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Smells like new car or rather like an old carriage? - Resolution of the decay behavior of odorants in vehicle cabins during usage

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Abstract

The typical new car smell is not only perceived directly after vehicle delivery. Vehicle interiors maintain their characteristic odors for a period of time during use even though the gas composition of the vehicle interior changes due to external influences. To obtain deeper insights into the odorant composition of a passenger cabin, this study aimed at characterizing the gas phase of two vehicle interiors at defined time intervals after vehicle delivery, and use by a customer in a controlled environment using a targeted odorant analysis. Thereby, the decrease in the general emissions in the cars did not coincide with the decay behavior of the odorants due to the chemical characteristics such as polarity of the odorants. Identification of the odorants in the vehicle interior during use revealed three groups of odor contributors exhibiting different decay behaviors: (i) odorants vaporizing rapidly via elevated temperature; (ii) odorants released by continued diffusion from materials; and (iii) fragrance chemicals of the customer. After 23 weeks of vehicle use, octanal, *p*-chloro-*m*-cresol, nonanal, *p*-*tert*-butylphenol, γ-nonalactone, and unsaturated aldehydes and ketones represented the most important odorants in the vehicle interior constituting the investigated car odor. The results of a descriptive sensory analysis corresponded with the identified odorants.

KEYWORDS
descriptive sensory analysis, gas chromatography–mass spectrometry/olfactometry, interior emissions, passenger cabin, smell, whole-vehicle test stand

1 | INTRODUCTION

In recent years, people spend more and more time in vehicles, for commuting, shopping, and other activities. The vehicle interior can therefore be considered to be part of the living environment. Recently, awareness about the air quality in general and especially the air quality in vehicles has increased.[1] As a consequence, research on the topic of indoor emissions in vehicles has gained momentum, and researchers focused, as a first approximation to the problem, on the total volatile organic compound (TVOC) concentration, and on individual volatile organic compounds (VOCs) that are present in high concentrations or have the potential to be harmful to human health.[1,2]

Several sources can be classified for VOC emissions in the vehicle interior. Thereby, outside air, factors introduced by the individual behavior of the driver and passengers in the passenger cabin such as

food consumption or transport of materials emitting volatiles, and the materials of the vehicle cabin have been reported to represent the main contributors.[3] However, outside air and the effect of the individual behavior of the passengers are highly individual and do not have a major impact on the vehicle interior air quality (VIAQ) within the first days and weeks after the handover.[4] The determining source of emissions has been reported to be the materials of the vehicle interior, comprising plastics, textiles, rubbers, leather, fibers, coatings, and auxiliaries such as adhesives and lubricants.[5]

The role of odorants with regard to VIAQ is only sparely discussed in the literature. On the contrary, parameters influencing the emissions and the air quality of the vehicle interior have been comparatively well-investigated.[6,7] Thereby, the temperature in the vehicle interior, vehicle make, age, and use of deodorizer products have been found to be important determinants of the qualitative and quantitative composition of VOCs that accumulate inside vehicles.[8] In addition, VOC concentrations in the vehicles have been reported to be strongly reduced under ventilation with settings comprising high air turnover rates and exchange with outdoor air, regardless of the selected ventilation mode.[8] However, instrumental analyses with respect to the VIAQ are mainly based on the comparison of the concentration of substances determined by gas chromatography-mass spectrometry (GC-MS).[1] As quantitatively dominating VOCs determined in GC experiments do not automatically represent the main odor contributors, odorants can only be elucidated by a targeted sensory analytical approach, which is conventionally achieved by coupling advanced GC-MS analyses with human sensory evaluation.[9] As a result, current knowledge about potent odorants which are commonly present at trace levels in the passenger cabin is very limited.[10]

In a previous study, we thus analyzed the causative odorants responsible for the typical new car odor.[11] We investigated two new cars of the same brand and model with different seat upholsteries directly after delivery in a whole-vehicle test stand for interior air emissions. Thereby, we identified the odor-active compounds by linking the chemical structures of the relevant odorants to the odor impressions obtained by a descriptive odor analysis, and we discussed the possible sources and formation pathways.[11] However, the typical new car smell is not only perceived directly after delivery. Vehicles maintain their typical odors for quite a period of time even though the gas composition of the vehicle interior changes during use due to elevated temperatures or ventilation.[4,5] Data about the change of the odorant composition in the vehicle interiors during usage are not yet available in the literature; one consideration is the potential decline of vehicle-specific smells, the other are additional odorants being potentially introduced into the passenger cabin depending on the individual driver's behavior and mode of vehicle usage.

The aim of this study was therefore to frame a case study that demonstrates that investigation of the changes in gas phase of the vehicle interior is achievable, and allows to pin down the main influencing factors for the development of a vehicle smell character that evolves over time. This case study required the development of an analytical approach to monitor the causative odorants at defined time intervals after vehicle delivery and during use.

Practical implications

Knowledge about the changes in odorant composition in the vehicle interior in the course of usage is scarce, and specifically the influence of temperature and ventilation on the decay of the odor in a passenger cabin is not known. We used advanced sensory analytical methods that combine GC analyses with human sensory evaluation to identify the odorants of two vehicles during use by a customer, and we thus provide a case study demonstrating that odor changes due to common usage can be monitored by this approach. A descriptive sensory analysis and identification of odorants at specific time intervals during vehicle use revealed that the increase in temperature in the vehicle cabin exerts a much more pronounced effect on the decrease in the odor of the vehicle cabin than ventilation of the vehicle interior. Mainly, aldehydes and unsaturated ketones represented the highest odor potency in the passenger cabin after 23 weeks of vehicle use. These findings provide the basis for further targeted odor investigations on the diverse emission sources of the passenger cabin.

To achieve this goal, the vehicles of our previous study[11] were handed over to a customer for use in his everyday life. The first vehicle was investigated after 2, 7, 14, and 22 weeks of use during summertime, and the second vehicle was investigated after 6 and 15 weeks of use by the same customer during usage in wintertime. The driver's behavior and the environmental conditions were according to common usage and were closely monitored. There was, for example, no transport of unusual odorous materials, and no food consumption, but the cars were solely used for commuting. In the course of the study, the odorants were sampled from the vehicles at defined time intervals in a whole-vehicle test stand and were immediately subjected to identification by means of gas chromatography-olfactometry (GC-O) and two-dimensional gas chromatography-mass spectrometry/olfactometry (2D-GC-MS/O). Additionally, the odor concentration of the vehicle interior air and the decrease in emissions of the passenger cabin were recorded correspondingly to each odor measurement. Furthermore, a descriptive odor profile analysis of the interior air was performed right after each measurement in case of the second vehicle.

2 | MATERIALS AND METHODS

2.1 | Investigated vehicles

Two identical vehicle models which were assembled on the same production line of a vehicle manufacturer were analyzed. Both cars were sedan vehicles, had four doors, and a separated luggage compartment. The interiors of the vehicles were equipped

identically except for their seat covers and design trim. Vehicle 1 was assembled with seats covered with black leather and had a sport trim, vehicle 2 was assembled with seats covered with black synthetic fabric and leatherette and had a standard trim. The vehicles were handed over in the fourth week after their production and were immediately analyzed in a whole-vehicle test stand. After the initial analysis, the vehicles were handed over to a customer for use during his everyday life. Vehicle 1 was delivered in February, and, after 2, 7, 14, and 22 weeks of use during summertime in Germany, measurements were taken in the whole-vehicle test stand, respectively. Meanwhile, vehicle 2 was delivered in October and was investigated after 6 and 15 weeks of use by the same customer during usage in wintertime.

