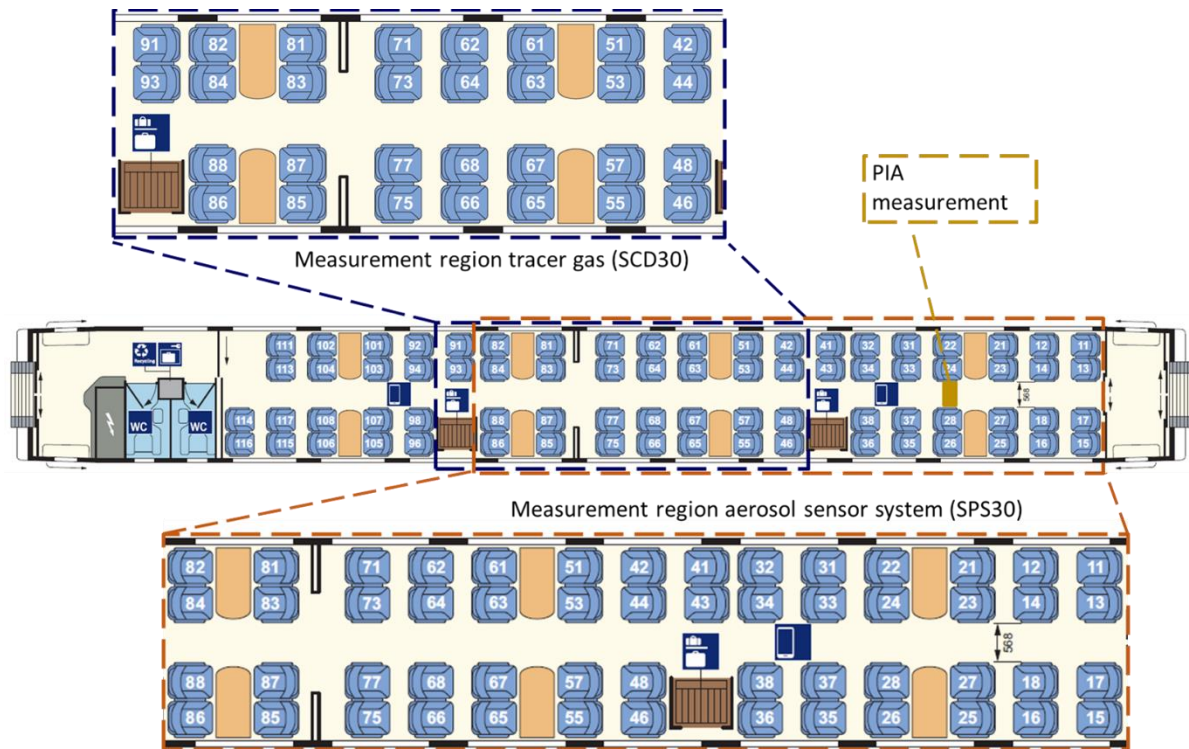


Figure 6: Seat-Layout of the test vehicle, according to DB Fahrzeuglexikon [30]. The tracer gas CO₂ measurements were conducted in the black marked area, the aerosol sensor system measurements in the brown marked area and the PIA measurements were conducted in the yellow-brown area.

4. Results

4.1. Tracer Gas Spreading

Beginning with the cooling scenario, the results from tracer gas spreading are discussed in this subsection, for cases without any mouth-nose cover, neither at the source nor at the receivers. Figure 7 shows the corresponding results of the tracer gas measurements for different source

locations (grey). Generally, the depicted data are averaged over a period of 5 minutes (the time slot right before the gas injection was stopped). The data is normalized in such a way that, a value of 1 corresponds to a homogeneous distribution of the introduced CO₂ within the compartment. Therefore, we use the injected CO₂ quantity (over an injection time of 20 minutes) and consider the gas amount leaving the cabin continuously through ventilation (with a fresh air flow rate of 870m³/h). As a result, a mean gas concentration of 158 ppm (above outside conditions), would arise under perfect mixing. This value is used for the normalization.

For the first case (Figure 7(a)) – source at seat position 61 – a significant concentration increase is detected for the row right behind the source location. The highest value of 1.05 was monitored on seat position 64, representing the seat diagonally behind the source. A significant concentration rise of over 0.5 is reported for the next two rows behind the source location, even across the aisle. The second case (Figure 7(b)), representing the source location on seat 63 near the aisle, reveals the highest concentration right next to the source (2.25 on seat 61). Here, a significant rise in concentration is detected two rows behind the source location and one row in front of the source. The third case (Figure 7(c)) (source location at seat 64) reveals the highest value of 3.78 on seat 62, neighboring the source position. However, significant concentration values above 0.5 can only be seen in the seat row behind the source. For the source position on seat 93 (Figure 7(d)), similar loads are found, compared to the source on seat 61 (Figure 7(a)). Summarizing the impact of the different source locations, one can state that the transport from the aisle seat towards the neighboring window seat seems to be higher than vice versa. Furthermore, the highest transport of tracer gas to a neighboring seat was detected when all seats faced in the same direction (typical front-to-back seating). In a longitudinal direction, a significant accumulation of the tracer gas is measured in the next two seat rows (in front, as well behind) depending where the source is positioned. Furthermore, the transport of the tracer gas across the aisle is suppressed to a certain degree but clearly exists and only weakly depends on the position of the source.

As a reminder: a value of 1 would be expected on all seats if the ventilation could enforce perfect mixing within the full compartment. However, for all cases, values above one are only found on directly neighboring seats, with regard to the source (in all directions). This highlights that the ventilation system in the train compartment is adjusted in such a way that local emissions are not mixed throughout the full compartment, but rather localized and mostly guided towards the exhaust openings close to the source.

