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Tobacco smoke-associated particulate matter emissions in a car cabin using the TAPaC platform

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2. Zusammenfassung

Zigarettenrauch enthält bis zu 5000 Inhaltsstoffe, von denen mindestens 250 gesundheitsschädlich und 98 krebserregend sind. Der freigesetzte Feinstaub erreicht hohe Konzentrationen in Innenräumen und ist somit besonders schädlich für Passivraucher (z.B. Kinder).

Ziel war es eine Messplattform zu etablieren, mit dessen Hilfe die Feinstaubexposition durch Zigarettenrauch im Fahrzeuginnenraum unter unterschiedlichen ventilatorischen Szenarien untersucht werden konnte. Zudem sollte der Einfluss verschiedener Tabakprodukte auf die Feinstaubkonzentration getestet werden.

Im ersten Teil dieser Dissertation wird die neuartige TAPaC Messplattform (tobacco-associated particulate matter emissions inside a car cabin: establishment of a new measuring platform) vorgestellt. Sie erlaubt die Auswirkungen verschiedener ventilatorischer Szenarien auf die Feinstaubemission von Zigarettenrauch im Auto besser beurteilen zu können. Da niemand gesundheitsschädlichem Tabakrauch ausgesetzt wird, kann sie ohne jegliche ethische Bedenken eingesetzt werden. Die Zigaretten werden hierbei einzeln auf der Beifahrerseite verraucht. Der beim Rauchen freigesetzte Feinstaub wird auf der Fahrerseite gemessen und in PM_{10} (Partikel mit einem aerodynamischen Durchmesser <10 µm), $PM_{2,5}$ (Partikel mit einem aerodynamischen Durchmesser <2,5 µm), und PM_1 (Partikel mit einem aerodynamischen Durchmesser <1 µm) unterteilt. Hierbei konnten unter der Verwendung von 3R4F Research Cigarettes extrem hohe Feinstaubmesswerte bei geschlossenen Fenstern und ausgeschalteter Lüftung nachgewiesen werden (PM_{10}: 1608 µg/m^3, $PM_{2,5}$: 1583 µg/m^3, PM_1: 1133 µg/m^3). Diese Daten stellen Durchschnittwerte nach 10-minütiger Messung dar. Auch konnte eine Reduktion der Feinstaubkonzentration (PM_{10}: -70,8 bis -74,4%, $PM_{2,5}$: -70,6 bis -74,3%, PM_1: -64,0 bis -68,0%) durch den Einsatz der Lüftung nachgewiesen werden.

Der zweite Teil dieser Dissertation befasste sich maßgeblich mit dem Einfluss unterschiedlicher ventilatorischer Szenarien auf die Feinstaubkonzentrationen im Auto. Unter Verwendung von drei unterschiedlichen Zigarettenprodukten (3R4F Research Cigarettes, Marlboro Red, Marlboro Gold) wurden insgesamt 7 ventilatorische Szenarien (Condition C1b–C7b) getestet. Für alle Szenarien, mit Ausnahme von C1b, war die Autolüftung auf Stufe 2/4 gestellt und in Richtung der Windschutzscheibe gerichtet. Die Szenarien beinhalteten: *Condition 1* (C1b) Fenster geschlossen, Autolüftung aus und externer Ventilator aus, *Condition 2* (C2b) Fenster 10 cm geöffnet und externer Ventilator aus, *Condition 3* (C3b) Fenster 10 cm geöffnet und

externer Ventilator auf höchster Stufe (3/3) an, *Condition 4* (C4b) Fenster halb geöffnet und externer Ventilator aus, *Condition 5* (C5b) Fenster halb geöffnet und externer Ventilator auf höchster Stufe (3/3) an, *Condition 6* (C6b) Fenster vollständig geöffnet und externer Ventilator aus und *Condition 7* (C7b) Fenster vollständig geöffnet und externer Ventilator auf höchster Stufe (3/3) an.

Es zeigten sich besonders hohe Feinstaubkonzentrationen bei Zigaretten, welche ohne Ventilation bei geschlossenem Fenster verraucht wurden. Unabhängig von der verwendeten Marke war die Feinstaubbelastung nach 10 min unter C1b (PM_{10}: 1272–1697 µg/m^3, $PM_{2,5}$: 1253–1659 µg/m^3, PM_1: 964–1263 µg/m^3) deutlich höher als unter C2b (PM_{10}: 67–84 µg/m^3, $PM_{2,5}$: 68–83 µg/m^3, PM_1: 66–79 µg/m^3), C3b (PM_{10}: 100–139 µg/m^3, $PM_{2,5}$: 99–138 µg/m^3, PM_1: 95–132 µg/m^3), C4b (PM_{10}: 84–94 µg/m^3, $PM_{2,5}$: 84–93 µg/m^3, PM_1: 81–89 µg/m^3), C5b (PM_{10}: 94–120 µg/m^3, $PM_{2,5}$: 93–119 µg/m^3, PM_1: 90–114 µg/m^3), C6b (PM_{10}: 155–196 µg/m^3, $PM_{2,5}$: 154–195 µg/m^3, PM_1: 148–184 µg/m^3), und C7b (PM_{10}: 74–99 µg/m^3, $PM_{2,5}$: 72–97 µg/m^3, PM_1: 69–93 µg/m^3). Ebenfalls wurden Feinstaubspitzenwerte bei 4,5 min und 10 min ausgewertet. Bei 4,5 min konnte PM_{10} unter C2b–C7b um 81,6–93,3% im Vergleich zu C1b reduziert werden. Bei 10 min sogar um 92,9–99,3%. Die 3R4F Zigarette hatte die höchste Feinstaubemission gefolgt von Marlboro Rod und Marlboro Gold. Zudem zeigte sich, dass die Feinstaubemission auch von den Tabakinhaltsstoffen und dessen Konzentrationen abhängig ist.

Die Etablierung der neuen Messplattform ermöglicht die Erforschung von Feinstaubexpositionen durch Zigarettenrauch im Auto ohne potentiell gesundheitliche Folgen. In Zusammenschau der Daten ließ sich nach Öffnen des Fensters und unter Einflussnahme verschiedener ventilatorischer Einstellungen eine deutliche Reduktion der Feinstaubkonzentration im Auto feststellen. Nichtsdestotrotz bleibt die Feinstaubbelastung im Autoinnenraum zu hoch und übersteigt die Richtwerte der *Air Quality Guidelines* aus dem Jahre 2021 der WHO. Die experimentell untersuchten Belüftungsszenarien sind somit insuffizient, da sie nicht vor der toxischen Feinstaubexposition durch Passivrauch beim Autofahren schützen können.

3. Summary

Tobacco smoke contains up to 5000 ingredients. While at least 250 are known to be hazardous to human health, 98 are cancerogenic. The released particulate matter (PM) reaches high concentrations in confined spaces and is therefore particularly unhealthy for passive smokers (e.g. children).

The aim of this study was to establish a new measuring platform to investigate the particulate matter emissions of cigarette smoke inside a car cabin under different ventilation conditions. Additionally, the influence of different tobacco products on particulate matter concentrations were tested.

The first part of this dissertation presents the TAPaC measuring platform (tobacco-associated particulate matter emissions inside a car cabin: establishment of a new measuring platform). It allows the researcher to evaluate the effect of different ventilation conditions on the PM emissions of tobacco smoke in a vehicle. Due to its unique ability to smoke cigarettes remotely without exposing any person to toxic tobacco smoke, it provided the ideal experimental setup. Cigarettes were smoked on the passenger's seat, while the PM emissions were measured on the driver's seat and differentiated into PM_{10} (particles with an aerodynamic diameter <10 µm), $PM_{2.5}$ (particles with an aerodynamic diameter <2.5 µm) and PM_1 (particles with an aerodynamic diameter <1 µm). 3R4F Research Cigarettes were investigated. The results showed extremely high mean PM values after 10 min measurement (PM_{10}: 1608 µg/m^3, $PM_{2.5}$: 1583 µg/m^3, PM_1: 1133 µg/m^3). Also, a reduction of PM (PM_{10}: -70.8 to -74.4%, $PM_{2.5}$: -70.6 to -74.3%, PM_1: -64.0 to -68.0%) was proven after the additional usage of in-vehicle ventilation.

The second part of this dissertation investigated the influence of 7 different ventilation conditions on PM concentrations inside the car cabin. Three different cigarette products (3R4F Research Cigarettes, Marlboro Gold, Marlboro Red) were investigated. Except for C1b, all tested conditions had the car ventilation turned on power level 2/4, with the air directed towards to windshield. The conditions comprised: *condition 1* (C1b) windows closed with the car ventilation turned off and the outside fan turned off, *condition 2* (C2b) window 10 cm opened and the outside fan turned off, *condition 3* (C3b) window 10 cm opened with the outside fan turned on at highest power level (3/3), *condition 4* (C4b) window half-opened and the outside fan turned off, *condition 5* (C5b) window half-opened with the outside fan turned on at highest

power level (3/3), *condition 6* (C6b) window fully opened and the outside fan turned off, and *condition 7* (C7b) window fully opened with the outside fan turned on at highest power level (3/3).

The generated data showed specifically high PM concentrations of cigarettes smoked without any ventilation and closed windows (C1b). Independent of the smoked tobacco product, PM emissions after 10 min under C1b (PM_{10}: 1272–1697 µg/m^3, $PM_{2.5}$: 1253–1659 µg/m^3, PM_1: 964–1263 µg/m^3) were higher than under C2b (PM_{10}: 67–84 µg/m^3, $PM_{2.5}$: 68–83 µg/m^3, PM_1: 66–79 µg/m^3), C3b (PM_{10}: 100–139 µg/m^3, $PM_{2.5}$: 99–138 µg/m^3, PM_1: 95–132 µg/m^3), C4b (PM_{10}: 84–94 µg/m^3, $PM_{2.5}$: 84–93 µg/m^3, PM_1: 81–89 µg/m^3), C5b (PM_{10}: 94–120 µg/m^3, $PM_{2.5}$: 93–119 µg/m^3, PM_1: 90–114 µg/m^3), C6b (PM_{10}: 155–196 µg/m^3, $PM_{2.5}$: 154–195 µg/m^3, PM_1: 148–184 µg/m^3), and C7b (PM_{10}: 74–99 µg/m^3, $PM_{2.5}$: 72–97 µg/m^3, PM_1: 69–93 µg/m^3). PM peak emissions were measured at 4.5 min and 10 min. Compared to C1b, PM_{10} under C2b–C7b reduced at 4.5 min and 10 min by 81.6–93.3% and 92.9–99.3%, respectively.

In addition, PM emissions varied depending on the smoked tobacco product. The highest concentrations were emitted by the 3R4F cigarettes, followed by Marlboro red and Marlboro gold. Therefore, PM emissions are dependent on the used tobacco ingredients and their concentrations.