The customer used the vehicles mainly for commuting to work and for shopping, with goods being transported that did not exert any unusual smells (typical household purchase), and traveled a monthly distance of approximately 2000 km. The vehicles were mainly moved in the city and on highways and were parked in a closed underground parking lot at home and in a parking garage at work. The customer did not use fragrances, stored smelling items as cheese, onions, and flowers, in the separated luggage compartment if necessary, and avoided bringing any fragrances into the interior of the vehicles. The air conditioning operated in automatic mode and airing of the vehicle interior air was only performed on hot days by driving with opened windows for a few minutes. The option of active ventilation by the air conditioning before driving was not used. During usage, a testo 175 H1 temperature data logger (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) recorded the temperature inside the vehicle at 20-minute intervals in a storage net of the back of the driver's seat.

2.2 | Chemicals

Diethyl ether (Et_2O; from Sigma-Aldrich, Steinheim, Darmstadt, Germany) was freshly distilled prior to use, and liquid nitrogen (Westfalen AG, Münster, Germany) was applied for the analyses. A solution of n-alkanes hexane to triacontane (C_6–C_{30}; all supplied from Sigma-Aldrich, Steinheim, Germany) in pentane was used to determine retention indices. Desorbed glass tubes (1/4 in. × 3 1/2 in.) containing 200 mg Tenax® TA 60/80 mesh (Supelco, Pennsylvania, USA) filled with silanized glass wool (Sigma-Aldrich, Steinheim, Germany) were used for the adsorption of air. The following reference substances were used for the identification of the odorants. Trivial names are given in brackets wherever applicable, and the corresponding suppliers are indicated in parentheses:

1-hexen-3-one ≥90%; 4-hydroxy-3-methoxybenzaldehyde (vanillin) ≥99% (ABCR, Karlsruhe, Germany); (*E*)-2-nonenal ≥97%; (*E*,*E*)-2,4-nonadienal ≥85%; (*E*,*Z*)-2,6-nonadienal ≥95%; 1-methyl butyl acetate ≥99%; 1-octen-3-one ≥96%; 2-methoxyphenol (guaiacol) ≥99%; 2-phenylethan-1-ol (phenethyl alcohol) >99%; 3-isopropyl-2-methoxypyrazine ≥97%; 3,7-di-methyl-3-octanol (tetrahydrolinalool) ≥97%; 4-(2,6,6-trimethyl-1-cyclohexenyl)-3-buten-2-one (β-ionone) >97%; 4-methylphenol (*p*-cresol) >98%; benzophenone ≥99%; benzothiazole ≥96%; exo-1,7,7-trimethylbicyclo[2.2.1]hept-2-ylacetate (isobornyl acetate) ≥95%; hexanal ≥98%; octanal ≥99%; trans-3,7-dimethyl-2,6-octadien-1-ol (geraniol) ≥98%; γ-nonalactone >98% (Aldrich, Steinheim, Germany); 2-acetyl-1-pyrroline >95%; tr-4,5-epoxy-(*E*)-2-decenal ≥97% (AromaLab, Freising, Germany); ethyl butanoate ≥98%; 1-octen-3-ol ≥98%; 4-allyl-2-methoxyphenol (eugenol) >98%; nonanal ≥95% (Fluka, Steinheim, Germany); decanal ≥98%; 1-(2,6,6-trimethyl-2-cyclohexen-1-yl)-2-buten-1-one (α-damascone) ≥95%; 3-methyl-4-(2,6,6-trimethyl-2-cyclohexen-1-yl)-3-buten-2-one (α-isomethylionone) ≥95%; 1,2,3,4-tetrahydronaphthalene (tetralin) >99.5%; 2,6-di-*tert*-butylphenol ≥99%; 2-methoxynaphthalene ≥99%; 2-methylpropyl acetate ≥99%; 3-isobutyl-2-methoxypyrazine ≥99%; 3-methylbutyl acetate >99.7%; 4-chloro-3-methylphenol (*p*-chloro-*m*-cresol) ≥99%; 5-ethylidene-2-norbornene ≥99%; butyl acrylate ≥99%; *p*-*tert*-butylphenol ≥99% (Sigma-Aldrich, Steinheim, Germany). Further compounds were synthesized as described in literature: 2-butyl-2-heptenal,[12] 2-propyl-2-octenal[12] and (*Z*)-2-butyl-2-octenal.[12,13]

2.3 | Sampling of vehicle interior air

The vehicles were heated on a test stand for the investigation of the interior air. The temperature of the test stand was set at 23°C and was purged with air which was purified by an activated carbon filter by means of an eightfold air exchange. Two sampling interfaces made of polytetrafluorethylene (PTFE) were installed in the doors on the front left side (interface 1) and rear right side (interface 2) replacing the windows, whereby the gaps between door frames and sampling interfaces were covered with aluminum foil. The interfaces contained a total of ten tubes and enabled sampling of air at the head level of the driver and codriver. Additionally, interface 1 was connected with a flame ionization detector (FID) Testa FID-2000 MP (Testa GmbH, München, Germany) for monitoring the total hydrocarbon volumetric concentration and a temperature sensor installed at the head position on the driver's seat. The online-FID and temperature sensor were linked with a data logger Almeno 2890-9 (Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany). Halogen light emitters were installed above the car to heat the passenger cabin with a radiant power of 400 W/m^2 on the roof surface as described in ISO 12219-1 (interior air of road vehicles - part 1: whole-vehicle test chamber - specification and method for the determination of volatile organic compounds in cabin interiors). The vehicles were parked in the test stand for one night with closed doors and installed interfaces before heating.

Air of the vehicle interior was sampled on glass tubes filled with Tenax® TA by means of Desaga pumps GS 301 (Sarstedt AG & Co. KG, Nümbrecht, Germany). The pumps were set with an air flow rate of 0.2 L/min, allowed sampling of a standard volume and were connected with moisture traps (economy moisture

trap 400 cc; from Supelco, Pennsylvania, USA) filled with blue gel (silica gel with a color indicator; from Sigma-Aldrich, Steinheim, Germany). The accuracy of the flow rate was checked with a DRYCAL flowmeter defender 510 (Mesa Laboratories, Lakewood, USA). Air of the vehicle interior was sampled after 3 h 30 min and 4 h 30 min heating the vehicle interior on the test stand onto ten tubes filled with Tenax® TA, respectively. Thereby, each tube was charged with 10 L air. No breakthrough was detected on backup tubes connected in series for the investigated odorants. As the further sample workup was solvent-based, the detection of the very volatile compounds was not possible due to coelution with the solvent. The first set of tubes served as backup samples, and the second set of tubes was subjected for the further sample workup as described in Section 2.4. Additionally, vehicle interior air was sampled in odor bags for a descriptive sensory evaluation and olfactometer tests between the sampling of the two sets of tubes after 4 h 20 min heating, respectively. Thereby, the air was sampled in odor bags made of Nalophan® with PTFE tubing by means of a vacuum container. After 5 h 30 min, the halogen radiators were switched off.