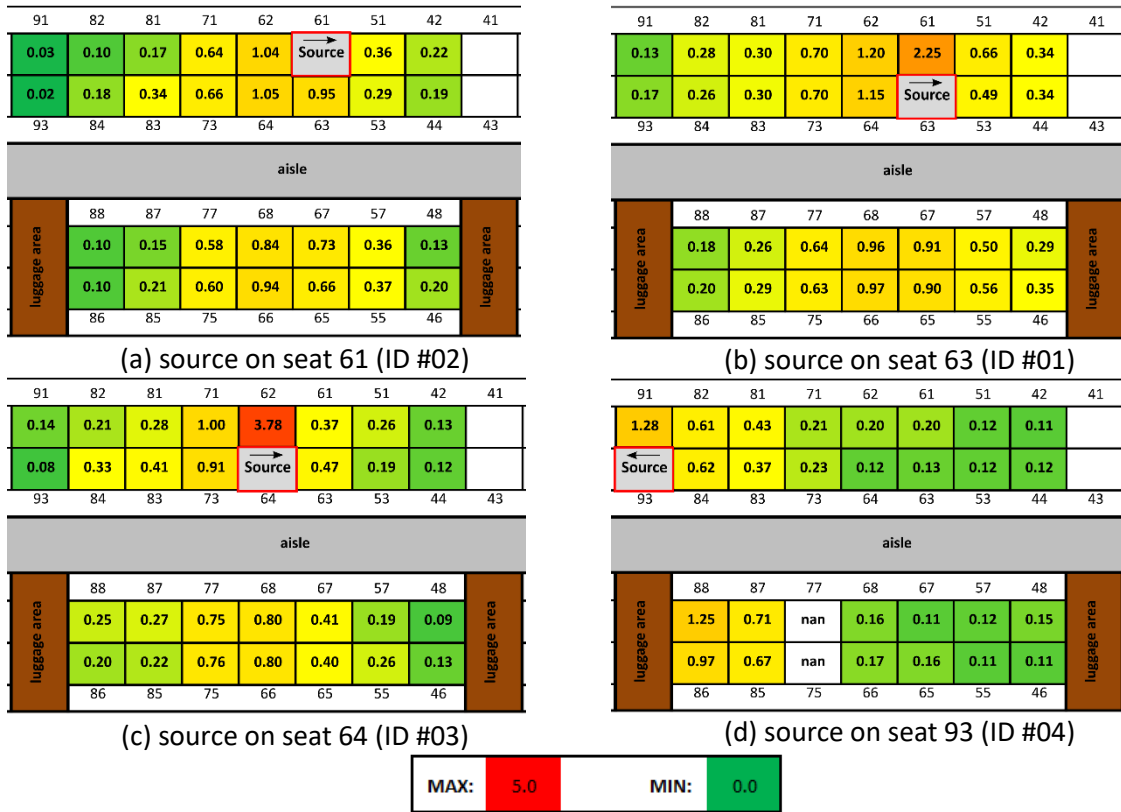


Figure 7: Results of tracer gas measurements during cooling scenario without any mask. The data is normalized with a concentration value, which considers the emitted amount of CO₂ and the amount of CO₂ leaving the cabin through ventilation. A value of 1 corresponds to a homogeneous distribution of the introduced tracer gas in the full compartment. a) results for the source at seat 61, b) for the source at seat 63, c) for the source at seat 64 and d) for the source located at seat 93.

4.2. Impact of Heating vs. Cooling Operation

As discussed in section 2.1, the investigated ICE 2 carriage contains additional heaters, both in the air distribution system and within the floor, which might result in different flow patterns within the compartment. Furthermore, the aerosol deposition characteristics of the HVAC system itself might be different for heating and cooling operations. Accordingly, tests with otherwise similar settings were performed for climate chamber temperatures of $T_{\text{chamber}} = +28^{\circ}\text{C}$ and -10°C . The resulting effects on the aerosol and tracer gas dispersion for the cases without any masks are discussed in this section.

Tracer gas measurements were conducted for different boundary conditions, in order to analyze the performance of the air conditioning system in heating and cooling mode. Figure 8 shows the results of the measurements for a cooling case (a), characterized by an ambient temperature of 28°C in the climate chamber, while (b) presents the results for a heating scenario, where the temperature in the climate chamber was set to -10°C . In both cases, the source was located at seat position 63 (indicated in gray surrounded by a red rectangle). The depicted data is normalized in the same way as described in section 4.1.

For the cooling scenario (Figure 8(a)), significantly higher values are noted compared to Figure 8(b). In Figure 8(a), the peak value of 2.25 occurred at seat position 61. Thus, the CO₂ has been directed to the window (right next to the source). The seat row right behind the source, also revealed higher gas concentration values, even across the aisle. It seems that the gas extended over two seat rows, especially the rows behind the source. Accordingly, flow occurs in a longitudinal direction, which is more pronounced in the direction where seats are located with a higher numbering, compared to the direction where seat number 42 and 41 are located. This phenomenon can also be seen in the heating scenario (see Figure 8(b)). Here, the two rows behind the source also revealed a significant

increase of tracer gas concentration. However, the maximum values in these rows were smaller by about 12%, in contrast to the cooling case.

Generally, for both cases, the released gas remains localized in the area where the source is placed. An increased tracer gas concentration is detected over two adjacent seat rows, at maximum. The positions at the end of the measurement area (at seat 82 to 93, as well as at 42 to 48) are not that much affected when compared to the seat in the vicinity of the source, with values <0.5 .

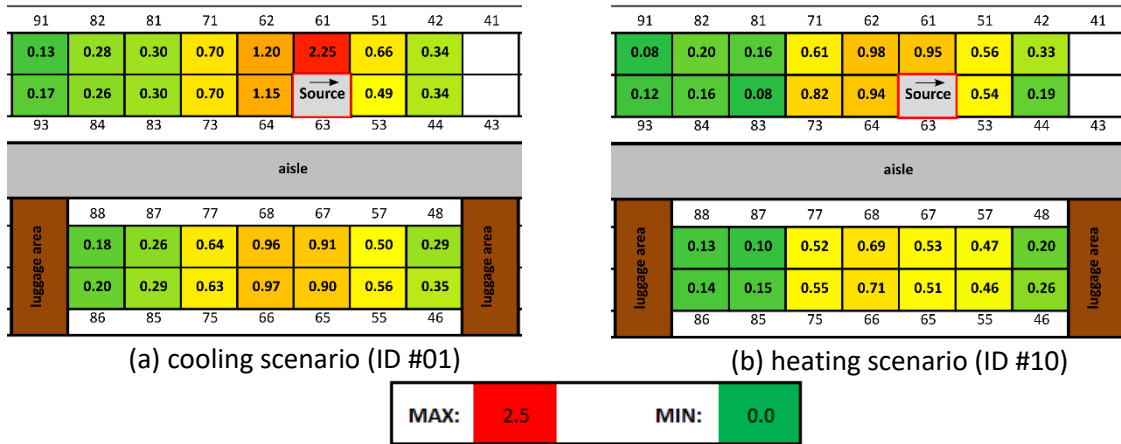


Figure 8: Results of tracer gas measurements. Normalized concentration distribution within the passenger compartment for a single source location and two temperature operational cases. a) cooling case characterized by an ambient temperature of 28°C and b) a heating case with -10°C as an ambient temperature. Both cases were without any masks.

4.3. Impact of Mouth-Nose Cover

Figure 9 reveals the impact of the usage of mouth-nose coverage (a three-layer surgical mask) on the aerosol particle spreading, compared to no coverage for the cooling scenario based on the Fine-Particle Aerosol Sensor System which was described in chapter 3.2.2. For these measurements, the enhanced aerosol source (Figure 5) was located at seat 24, which is marked with an 'S' in Figure 9, and the SPS30 sensors were located in the breathing zones of the other passengers, i.e., at a height of 1.1 m for sitting passengers and at a height of 1.7 m for passengers standing in the aisle. The displayed particle numbers $N_{mean,frac}$ for the size distribution of 0.3 to 2.5 μm are normalized to the averaged particle number getting discharged by the particle source and to the volume flow of the source, compared to the average volume flow of a passenger during tidal breathing. It should be noted that the surgical mask was only placed at the aerosol source, i.e., the index passenger; additional masks on the receivers would lead to another reduction of the inhaled aerosols by a factor x , which strongly depends on the type of mask and the fitting in the facial area.