The establishment of the new measuring platform enables researchers to investigate particulate matter emissions of cigarette smoke in car cabin without potential health risks. The data shows that vehicle ventilation during a smoking session can reduce PM concentration significantly. Nevertheless, the recommended PM thresholds by the WHO in 2021 (air quality guidelines) are exceeded by far. Therefore, the experimentally investigated ventilation conditions are insufficient and cannot protect passengers from inhaling harmful second-hand smoke.

4. Abkürzungsverzeichnis

AETSE	automatic tobacco smoke emitter
ANOVA	english: analysis of variance deutsch: Varianzanalyse
C1a	english: all windows closed and the car ventilation was turned off deutsch: alle Fenster geschlossen, Autolüftung aus
C2a	english: all windows closed and the car ventilation turned on power level 2/4, with the air directed towards the windshield deutsch: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und auf die Windschutzscheibe gerichtet
C3a	english: all windows closed and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet deutsch: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und auf die Windschutzscheibe und Füße gerichtet
C4a	english: all windows closed with the car ventilation turned on power level 2/4, with the air directed towards body and head deutsch: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und auf den Körper und Kopf gerichtet
C1b	english: windows closed, car ventilation turned off, outside fan turned off deutsch: Fenster geschlossen, Autolüftung aus, externer Ventilator aus
C2b	englisch: window 10 cm opened, car ventilation turned on, outside fan turned off deutsch: Fenster 10 cm geöffnet, Autolüftung an, externer Ventilator aus
C3b	english: window 10 cm opened, car ventilation turned on, outside fan turned on at highest power level (3/3)

	deutsch: Fenster 10 cm geöffnet, Autolüftung an, externer Ventilator auf höster Stufe (3/3) an
C4b	english: window half-opened, car ventilation turned on, outside fan turned off
	deutsch: Fenster halb geöffnet, Autolüftung an, externer Ventilator aus
C5b	english: window half-opened, car ventilation turned on, outside fan turned on at highest power level (3/3)
	deutsch: Fenster halb geöffnet, Autolüftung an, externer Ventilator auf höster Stufe (3/3) an
C6b	english: window fully opened, car ventilation turned on, outside fan turned off
	deutsch: Fenster vollständig geöffnet, Autolüftung an, externer Ventilator aus
C7b	english: window fully opened, car ventilation turned on, outside fan turned on at highest power level (3/3), car ventilation turned on
	deutsch: Fenster vollständig geöffnet, Autolüftung an, externer Ventilator auf höster Stufe (3/3) an
C_{mean}	englisch: mean concentration
	deutsch: durchschnittliche Konzentration
COPD	english: chronic obstructive pulmonary disease
	deutsch: chronisch obstruktive Lungenerkrankung
CSD	english: cigarette smoking device
	deutsch: Zigarettenrauchmaschine
LAS	english: Laser Aerosol Spectrometer
	deutsch: Laser Aerosol Spektrometer
p	english: probability value
	deutsch: Signifikanzwert
pAVK	english: peripheral artery disease

	deutsch: periphere arterielle Verschlusskrankheit
PM	english: particulate matter
	deutsch: Feinstaub
PM$_{10}$	english: particles with an aerodynamic diameter <10 µm
	deutsch: Partikel mit einem aerodynamischen Durchmesser <10 µm
PM$_{2,5}$	english: particles with an aerodynamic diameter $<2,5$ µm
	deutsch: Partikel mit einem aerodynamischen Durchmesser $<2,5$ µm
PM$_{1}$	english: particles with an aerodynamic diameter <1 µm
	deutsch: Partikel mit einem aerodynamischen Durchmesser <1 µm
TAPaC	tobacco-associated particulate matter emissions inside a car cabin
WHO	english: World Health Organization
	deutsch: Weltgesundheitsorganisation

5. Übergreifende Zusammenfassung

5.1. Einleitung

Feinstaub ist in nahezu allen Innenräumen und der Umgebung in unterschiedlicher Konzentration vorhanden. Er wird abhängig von seiner Größe in PM_{10} (Partikel mit einem aerodynamischen Durchmesser <10 µm) $PM_{2,5}$ (Partikel mit einem aerodynamischen Durchmesser <2,5 µm) und PM_1 (Partikel mit einem aerodynamischen Durchmesser <1 µm) unterteilt und gemessen. Im Jahr 2021 aktualisierte die WHO ihre „Air Quality Guidelines“(1). Sie empfiehlt einen 24h Durchschnittswert von $PM_{2,5}$ ≤15 µg/m^3 und PM_{10} ≤45 µg/m^3 nicht zu überschreiten.

Durch den Verbrennungsprozess von Tabak entsteht Feinstaub mit vornehmlich kleinen Partikeln (PM_1) (2). Diese feinen Partikel können aus unterschiedlichsten toxischen Inhaltsstoffen bestehen und aufgrund ihrer sehr geringen Größe tief in die Lunge inhaliert werden. Je kleiner der Feinstaub desto tiefer kann dieser inhaliert werden. Durch Absorption über Alveolen erreicht der Feinstaub die systemische Zirkulation (3,4) und kann somit jedem Organ im Körper Schaden zufügen. Der durch Zigarettenrauch freigesetzte Feinstaub enthält über 5000 chemische Inhaltstoffe von denen mindestens 98 krebserregend sind (5). Unterschiedlichste Krankheitsbilder (Asthma, COPD, Karzinome, pAVK, etc.) können hierdurch erwiesenermaßen ausgelöst bzw. verursacht werden (6). Insbesondere Kinder stellen gefährdete Gruppen dar, nicht nur weil sie oftmals unfreiwillige Opfer des giftigen Rauches werden, sondern auch weil sie aufgrund ihrer physiologisch erhöhten Atemfrequenz und kleineren Lungen mehr Feinstaub pro Kilogramm Körpergewicht inhalieren (7–9). Studien haben gezeigt, dass Lungenerkrankungen bei passivrauchenden Kindern deutlich öfter auftreten (1,9,10). Nach Schätzungen der WHO sterben jährlich ca. 1,2 Millionen Menschen durch Passivrauchen (11,12).

Feinstaub, welcher beim Rauchen in einem Fahrzeug freigesetzt wird, ist nicht nur für den Raucher selbst, sondern auch für die passivrauchenden Insassen (u.a. Kinder) extrem schädlich (13). Daher ist es von äußerster Wichtigkeit, die Gesellschaft anhand validierter Daten über die Auswirkungen von Tabakkonsum im Auto zu informieren.

Vorangegangene Studien maßen bereits die Feinstaubexposition im Auto unter verschiedenen ventilatorischen Szenarien (13–20). Hierbei nutzen Sie freiwillige Raucher. Da jeder Raucher ein individuelles Rauchverhalten hat und somit unterschiedlich viele Züge und Zeit benötigt um eine Zigarette zu konsumieren, erschien es uns sinnvoll dieses Verfahren zu optimieren und standardisieren. Daher etablierten wir eine neue Messplattform in der TAPaC Studie (21). Diese ermöglichte ein automatisiertes Rauchen ohne Personen dem toxischen Zigarettenrauch auszusetzen. Aus gesundheitlicher und ethischer Sicht war diese Methode somit vollkommen unbedenklich.

Im Rahmen der vorliegenden Studien galt es zuerst die TAPaC Messplattform zu etablieren und zu nutzen, um die Feinstaubbelastung während und nach dem Konsum einer Zigarette zu messen. Es sollte gezeigt werden, dass die Messplattform reproduzierbare Daten generiert, welche mit anderen Studien vergleichbar sind. Hierzu wurde an der Position des Fahrers (bei rauchendem Beifahrer) die Feinstaubexposition gemessen und in PM_{10}, $PM_{2,5}$ und PM_1 unterteilt. Unterschiedliche ventilatorische Szenarien mit drei verschiedenen Zigarettenprodukten wurden untersucht. Ziel war es, herauszufinden unter welchem der getesteten Szenarien die geringste und die höchste Feinstaubbelastung im Autoinnenraum zu messen ist. Zudem sollten Größenanteile des Feinstaubs ($PM_{10-2,5}$, $PM_{2,5-1}$, and PM_1) gemessen und abhängig von dem verwendeten Lüftungsszenarium und Tabakprodukt miteinander verglichen werden. Ein weiteres Ziel bestand darin herauszufinden, ob ein Unterschied der Feinstaubkonzentration im Fahrzeuginnenraum durch das Verrauchen unterschiedlicher Zigarettenprodukte nachweisbar ist. Anhand der erhobenen Daten sollte untersucht werden, ob die Feinstaubexposition durch Zigarettenrauch im Fahrzeuginnraum durch unterschiedliche ventilatorische Szenarien und Tabakprodukte variiert.

5.2. Darstellung der Publikationen

Die erste Publikation (TAPaC – tobacco-associated particulate matter emissions inside a car cabin: establishment of a new measuring platform) dieser Dissertation befasste sich maßgeblich mit der Etablierung der neuen TAPaC Messplattform sowie mit der Vorstellung erster gesicherter Daten (21).

Die Messplattform besteht aus einem Mitsubishi Spacerunner (Baujahr 1991–1998) mit einem Innenraumvolumen von 3,709 m^3 (22). Dieser wurde in einer angemieteten Garage der Goethe Universität Frankfurt am Main abgestellt. Ein „automatic environmental tobacco smoke emitter“ (AETSE) (konstruiert durch Schimpf-Ing, Trondheim, Norwegen) wurde hinter dem

Beifahrersitz platziert (23). Dieser besteht aus einer 200 ml fassenden Glasspritze, dessen Kolben mit einem Schrittmotor angetrieben wird. Ein negatives Druckverhältnis wird durch die Rückwärtsbewegung des Kolbens erzeugt, woraufhin sich die Spritze mit Rauch füllt. Bei Vorwärtsbewegung des Kolbens kommt es zum Austreiben des Rauchs aus der Glasspritze. Der AETSE wurde mithilfe eines dünnen Schlauchs aus Polyamid mit einem „cigarette smoking device“ (CSD, Zigarettenrauchmaschine) (hergestellt durch Daniel Müller, Institut für Arbeits-, Sozial- und Umweltmedizin, Goethe Universität Frankfurt und Norbert Defner, Arbeitsbereich Physiologie, Universitätskrankenhaus Frankfurt) verbunden (21). Dieses befindet sich auf dem Beifahrersitz und ermöglicht das automatische Verrauchen und Löschen einer Zigarette. Ein Laser Aerosol Spektrometer (LAS) der Firma Grimm (Model 11-R) wurde auf dem Dach des Fahrzeugs platziert. Es saugt Luft aus dem Inneren des Fahrzeugs über einen Polyvinylchloridschlauch an. Das Ende des Schlauchs wurde auf dem Fahrersitz in einer Höhe von 63 cm über der Sitzfläche und 70 cm entfernt von der Zigarette befestigt. Das LAS misst alle 6 Sekunden die Feinstaubkonzentration und differenziert diese nach ihrer Partikelgröße in PM_{10}, $PM_{2,5}$ und PM_1. Zwei Ventilatoren (Modell: Master BML 4800) wurden im Autoinnenraum platziert. Sie konnten mit einer Fernbedienung ein- und ausgeschaltet werden und dienten der suffizienteren Entlüftung des Autos nach jeder verrauchten Zigarette. Der Untersucher musste lediglich die Heckklappe des Autos öffnen und der Feinstaub wurde mithilfe der Ventilatoren aus dem Auto und der Garage herausgeblasen. In der TAPaC Studie (a) wurden vier verschiedene Szenarien (C1a–C4a) getestet. Sie wurden unterteilt in:

C1a: alle Fenster geschlossen, Autolüftung aus

C2a: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und gerichtet auf die Windschutzscheibe

C3a: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und gerichtet auf die Windschutzscheibe und Füße

C4a: alle Fenster geschlossen, Autolüftung auf Stufe 2/4 und gerichtet auf den Körper und Kopf

Die 3R4F Referenzzigarette (Teer: 9,4mg, Nikotin: 0,73mg, CO: 12mg) wurde für die Experimente der ersten Studie verwendet (8). Jedes Szenario wurde 24-mal getestet.
Es wurde ein Standardprotokoll festgelegt, nach welchem alle Zigaretten verraucht werden

mussten. Nach dem automatischen Entzünden der Zigarette durch die Zigarettenrauchmaschine folgten zwei kurz aufeinander folgende Züge. Danach wurden einzelne Züge im 30 Sekunden Intervall für jeweils 3 Sekunden fortgesetzt bis nach 4,5 min eine maximale Anzahl von 10 Zügen erreicht wurde. Die Zigarette wurde daraufhin automatisch ausgestoßen und in einer Petrischale mit Wasser erloschen. Jeder Messzyklus dauerte 10 Minuten und bestand aus 101 einzelnen Messungen, welche vom LAS durchgeführt wurden. Die Durchführung der Untersuchungen konnte in drei Intervalle unterteilt werden. Während des ersten Intervalls wurde die aktuelle Feinstaubbelastung des Fahrzeuginnenraums nach Minimum 5-minütiger Entlüftung bestimmt. Das zweite Intervall begann mit dem Anzünden der Zigarette und endete nach 4,5 min mit dem Erlöschen der Zigarette. Das dritte Intervall bestand aus einer 5,5-minütigen Messphase nach dem Erlöschen der Zigarette bis zum Beginn der Entlüftung des Autos und der Garage. Zur Datenerhebung wurde zum einen die durchschnittlichen Feinstaubkonzentrationen (C_{mean}) nach 4,5 min und 10 min herangezogen. Zum anderen wurden Feinstaubspitzenwerte bei 4,5 min und 10 min ermittelt. Diese wurden aus dem Durchschnitt der jeweils 46. und 101. Messung ermittelt.

Zur Datenanalyse wurde Prism Version 6 verwendet. Zur Kalkulation der Standardabweichung wurden folgenden Tests genutzt: Shapiro-Wilk, D´Agostino-Pearson und Kolmogorov-Smirnov. Zudem wurden eine einfaktorielle Varianzanalyse (ANOVA) mit nachfolgendem Tukey-Mehrvergleichstest durchgeführt. Das Signifikanzniveau wurde hierbei auf p=0,05 festgelegt. Die durchschnittlichen Feinstaubkonzentrationen nach 4,5 min lagen bei PM_{10}: 479–1150 µg/m^3, $PM_{2,5}$: 475–1132 µg/m^3 und PM_1: 429–862 µg/m^3. Die Messdaten zeigten eine signifikante Erhöhung (p<0,0001) von PM_{10}, $PM_{2,5}$, und PM_1 nach 4,5 min zwischen C1a zu C2a–C4a. Die Feinstaubkonzentration von $PM_{2,5}$ nach 4,5 min konnte um 47–58% unter C2a–C4a im Vergleich zu C1a reduziert werden. Es konnte kein signifikanter Unterschied (p=0,0752–0,9999) zwischen den Messdaten von C2a, C3a und C4a nach 4,5 min festgestellt werden. Die durchschnittlichen Feinstaubkonzentrationen nach 10 min lagen bei PM_{10}: 411–1608 µg/m^3, $PM_{2,5}$: 407–1583 µg/m^3 und PM_1: 362–1133 µg/m^3. Im Vergleich zwischen C1a zu C2a–C4a besteht nach 10-minütiger Messung ein signifikanter Unterschied (p<0,0001). Unter C2a–C4a sank die Feinstaubkonzentration von $PM_{2,5}$ um 74,3% im Vergleich zu C1a. Die niedrigsten Feinstaubkonzentrationen nach 10 min konnten unter C3a gemessen werden (PM_{10}: 411 µg/m^3, $PM_{2,5}$: 407 µg/m^3 PM_1: 362 µg/m^3). Allerdings konnte auch nach 10 min kein signifikanter Unterschied (p=0,5460–0,9999) der Messdaten unter C2a–C4a festgestellt werden.

Die Feinstaubspitzenwerte waren am höchsten unter C1a bei 4,5 min (PM_{10}: 2207 µg/m^3, $PM_{2,5}$: 2166 µg/m^3, PM_1: 1375 µg/m^3) gefolgt von 10 min (PM_{10}: 1989µg/m^3, $PM_{2,5}$: 1959 µg/m^3, PM_1: 1375 µg/m^3). Ein signifikanter Unterschied (p<0,0001) der Feinstaubspitzenwerte nach 4,5 min und 10 min konnte zwischen C1a und C2a–C4a ermittelt werden. Es bestand kein signifikanter Unterschied zwischen den Feinstaubspitzenwerten unter C2a–C4a (4,5 min: p=0,2191–0,9973, 10 min: p=0,9977–0,9999). Die Feinstaubspitzenwerte variierten unter C2a–C4a nach 4,5 min (PM_{10}: 630–845 µg/m^3, $PM_{2,5}$: 625–836 µg/m^3, PM_1: 543–693 µg/m^3) und nach 10 min (PM_{10}: 124–130 µg/m^3, $PM_{2,5}$: 124–129 µg/m^3, PM_1: 118–124 µg/m^3). Prozentual zeigte sich unter C1a der Anteil an PM_1 mit 74,9% nach 4,5 min und 70,5% nach 10 min niedriger als unter C2a-C4a. Hier lag PM_1 nach 4,5 min zwischen 86,2–89,5% und nach 10 min zwischen 86,8–89,6%. Die Feinstaubkonzentrationen größerer Partikel lag unter C1a nach 4,5 min ($PM_{10-2,5}$: 1,6%, $PM_{2,5-1}$: 23,5%) und nach 10 min ($PM_{10-2,5}$: 1,5%, $PM_{2,5-1}$: 28%) im Vergleich zu C2a–C4a nach 4,5 min ($PM_{10-2,5}$: 0,8–1%, $PM_{2,5-1}$: 9,7–12,8%) und 10 min ($PM_{10-2,5}$: 0,7–0,9%, $PM_{2,5-1}$: 9,7–12,3%) höher.

Die zweite Publikation (b) (Impact of different ventilation conditions on tobacco smoke-associated particulate matter emissions in a car cabin using the TAPaC platform) dieser Dissertation nutze die in der ersten TAPaC Studie vorgestellte Messplattform, das standardisierte Rauchprotokoll, das Verfahren der Datenanalyse und die statistische Analyse, welche ohne Änderungen übernommen wurden (27). Um die Auswirkung von Fahrtwind auf die Feinstaubkonzentration im Autoinnenraum zu analysieren wurden neue Belüftungsszenarien untersucht. Für alle verwendeten Szenarien wurde mit Ausnahme des ersten Szenarios (C1b) die interne Lüftung des Autos auf die Windschutzscheibe gerichtet und auf halber Stärke (2/4) eingestellt. Nur das Beifahrerfenster wurde geöffnet (C2b–C7b). Daraus ergeben sich die folgenden Einstellungen:

C1b: Fenster geschlossen, Autolüftung aus, externer Ventilator aus

C2b: Fenster 10 cm geöffnet, externer Ventilator aus

C3b: Fenster 10 cm geöffnet, externer Ventilator auf höchster Stufe (3/3) an

C4b: Fenster halb geöffnet, externer Ventilator aus

C5b: Fenster halb geöffnet, externer Ventilator auf höchster Stufe (3/3) an

C6b: Fenster vollständig geöffnet, externer Ventilator aus

C7b: Fenster vollständig geöffnet, externer Ventilator auf höchster Stufe (3/3) an

Zur Simulation des Fahrtwindes wurde außerhalb des Autos ein zusätzlicher Ventilator (Modell: TTV 4500 HP) montiert und auf die höchste Stufe (3/3) gestellt. Der Ventilator befand sich an der Beifahrerseite auf 1,13 Meter Höhe und mit 20 cm Abstand zur äußersten frontal gelegenen Fensterkante. Hierunter konnte in 5 cm Entfernung eine Windgeschwindigkeit von 25,1–25,8 km/h und in ein Meter Entfernung eine Windgeschwindigkeit von 15,9–17,4 km/h gemessen werden.

Für die Experimente wurden 3 Zigarettenprodukte mit unterschiedlichen Tabakgemischen verwendet: Marlboro Red (Teer: 10mg, Nikotin: 0,8mg, CO: 10mg), Marlboro Gold (Teer: 6mg, Nikotin: 0,5mg, CO: 7mg), 3R4F Referenzzigarette (Teer: 9,4mg, Nikotin: 0,73mg, CO: 12mg) (24–26).

Nach 4,5 min zeigten sich die Feinstaubkonzentrationen unter den verwendeten Szenarien (C1b–C7b) deutlich erhöht (PM_{10}: 87,6–1218 µg/m^3, $PM_{2,5}$: 86,8–1198 µg/m^3, PM_1: 84,3–959,7 µg/m^3). Auch nach 10 min blieben die Feinstaubkonzentrationen hoch (PM_{10}: 68,7–1697 µg/m^3, $PM_{2,5}$: 68,2–1659 µg/m^3, PM_1: 66,1–1263 µg/m^3). Feinstaubspitzenwerte bei 4,5 min (PM_{10}: 106,5–2261 µg/m^3, $PM_{2,5}$: 106,3–2217 µg/m^3, PM_1: 103–1442 µg/m^3) und bei 10 min (PM_{10}: 14,6–2185 µg/m^3, $PM_{2,5}$: 14,5–2146 µg/m^3, PM_1: 13,5–1421 µg/m^3) waren ebenfalls deutlich erhöht. Im Vergleich zwischen den Szenarien C1b und C2b–C7b bestand ein signifikanter Unterschied ($p<0{,}0001$), da die Feinstaubkonzentrationen beim Verrauchen ohne jegliche Ventilation (C1b) mit Abstand am höchsten waren. Die durchschnittlichen Feinstaubkonzentrationen waren nach 4,5 min und 10 min unter C2b–C7b um mehr als 90% geringer als unter C1b. In den meisten Fällen konnte kein signifikanter Unterschied ($p>0{,}05$) zwischen C2b–C7b festgestellt werden. Alle Ausnahmen wurden in Tabelle S2 der zweiten Publikation aufgeführt (27). Die vergleichsweise niedrigsten Feinstaubkonzentrationen konnten mit Marlboro Gold unter C2b gemessen werden. Hier bestand nach 4,5 min eine durchschnittliche $PM_{2,5}$ Konzentration von 106,1 µg/m^3 und nach 10 min von 82,6 µg/m^3. Auch die Feinstaubspitzenwerte von $PM_{2,5}$ waren mit 106,3 µg/m^3 nach 4,5 min und 23,7 µg/m^3 nach 10 min am niedrigsten.