2.4 | Instrumental-olfactometric analyses

Each adsorption tube was extracted by purging 5 ml diethyl ether through the tube with the aim to isolate the odorants in the form of a liquid extract. Ten extracts were combined to receive an extract of vehicle interior emissions and odorants in diethyl ether, thus finally representing 100 L of collected air. To remove non-volatile constituents of the extract, as dust and air-borne particles, which were present after elution, the solvent-assisted flavor evaporation (SAFE) technique was applied.[14] The subsequent distillation steps of the extract and the instrumental setup for the identification of the odorants, the gas chromatography-olfactometry (GC-O) and two-dimensional gas chromatography-mass spectrometry/olfactometry (2D-GC-MS/O) systems are described in detail in our previous studies.[10,11] Identification of odorants was achieved by comparing the respective odor qualities (O), retention indices (RI) on two capillaries with different polarities (DB-FFAP and DB-5), and the mass spectra (MS) with the data of the respective reference compounds (RC). The indicated RI are average values of measurements on different instruments of our research group and are in accordance with literature data (if available).

To determine the potential impact of the individual odor-active compounds in the distillates obtained from air samples of the vehicle interior, the odorants were ranked by means of comparative odor extract dilution analysis (cOEDA).[15,16] To this aim, the concentrated distillates of the samples were diluted stepwise with diethyl ether (ratio 1 + 1; v/v), resulting in twelve solutions for each sample with odor dilution (OD) factors from 2 to 4096. Each dilution was analyzed by GC-O, and for each odorant, the OD factor was determined on a DB-FFAP column. The resulting OD factor represents the last dilution in which the odor of the corresponding substance was still perceivable. To avoid potential overlooking of odorants and to rule out the potential bias due to specific anosmia, two panelists performed at least one GC-O analysis of the undiluted distillate (OD 1) and the dilution OD 32 of each sample.

2.5 | Sensory evaluations

2.5.1 | Descriptive analysis

The descriptive sensory analysis was performed by eight trained volunteers (three males, five females; age range: 22–30 years) from the Chair of Aroma and Smell Research, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Germany. The panelists had a normal olfactory function at the time of examination and exhibited no known illness during the testing. The members of the descriptive sensory analysis were weekly trained in perceiving and describing odor qualities of about 150 odors which covered typical odorants from the food as well as from the non-food sector.

Presentation of the odor samples in odor bags was performed according to the automotive standard ISO 12219-7 (odor determination in interior air of road vehicles and test chamber air of trim components by olfactory measurements) with the odor presentation device PureSniff II (Olfasense GmbH, Kiel, Germany). Thereby, the samples were presented for 2.5 seconds with a volume flow of 20 L/min to the panelists. The descriptive odor analysis was carried out according to ISO 13299 (sensory analysis - methodology general guidance for establishing a sensory profile). In the first step of the sensory evaluation, the panelists were invited to name the perceived odor impressions. In a second step, the compiled odor attributes were discussed within the panel and attributes with an agreement of at least the half of the panel were selected. In a third step, the panelists were asked to evaluate the intensities of the selected attributes and to rate the total intensity on a scale from 0 (no perception) to 10 (strong perception). Five smell sticks containing ethyl methyl propanoate, benzothiazole, decanoic acid, (*E*)-2-nonenal, and hexanal, and a sensory glass comprising pine shavings were used as references for the ratings of the odor attributes fruity, rubber-like, plastic-like, fatty/cardboard-like, green, and wood-like, respectively.

The descriptive sensory analysis was only performed on samples of vehicle 2. Vehicle 1 was handed over to the customer for use shortly before the beginning of the COVID-19 pandemic in 2020. Thus, it was not possible to perform a sensory analysis during vehicle usage with a sufficient number of trained panelists as this was prevented by the local lockdown restrictions.

2.5.2 | Olfactometer analysis

Investigations on the odor thresholds of the air samples of the vehicle interiors were conducted with five volunteers (three males, two females; age range: 27–59 years) from the Chemistry Department of the BMW Group in Munich, Germany. The panelists had a normal

olfactory function at the time of examination, exhibited no known illness during the testing, and had been working in the field of vehicle interior emissions and odor evaluation for several years. The experiments were conducted according to DIN EN 13725 (air quality - determination of odor concentration by dynamic olfactometry) with an olfactometer TO8 (ecoma GmbH, Honigsee, Germany). The presentation time of the odor samples was set to 2.2 seconds. As a result of the investigations, the odor concentration of the mixtures of odorants (ou_E/m^3) of the odor samples were calculated as the geometric mean of three replicate measurements. However, for absolute quantitative ratings of the odor threshold on the vehicle interior, the concentration of all odorants would be required.

3 | RESULTS & DISCUSSION

3.1 | Influence of temperature and ventilation on the odor and emissions of the vehicle interior

The vehicles that were provided for customer usage were tested in a whole-vehicle test stand under thermal exposure. A summary of the conducted measurements including the odor concentrations, the recorded decrease in TVOC-FID levels of the respective vehicles, and the maximum temperature of the vehicle interior in each case is given in Table 1.

Vehicle 1 was examined in short intervals during the initial phase, followed by a monitoring at longer intervals versus the later phase of use. From the start, a considerable decrease in the odor concentration (from 304 to 109 ou_E/m^3) and the level of total emissions (to 46% of the initial value) were observed between the first and second measurement. The maximum temperature in the vehicle interior (35°C) was reached during the heating process within the whole-vehicle test stand. After 7 weeks of use, the odor concentration value decreased further to 96 ou_E/m^3, while the total concentration of emissions in the vehicle interior remained the same. Comparing the results of the fourth and fifth measurement, the odor concentration initially decreased to 43 ou_E/m^3, but then remained at the same level. Emissions, on the other hand, continued to decrease again to 22% and 14% of the initial value, respectively, corresponding with additional temperature maxima of 41°C and 49°C in the vehicle interior. A similar behavior was observed for vehicle 2: a strong decrease in the odor concentration (from 287 to 68 ou_E/m^3) as well as emissions (to 39% of the initial value) was apparent after 6 weeks of usage. Further use of the vehicle during wintertime with low outdoor temperatures led to a continued decrease of the odor concentration to 45 ou_E/m^3; the total emission concentration, on the other hand, remained at a similar level.

Comparing the results of vehicle 1 and vehicle 2, both odor concentration values of mixtures of odorants were at a similar level at delivery, even though the vehicles were provided equipped with different seat upholsteries. Driving caused a lower concentration of odorants and total emissions in vehicle 2 after 6 weeks of usage (odor concentration: 68 ou_E/m^3; TVOC-FID: 39%) than in vehicle 1 after 7 weeks (odor concentration: 96 ou_E/m^3; TVOC-FID: 46%). For both vehicles, the maximum temperature reached 35°C in the whole-vehicle test stand until this time. After 14 weeks use of vehicle 1 and 15 weeks use of vehicle 2, the concentration of odorants was at a similar level, although the passenger cabin of vehicle 1 exceeded the measurement temperature of 35°C with a total of seven times during driving (see Figure 1).