As one can see in Figure 9(a), for the scenario without mouth-nose coverage, and in Figure 9(b), with coverage, the sensors on the seats in the vicinity of the source measure a higher particle concentration compared to the seats further away from the source. This area with increased particle numbers comprises the seat row of the source and the one to the front and the back of the source. This is similarly reported for the corresponding row across the aisle. The highest concentration of particles was detected for the case with no mouth-nose coverage on the seat next to the source, in the window seat, see Figure 9(a). The average particle number on this seat is approximately 0.35% of the induced particles. This particle concentration is about twice as high as the case with mouth-nose coverage on the same seat in Figure 9(b), which only shows a concentration of about 0.20%. Also, for all the other seats, the measured concentration is lower or equal at the case with mouth-nose coverage. Furthermore, the peak value of 0.25% is found directly behind the source for the case with mouth-nose-coverage. The sensors in the vicinity that are located in the aisle (round markers) and in the area of fresh air supply beneath the ceiling (square markers) show the same effect.

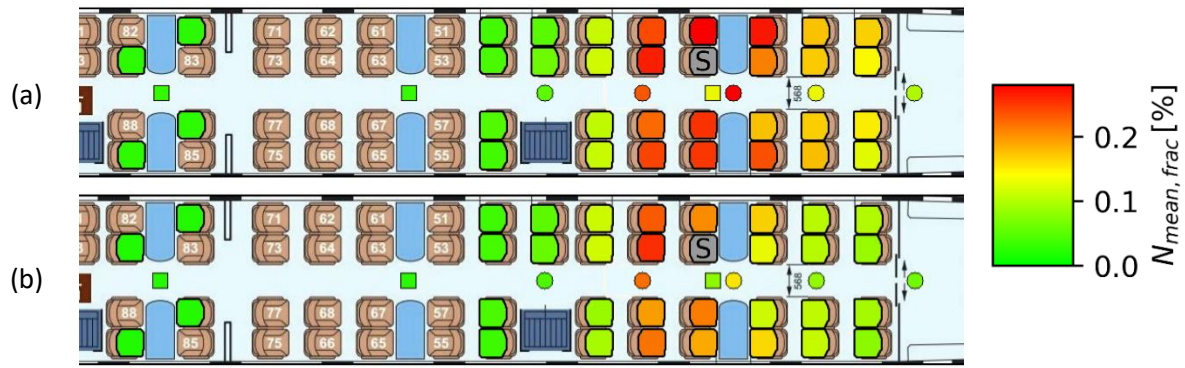


Figure 9: Fraction of inhaled aerosols compared to the number of produced aerosols at the source. (a) Case without mouth-nose cover (ID #01) and (b) with a mouth-nose cover at the source (ID #05).

4.4. Impact of fresh air rate

Figure 10 shows the influence of the variation of the fresh air rate in the train compartment during the cooling scenario with an ambient air temperature of $T=28^{\circ}\text{C}$ and the source on seat 24 with a nose-mouth cover. During the measurements, the fresh air rate was modified between the rates $610 \text{ m}^3/\text{h}$, $870 \text{ m}^3/\text{h}$ and $1110 \text{ m}^3/\text{h}$. Comparing Figure 10(a) and Figure 10(b), the particle concentration decreases with increasing fresh air rate on almost all seat-positions, three or less rows away from the source, as the fresh air rate rises from 610 to $870 \text{ m}^3/\text{h}$. For seats further away, no difference is visible in the color-coded images. However, looking into the data tables (see Appendix B) one finds, that the average aerosol load on the four seats in the left side of the compartment, i.e., far away from the source, decreases from 0.022% at $610 \text{ m}^3/\text{h}$ to 0.019% at $870 \text{ m}^3/\text{h}$ and further to 0.015% at $1110 \text{ m}^3/\text{h}$. This finding supports the small, but existing effect of increased fresh air rate on the aerosol concentration. This is also confirmed by looking at the average aerosol load on the four seats with the highest values. Here the load decreases from 0.258% at $610 \text{ m}^3/\text{h}$ to 0.227% at $870 \text{ m}^3/\text{h}$ and further to 0.214% at $1110 \text{ m}^3/\text{h}$.

Regarding the spatial distribution, the highest particle concentrations for the two cases with 610 and $870 \text{ m}^3/\text{h}$ fresh air rate could be measured in the row directly behind the source, where the values were significantly higher than on the seats opposite the source, across the table. A similar particle concentration distribution can be seen for both scenarios across the aisle but with slightly lower values. In the scenario with a fresh air rate of $1110 \text{ m}^3/\text{h}$ in Figure 10(c), the maximum concentration occurs directly next to the source on the seat window-seat which marks the first big difference to the two cases with lower fresh air supply. Also, the concentration for this seat and the seats across the table in front of the source are higher than for the scenarios with a fresh air rate of $870 \text{ m}^3/\text{h}$, whereas, the concentration decreases or stays constant on all other seats (see Appendix B).

For all three cases, the flow structure in the compartment seems to favor the transport of the particles to the back of the source, which can be seen by the particle distribution on the seats and also in the aisle (round sensor markers).

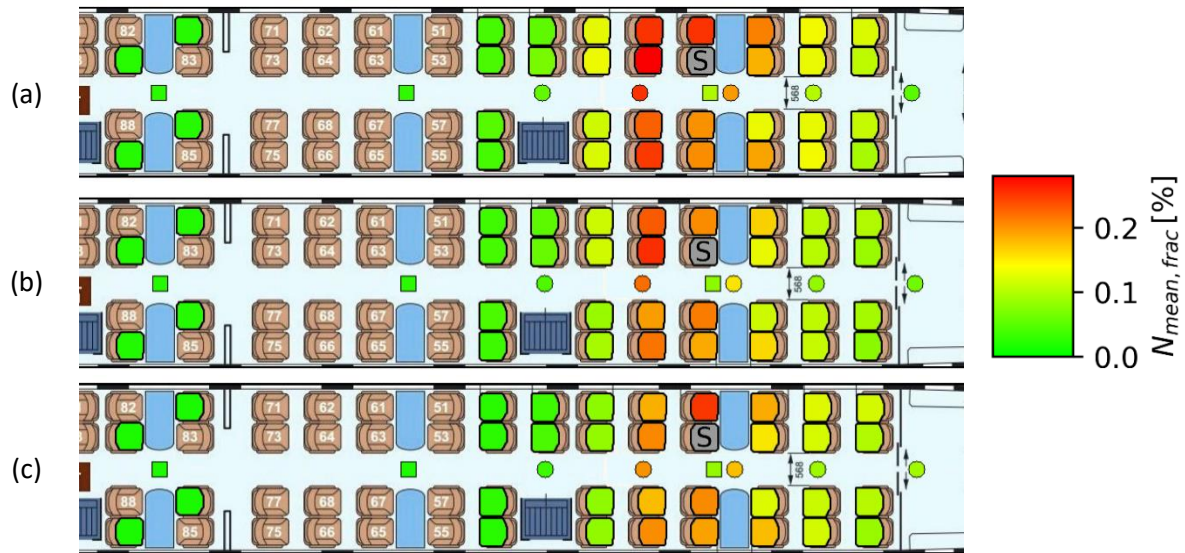


Figure 10: Fraction of inhaled aerosols compared to the number of produced aerosols at the source with mouth-nose cover for a fresh air rate of (a) case ID #07, 610 m³/h, (b) case ID #05, 870 m³/h and (c) case ID #08, 1110 m³/h.