Feinstaubspitzenwerte unter C2b–C7b bei 4,5 min und 10 min waren 77,2–99,3% geringer als unter C1b. Ein signifikanter Unterschied der Feinstaubspitzenwerte ($p<0,0001$) zwischen C1b und C2b–C7b konnte festgestellt werden.

C1b verzeichnete im Vergleich zu C2b–C7b den prozentual geringsten Anteil an PM_1 mit lediglich 71–76%. Die Konzentration von $PM_{2,5-1}$ war unter C1b mit 23–27% am höchsten von allen getesteten Szenarien. Die prozentualen Anteile unter C2b–C7b variierten für PM_1 von 92–96% und $PM_{2,5-1}$ von 3–6%. Niedrige Anteile von $PM_{10-2,5}$ mit 0,4–2,4% konnte unter allen untersuchten Szenarien (C1b–C7b) berechnet werden.

5.3. Diskussion

Das Wissen über Feinstaub und dessen potenziell schädliche Wirkung hat in den vergangenen Jahrzehnten deutlich zugenommen (28,29) Einer der schädlichsten Feinstauberzeuger, die Zigarette, ist jedoch weiterhin weltweit verbreitet und in allen Bevölkerungsschichten und Altersklassen vorzufinden (30). Zigarettenkonsum in öffentlichen Innenräumen wird international zunehmend eingeschränkt (31,32). Im Auto ist dies jedoch in den meisten Ländern dieser Welt uneingeschränkt erlaubt. Hierbei können extrem hohe Konzentrationen an Feinstaub erreicht werden, welche nicht nur dem Raucher, sondern auch dessen Mitinsassen schädigen. Vor allem Kinder und schwangere Frauen sind durch Passivrauch in besonderem Maße gefährdet (33,34). Sie sind wehrlose Opfer der rauchenden Gesellschaft. Es ist daher von äußerster Wichtigkeit, sowohl die Gesellschaft als auch internationale Institutionen und Regierungen anhand validierter Daten auf die Schädlichkeit von Passivrauch aufmerksam zu machen. Da Rauchen in Innenräumen wie beispielweise dem Auto weit verbreitet ist, beschäftigten sich bereits einige vorangegangene Studien mit dieser Thematik (13–20). Sie alle hatten gemein, dass eine aktiv rauchende Person im Auto eingesetzt wurde um den Feinstaub zu generieren und zu messen. Obwohl dieser Versuchsaufbau ein realistisches Szenario darstellt, ist zu bemängeln, dass jeder Raucher ein individuelles Rauchverhalten aufweist (35). So unterscheidet sich nicht nur die Anzahl der Züge pro Zigarette, sondern auch das inhalierte Volumen. Um diesen Vorgang zu optimieren und zu standardisieren, wurde mit der TAPaC Studie eine neue Messplattform etabliert. Da sich mit ihrer Hilfe der Untersucher keinem schädlichem Tabakrauch aussetzen musste, konnte sie ethisch vollkommen unbedenklich eingesetzt werden.

Die Experimente der ersten TAPaC Studie fokussierten sich zunächst auf den Einfluss der internen Lüftungsanlage des Autos auf die Feinstaubkonzentrationen im Fahrzeuginnenraum. Unter allen getesteten Lüftungsszenarien konnten extrem hohe Feinstaubwerte festgellt werden. Es konnte jedoch gezeigt werden, dass die Hinzunahme der internen Lüftung des Autos zu einer signifikanten Reduktion der Feinstaubkonzentration im Vergleich zu einem unbelüfteten Auto führte. Beispielsweise konnte die $PM_{2,5}$ Konzentration nach 10 min mit eingeschalteter Belüftung um 71–74% im Vergleich zu ohne Belüftung reduziert werden. Vergleichbare $PM_{2,5}$ Konzentrationen konnte Sendzik et al. in seiner Studie unter ähnlichen ventilatorischen Bedingungen nachweisen (15). Interessant ist zudem, dass sich die Feinstaubkonzentration ohne Belüftung von 4,5 min bis 10 min auf einem konstant hohen Plateau hält. Aufgrund der niedrigen Luftwechselrate bei geschlossenem Fenster und ausgeschalteter Lüftung bleibt die Feinstaubkonzentration auch nach Erlöschen der Zigarette hoch (36). Wohingegen unter eingeschalteter Lüftung ein deutlicher Abfall (13,8–22,2%) der Feinstaubkonzentration zu sehen ist. Auch die Feinstaubspitzenwerte waren in der ersten TAPaC Studie in allen getesteten Szenarien drastisch erhöht und sanken unter Hinzunahme der internen Lüftung deutlich schneller ab als ohne. Der größte prozentuale Anteil der Feinstaubemissionen in allen Szenarien war PM_1 mit 70,5–89,6% nach 10 min. Der Feinstaubanteil größerer Partikel war nach 10 min unter C1a ($PM_{10-2,5}$: 28%, $PM_{2,5-1}$: 1,5%) höher als unter C2a–C4a ($PM_{10-2,5}$: 9,7–12,3%, $PM_{2,5-1}$: 0,7–0,9%). Dies liegt an der schnelleren Sedimentierung von schwereren Partikeln durch Gravitation (37,38). Allerdings kommen hier auch andere Effekte zum Tragen wie beispielweise Luftfeuchte, Temperatur, Luftverwirbelungen, Oberflächenstruktur der Partikel, Thermophorese, Turbophorese und elektrostatische Effekte (39,40).

Die zweite Studie nutzte die bestehende TAPaC Messplattform und erweiterte die Experimente, indem sie drei verschiedene Tabakprodukte unter sieben verschiedenen Belüftungsszenarien miteinander verglich. Um Fahrtwind simulieren zu können, wurde ein Ventilator an dem Fenster des rauchenden Beifahrers (Position der Zigarettenrauchmaschine) befestigt. In den Versuchen der zweiten Studie wurde nun der Einfluss von Fahrtwind bei unterschiedlich weit geöffnetem Beifahrerfenster auf die Feinstaubkonzentration im Autoinnenraum untersucht. Wie zu erwarten war, waren auch hier die Feinstaubkonzentrationen ohne jegliche Belüftung extrem hoch. So sank beispielweise die $PM_{2,5}$ Konzentration nach 10 min unter C2b–C7b um mehr als 87% im Vergleich zu C1b. Müller et al. untersuchte die Feinstaubkonzentrationen von Zigarettenrauch in einer Telefonzelle mit geöffneter und geschlossener Tür. Auch er konnte hierbei eine deutliche Reduktion von bis zu 90% bei geöffneter Tür nachweisen (41). Um den Einfluss von unterschiedlichen Tabakgemischen auf die Feinstaubkonzentration im Fahrzeuginnenraum bei verschiedenen Lüftungsszenarien zu untersuchen, wurden in der zweiten Studie Marlboro Red, Marlboro Gold und die 3R4F Referenzzigarette verwendet (24–26). Hierbei konnte festgestellt werden, dass unterschiedliche Lüftungsszenarien (C2b–C7b) nur in einzelnen Fällen zu einem signifikanten Unterschied der Feinstaubkonzentration führt. Zudem stellte sich heraus, dass Marlboro Gold im Allgemeinen niedrigere Feinstaubemissionen aufwies als Marlboro Red und die 3R4F Referenzzigarette. Dies lässt sich vermutlich auf das spezifische Tabakgemisch und den verwendeten Zigarettenfilter zurückführen (40). Die Konzentrationen der Feinstaubspitzenwerte unter C1b von 4,5 min auf 10 min verhielten sich konstant. Im Gegensatz dazu konnten die Feinstaubspitzenwerte unter C2b–C7b von 4,5 min bis 10 min um maximal 91,8% reduziert werden. Diese extrem starken Unterschiede sind auf die Luftwechselrate zurückzuführen, welche bei geschlossenen Fenstern und ohne Lüftung extrem gering ist (36).

Da sehr viele Faktoren auf die Konzentration von Feinstaub im Autoinnenraum Einfluss nehmen, ist es schwierig die genaue Ursache der unterschiedlichen Feinstaubemission unter C2b–C7b zu bestimmen. Die Luftwechselrate kann beispielweise durch die Weite der Fensteröffnung, Fahrtwind und die Lüftung beeinflusst werden (36). Zudem werden, in Abhängigkeit der Fensteröffnung, durch den Fahrtwind am Auto interne und externe Druckgradienten gebildet, welche Einfluss auf Luftströme nehmen (42)

Die prozentualen Anteile der Feinstaubkonzentrationen waren vergleichbar mit denen der ersten Studie. Der Hauptanteil der Feinstaubemissionen bestand aus PM_1 (71–97%), gefolgt von $PM_{2,5-1}$ (3–27%) und $PM_{10-2,5}$ (0,3–2,4%). Wie hierbei ersichtlich wird, produziert die Verbrennung von Tabak ein besonders hohen Anteil an feinem Feinstaub (PM_1) (2). Dies ist alarmierend, da sehr kleine Partikel ($PM_{2,5}$, PM_1) besonders tief inhaliert werden und in die systemische Blutzirkulation diffundieren können (43).

Die Etablierung der TAPaC Messplattform erlaubt es dem Forscher Feinstaubmessungen von Zigarettenrauch im Autoinnenraum durchzuführen, ohne sich dabei selbst zu gefährden. In beiden Studien konnten extrem hohe Feinstaubwerte nachgewiesen werden. Zudem zeigten sie, dass die Erhöhung der Luftwechselrate durch Lüftung, Öffnung des Fensters oder Fahrtwind eine Verringerung der Feinstaubkonzentrationen im Fahrzeuginnenraum ermöglicht.