The results show a clear correlation between the decrease in the general emissions and increase of temperature in the vehicle interior. This behavior has already been shown in a number of studies.[6,7] Direct sunlight can heat components such as the instrument panel, resulting in an increase of evaporation of compounds with higher boiling points into the gaseous phase. If a vehicle is subsequently opened, volatile compounds can escape from the passenger cabin, before redeposition on surfaces can occur, an effect which is also

TABLE 1 Summary of the conducted measurements for vehicle 1 and 2 in the whole-vehicle test stand

	Measurement	Time of use	Odor concentration	TVOC-FID	Max temperature in vehicle interior during usage
Vehicle 1	1	- (delivery)	304 ou_E/m^3	100%	-
	2	2 weeks	109 ou_E/m^3	46%	24°C (test stand: 35°C)
	3	7 weeks	96 ou_E/m^3	46%	30°C (test stand: 35°C)
	4	14 weeks	43 ou_E/m^3	22%	41°C
	5	23 weeks	43 ou_E/m^3	14%	49°C
Vehicle 2	1	- (delivery)	287 ou_E/m^3	100%	-
	2	6 weeks	68 ou_E/m^3	39%	25°C (test stand: 35°C)
	3	15 weeks	45 ou_E/m^3	37%	23°C (test stand: 35°C)

Note: In addition, the odor concentrations, decrease in TVOC-FID levels of the respective vehicles as well as the maximum temperature in the vehicle interior during usage between previous and following measurement are shown. If the maximum temperature was recorded in the course of a measurement in the whole-vehicle test stand, these values are additionally provided in brackets.

ou_E/m^3 odor concentration of mixtures of odorants measured via an olfactometer test according to DIN EN 13725; *TVOC-FID* total volatile organic compound value specified in percentage of the initial value of the first measurement recorded via an online-FID determination during thermal exposure in the whole-vehicle test stand as described in ISO 12219-1.

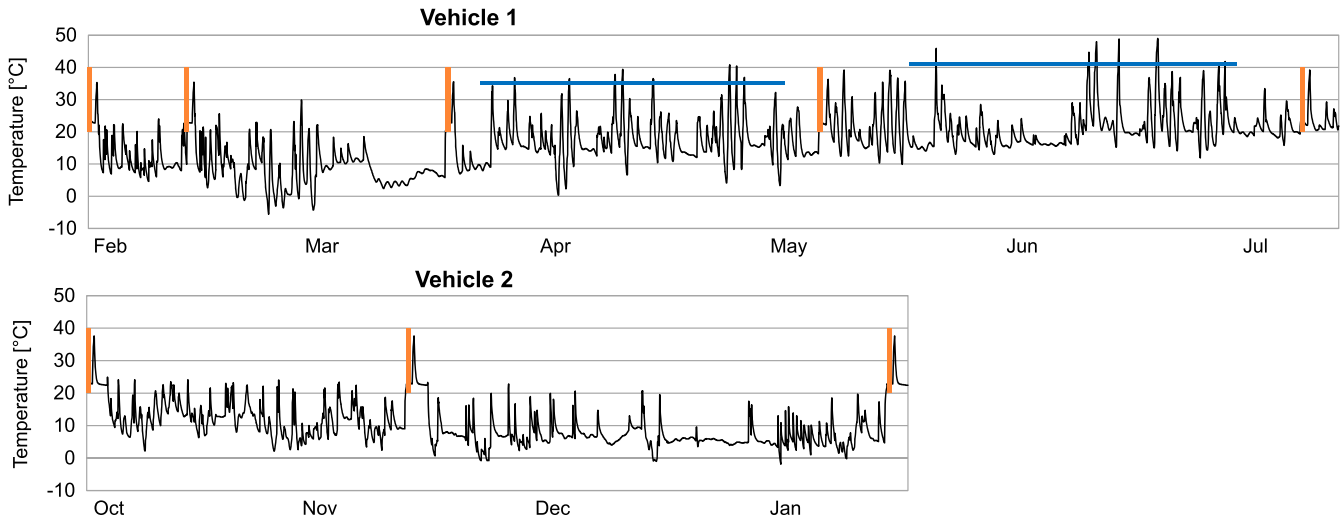

FIGURE 1 Temperature profiles in the passenger cabins of vehicle 1 (top) and 2 (bottom) during use. Elevated levels of temperature in the vehicle cabins caused in the course of the measurements in the whole-vehicle test stand are marked with orange lines. In addition, new temperature maxima compared with the previous measurement in the cabin of vehicle 1 recorded during use are marked with a blue line

known as fogging.[17] However, the contained odorants of the vehicle interior apparently followed a different decay behavior with respect to the quantitatively dominating emissions. The odor concentration values decreased successively after each measurement, whereas the TVOC-FID values remained the same in case of measurements without preceding new temperature maxima in the vehicle interior during usage. Emissions in the passenger cabin have commonly been reported to mainly contain apolar aliphatic and aromatic hydrocarbons as well as semi-polar alcohols and carbonyl compounds, albeit the latter being present in lower concentrations.[18,19] However, the odorants of the two investigated vehicles that had been detected in our previous study can be classified as being predominantly semi-polar.[11] As a consequence, divergences in decrease of the respective substance classes as a result of the polarity of the compounds are likely and might be proposed to result in a different fogging behavior. Apart from that, other influencing factors such as the number of air changes due to entering and leaving the car, the ventilation during driving as well as the air humidity are to be considered with respect to the observed decay behavior.[20]

In this study, we found that ventilation of the passenger cabin had indeed an influence on the odor and general level of emissions. However, this influence was not as pronounced as that induced by an increase of the temperature in the passenger cabin. After customer usage of 6 and 7 weeks, respectively, a more significant decrease in the odor concentration and TVOC-FID value was observed for vehicle 2, even though vehicle 2 was investigated one week earlier after delivery than vehicle 1, and was additionally used during wintertime. The temperature profiles of the two vehicles in Figure 1 show that vehicle 1 was not in use for a period of two weeks prior to the third measurement due to local lockdown restrictions during the COVID-19 pandemic, as revealed by the absence of temperature rises in the vehicle interior between March and April. As a result, the interior of vehicle 1 was less ventilated, yielding a higher odor concentration.

Furthermore, the data indicate that the driver himself had a relevant impact on VIAQ, which becomes evident in the last measurement of vehicle 1. While the emissions in the vehicle continued to decrease, the odor concentration remained the same. It is very likely that the customer introduced additional odorants into the vehicle interior.

3.2 | Decay behavior of odorants in two vehicles during usage

Within our previous study, we investigated the odorants with their respective OD factors in the passenger cabins of vehicle 1 and 2 directly right after delivery, and succeeded in identifying the main odor contributors on a molecular basis. Additionally, we quantified important odorants of the vehicle interior by means of internal standard addition and discussed formation pathways and possible sources of odorants.[11] In the present investigation, we built on this knowledge and followed the OD development of the respective substances over time. For a better comparison between the OD factors of the measurements of vehicle 1 after 2, 7, 14, and 23 weeks usage and of vehicle 2 after 6 and 15 weeks usage, respectively, the results are provided in consecutive order in Table 2 (vehicle 1) and Table 3 (vehicle 2). The odorants that were successfully identified right after delivery are assigned to several substance classes, comprising saturated and unsaturated aldehydes, unsaturated ketones, rose ketones, esters, phenolic and benzene derivatives, and pyrazines.