4.5. Time-constant of the local concentration

Figure 11 shows the time evolution of the local particle concentration for an example seat. The different colors represent the different particle size bins of the SPS30 sensor. The measurement run is started at $t = 0$ min and the emission of the source begins simultaneously. After 20 mins, i.e., after almost stable conditions are reached, the aerosol generator is stopped, while the measurement system continues to record the decay curves. The latter are fitted using an exponential function, see the inset of Figure 11, to determine the time-constants for the decay of the local concentrations in the passenger compartment on the seats after the ‘infected’ passenger left the train.

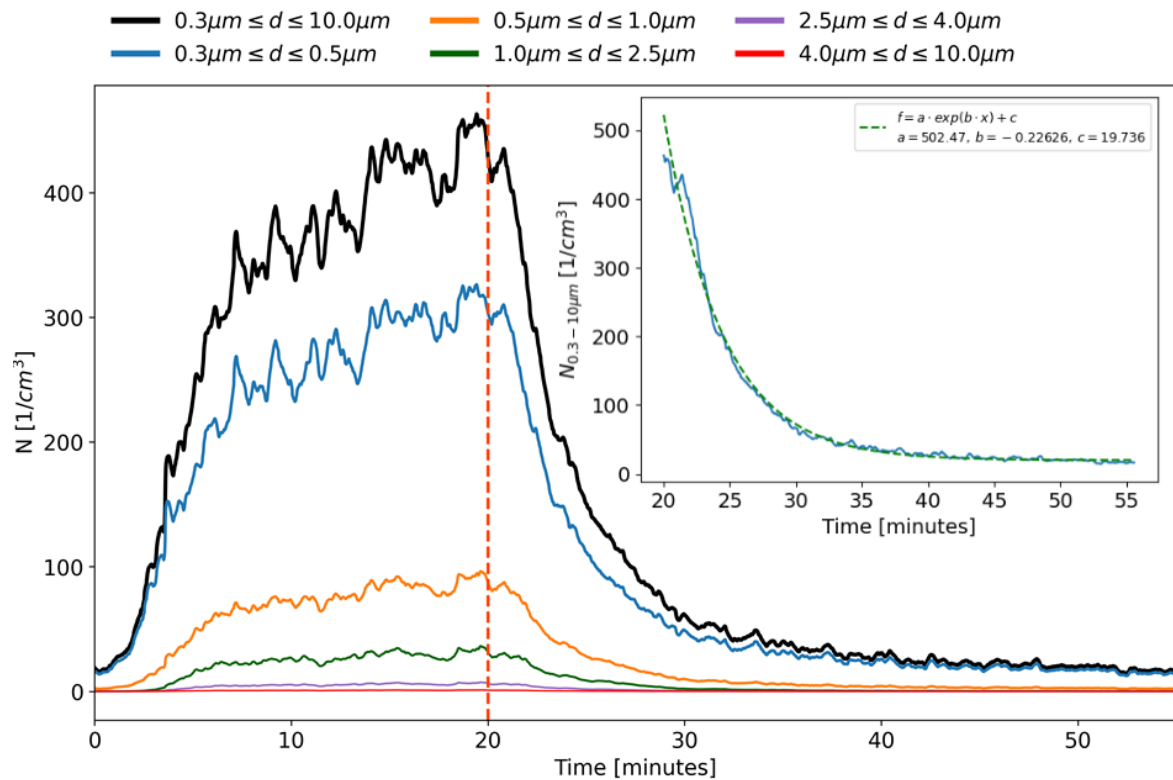


Figure 11: Time evolution of the local particle concentration on an example seat (25) for case ID #05 (source on 24 with mouth-nose coverage).

It is found that the decay time-constant of the local particle concentration on this selected seat in the vicinity of the source, but on the other side of the aisle, is less than five minutes, meaning that less than five minutes after a possibly contaminant-spreading person leaves the train, the concentrations drop below $1/e$ of the stationary values. In other words, approximately 3.3 mins after stopping the emission, the HVAC system reduces the local particle concentration by a factor of two. It should be noted that the nominal air change per hour (ACH) of the train's HVAC system, based on the nominal supply air rate into the compartment (not to be confused with the fresh air rate, which is much lower), amounts to $ACH_{supply} \approx 23.9 \text{ h}^{-1} (= 0.40 \text{ min}^{-1})$. Accordingly, the time constant for a nominal complete air change in the compartment, based on the supply air rate, amounts to $\tau_{supply} \approx 2.5 \text{ min}$. For a comparison, the time constant, based on the standard fresh air rate of $870 \text{ m}^3/\text{h}$ in this study, amounts to $\tau_{fresh} \approx 7.5 \text{ min}$ ($ACH_{fresh} \approx 8.0 \text{ h}^{-1}$). To conclude, we can summarize that the measured decay time constant lies between the time constants of the air change rate based on the supply and the fresh air rate.

In Figure 12 we present for all investigated seats for the case with $870 \text{ m}^3/\text{h}$ fresh air (case ID #05) the time constants ($\tau_{1/2} [\text{min}]$), i.e., the time that is needed after stopping the emission of the source until the local aerosol concentration decreases to 50% of its steady state value.

	14.17					8.15	5.90	3.69	1.98	2.42	3.25	4.94	5.62		16
13.60						7.62	6.04	4.13	2.02	S	4.37	5.07	5.65		12
															8
	12.93					8.28		4.89	2.37	2.49	4.11	4.83	5.56		4
13.59						8.22		4.75	2.19	2.65	3.16	4.99	5.74		0

Figure 12: Decay time constants ($\tau_{1/2} [\text{min}]$) for case ID #05 (source on 24 with mouth-nose coverage).

The first thing to notice is that the time constants increase with increasing distance from the source. This behavior can be explained by the traveling times of the aerosol particles, i.e., in the vicinity of the source, the decay of the concentration starts very soon after stopping of the emission, see also Figure 11, whereas, the decay of the concentration starts delayed with regard to the stopping of the emission further away. The second point to notice is that the half-life times correlate with the mean aerosol concentration in a way, that high aerosol concentrations ($>0.2\%$), in specific directly behind (i.e. left of the "S" in the image) and neighboring the source (Figure 10(b)), are connected to fast decay time constants ($<3 \text{ min}$) (Figure 12). This is shown in Figure 13, where the decay time constant is plotted against the local aerosol load.

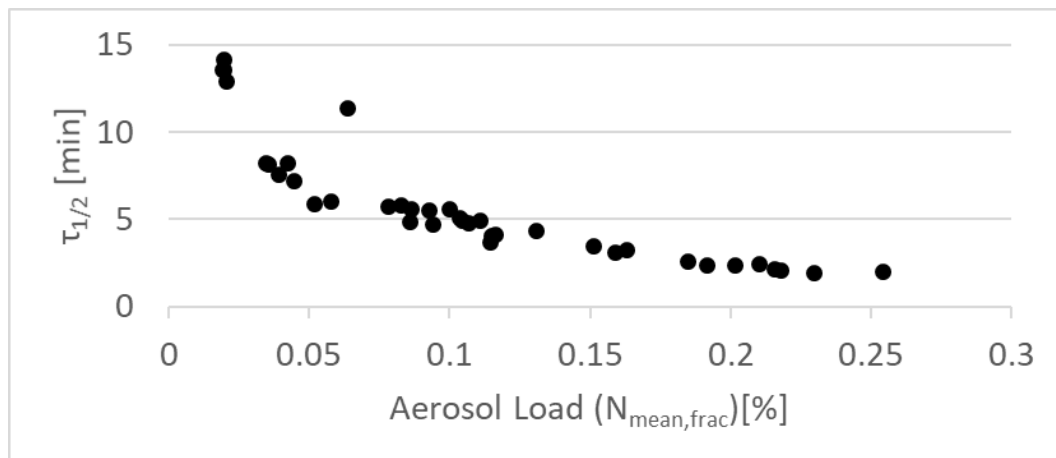


Figure 13: Correlation of decay time constants ($\tau_{1/2} [\text{min}]$) and aerosol load for case ID #05 (source on 24 with mouth-nose coverage).