Dennoch war in allen getesteten Szenarien die Feinstaubkonzentration weiterhin deutlich erhöht, sodass trotz aller getroffenen Maßnahmen von einer gesundheitsschädlichen Exposition durch Passivrauch auszugehen ist. Die Daten zeigten einmal mehr, dass ein generelles Tabakverbot in Innenräumen zum Schutz der allgemeinen Bevölkerung sinnvoll wäre.

6. Übersicht über die zur Veröffentlichung angenommenen Manuskripte

TAPaC—tobacco-associated particulate matter emissions inside a car cabin: establishment of a new measuring platform

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Impact of different ventilation conditions on tobacco smoke-associated particulate matter emissions in a car cabin using the TAPaC platform

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7. Publikationen

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METHODOLOGY **Open Access**

TAPaC—tobacco-associated particulate matter emissions inside a car cabin: establishment of a new measuring platform

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Abstract

Background: Particulate matter (PM) emission caused by tobacco combustion leads to severe health burdens worldwide. Second-hand smoke exposure is extraordinarily high in enclosed spaces (e.g., indoor rooms, car cabins) and poses a particular threat to the health of vulnerable individuals (e.g., children, elderly, etc.). This study aimed to establish a new measuring platform and investigate PM emissions under four different ventilation conditions inside a car cabin without exposing any person to harmful tobacco smoke.

Methods: PM concentrations were measured during the smoking of 3R4F reference cigarettes in a Mitsubishi Space Runner (interior volume 3.709 m^3). The cigarettes were smoked with a machine, eliminating exposure of the researchers. Cigarettes were extinguished 4.5 min after ignition, and PM measurements continued until 10 min after ignition.

Results: High mean PM concentrations were measured for cigarettes without ventilation after 4.5 min (PM$_{10}$: 1150 µg/m^3, PM$_{2.5}$: 1132 µg/m^3, PM$_1$: 861.6 µg/m^3) and after 10 min (PM$_{10}$: 1608 µg/m^3, PM$_{2.5}$: 1583 µg/m^3, PM$_1$: 1133 µg/m^3)**.** 3R4F smoked under conditions with turned on ventilation resulted in reduction of PM compared to those smoked without ventilation after 4.5 min (PM$_{10}$:-47.5 to -58.4%, PM$_{2.5}$:-47.2 to -58%, PM$_1$:-39.6 to -50.2%) and after 10 min (PM$_{10}$:-70.8 to -74.4%, PM$_{2.5}$:-70.6 to -74.3%, PM$_1$:-64.0 to -68.0%). Cigarettes smoked without ventilation generated high PM peaks at 4.5 min (PM$_{10}$: 2207 µg/m^3, PM$_{2.5}$: 2166 µg/m^3, PM$_1$: 1421 µg/m^3) and at 10 min (PM$_{10}$: 1989 µg/m^3, PM$_{2.5}$: 1959 µg/m^3, PM$_1$: 1375 µg/m^3). PM peaks of cigarettes smoked under different ventilation modes varied at 4.5 min (PM$_{10}$: 630-845 µg/m^3, PM$_{2.5}$: 625-836 µg/m^3, PM$_1$: 543 - 693 µg/m^3) and 10 min (PM$_{10}$: 124 - 130 µg/m^3, PM$_{2.5}$: 124 - 129 µg/m^3, PM$_1$: 118 - 124 µg/m^3).

Conclusion: The new measuring platform provides a safer way for researchers to investigate PM emissions of cigarettes. These data are comparable to published research and show that smoking in a parked vehicle with the windows closed generates harmful PM emissions even when the vehicle ventilation is in operation. Future studies should be carried out using the new measuring platform investigating PM exposure and PM distribution of in-vehicle smoking under a wide range of conditions.

Keywords: Indoor air pollution, In-cabin PM concentration, Smoking in vehicles, Passive smoke, Environmental tobacco smoke, Second-hand smoke

Background

During the past decades, the knowledge about environmental air pollution and its threat to human health has increased significantly. Particulate matter (PM) emitted when a cigarette is smoked is highly carcinogenic. Tobacco smoke contains more than 5000 chemical

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substances, about 98 of which are proven to cause cancer, while many others are yet to be identified [1]. In addition, the toxic mixture of tobacco smoke affects multiple organ systems and leads to a large number of complications and diseases (e.g., cancer, asthma, etc.) [2, 3]. PM can be divided into PM_{10}, $PM_{2.5}$, and PM_1. PM_{10} includes all particles with a size (aerodynamic diameter) ≤ 10 µm, $PM_{2.5}$ includes all particles ≤ 2.5 µm, and $PM_1 \leq 1$ µm [4]. Smaller particles pose a greater threat to our health than relatively large particles as they can penetrate deeper into the lungs and get absorbed by the bloodstream, and reach the systemic circulation [5, 6]. Combustion sources (e.g., tobacco) primarily generate small particles [7]. The 2021 updated air quality guidelines of the World Health Organization (WHO) recommend a 24-h mean $PM_{2.5}$ of ≤ 15 µg/m^3, and a 24-h mean of 45 µg/m^3 for PM_{10} [8]. According to Schramm et al., the sidestream smoke of cigarettes has a higher PM mass than mainstream smoke [9].

Although about 7 million tobacco smokers die per year because of their smoking, an estimated 1.2 million non-smokers die of exposure to second-hand smoke (SHS) according to WHO data [10]. This is a dramatic number since the people affected by the associated burden are not actively deciding to smoke but are often exposed involuntarily and are at substantial risk for diseases such as chronic inflammatory diseases of the airways, asthma, chronic obstructive pulmonary disease, and lung or breast cancer [11]. As studies have shown, children are particularly susceptible to SHS. Due to their smaller lungs and higher respiratory rates, children inhale more particles per kg body weight than adults [12–14]. Pulmonary and respiratory diseases are significantly more common in children exposed to SHS than those not exposed [8, 13, 15]. To reduce the individual and economic burden caused by SHS, many countries have banned smoking in public places such as restaurants, cinemas, and bars [16–18]. Nevertheless, indoor smoking in private households or vehicles is legal in most countries, posing a great risk of exposure to second-hand smoke and the development of SHS-associated diseases [19]. Tobacco consumption inside cars is widespread. One or more windows are frequently opened to improve ventilation and diminish passive exposure. Nevertheless, PM exposure is increased even in vehicles with open windows [20, 21].

This study introduces a newly-designed, standardized approach for measuring PM concentrations (PM_{10}, $PM_{2.5}$, and PM_1) inside a car cabin under different conditions without exposure of any person, posing a clear advantage over similar previous studies [20, 21]. This new platform is an improvement to the established platform of the Tobacco Smoke Particles and Indoor Air Quality (ToPIQ) as well as modified ToPIQ-2 studies [22, 23]. The aims of this study were (1) to mimic exposure of the car occupants and the driver to second-hand smoke emitted by a passenger in a standardized experimental setting and (2) to quantify the associated burden of particulate matter associated with this second-hand smoke.

Methods

Experimental setup

For measuring PM emissions of tobacco combustion products inside a car cabin, a Mitsubishi Space Runner 1991–1998 (syn. Mitsubishi Expo LRV) was parked in a garage at the Goethe-University of Frankfurt. The car had a total passenger and cargo volume of 3.709 m^3 [24].

To avoid health risks caused by actively smoking tobacco, an automatic environmental tobacco smoke emitter (AETSE), equivalent to the ToPIQ-2 studies [23], was integrated into the car cabin. This machine was developed and constructed by Schimpf-Ing (Trondheim, Norway) and consisted of a smoke pump with a microcontroller unit that drove a stepper motor to move a plunger inside a 200 ml glass syringe [23]. The smoke pump was placed behind the passenger´s seat (Fig. 1B) and was connected to the cigarette smoking device via a polyamide tube (constructed by Daniel Müller, Institute of Occupational Medicine, Social Medicine and Environmental Medicine, Goethe University Frankfurt and Norbert Deffner, Workshop of physiology, University Hospital Frankfurt, Germany). The cigarette smoking device (simulating a smoking person) was placed on the passenger´s seat and was controlled by the microcontroller unit of the AETSE. The cigarettes were pushed manually into the mounting device holding the cigarette in a stable position (Fig. 1B, D). The cigarettes were lit by an automatic cigarette lighter. After the combustion phase, the cigarettes were expelled into a water bath to extinguish the cigarettes.

For air exchange, two fans (Model: Master BML 4800) were installed inside the car, one between the two front seats and one on the folded back rear seat next to the AETSE (Fig. 1B). For better ventilation of the car cabin, the researcher can open the tailgate and turn on the fans inside the car by remote control, thus blowing the cigarette smoke outside the garage. While cigarette combustion and ventilation of the vehicle, the researcher observes the experiment from a safe distance of approximately five meters outside the garage.

For future studies, two additional fans (Model: Trotec TTV 4500 HP) were pre-installed, one on each side of the front side windows outside the vehicle (Fig. 1A), producing a constant and reproducible airstream (airstream simulation). The fans have three power levels and can operate in three different modes. These modes can be distinguished by the airflow velocity in a distance of 1 m

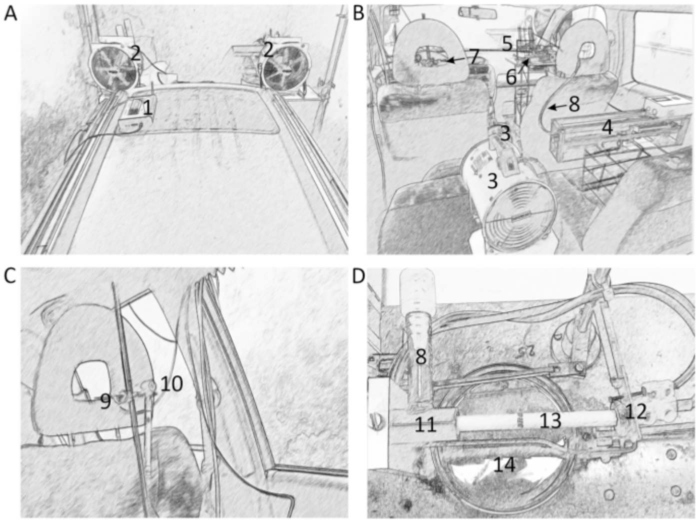

Fig. 1 Measuring platform. Notes: **A** Outside. **B**-**D** Inside. A-1: Portable mini laser aerosol spectrometer (LAS, Grimm model 11-R). A-2: Fan (Model: Trotec TTV 4500 HP). B-3: Fan (Model: Master BML 4800). B-4: Automatic environmental tobacco smoke emitter (AETSE) B-5: Cigarette smoking device. B-6: Arrow marks the position of the cigarette. B-7: Arrow marks the suction point. B-8, D-8: Movable tube connecting the AETSE with the cigarette smoking device. C-9: Mobile tube connected to the LAS placed on the car roof (enables the LAS to suck interior vehicle air). C-10: Sensor for temperature, relative humidity, and air velocity (Grimm model 1.154). D-11: Cigarette mounting device. D-12: Automatic cigarette igniter. D-13: Cigarette. D-14: Petri dish filled with water

and include power level 1/3 with an airflow velocity of 0 km/h, power level 2/3 with an airflow velocity of 7.4 – 8.5 km/h, and power level 3/3 with an airflow velocity of 23 – 30.6 km/h. The Trotec TTV 4500 HP fans were not used in this study.