3.2.1 | Decay of odorants in a vehicle with leather upholstery during usage in summer

The identified odorants of the passenger cabin of vehicle 1 after 2 weeks usage correspond to the same substance classes as those

TABLE 2 Odor-active compounds identified in distillates obtained from five air samples of the passenger cabin of vehicle 1 sampled after delivery, 2, 7, 14, and 23 weeks of usage during summer, respectively

No.	Odorant	Odor quality	RI value on		Odor dilution (OD) factors after					Identification
			DB-FFAP	DB-5	vehicle delivery	2 weeks vehicle use	7 weeks vehicle use	14 weeks vehicle use	23 weeks vehicle use	
1	Hexanal	Grassy	1080	800	2048	512	256	32	64	RI, O, MS, RC
2	Benzothiazole	Rubber-like, car tire-like	1937	1227	1024	512	≥32	≥32	≥32	RI, O, MS, RC
3	2-Propyl-2-octenal	Cardboard-like, citrus-like, soapy	1565	1278	1024	256	256	128	128	RI, O, MS, RC
4	(*E*)-2-Nonenal	Fatty, cardboard-like	1523	1160	1024	256	128	128	128	RI, O, MS, RC
5	β-Ionone	Violet-like, flowery	1918	1483	512	128	256	32	64	RI, O, MS, RC
6	2-Methylpropyl acetate	Fruity, apple-like	1016	770	512	64	64	16	2	RI, O, MS, RC
7	1-Hexen-3-one	Super glue-like, lighter gas-like	1096	774	512	64	32	16	8	RI, O, MS, RC
8	*p*-Cresol	Horse stable-like, fecal	2078	1085	512	8	8	4	2	RI, O, MS, RC
9	1-Octen-3-one	Mushroom-like	1291	979	256	128	128	64	128	RI, O, MS, RC
10	(*Z*)-2-Butyl-2-octenal	Cardboard-like, citrus-like, soapy	1646	1369	256	128	32	16	16	RI, O, MS, RC
11	(*E*,*Z*)-2,6-Nonadienal	Cucumber-like	1581	1153	128	128	64	32	64	RI, O, MS, RC
12	α-Isomethyl ionone	Flowery, rose-like	1802	1473	128	64	64	16	16	RI, O, MS, RC
13	(*Z*)-2-Nonenal	Fatty, cardboard-like	1494	1145	128	64	32	16	32	RI, O, MS, RC
14	Guaiacol	Smoky, smoked ham-like	1852	1087	128	32	16	32	32	RI, O, MS, RC
15	α-Damascone	Flowery, apple-juice-like	1735	1388	64	64	64	128	512	RI, O, MS, RC
16	Ethyl butanoate	Fruity, strawberry-like	1034	805	64	64	64	64	16	RI, O, MS, RC
17	Octanal	Citrus-like, soapy	1280	1002	64	64	32	32	32	RI, O, MS, RC
18	*p*-Chloro-*m*-cresol	Leather-like, phenolic	2462	1297	64	64	32	32	32	RI, O, MS, RC
19	Nonanal	Soapy, citrus-like	1387	1105	64	64	32	16	32	RI, O, MS, RC
20	2-Butyl-2-heptenal	Cardboard-like, citrus-like, soapy	1554	1272	64	64	32	16	16	RI, O, MS, RC
21	3-Methylbutyl acetate	Banana-like, fruity	1132	878	64	64	32	16	<1	RI, O, MS, RC
22	Butyl acrylate	Mushroom-like, geranium-like	1168	900	64	64	32	4	4	RI, O, MS, RC
23	Unknown	Waxy, phenolic	2225	1319	64	32	16	16	8	-
24	(*E*,*E*)-2,4-Nonadienal	Fatty, nutty	1690	1213	64	32	16	2	<1	RI, O, RC
25	2-Methoxynaphthalene	Phenolic, leather-like	2164	1456	64	32	8	16	16	RI, O, MS, RC
26	3-Isobutyl-2-methoxypyrazine	Bell pepper-like, pea-like	1510	1177	64	16	16	16	16	RI, O, RC
27	Pentyl acetate	Fruity	1052	847	64	16	8	16	16	RI, O, MS, RC
28	Vanillin	Vanilla-like	2539	1399	64	2	2	1	16	RI, O, MS, RC
29	*p-tert*-Butylphenol	Phenolic, moldy	2250	1292	32	32	32	32	32	RI, O, MS, RC

(Continues)

TABLE 2 (Continued)

No.	Odorant	Odor quality	RI value on		Odor dilution (OD) factors after					Identification
			DB-FFAP	DB-5	vehicle delivery	2 weeks vehicle use	7 weeks vehicle use	14 weeks vehicle use	23 weeks vehicle use	
30	Benzophenone	Phenolic, flowery	2470	1624	32	32	16	4	16	RI, O, MS, RC
31	5-Ethylidene-2-norbornene	Grassy, cucumber-like	1090	921	32	32	8	1	1	RI, O, MS, RC
32	γ-Nonalactone	Coconut-like	2025	1268	32	8	16	8	16	RI, O, MS, RC
33	2-Acetyl-1-pyrroline	Popcorn-like, roasty	1321	932	32	8	8	4	4	RI, O, RC
34	Decanal	Soapy	1487	1233	32	1	<1	<1	<1	RI, O, MS, RC
35	Tetralin	Moldy, green	1506	1177	8	16	16	32	8	RI, O, MS, RC
36	Geraniol	Flowery	1830	1255	<1	<1	32	32	32	RI, O, MS, RC
37	Unknown	Resin-like	1859	1268	<1	<1	<1	1	64	-
38	Isobornyl acetate	Moldy	1557	1286	<1	<1	4	4	16	RI, O, MS, RC
39	Tetrahydro linalool	Citrus-like	1413	1135	<1	<1	4	2	16	RI, O, MS, RC
40	Phenethyl alcohol	Rose-like, flowery	1900	1135	<1	<1	4	1	32	RI, O, MS, RC
41	1-Octen-3-ol	Mushroom-like	1441	987	<1	<1	<1	1	64	RI, O, MS, RC
42	Eugenol	Clove-like	2151	1361	<1	<1	<1	<1	32	RI, O, MS, RC

Note: Displayed are the OD factors of the odorants (according to their descending OD factors perceived on capillary DB-FFAP), and the respective retention indices and identification criteria
OD odor dilution factor on capillary DB-FFAP according to Grosch[16]; *RI* retention index according to Van den Dool and Kratz[40]; *O* odor quality perceived at the sniffing port; *MS* mass spectrum; *RC* comparison of the respective data with a reference compound. The panelist exhibited a higher odor threshold for benzothiazole after an illness between the second and third measurement; therefore, the values beginning from the third measurement cannot be used for interpretation. OD factors identified in the distillate of the sample obtained directly after vehicle delivery were previously published.[11]

TABLE 3 Odor-active compounds identified in distillates obtained from three air samples of the passenger cabin of vehicle 2 sampled after delivery, 6 weeks, and 15 weeks usage during winter