4.6. Dilution of HVAC System

The dilution of the HVAC system is investigated by means of PIA. The particle source was positioned in the suction region of seat 31, with the data acquisition taking place in the aisle at the inlet region between seats 24 and 28.

A PIA measurement run started with 5 minutes of zero-concentration measurements for plausibility. Afterwards, the particle generation from the source was activated and kept active for 20 minutes, then it was turned off again. Finally, for 15 to 25 more minutes, the dilution and removal of the aerosol within the compartment was measured.

An example of a measurement run with the source positioned in the foot space of seat 31, no filter within the HVAC system and an outside temperature of 28°C, is presented in Figure 14. The raw count of detected particles is presented as a function of the measurement time (light blue line) with a sliding median (0.5 minutes window) given in red. The activation (2) and deactivation (3) of the source are indicated by two vertical dashed blue lines. An average zero concentration (1) below one particle count is reported. With the activation of the source, the particle number increases to a plateau region starting at $t = 17$ mins. With the deactivation of the source, an exponential decay of the particle number occurs (4). A quantitative comparison of different cases is possible by means of the median of the particle number within the plateau region, marked by (5), which is determined for the 5 minutes prior to the deactivation of the source.

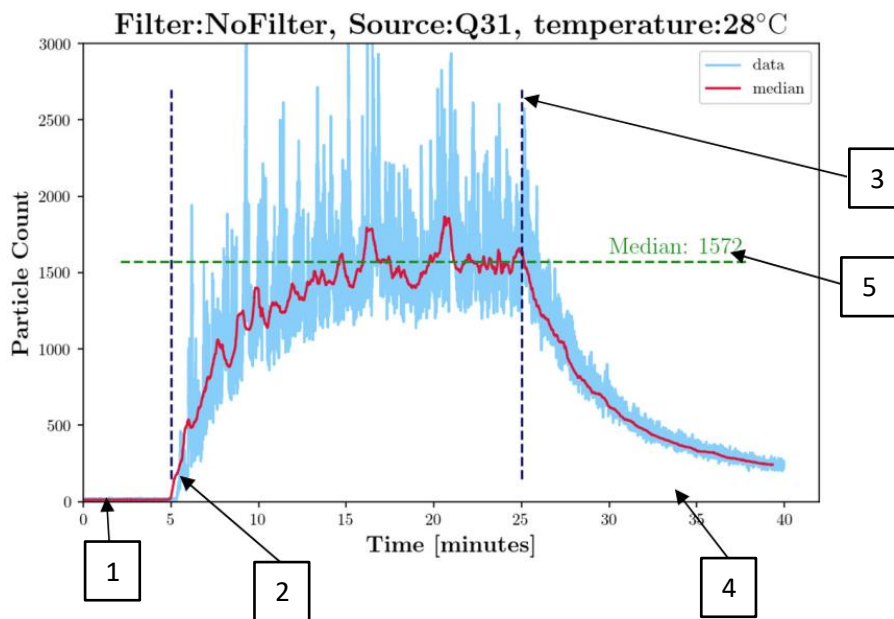


Figure 14: Particle count determined by the PIA method for an example case with the source positioned at seat 31, no filter within the HVAC system and an outside temperature of 28°C. (1) 5 minutes pre-conditioning, (2) start of saliva aerosol generation, (3) end of saliva aerosol generation after 20 minutes of generation, (4) decay curve for 15 to 25 minutes after end of saliva generation, (5) calculated median value within five minutes before end of saliva generation.

Following the scaling procedure described in section 3.2.3, Figure 15(a) presents a scaled version of Figure 14 with identically chosen markings. It is apparent that, over the measurement duration, the extrapolated particle number ($\dot{N}_{Ceiling}$) with respect to the source ($\dot{N}_{Source}$) increases to a median value in the plateau region of 2.21. This is because particles from the compartment are recirculated through the HVAC system and reenter the compartment through the ceiling.

Furthermore, a curve fit is employed to the tail of the scaled curves to estimate the parameters of the following function to describe the exponential decay:

$$f(t) = A \cdot e^{K \cdot (t-D)} + C$$

Afterwards, the determination of the half-life based on the fitting parameter is possible.

In order to compare the HVAC system, the previously mentioned three temperature cases for chamber temperatures of 28°C, 10°C and -10°C were investigated. Additionally, the source position was moved to seat 111 for the 28°C case. The results are compiled in Table 3. For the source position at seat 31, the particle count reflected by the median value decreases with decreasing temperature, from 2.21 to 0.99. This is easily accounted for by the significantly lower absolute humidity of the fresh air which helps to disperse the aerosols. And yet, no clear trend is visible from the half-life of the three data points: $T = 28^{\circ}\text{C}$ and 10°C behave mostly the same with a half-life close to each other (2.88 and 2.69 minutes), while for $T = -10^{\circ}\text{C}$ a higher half-life of 3.30 minutes is determined.

For the altered source position at seat 111, the particle number is suppressed compared to the 28°C case at the reference position. This finding confirms the impact of the source position on the particle concentration at the measurement position. Possible explanations could be that a) the recirculated / waste air split rate differs along the compartment; b) different recirculation pipe lengths lead to different deposition rates; or c) the suction system is not capable of extracting all of the supplied aerosol particles, which partially remain in the region of the source. The latter is supported by the significantly increased half-life, as the effect of the aerosol dilution and removal is superimposed by the aerosol being transported along the compartment to the measurement point.

Table 3: Comparison of the HVAC system for different scenarios without filters.

CASE ID	SOURCE POSITION	T _{CHAMBER} MEIKE	MEDIAN (NORMALIZED)	HALF-LIFE [MINUTES]
#15	31	28°C	2.21	2.88
#19	31	10°C	1.69	2.69
#21	31	-10°C	0.99	3.30
#23	111	28°C	1.54	5.05

4.7. Impact of Air-Filter

As part of this study, the impact of different air filters on the aerosol spreading was investigated and compared to the previously discussed reference case (section 4.6). First of all, a used G4 filter was tested as it represents the typical operation scenario; secondly, the performance of a new G4 filter was measured; and thirdly, a higher class M5 filter was investigated. All given filter classes follow the classification in the standard EN 779 [23]. The investigation focused on the named filters, since higher class filters do come along with an increased pressure resistance and, hence, the HVAC system was expected not to be able to overcome the additional pressure drop over a fine or even ultra-fine particle filter. Hence, we varied the filters to only one class finer than the standard filter of the test facility, which is a G4-class filter.