Measuring system

PM measurements were carried out by a portable mini Laser Aerosol Spectrometer (LAS) Grimm Model 11-R. The LAS was positioned on the car top on the driver´s side (Fig. 1A). It can differentiate PM measurements into PM_{10}, $PM_{2.5}$, and PM_1). Via a movable tube mounted on the passenger´s seat, 63 cm above the seating surface, the LAS can suck in interior vehicle air. This tube was positioned 70 cm away from the cigarette, 105 cm from the passenger´s side window, 34 cm from the driver´s side window, and 65 cm away from the steering wheel (Fig. 1C). Measurements were taken every 6 s. Temperature and relative humidity were measured at a device positioned 3 cm laterally to the tube at the same height. Only the on-board ventilation system that came with the vehicle was used for this experiment. It has four different power levels. For this study, only power level 2/4 was applied.

The SHS-dependent concentrations of PM inside the vehicle were measured under 4 different ventilation conditions. These comprised: *condition 1* (C1) all windows closed and the car ventilation was turned off, *condition 2* (C2), all windows closed and the car ventilation turned on power level 2/4, with the air directed towards the windshield, *condition 3* (C3), all windows closed and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet, and *condition 4 (*C4), all windows closed with the car ventilation turned on power level 2/4, with the air directed towards body and head.

Tobacco products

The 3R4F reference cigarettes used in this study yield an average of 9.4 mg tar, 0.73 mg nicotine and 12 mg carbon monoxide [25].

Smoking protocol

All cigarettes tested followed the same smoking protocol. Automatic ignition of the cigarette by the cigarette smoking device was followed by two initial puffs. The interval between the two initial puffs was one second. Two subsequent cigarette puffs per minute with a time interval of

30 s were taken. Each puff had a duration of 3 s and a volume of 40 ml. After a total of 10 puffs, the cigarette was expelled from the cigarette smoking device and extinguished in a petri dish filled with water. The cigarette smoking device was restarted after 5 min of extensive full vehicle ventilation. Each condition was repeated 24 times, accounting for a total number of 96 smoked cigarettes. Combustion of cigarettes that extinguished prematurely had to be repeated. They were not considered for the subsequent data processing.

Data processing and analysis

Each measuring period was divided into three intervals. The *first interval* started with a baseline PM measurement which was acquired after thorough vehicle ventilation for at least five minutes after each smoked cigarette. The *second interval* consisted of the time between ignition and extinction of the cigarette lasting for 4.5 min (combustion phase). The *third interval* lasted for at least 5.5 min and represents the phase of post-combustion. Every 6 s, the LAS measures PM_{10}, $PM_{2.5}$, and PM_1 concentrations. Each evaluated cigarette dataset consists of 101 single measurements resulting in exactly 10 min.

PM_{10}, $PM_{2.5}$, and PM_1 are average concentrations after a given period of time. They are measured after 4.5 min (1. – 46. measurement) and after 10 min. (1 – 101. measurement). PM peaks represent single values of measurements at 4.5 min (46. measurement) and at 10 min (101. measurement).

Statistical analysis

Statistical evaluation of data was performed by using Prism version 6 (GraphPad Software, La Jolla California, USA, www.graphpad.com). Shapiro–Wilk, D`Agostino-Pearson, and Kolmogorov–Smirnov tests were used to determine standard distribution (passed). A one-way analysis of variance (ANOVA) with Tukey's multiple comparison test followed. Level of significance was set at $p = 0.05$.

Table 1 Mean concentrations (A) and peak emissions (B) of particulate matter (PM_{10}, $PM_{2.5}$, PM_1)

Condition	Minutes after ignition	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	PM_1 (μg/m^3)
C1	4.5	A: 1150 ± 462 B: 2207 ± 1294	A: 1132 ± 452 B: 2166 ± 1251	A: 861.6 ± 271 B: 1421 ± 516
	10	A: 1608 ± 461 B: 1989 ± 438	A: 1583 ± 451 B: 1959 ± 428	A: 1133 ± 245.9 B: 1375 ± 214
C2	4.5	A: 478.8 ± 37 – 58.4% B: 630.2 ± 45.5 – 71.5%	A: 475.2 ± 36 – 58% B: 624.6 ± 44.7 – 71.2%	A: 428.7 ± 246 – 50.2% B: 543.2 ± 32.4 – 61.8%
	10	A: 412.4 ± 30.2 – 74.4% B: 129.8 ± 13.4 – 93.5%	A: 409.5 ± 29.9 – 74.1% B: 129.4 ± 13.5 – 93.4%	A: 369.3 ± 24.8 – 67.4% B: 123.9 ± 13.1 – 91%
C3	4.5	A: 489.8 ± 71.2 – 57.4% B: 667.2 ± 129 – 69.8%	A: 485.2 ± 70.1 – 57.1% B: 660.3 ± 126 – 69.5%	A: 430.2 ± 53.3 – 50.1% B: 558.9 ± 91.8 – 60.7%
	10	A: 410.6 ± 62.4 – 74.5% B: 124 ± 24.8 – 93.8%	A: 407.1 ± 61.5 – 74.3% B: 123.7 ± 24.7 – 93.7%	A: 362.1 ± 48.7 – 68% B: 118.2 ± 22.6 – 91.4%
C4	4.5	A: 603.7 ± 59.9 – 47.5% B: 845.3 ± 203 – 61.7%	A: 597.4 ± 58.4 – 47.2% B: 836 ± 199 – 61.4%	A: 520.3 ± 38.6 – 39.6% B: 692.5 ± 133 – 51.3%
	10	A: 469.9 ± 45.6 – 70.8% B: 125.6 ± 17 – 93.7%	A: 465.5 ± 44.5 – 70.6% B: 125.2 ± 16.9 – 93.6%	A: 407.7 ± 30.2 – 64% B: 118.2 ± 15.6 – 91.4%

Notes: Mean concentrations (C_{mean}) and peak emissions of PM_{10}, $PM_{2.5}$, and PM_1 with given standard deviation (SD) of 3R4F reference cigarettes under four different conditions (C1 – C4). Deviation of C_{mean} PM and PM peaks from 3R4F reference cigarette C1 in percentage after 4.5 min and 10 min, respectively. Condition 1 (C1): All windows closed, and the car ventilation turned off. Condition 2 (C2): All windows closed, and the car ventilation turned on power level 2/4, with air directed towards the windshield. Condition 3 (C3): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet. Condition 4 (C4): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards body and head. A: C_{mean} after 4.5 min and 10 min. B: Mean peak emissions at 4.5 min and 10 min.

Results

The baseline PM_{10}, $PM_{2.5}$, and PM_1 after a ventilation interval of at least 5 min were 30.6 ± 11.5 μg/m^3, 27.9 ± 11 μg/m^3, and 24.6 ± 11.2 μg/m^3, respectively.

PM_{10}, $PM_{2.5}$, and PM_1 mean concentrations (C_{mean}) after 4.5 min, smoked without any ventilation (C1), were significantly higher ($p < 0.0001$) than PM concentrations with the three other ventilation conditions (C2 – C4). C_{mean} PM_{10} during experimental conditions C2 – C4 was 47.5 to 58.4% lower compared to C1. $PM_{2.5}$ and PM_1 at C2 – C4 were 39.6 – 58% lower than at C1 (Table 1). No significant difference could be seen comparing C2 – C4 ($p = 0.0752 – 0.9999$). Nevertheless, C4 presented slightly higher PM C_{mean} than C2 and C3 after 4.5 min.

PM C_{mean} after 10 min under C1 were significantly higher ($p < 0.0001$) than those smoked under C2 – C4. The PM_{10} mean value of cigarettes smoked under C1 was 290% higher than under C2. $PM_{2.5}$ and PM_1 mean values under C1 were 287% and 207% higher than their counterparts of C2 (Table 1).

The highest PM mean values showed the 3R4F reference cigarette without ventilation (Fig. 2). 3R4F reference cigarettes of C2 – C4 showed similar PM mean values. Here, the largest difference could be observed comparing PM_{10} of C3 and C4. Directing the ventilation towards the body and head (C4) led to a 14% increase of PM_{10} compared to C3 (ventilation towards windshield and feet). Although different ventilation directions (C2 – C4) did not show any significant differences in $PM_{10,}$ $PM_{2.5}$, and PM_1 ($p = 0.5460 – 0.9999$), we saw a trend regarding the PM values measured during C4 that were slightly higher than those of C2 and C3 after 10 min.

PM peaks at 4.5 min and 10 min were the highest during ventilation condition C1. PM peaks at 4.5 min and 10 min showed significant differences ($p < 0.0001$) when

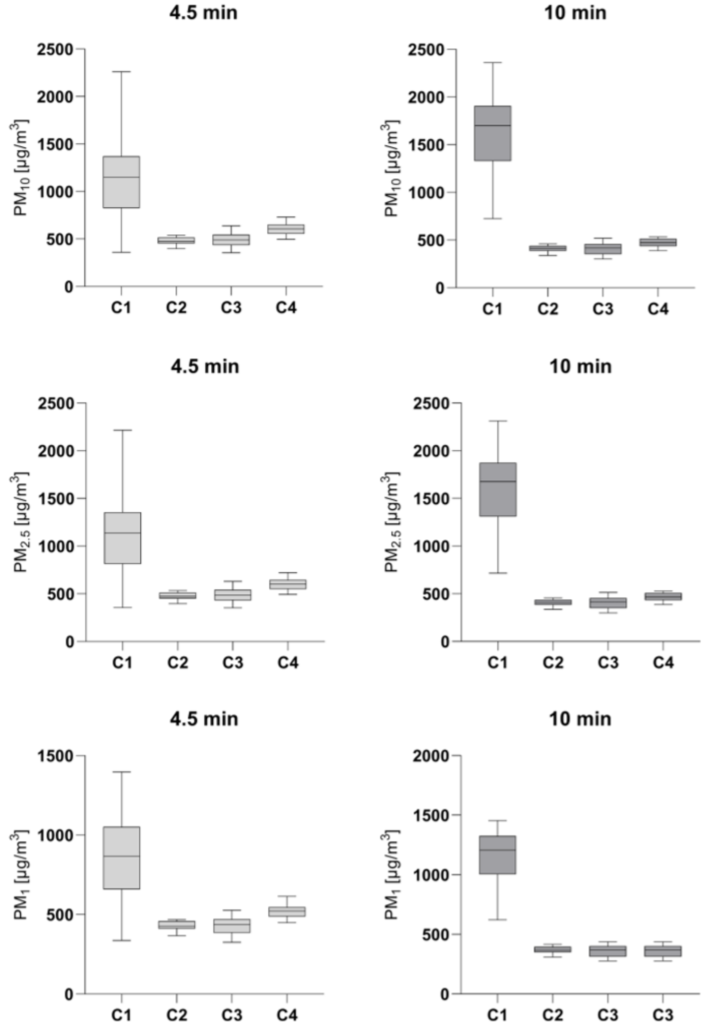

Fig. 2 Boxplots (min to max whiskers) graphically display data seen in Table 1. Notes: PM: Particulate matter. Condition 1 (C1): All windows closed, and the car ventilation turned off. Condition 2 (C2): All windows closed, and the car ventilation turned on power level 2/4, with air directed towards the windshield. Condition 3 (C3): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet. Condition 4 (C4): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards body and head

ventilation condition C1 was compared with conditions C2 – C4. No significant differences could be seen comparing PM peaks of C2 – C4 at 4.5 min ($p = 0.2191 – 0.9973$) with respective PM peaks at 10 min ($p = 0.9977 – 0.9999$).