No.	Odorant	Odor quality	RI value on		Odor dilution (OD) factors after			Identification
			DB-FFAP	DB-5	vehicle delivery	6 weeks vehicle use	15 weeks vehicle use	
1	1-Octen-3-one	Mushroom-like	1291	979	512	128	128	RI, O, MS, RC
2	2-Methylpropyl acetate	Fruity, apple-like	1016	770	512	128	16	RI, O, MS, RC
3	(*E*)-2-Nonenal	Fatty, cardboard-like	1523	1160	256	256	128	RI, O, MS, RC
4	2-Propyl-2-octenal	Cardboard-like, citrus-like, soapy	1565	1278	256	128	128	RI, O, MS, RC
5	5-Ethylidene-2-norbornene	Grassy, cucumber-like	1090	921	256	128	64	RI, O, MS, RC
6	Hexanal	Grassy	1080	800	256	64	64	RI, O, MS, RC
7	2-Butyl-2-heptenal	cardboard-like, citrus-like, soapy	1554	1272	128	128	128	RI, O, MS, RC
8	(*Z*)-2-Butyl-2-octenal	Cardboard-like, citrus-like, soapy	1646	1369	128	128	128	RI, O, MS, RC
9	(*E*,*Z*)-2,6-Nonadienal	Cucumber-like	1581	1153	128	64	16	RI, O, MS, RC
10	1-Hexen-3-one	Super glue-like, lighter gas-like	1096	774	64	64	64	RI, O, MS, RC
11	Nonanal	Soapy, citrus-like	1387	1105	64	64	32	RI, O, MS, RC
12	(*Z*)-2-Nonenal	Fatty, cardboard-like	1494	1145	64	64	32	RI, O, MS, RC
13	β-Ionone	Violet-like, flowery	1918	1483	64	32	256	RI, O, MS, RC
14	Decanal	Soapy	1487	1233	64	32	16	RI, O, MS, RC
15	Octanal	Citrus-like, soapy	1280	1002	64	32	8	RI, O, MS, RC
16	(*E*,*E*)-2,4-Nonadienal	Fatty, nutty	1690	1213	64	32	2	RI, O, RC
17	1-Octen-3-ol	Mushroom-like	1441	987	64	16	16	RI, O, MS, RC
18	Butyl acrylate	Mushroom-like, geranium-like	1168	900	64	16	8	RI, O, MS, RC
19	Eugenol	Clove-like	2151	1361	64	16	<1	RI, O, MS, RC
20	Vanillin	Vanilla-like	2539	1399	32	64	16	RI, O, MS, RC
21	Benzothiazole	Rubber-like, car tire-like	1937	1227	≥32	≥32	≥32	RI, O, MS, RC
22	Guaiacol	Smoky, smoked ham-like	1852	1087	32	32	16	RI, O, MS, RC
23	3-Methylbutyl acetate	Banana-like, fruity	1132	878	32	16	8	RI, O, MS, RC
24	*p*-*tert*-Butylphenol	Phenolic, moldy	2250	1292	32	16	8	RI, O, MS, RC
25	Unknown	Mushroom-like	1392	1078	32	16	8	-
26	2,6-Di-*tert*-butylphenol	phenolic	2303	1516	32	8	16	RI, O, MS, RC
27	γ-Nonalactone	Coconut-like	2025	1268	32	8	4	RI, O, MS, RC
28	3-Isopropyl-2-methoxypyrazine	Bell pepper-like, pea-like	1416	1099	16	32	32	RI, O, RC
29	trans-4,5-Epoxy-(*E*)-2-decenal	Metallic	1983	1375	16	8	8	RI, O, RC
30	*p*-Cresol	Horse stable-like, fecal	2078	1085	8	4	32	RI, O, MS, RC
31	Pentyl acetate	fruity	1052	847	4	16	32	RI, O, MS, RC
32	Ethyl butanoate	fruity, strawberry-like	1034	805	4	4	2	RI, O, MS, RC
33	α-Damascone	Flowery, apple-juice-like	1735	1388	2	128	128	RI, O, MS, RC
34	Unknown	Pencil-like	1840	-	<1	32	<1	-

Note: Displayed are the OD factors of the odorants (according to their descending OD factors perceived on capillary DB-FFAP), and the respective retention indices and identification criteria

OD odor dilution factor on capillary DB-FFAP according to Grosch[16]; *RI* retention index according to Van den Dool and Kratz[40]; *O* odor quality perceived at the sniffing port; *MS* mass spectrum; *RC* comparison of the respective data with a reference compound. The panelist exhibited a higher odor threshold for benzothiazole after an illness before the measurements; therefore, these values cannot be used for interpretation. OD factors identified in the distillate of the sample obtained directly after vehicle delivery were previously.[11]

odor-active compounds measured directly after delivery (see Table 2). A decrease in OD factors of one to two dilution steps was evident for almost all odorants. The most important decrease in OD factors was obtained for the odorants 2-methylpropyl acetate, 1-hexen-3-one, and *p*-cresol, which were perceived with OD 512 after vehicle delivery, but with OD 64 or lower already after 2 weeks. In addition, a strong decrease in the OD factors of vanillin and decanal was observed. In the third measurement after 7 weeks usage, most of the identified odorants remained with the same OD factors and did not reveal any further relevant changes. An increase or decrease in OD factors was solely observed for a few compounds such as hexanal, β-ionone, and (*Z*)-2-butyl-2-octenal, whereas for decanal no more smell was perceived during GC-O. Furthermore, four odor-active compounds were additionally identified: isobornyl acetate, tetrahydro linalool and phenethyl alcohol were present with OD 4, and geraniol was identified with OD 32. However, the OD factor of benzothiazole cannot be used for unequivocal interpretation beginning from the third measurement, as the perception of this compound changed after an illness of the respective panelist, resulting in a higher odor threshold for solely this specific odorant.

The analysis of the fourth measurement (obtained after 14 weeks usage) revealed lower OD factors for almost all odorants. By contrast, OD factors of the odorants of the fourth and fifth measurement barely differed, with the sole exception of the newly detected substances: The odorants which were additionally recorded in the third measurement gave even higher OD factors in a range of OD 16–32. Additionally, 1-octen-3-ol, eugenol, and a resin-like smelling unknown substance were detected with similar OD factors. The flowery, apple-juice-like smelling α-damascone achieved the highest OD factor (OD 512) in the measurement after 23 weeks and became increasingly important during the use of vehicle 1. Likewise, the OD factor of vanillin increased again. Overall, a number of compounds elicited a relatively high odor potency both at the time of vehicle delivery and at the final determinations, which could mainly be assigned to the group of unsaturated aldehydes and ketones, namely 2-propyl-2-octenal, (*E*)-2-nonenal, 1-octen-3-one and (*E*,*Z*)-2,6-nonadienal. Apart from that, a series of initially less important compounds only barely decreased their odor potency during usage and thus remained quite persistent; among these were octanal, *p*-chloro-*m*-cresol, nonanal, *p*-tert-butylphenol, and γ-nonalactone.

3.2.2 | Decay of odorants in a vehicle with synthetic fabric and leatherette upholstery during usage in winter

In vehicle 2, the same odorants were detected in the measurements after delivery and after 6 and 15 weeks of usage (see Table 3). The odor potency of the identified compounds decreased throughout the measurements, whereby the OD factors were in a similar range compared with those in the corresponding measurements of vehicle 1. The group of the unsaturated aldehydes and ketones showed also high OD factors at the beginning as well as at the end of the measurements and hardly showed any decay behavior. The rose ketones β-ionone and α-damascone increased their OD factors in the course of the measurements, similar to the findings obtained for vehicle 1. However, a pencil-like smelling unknown substance was additionally detected on the DB-FFAB capillary column in the second measurement at week 6.