In Figure 15, the time series of the normalized aerosol number are shown. Among all the curves, a similar behavior is observed: close to zero-concentration before the activation of the source. Here, some contamination is reported for the used G4 filter. After the activation of the source, the particle number increases to a plateau region, followed by exponential decay after the source is turned off. The best performance, indicated by the lowest median value of 1.68, is achieved by the used G4 filter, whereas, the other three filters perform similarly with median values between 2.21 and 2.28. This is unexpected as the highest filter class (M5) performs in a similar way to the case without a filter or a new G4 filter, meaning that, for aerosols, filters up to M5 show no impact. On the other hand, this indicates that a used G4 filter operates at a higher filtering level (for the aerosol particles) which may be due to a higher occupancy of dust and dirt and, thus, smaller filtering pores. Here, it should be noted, that the fresh air volume flow rate, sucked from outside, was controlled and measured during the tests. However, the supply air volume flow rate in the compartment might change for different cases. The nominal value for the supply air flow rate amounts to 2,600 m³/h but

it is automatically controlled by the HVAC system, which sets the frequency of the supply air fans and cannot be monitored. As a consequence, the application of a different filter or the removal of the filter can influence the supply air volume flow rate. The same holds for different configurations (+28°C, +10°C and -10°C), where a different control algorithm might change the supply air volume flow rate. Taking these effects into consideration, the unexpected filtering behavior can be explained. Finally, it should be noted that the results of the measurements are still highly valuable despite the unknown effect of the HVAC's supply air flow rate, since they show what really happens if the filter in a system as complex as an ICE train is changed and that a change to higher filter classes does not automatically result in reduced aerosol loads, which would be expected from laboratory tests if all other parameters were kept constant.

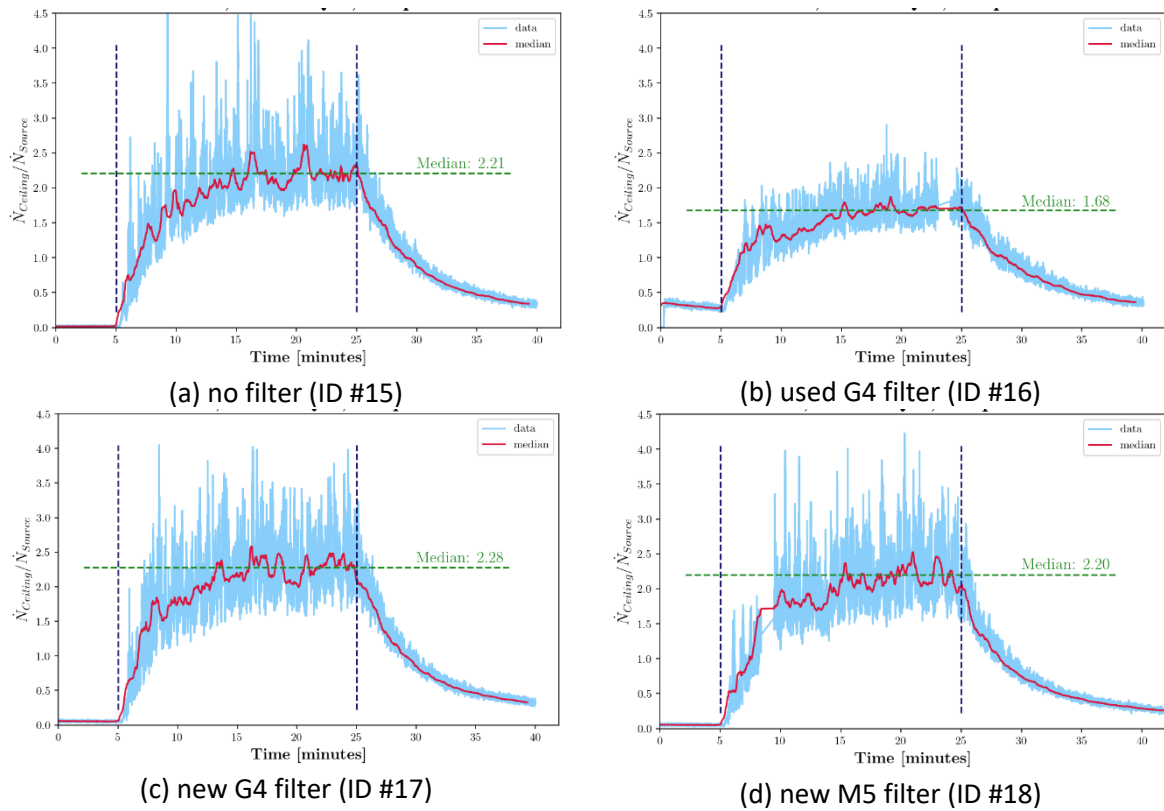


Figure 15: Normalized particles rates recorded in the supply air flow just below the ceiling within the compartment for (a) no filter, (b) a used G4 filter, (c) a new G4 filter and (d) a new M5 filter.

An overview of the results for all investigated scenarios for different filters is presented in Table 4. For the source seat position 31, the best measured performance is determined for the used G4 filter with the absolute lowest median value of 0.96 for the -10°C case. Still, the differences for +/-10°C are negligibly small when comparing the no filter scenario to the G4 filter. For the alternate source position at seat 111, a normalized particle number median of about 1.54 (no filter) down to 1.30 (M5 filter) is reported. The used G4 filter performs slightly better than the new one (1.42 vs. 1.49).

The half-life reported in Table 4 is clearly grouped by the source position: the source position at seat 31 exhibits a half-life between 2.5 and 3.8 minutes while, for the source at seat position 111, a time between 5.0 and 5.6 minutes is found. We expect that the reason for this dependency can be found in the pipe system of the exhaust air, see Figure 2(a). The fraction of recirculated and waste air will depend on the position of the exhaust. If the exhaust from the passenger compartment is close to a recirculating riser duct, then more will be recirculated, if the exhaust is close to the waste air channel, then less will be recirculated.

Table 4: Performance comparison for different filters and temperature scenarios.

CASE ID	FILTER	SOURCE POSITION	T _{CHAMBER} MEIKE	MEDIAN (NORMALIZED)	HALF-LIFE [MINUTES]
#15	No Filter	31	28°C	2.21	2.88
#16	G4old	31	28°C	1.68	3.83
#17	G4new	31	28°C	2.28	2.63
#18	M5	31	28°C	2.20	2.80
#19	No Filter	31	10°C	1.69	2.69
#20	G4old	31	10°C	1.74	2.58
#21	No Filter	31	-10°C	0.99	3.30
#22	G4old	31	-10°C	0.96	3.21
#23	No Filter	111	28°C	1.54	5.05
#24	G4old	111	28°C	1.42	5.12
#25	G4new	111	28°C	1.49	5.57
#26	M5	111	28°C	1.30	5.28

5. Discussion

The investigations carried out on the test vehicle revealed that the spreading of aerosols within the passenger compartment takes place primarily directly and with limited travel length. The particles do not spread in great concentrations over the air conditioning system and, therefore, not throughout the entire vehicle.

5.1. Derivation of Measures

Independently from a virological assessment (which was not part of this study), the results obtained in this project do allow a basic assessment of measures for safeguarding railway operations during the COV2-pandemic. They agree with the information and recommendations for travelling in Germany as issued by the RKI authority in early 2021 (cf. to [31]). The most prominent points are:

- A minimum distance of 1.5 m should be maintained in public, wherever possible
- A medical face mask must be worn in certain public areas when one cannot maintain the minimum distance of 1.5 m from other people.
- Ventilate whenever possible.