PM_{10}, $PM_{2.5}$, and PM_1 decreased from the baseline by 9.9%, 9.6%, and 3.2% respectively, comparing the peaks at 4.5 min and 10 min. PM peaks at 4.5 min decreased by up to—71.5% comparing C1 with conditions C2 – C4. After 10 min, a maximum PM reduction of 93.8% was seen comparing C1 and conditions C2 – C4.

Particle distribution is illustrated in Fig. 3. Looking at C_{mean} of measurement ranges, PM_1 accounted for 74.9% of total PM at 4.5 min and 70.5% at 10 min emitted under C1. $PM_{2.5-1}$ made up 23.5%, and 28%, while $PM_{10-2.5}$ only accounted for 1.5 – 1.6% of PM emissions under C1. Condition 2 showed the highest amount of PM_1 with 89.5% of total PM, closely followed by C3 (88.2% of total PM) and C4 (86.8% of total PM). $PM_{2.5-1}$ of C2-C4 varied between 9.7 – 12.8% of total PM, while $PM_{10-2.5}$ made up only 0.70 – 1%. Only minor variations could be seen comparing PM_{10}, $PM_{2.5}$, and PM_1 emissions after 4.5 min and 10 min.

At all PM measurements, the temperature inside the car cabin varied between 17 – 21 °C. Relative humidity inside the cabin was between 42—55%.

Discussion

The presented study describes a newly developed experimental approach to quantify PM emissions of second-hand smoke in a vehicle. The data demonstrate that in-vehicle smoking generates harmful particle emissions of varying diameters even with the vehicle ventilation system turned on. If the experimental setting mimicked a scenario with no ventilation initiated by the car occupants, the particle load was significantly higher when the ventilation was started, albeit the differences in particle load exposure between the ventilation conditions were minimal.

Prior studies have investigated tobacco smoke pollution in cars under in vivo conditions exposing human smokers [20, 21, 26–31]. Thus, acquired data of $PM_{2.5}$ by Sendzik et al. under similar ventilation conditions resulted in comparable PM concentration levels as in this study [21]. There are important ethical concerns regarding the exposure of humans to toxic tobacco smoke for research purposes. Therefore, the strength of this study is to introduce a new mechanical system that allows research on second-hand tobacco smoke to be conducted without exposing the researchers or any other person to tobacco smoke. The highly standardized smoking procedure ensures optimal data acquisition and comparison. During conditions C2—C4, the on-board ventilation system of the car was kept on power level 2/4 as we considered it a realistic setting for drivers to use. Although temperature and relative humidity may impact PM concentrations, they were intentionally left uncontrolled, which might seem as a limitation of this study. This experimental approach was chosen because it imitates real-life driving conditions in a car without air-conditioning or heat [32, 33]. As

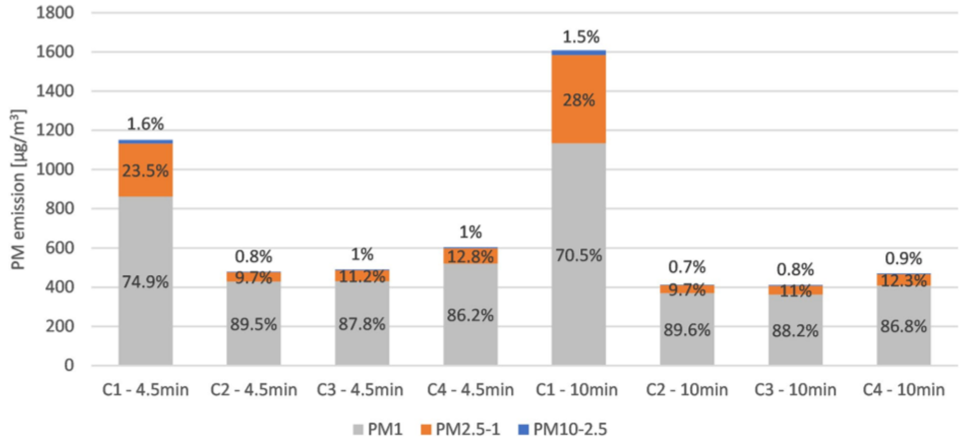

Fig. 3 Distribution pattern of mean concentrations $PM_{10-2.5}$, $PM_{2.5-1}$, and PM_1 after 4.5 min and 10 min. Notes: PM was generated by smoking cigarettes in a compact car. PM: Particulate matter. Condition 1 (C1): All windows closed, and the car ventilation turned off. Condition 2 (C2): All windows closed, and the car ventilation turned on power level 2/4, with air directed towards the windshield. Condition 3 (C3): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet. Condition 4 (C4): All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards body and head

mentioned in previous ToPIQ studies, the AETSE cannot exactly imitate a real smoker [22, 23, 34, 35]. Therefore, it was surprising that the PM data could be compared with data originating from research using human smokers. In contrast to ToPIQ I, the ToPIQ II study design used a larger smoking chamber (2.88 m^3), thus being more comparable to the interior car volume of the Mitsubishi Space Runner (3.709m^3) [23, 24]. Due to the larger interior volume of the car, the reference cigarettes $PM_{2.5}$ exposure measured in the ToPIQ II study by Gerber et al. is about 9% higher than the corresponding PM values presented in this study [23]. The influence of varying interior volumes on PM burden should be the focus of future studies.

The findings of extremely high PM values after 10 min of cigarette smoking without any ventilation were alarming. Further, the 3R4F reference cigarettes smoked under diverse ventilation conditions displayed similarly high PM levels (no significance, $p > 0.05$). The mean concentrations of PM were 3—4 times less compared to cigarettes smoked without ventilation. Under C3, PM_{10}, $PM_{2.5}$, and PM_1 decreased by 74.5%, 74.3%, and 68%, respectively, after 10 min compared to C1, representing the highest reduction of PM for the investigated ventilation conditions. On the contrary, the lowest decrease of PM after 10 min was measured under C4 (Table 1).

Even after 10 min, the measured C_{mean} of PM_{10} (>400 µg/m^3) had exceeded the WHO 24 h threshold by more than factor 9. PM_{10} concentrations of cigarettes smoked without ventilation were 35 times higher than the recommended WHO threshold for PM_{10} [8]. Moreover, these high PM concentrations drastically exceeded the measurements conducted by Dröge et al. (traffic PM measurements inside a driving vehicle cabin, among others, with closed windows) showing $PM_{2.5}$ values of 5.2 – 23.2 µg/m^3 and PM_1 values that ranged from 4.9 – 22.6 µg/m^3 [36]. The higher C_{mean} values after 10 min compared to C_{mean} after 4.5 min under C1 is due to the sustained high plateau concentration after the cigarette has been extinguished. The reduction of PM concentrations from 4.5 min to 10 min by 13.8 – 22.2% under C2 – C4 demonstrates the effect of in-vehicle ventilation during a smoking session. Ventilation dilutes the in-cabin air with ambient air, thus increasing the air exchange rate and decreasing the PM concentration [31, 37]. It is not yet known whether the ventilation produces an airstream that pushes PM into the back of the vehicle, thereby increasing the PM concentration where children are usually seated. Experiments have already indicated that smoking a cigarette with an opened window does not decrease the PM exposure in the back seat [38]. Although smoking with one or more opened windows increases the air exchange rate, the SHS exposure is still highly elevated [20, 38–40]. Schober et al. compared the PM emissions of IQOS, E-Cigarettes and tobacco cigarettes under six different ventilation conditions in various cars with varying interior volumes [41]. Combustion of tobacco cigarettes reached higher emissions of $PM_{2.5}$ (64—1988 µg/m^3) than IQOS or E-Cigarettes. Compared to our investigation ($PM_{2.5}$: 407—1583 µg/m^3), their $PM_{2.5}$ emission range is wider due to different experimental conditions [41]. Sohn et al. measured the PM emissions of cigarettes under three different ventilation conditions [20]. Similar to our study, they divided the measurements into three phases: The pre-smoking phase, smoking phase, and post-smoking phase. While they concluded that the $PM_{2.5}$ concentration exceeded the US National Ambient Air Quality Standard of 35 µg/m^3, their investigation lacks differentiation of PM_{10} and PM_1 emissions. Neither of the two aforementioned study designs investigated the effect of the on-board ventilation system on PM emissions as presented in our research model [20, 41].

Figure 3 differentiates PM into $PM_{10\text{-}2.5}$, $PM_{2.5-1}$, and PM_1, thus comparing the individual mass of different particle sizes created through cigarette combustion. After 10 min 70.5—89.6% of the total PM mass is ≤ 1 µm, while $PM_{2.5-1}$ accounts for 9.7—28% and $PM_{10\text{-}2.5}$ for 0.7—1.5%. Due to gravitational settling, coarse particles have faster deposition rates than fine particles [42, 43]. Nevertheless, the deposition rate of PM is highly variable and depends on many factors (e.g., humidity, temperature, air turbulence, surface roughness, thermophoresis, turbophoresis, spatial distribution, electrostatic effects) [33, 44]. In contrast to the PM fractions $PM_{2.5-1}$ and PM_1, $PM_{10\text{-}2.5}$ is more impacted by gravity [33]. Therefore, the high concentration of fine particles after 10 min is due to slow gravitational sedimentation and high fine particle generation during cigarette combustion [7, 42, 45]. The portion of PM_1 was 16.3 – 19.1% higher for C2 – C4 compared to C1 after 10 min. That is likely caused by the ventilation, creating air turbulence leading to slower gravitational sedimentation of fine particles [33].