3.2.3 | Decay of the odor of the passenger cabin: Classification of odorants according to their formation and occurrence

Volatile compounds in the vehicle interior have been reported to show different decay behavior due to their structural diversity and different physical properties.[21] Sato (2004) described the following three groups of vehicle interior emissions during usage[4]:

- vaporization rate-controlled substances, which vaporize rapidly after production or assembly of the material due to their low boiling points
- diffusion rate-controlled substances, which are constantly released into the vehicle interior as a result of diffusion within the materials
- substances brought into the vehicle cabin by the passengers

The odorants of the vehicle interior which were detected in the course of the usage experiments of this study can also be assigned to these groups. However, odorants can be assigned to several groups as they may stem from a variety of emission sources, and even potentially from diverse formation pathways.[10,22,23]

The odorants 2-methylpropyl acetate, 1-hexen-3-one, (*Z*)-2-nonenal, guaiacol, decanal, *p*-cresol, and vanillin may be assigned to the group of vaporization rate-controlled substances. For these odor-active compounds, a strong decrease in the OD factors was observed after the initial heating at the whole-vehicle test stand. During usage, the OD factors of these substances changed only slightly. Additional temperature maxima in the passenger cabin of vehicle 1 during driving resulted in a strong decrease in the OD factors of β-ionone, butyl acrylate, 3-methylbutyl acetate, and (*E*,*E*)-2,4-nonadienal. Since the boiling points of these substances are considerably higher than 100°C, it can be assumed that these odorants were released mainly from components exposed to direct sunlight, and thus from materials that encountered strongly elevated temperatures. The air temperature of the vehicle interior can easily exceed temperatures of 65°C during summer, and assemblies such as the dashboard, door trim, and rear parcel shelf can rise to much higher temperatures during exposure to direct sunlight.[5]

The second group of substances is thought to be prone to diffusion of the volatile compounds from within the materials of the vehicle interior. The sources of these compounds can be very diverse and can be both visible as well as non-visible, and major as well as minor components.[24,25] As a result, these substances diffuse

into the passenger cabin over an extended period of time, which can last months or even years.[26] The following compounds may be assignable to this category: octanal, *p*-chloro-*m*-cresol, nonanal, *p*-*tert*-butylphenol, γ-nonalactone, and the group of unsaturated aldehydes and ketones. After 15 or 23 weeks of usage, these compounds represented the most important odorants in the vehicle interior, and still created a typical new car odor in the investigated vehicles. As a consequence, to specifically design the new car odor and improve the VIAQ, it is important to replace or prevent the formation of especially these odorants.

The last group of substances in the vehicle interior comprises the odorants which were detected for the first time in the course of our present determinations, and additionally β-ionone and α-damascone which both increased with their OD factors during the period of usage. These compounds were obviously brought into the vehicle cabin by the passengers, and finally contributed with relevant impact to the overall odor in vehicle 1 in the last measurement (at 23 weeks). The identified odorants are typical representatives of natural products and are common fragrance chemicals used in perfumery or essential oils.[27–29] Even the mushroom-like smelling 1-octen-3-ol, being a potential derivative of 1-octen-3-one, is commonly found in manifold applications. Based on these observations, the driver of the two vehicles additionally provided all his cosmetic products for odor analysis. Thereby, geraniol, phenethyl alcohol, and eugenol were identified as main ingredients in his detergent, fabric softener, and hairspray, respectively. Interestingly, a sensory analysis of the surfaces of the seats and headrests with regard to fragrances after the fifth analysis (at 23 weeks) did not reveal any peculiarities. However, the unrolled seat belt of the driver's seat exhibited the characteristic fragrance smell of the provided cosmetics, indicating a strong smell adsorbing potency of the seat belt material through direct body and skin contact. In case of vehicle 2, no additional odorants were identified in the third measurement. According to the customer, the same cosmetic products were used during his everyday life. Due to the use of the vehicle in the cold season, it is possible that less odorants entered the vehicle interior due to the fact that the driver was wearing long-sleeved clothing.

All in all, we could demonstrate that, in general, both vehicles were not identical in the decay of their odorants and also up-build of novel odors due to the passengers' characteristics. However, they were still surprisingly similar considering the use of the vehicles during different seasons, and with different driving regimes. In addition to the temperature and the number of air changes in the vehicle interior, ambient traffic conditions and parking also may have a strong influence on the decay behavior of the odorants.[30] Nonetheless, we could show that after termination of the measurements over an extended period of time, many odorants from materials of the vehicle interior were still detectable. Consequently, suppliers and manufacturers should not only be focused on the design of materials and their general functionalities but should also pay higher attention to achieve controlled emissions and odors during their lifetime, thus providing higher quality in VIAQ. In this respect, one should not only consider the experience of the driver but also of those commuting as passengers, and maybe even for extended periods of time. In such respect, we finally want to draw the reader's attention to the fact that especially the passengers of young age have been shown by our group to be exceptionally sensitive to smells.[31,32] Albeit these young travelers being impacted by such emissions is, to the best of our knowledge, nowhere considered in the current literature.

3.3 | Descriptive sensory analysis of air samples of a vehicle with synthetic fabric and leatherette upholstery during usage

A descriptive odor profile analysis was additionally performed with undiluted air samples of vehicle 2 after each vehicle measurement. During the discussion of the odor attributes, the trained panel agreed on the odor impressions fruity, rubber-like, plastic-like, wood-like, fatty/cardboard-like, and green, which were evaluated on a scale from 0 (no perception) to 10 (strong perception). Furthermore, the total intensity was rated on the same scale. The results are displayed in Figure 2.

In the first vehicle measurement, the odor impressions rubber-like, plastic-like, wood-like, and fatty/cardboard-like were ranked with similar intensities (3.5–4). Thereby, the attribute green was rated with the highest perceived odor intensity,[5] while the impression fruity was rated with the lowest intensity (2.5). In the second measurement, the odor attributes fruity and wood-like were ranked with the same odor intensities, whereas for all other odor impressions, a decrease was observable. A further decrease in the intensities of all odor impressions was observed in the third vehicle