From the results in LUQAS, it can be seen that the concentration of particles decreases significantly with increasing distance. Even the 'worst-case place' is exposed to not more than 0.35% of the particles leaving the mouth and nose of an infected passenger. In all other seats, the concentration is significantly lower. Thus, controlling occupation is an effective measure that creates sufficient space between the passengers so that they can maintain an adequate distance whilst travelling on the train. Consequently, in the pandemic, DB and other operators continued to run trains according to schedule, in spite of low passenger numbers.

During the pandemic (in year 2021), it became compulsory to wear a medical-grade mask (surgical mask or FFP2 mask) when using any form of public transport throughout Germany, as well as at stations, stops and on platforms. The results from LUQAS show that, during the pandemic, this is a crucial and highly effective measure against the spreading of aerosol particles. Whereas the effect on large droplets can clearly be seen by a simple comparison of the data sheet of the mask with the degree of separation and the size distribution of the particles, there is also a surprising effect against small aerosol particles. By reducing the momentum of exhaled aerosols by using a mask, the aerosols more easily follow the air flow generated by the HVAC installations and are quickly transported outside.

Whenever the necessary technology is present, in S-Bahn trains, the automatic door opening at stops seems to be beneficial. This enables fast boarding and disembarking without touching any surfaces and it also lets fresh air circulate in the carriages. The vehicles' climate control systems pump fresh air through the trains, helping to further minimize the concentration of aerosols. In LUQAS, during the measurements in DIRK, which is a long-distance train coach, no influence of the door opening on particle distribution could be found.

A further result of LUQAS was that any technical solutions for air purification within the air conditioning system will only be effective to a limited extent. Aerosol particles are reduced by number and size in the air duct and the concentration of particles is decreased by the high fresh air rates provided by the HVAC-units.

5.2. Transferability of the Results to other Train Compartments

For assessing the transferability of the achieved results to other train compartments, fleet-relevant investigation scenarios were created in order to define the relevant characteristics of the wagon types used in the DB vehicle fleet. Classified as 'relevant' were the characteristics that significantly influenced the extent to which the distribution of aerosol particles was influenced in the achieved measurements and simulations. Main clustering categories were:

- climatic concepts;
- operational concepts;
- interior concepts; and
- passenger behavior.

Within these four main categories, various sub-categories and therein contributing parameters were distinguished. For the most extensive, aerosol-spreading-relevant category, the climatic concept, the sub-categories: 'air supply', 'recirc air', 'exhaust air', 'heating mode', 'cooling mode', 'control strategy' and 'pressure safety' were captured. Herein, e.g., for the air supply the different features: 'floor supply', 'ceiling supply, full trickle ceiling', 'ceiling supply, two-part linear', 'ceiling supply, flexible grid channel', 'under-window supply', 'lateral window supply' and 'mixed air supply' were identified. The other main categories comprise, e.g., 'door-openings' within the operational concepts, the 'seat classes', 'seat arrangements' and whether tables were present within the interior concept category and the 'typical travel time' or the 'mean occupation' within the passenger behavior category. In total more than 60 features which were found in the different coaches were categorized. In total more than 14 thousand coaches were considered – about 10,000 regional and 4,300 long distance vehicles. For each of them and for each feature, e.g. "is supply air coming from above?" or "does the coach have a pipe-guided exhaust air?" or "is a floor-heating installed?", the comparability to the DIRK test vehicle was evaluated.

This assessment resulted in different degrees of correspondence for all kinds of clusters and coaches. For coaches that had an operational, interior and HVAC-concept similar to the DIRK test vehicle (e.g., with similar fresh air rates and supply air from the ceiling and waste air suction along the floor), the assessment resulted in a high degree of correspondence (>90%). This was found for all ICE 1 and ICE 2 coaches where 90% of the evaluated parameter are the same as in the investigated DIRK test vehicle. Hence, we expect a high transferability of the presented results to these coaches.

But also, for the latest series of ICE trains, an intermediate degree of correspondence ($\approx 60\%$) was found, mainly justified by the current guidelines [22] [32], that prescribe the thermal comfort and air quality in trains. Here, deviations are essentially caused by a different exhaust air configuration, a mixed fresh air supply during heating operation and the absence of a floor-heating system. For parameter configurations where these differences play only a minor role, e.g., cooling operation in summer, we expect a high transferability of the results obtained in the DIRK test vehicle. However, if local details or precise quantitative values for the spreading behavior and the decay curves are of

interest, additional measurement campaigns or validated simulations must be performed within the coach configuration of interest.

For example, the specific fresh air rate (per seat/passenger) is prescribed in the existing guidelines for thermal comfort to be between 10 and 20 m³/h for a long-distance train. For regional trains, specific fresh air rate has to be between 10 and 15 m³/h and, for suburban trains, between 8 and 12 m³/h, depending on the defined category. In the LUQAS research project, the fresh air rate in the DIRK varied from 8 to the maximum possible fresh air flow rate per passenger while measuring the particle distribution. This made it possible to determine the influence of the parameter 'fresh-air-rate' and to transfer the results to similar concepts, depending on the degree of similarity of all the other parameters.

In conclusion, we expect the impact of the masks, the fresh air rate and the implementation of different filters to be transferable to other train configurations. Other results, especially the quantitative aerosol spreading results will locally differ for other trains, in specific if there are different resulting air flow patterns in the compartment caused by, e.g., different supply and exhaust air configurations.

6. Summary and Conclusions

This paper presents the approach and results of an investigation of possible propagation paths of aerosol particles in a rolling stock passenger compartment. Investigations were undertaken by extensive measurements in a stationary test vehicle (DIRK – ICE 2 rail car), by applying a CO₂ tracer gas measurement technique, a laser-based Particle Image Analysis technique and particulate matter sensors. Furthermore, in this study, constant and reproducible ambient conditions for the DIRK test vehicle were provided by the MEiKE climatic chamber.

It has been shown that aerosol contamination factors above 0.1% only occur at a restricted distance over a few seat rows, decaying to values of 0.015-0.026% with increasing distance, at the other end of the compartment. In the measurements, the maximum percentage of particles exhaled by a passenger and inhaled by another passenger is less than 0.35% (without the use of face masks). For example, assuming a normally breathing person with ~2000 aerosol particles per minute exhalation would result in an inhalation of 7 aerosol particles/minute (=0.35% of those exhaled) on the highest contaminated neighboring seat. A multiplication to account for the travel duration and an assumption of the virus quota per exhaled particle will result in the number of inhaled viruses. A mouth-nose-protection (surgical mask) reduces this maximal value by 27%. Here, only the effect of the mask at the source was considered, an additional reduction of inhaled aerosols will be achieved when the receivers also wear masks. Furthermore, the use of a mouth-nose-cover strongly reduced the dispersion lengths within the passenger compartment. Although it was not the scope of the present study to perform a virological/medical assessment, the results of the percentage of inhaled particles can be used as input. It is also shown that the decay time-constant of the local particle concentration on the seats close to the source is less than five minutes, i.e., less than five minutes after an infected person leaves the train, the concentration drops below 1/e of the stationary values. In other words, approximately 3.3 minutes after stopping the emission, the HVAC system reduces the local particle concentration by a factor of two.

Increasing the filter grade (M5), in contrast to a common G4 filter, does not significantly influence the reduction of the particle load. Furthermore, in heating conditions, similar results are obtained regarding the half-life of the aerosol load as for the analyzed cooling cases. However, regarding the number of aerosols transported through the HVAC system, a reduction by a factor of about two was found for heating, compared to cooling mode.

Finally, it is concluded that the propagation aerosol particles from one passenger to another by the indirect method, i.e., from one passenger to another passenger via the air conditioning system, is nearly irrelevant compared to the propagation method directly from one passenger to another.

However, it should be noted, that there is non-zero aerosol transport via the HVAC system, resulting in locally inhaled particles far away from the source, at around 0.015-0.026%, depending on the fresh air rate and whether a mask is used, which is more than one order of magnitude lower (92.6%) than on the most contaminated seats. The implementation of additional measures in the HVAC system could only reduce the pollution by this amount. Hence, even if such measures are valuable for the overall aerosol load in the full compartment, the peak loads on the most contaminated seats in the vicinity of the source would only be reduced by approximately 0.02% of inhaled aerosols, i.e., a relative reduction of $\approx 7.4\%$ on the most contaminated seats.

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Appendix – additional measurement data

A – Tracer Gas Analysis

Table 5: $\Delta CO_2 = CO_2^{i,seat} - CO_2^{i,background}$ for the cooling scenario. Values [ppm] on all seats (horizontal) for all studied cases (vertical).

	42	44	46	48	51	53	55	57	61	62	63	64	65	66	67	68	71	73	75	77	81	82	83	84	85	86	87	88	91	93
ID #01	54	53	55	45	104	78	89	78	356	190	source	181	142	153	144	151	110	111	100	101	48	44	48	41	45	32	41	29	21	26
ID #02	34	29	31	20	57	46	59	56	source	164	150	166	104	148	115	133	100	104	94	92	27	16	53	29	33	16	23	16	5	2
ID #03	20	19	21	15	41	29	42	30	58	598	74	source	63	126	65	127	158	144	120	119	45	33	66	53	35	31	43	39	23	13
ID #04	18	20	18	24	19	19	18	19	31	32	20	20	26	26	18	25	33	36	nan	nan	68	96	59	98	106	153	112	197	203	source
ID #05	45	40	43	38	95	70	80	67	249	180	source	173	130	152	135	147	99	106	90	88	44	25	49	23	23	22	33	10	4	11
ID #06	56	42	46	34	107	75	nan	nan	361	149	source	145	120	127	121	117	79	95	84	70	34	18	45	27	34	16	31	15	1	18

Table 6: $\Delta CO_2 = CO_2^{i,seat} - CO_2^{i,background}$ for the heating scenario. Values [ppm] on all seats (horizontal) for all studied cases (vertical).

	42	44	46	48	51	53	55	57	61	62	63	64	65	66	67	68	71	73	75	77	81	82	83	84	85	86	87	88	91	93
ID #10	52	30	40	32	89	85	73	75	150	154	source	148	81	111	84	109	96	130	86	82	25	31	13	25	23	22	16	21	13	20
ID #11	47	34	49	31	nan	nan	88	79	source	160	194	154	139	143	124	135	95	111	96	94	32	31	53	36	41	29	47	35	17	21
ID #12	27	22	27	10	56	45	38	31	71	760	76	source	72	131	74	149	107	131	111	96	36	22	41	36	8	14	21	29	2	0
ID #13	12	6	8	5	nan	nan	7	13	0	4	7	6	8	1	7	8	5	5	7	6	38	54	33	21	13	35	11	34	96	source
ID #14	47	32	32	39	nan	nan	38	43	38	57	source	57	59	58	43	51	58	48	51	62	21	14	33	13	32	18	40	18	10	4

B – Saliva Spreading (SPS30 Measurements)

Table 7: SPS30 measurements: $N_{mean,frac} = N_i / N_{source}$ for the cooling scenario. Values [%] on all seats (horizontal) for all studied cases (vertical).

	11	12	13	14	15	16	17	18	21	22	23	24	25	26	27	28	31	32	33	34	35	36	37	38	41	42
ID #01	0.163	0.171	0.140	0.167	0.126	0.174	0.147	0.165	0.266	0.350	0.208	source	0.235	0.249	0.172	0.252	0.238	0.112	0.263	0.117	0.241	0.112	0.221	0.107	0.051	0.038
ID #05	0.100	0.104	0.086	0.103	0.078	0.111	0.092	0.107	0.163	0.201	0.131	source	0.159	0.185	0.115	0.210	0.230	0.114	0.254	0.116	0.215	0.094	0.191	0.086	0.052	0.035
ID #07	0.122	0.136	0.106	0.131	0.094	0.137	0.110	0.130	0.209	0.252	0.180	source	0.188	0.201	0.132	0.199	0.251	0.128	0.281	0.134	0.248	0.122	0.226	0.116	0.053	0.039
ID #08	0.119	0.125	0.099	0.120	0.086	0.118	0.102	0.113	0.184	0.249	0.151	source	0.174	0.189	0.123	0.202	0.182	0.079	0.203	0.083	0.201	0.082	0.174	0.080	0.034	0.023

Table 8: continue of Table 7

	43	44	46	48	81	84	86	87	entr- ance	aisle 14	aisle 34- 24	aisle 33	aisle 43
ID #01	0.062	0.041	0.038	0.046	0.025	0.026	0.026	0.026	0.099	0.132	0.299	0.231	0.052
ID #05	0.058	0.039	0.034	0.042	0.019	0.019	0.019	0.021	0.064	0.083	0.151	0.218	0.044
ID #07	0.068	0.041	0.039	0.049	0.022	0.023	0.021	0.022	0.052	0.102	0.193	0.252	0.055
ID #08	0.042	0.025	0.022	0.027	0.015	0.016	0.015	0.015	0.091	0.089	0.173	0.198	0.034

Table 9: SPS30 measurements: Raw number of measured particle concentration [1/cm3] on all seats (horizontal) for all studied cases (vertical).

	11	12	13	14	15	16	17	18	21	22	23	24	25	26	27	28	31	32	33	34	35	36	37	38	41	42
ID #01	434	457	374	444	337	463	392	439	709	932	555	source	626	665	459	672	635	298	701	311	643	298	589	286	135	101
ID #05	265	277	228	274	207	294	245	284	433	535	347	source	421	491	305	558	609	304	675	308	572	249	508	228	137	94
ID #07	323	360	282	347	249	362	293	343	553	666	478	source	499	533	349	526	665	340	745	354	656	322	599	306	141	104
ID #08	313	331	262	316	226	312	271	298	485	659	398	source	460	501	326	535	479	209	537	219	531	215	460	212	91	61

Table 10: continue of Table 9

	43	44	46	48	81	84	86	87	entr- ance	aisle 14	aisle 34-24	aisle 33	aisle 43
ID #01	164	109	101	122	67	69	69	69	263	351	797	616	139
ID #05	153	104	91	112	51	51	51	54	169	219	401	578	118
ID #07	181	108	104	130	58	60	56	57	137	270	510	667	147
ID #08	111	65	59	72	40	43	40	41	241	235	456	522	90