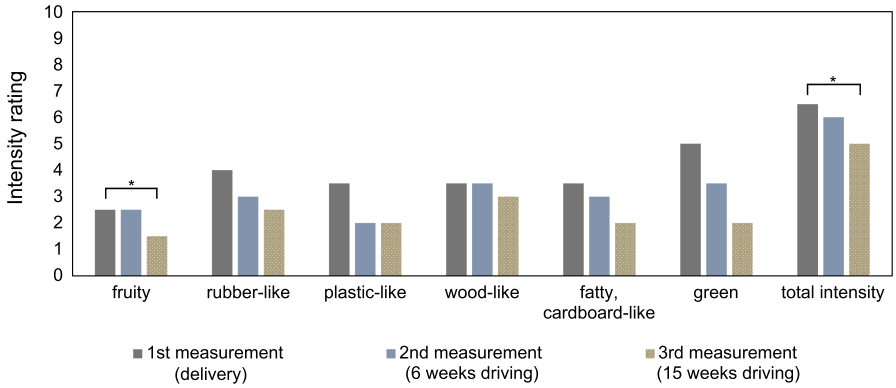

FIGURE 2 Odor intensities of the descriptive odor profile analysis of undiluted air samples of vehicle 2 after delivery (gray), 6 weeks usage (blue) and 15 weeks usage (brown). These data are displayed as the median values of the sensory evaluation ($n = 8$) on a scale from 0 (no perception) to 10 (strong perception). Significant differences between the samples are marked as * for $p \leq 0.05$ (Wilcoxon-test)

measurement with the exception for the attribute plastic-like. The odor impressions rubber-like and wood-like displayed the highest perceived intensities with 2.5 and 3 in the third measurement. A significant decrease in the intensity of the odor impression fruity was observed between the first and the third vehicle measurement. The overall intensity was initially rated with an intensity of 6.5 and then decreased to an intensity of 5 over the course of the measurements. Thereby, the decrease in the overall intensity between the first and third vehicle measurement was significant.

Many fruity smelling compounds, namely 2-methylpropyl acetate, ethyl butanoate, 1-methylbutyl acetate, 3-methylbutyl acetate, α-damascone, and β-ionone, were identified via GC-MS/O and may contribute to the fruity odor impression. When comparing the decrease in the OD factors of these odorants with the decrease in the evaluated intensities, only 2-methylpropyl acetate and 3-methylbutyl acetate demonstrated a similar decay behavior. All other fruity smelling odorants showed constant or increasing OD factors. Therefore, it can be assumed that 2-methylpropyl acetate and 3-methylbutyl acetate had the highest odor potency and were the main contributors for the odor impression fruity. Similar observations were made for the odor impression green. Only the grassy, cucumber-like smelling 5-ethylidene-2-norbornene and cucumber-like smelling (*E*,*Z*)-2,6-nonadienal exhibited a continuous decrease in their OD factors in the course of the vehicle measurements. On the contrary, compounds such as hexanal and 3-isopropyl-2-methoxypyrazine, which may also contribute to the odor impression green, exhibited a different decay behavior. Consequently, it can be expected that these two odorants had minor impact with regard to the perception of the odor attribute green during the profile analysis. In the case of the fatty/cardboard-like smelling compounds (*E*)-2-nonenal and 2-propyl-2-octenal, a clear correlation could be observed for the decay of the perceived intensity and their OD factors. On the contrary, for the odor impression rubber-like, no conclusion was possible. Benzothiazole was the only compound with a rubber-like odor quality, however, no absolute OD values could be determined for this compound during OEDA.

For the odor attributes wood-like and plastic-like, no alignment with specific odorants was possible. It is a known phenomenon that mixtures of odorants can evoke odor impressions that are not represented by single components.[33] In this respect, both odor impressions (wood-like and plastic-like) are known to be composed of complex odorant mixtures.[34,35] In our previous study, we assigned hexanal, (*E*)-2-nonenal, octanal and vanillin as odorants being potentially responsible for the wood-like odor impression, and 1-hexen-3-one and 1-octen-3-one as potential contributors to the plastic-like odor impression.[11] These compounds have been responsible for the characteristic odor in reconstitution experiments in wood and artificial leather, respectively.[36,37] The decay behavior of 1-hexen-3-one and 1-octen-3-one matched very well with the sensory results after the two measurements of vehicle 2, supporting the assumption that these two odorants are likely contributors to the plastic-like odor impression. In the case of the compounds that generated the wood-like odor impression, no clear correlation can be identified. It may be assumed that other odorants also play a role in the perception of this odor impression. However, Ghadiriasli (2018) identified 97 odorants in oak wood whereby the causative odorants primarily belonged to the groups of terpenes, mono- and sesquiterpenes, aldehydes, acids, and lactones, as well as to substances generally baring a phenolic core moiety.[34] As a consequence, many different compounds obviously play an important role in the typical smell of wood and depending on the type of wood, different odorants can be characterized.[9]

The results of the sensory analysis further support our findings on the odorant composition of the new car smell phenomenon. The vehicle measurements show a clear correlation between the results of the sensory analysis and the identified odorants, with the sole exception of the wood-like odor impression. These findings allow further pinpointing of odorants with high potency that cause the typical new car odor during use in the investigated vehicle. From this study, we conclude that it is important to primarily reduce or remove 2-methylpropyl acetate, 3-methylbutyl acetate, 5-ethylidene-2-norbornene, (*E*,*Z*)-2,6-nonadienal, (*E*)-2-nonenal, 2-propyl-2-octenal, 1-hexen-3-one, and 1-octen-3-one from the components of the vehicle interior when aiming at sustainably improving the odor of new cars.

4 | CONCLUSION

Overall, our present investigation of the smell, the odorant composition and the emission profiles of vehicle interiors at defined time intervals after vehicle delivery and usage provided insights into the development over time of the typical new car smell. The vehicle measurements showed a clear correlation between the decrease in the general emissions and elevated levels of temperature in the vehicle interior. However, the investigated odorants provided a different decay behavior which is likely due to their deviating polarity from the overall emission substance profiles. Among the identified odor-active compounds specific compounds showed different decay behaviors and could thus be assigned to different groups. First, odorants were detected which vaporize rapidly from components exposed to direct sunlight like 1-hexen-3-one, (*Z*)-2-nonenal, guaiacol, decanal, *p*-cresol, and vanillin. Second, odorants were likely to be released by diffusion from the materials of the vehicle interior. Thereby, octanal, *p*-chloro-*m*-cresol, nonanal, *p*-*tert*-butylphenol, γ-nonalactone, and the group of unsaturated aldehydes and ketones represented the most important odorants in the vehicle interior at the end of the measurements. Third, natural products and typical fragrance chemicals commonly used in perfumery or essential oils, namely geraniol, tetrahydro linalool, phenethyl alcohol, and isobornyl acetate were presumably brought into the vehicle interior by the driver. A descriptive sensory analysis revealed a correlation between the results of the sensory analysis and the identified odorants.

This study demonstrates that targeted and combinatory sensory and instrumental analyses of odorants are needed to generate

a fundamental understanding of the odorant composition of new car smell, and the impact of usage by the consumer. These results lay the foundation for further targeted odor investigations on selected emissions sources of the vehicle interior. Possible attempts could be the investigation of components by means of emission test chambers or the use of machine (sensor-based) olfaction in the vehicle interior.[38,39] The main strategy for a sustainable reduction of the odor in vehicles and improvement of the VIAQ, however, is the modification of the components in the vehicle interior thereby considering not only functionality but also human sensory quality and avoidance of emissions.

AUTHOR CONTRIBUTION

Florian Buchecker: Investigation, Conceptualization, Methodology, Visualization, Project administration, Funding acquisition, and Writing—original draft. **Helene M. Loos**: Conceptualization, Methodology, Supervision, and Writing—review & editing. **Andrea Buettner**: Funding acquisition, Supervision, and Writing—review & editing.

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CONFLICT OF INTEREST

No conflict of interest declared.

DATA AVAILABILITY STATEMENT

The data presented in the manuscript have not been made available.

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