A high concentration of small particles < 2.5 µm is particularly alarming, as they can penetrate deeply into the respiratory system causing severe health burdens [46]. Children exposed to small particles are especially vulnerable and can develop various diseases (asthma, cancer, decreased lung function, otitis, neurobehavioral problems, etc.) [47, 48]. In 2010, additional health care services for US children aged 3–14 of 62.9 million dollars were linked to preventable SHS [49]. An observational study carried out in Italy showed that children were exposed to in-cabin SHS in 0.9% of passing by vehicles [50]. Therefore, children should be protected from SHS by law, prohibiting in-door (in-vehicle) smoking.

The on-board ventilation system (C2 – C4) drastically reduced the PM peaks after 4.5 min and 10 min.

Compared to C1, it decreased PM_{10}, $PM_{2.5}$, and PM_1 peaks at 4.5 min by 61.7—71.5%, 61.4—71.2%, 51.3—61.8%, and at 10 min by 93.5 – 93.8%, 93.4 – 93.7%, and 91 – 91.4%, respectively (Table 1). Therefore, the majority of PM concentration peaks (>61%) is reduced at the end of the second interval (after 4.5 min).

In 2019 Campagnolo et al. accurately showed a correlation of PM concentration inside a car cabin depending on the emission standard of the car driving ahead. New emission standard cars (Euro 6) generate 34% less $PM_{0.3-1}$ for the following car than compared to its older predecessors (i.e., Euro 0–2) [51]. This study presents a great example of the benefit of strict PM emission laws for vehicles.

The new measuring platform poses multiple opportunities for future investigations. PM exposure under diverse ventilation scenarios with different degrees of window openings is of the highest interest. The two outside fans can be used at different power levels to simulate an airstream around a moving vehicle. Measurements during this simulation may add important data about PM exposure during a car drive with opened windows. The influence of air conditioning could be investigated in upcoming studies. The cigarette smoking device can aid in investigating the effects of chain-smoking on PM concentration in a vehicle. Positioning multiple LAS at different locations inside the car cabin could generate important data about the distribution of SHS inside the car cabin under various ventilation conditions simultaneously.

Conclusion

The presented new platform enables researchers to safely measure PM emissions from tobacco products in a car cabin without exposure to SHS. Investigating and comparing the effects of multiple different ventilation scenarios on PM concentrations is important for future studies. This study demonstrates the vast PM burden created by smoking in cars and shows the importance of banning smoking in cars. We hope that investigations carried out may aid in encouraging governments and people to create a smoke-free world.

Abbreviations

AETSE: Automatic environmental tobacco smoke emitter; ANOVA: Analysis of variance; C1: All windows closed, and the car ventilation turned off; C2: All windows closed, and the car ventilation turned on power level 2/4, with air directed towards the windshield; C3: All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards the windshield and feet; C4: All windows closed, and the car ventilation turned on power level 2/4, with the air directed towards body and head; C_{mean}: Mean concentration; LAS: Laser aerosol spectrometer; p: Probability value; PM: Particulate matter; SHS: Second-hand smoke; ToPIQ: Tobacco Smoke Particles and Indoor Air Quality; WHO: World Health Organization; 3R4F: 3R4F reference cigarettes.

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Authors' contributions

This article is part of the thesis by LP. MB, LP, and DAG contributed significantly to the conception, design, and setup of the new measuring platform. All experimental investigations and analyses were carried out by LP. The manuscript was written by LP and critically reviewed by MB, DB, JD, and DAG. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Impact of different ventilation conditions on tobacco smoke-associated particulate matter emissions in a car cabin using the TAPaC platform

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Despite antagonizing attempts from the tobacco industry, passive inhalation of tobacco smoke is known to be cancerogenic and toxic to human health for decades. Nonetheless, millions of non-smoking adults and children are still victims of second-hand smoke. Accumulation of particulate matter (PM) in confined spaces such as the car are particularly harmful due to high concentrations. We here aimed to analyze the specific effects of ventilation conditions in the setting of a car. By the use of the measuring platform TAPaC (tobacco-associated particulate matter emissions inside a car cabin), 3R4F reference cigarettes, Marlboro red, and Marlboro gold were smoked in a car interior with a volume of 3.709 m^3. Seven different ventilation conditions (C1–C7) were analyzed. Under C1, all windows were closed. Under C2–C7, the car ventilation was turned on power level 2/4 with the air directed towards the windshield. Only the passenger side window was opened, where an outer placed fan could create an airstream speed of 15.9–17.4 km/h at one meter distance to simulate a driving car. C2: Window 10 cm opened. C3: Window 10 cm opened with the fan turned on. C4: Window half-opened. C5: Window half-opened with the fan turned on. C6: Window fully opened. C7: Window fully opened with the fan turned on. Cigarettes were remotely smoked by an automatic environmental tobacco smoke emitter and a cigarette smoking device. Depending on the ventilation condition the cigarettes emitted different mean PM concentrations after 10 min under condition C1 (PM$_{10}$: 1272–1697 µg/m^3, PM$_{2.5}$: 1253–1659 µg/m^3, PM$_1$: 964–1263 µg/m^3) under C2, C4, and C6 (PM$_{10}$: 68.7–196.2 µg/m^3, PM$_{2.5}$: 68.2–194.7 µg/m^3, PM$_1$: 66.1–183.8 µg/m^3) C3, C5, and C7 (PM$_{10}$: 73.7–139 µg/m^3, PM$_{2.5}$: 72–137.9 µg/m^3, PM$_1$:68.9–131.9 µg/m^3). Vehicle ventilation is insufficient to protect passengers from toxic second-hand smoke completely. Brand-specific variations of tobacco ingredients and mixtures markedly influence PM emissions under ventilation conditions. The most efficient ventilation mode to reduce PM exposure was achieved by opening the passenger´s window 10 cm and turning the onboard ventilation on power level 2/4. In-vehicle smoking should be banned to preserve innocent risk groups (e.g., children) from harm.

Abbreviations

AETSE	Automatic environmental tobacco smoke emitter
ANOVA	Analysis of variance
C_{mean}	Mean concentration
C1	Windows closed, car ventilation turned off, fan turned off
C2	Window 10 cm opened, car ventilation turned on, with the air directed towards the windshield
C3	Window 10 cm opened, car ventilation turned on, with the air directed towards the windshield, fan turned on
C4	Window half-opened, car ventilation turned on, with the air directed towards the windshield
C5	Window half-opened, car ventilation turned on, with the air directed towards the windshield, fan turned on

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C6	Window fully opened, car ventilation turned on, with the air directed towards the windshield
C7	Window fully opened, car ventilation turned on, with the air directed towards the windshield, fan turned on
FCTC	Framework Convention on Tobacco Control
LAS	Laser aerosol spectrometer
MR	Marlboro red
MG	Marlboro gold
p	Probability value
PM	Particulate matter
s	Seconds
SHS	Second-hand smoke
ToPIQ	Tobacco smoke particles and indoor air quality
WHO	World Health Organization
3R4F	3R4F reference cigarettes

Despite years of subversive manipulations by the tobacco industry, many governments began to recognize the health threat caused by passive tobacco exposure in the past decades and passed legislation (e.g., banning smoke from public places, increasing taxes, prohibiting tobacco advertisement, integrating graphic warnings on packages)[1,2]. Nonetheless, the prevalence of tobacco consumption was only reduced by an estimated 10.4% since the beginning of the twenty-first century. Therefore, approximately 20.4% of the world's population (aged $\geq$ 15) was still consuming tobacco products in 2020[3]. The global tobacco epidemic results in about eight million deaths per year, representing the most preventable cause of death worldwide[4]. Potentially deadly diseases, including cancer, cardiovascular, and pulmonary diseases[5,6] can be linked to the hazardous smoke generated by cigarette combustion. The smoke contains over 5000 chemicals, many are known to be toxic[7–9].

Also, non-smokers can be harmed by second-hand smoke (SHS), accounting for approximately 1.2 million deaths per year[4,10]. Children represent a group of particularly vulnerable individuals not able to defend themselves from second hand smoke (SHS) exposure. Many diseases during childhood can be linked to SHS (e.g., asthma, leukemia, bronchitis, otitis media, sudden infant death syndrome, etc.)[11,12]. Even prenatal tobacco smoke exposure can already harm the infant through the induction of different molecular and genetic mechanisms leading to poor birth outcomes and fetal maldevelopment[12]. In addition, infants take up high doses of particles per kg bodyweight from SHS. Fine and ultra-fine particles, in particular, are deposited in high concentrations in the alveolar and head regions of the infant and can lead to various avoidable diseases[13].

Measurements of particulate matter (PM) emissions from cigarette smoke can aid in determining their danger to human health. PM is differentiated according to its size into PM_{10} (particles $\leq$ 10 µm), $PM_{2.5}$ (particles $\leq$ 2.5 µm), and PM_1 (particles $\leq$ 1 µm)[14]. In 2021, the WHO published its updated air quality guidelines. They recommended a maximum 24-h PM_{10} of 45 µg/m^3, while $PM_{2.5}$ should not exceed 15 µg/m^3 [15].

The development of an automatic environmental tobacco smoke emitter (AETSE) has enabled recent investigators to measure the PM emissions of tobacco smoke without being exposed to the harmful SHS. So far, this new technique has mainly been used under indoor conditions[16]. Therefore, it is of tremendous interest to investigate PM accumulations under in-vehicle conditions. Utilizing the Mitsubishi Space Runner with its integrated AETSE and cigarette smoking device from the TAPaC study presents the ideal platform for this research, which would otherwise have been unethical due to the exposure to tobacco smoke[17].

When smoking in a confined space such as a car, smokers usually try to prevent too high concentrations of smoke due to ocular discomfort with irritation of the conjunctiva. However, precise knowledge on how to reduce smoke concentrations is not available and drivers either tend to open windows or activate ventilation or combine both measures.

We here aimed to investigate the effect of 7 different ventilation scenarios on the PM concentration in a driver´s cabin by comparing PM emissions of three tobacco products with varying ingredients and mixtures under simulated driving conditions.

Methods

Experimental setup.

The methodological setup has been described earlier in the TAPaC study by Pitten et al.[17]. In brief, a compact car (Mitsubishi Space Runner 1991–1999) was stationed in a garage and equipped with an automatic environmental tobacco smoke emitter (AETSE) and a laser aerosol spectrometer (LAS) Grimm Model 11 R. Just before the measurements started, the LAS was calibrated by Grimm Group in November 2021. The car itself has a total interior volume of 3.709 m^3 [18]. The AETSE consists of a plunger inside a 200 ml glass syringe. As the plunger moves back, a negative pressure is created, and the syringe is filled with smoke. The smoke is expelled through the forward movement of the plunger, thus imitating a smoking process[16]. The AETSE was positioned behind the driver's seat and connected via a polyamide tube with the cigarette smoking device which was located on the passenger´s seat. The expelled smoke from the AETSE was transferred via a polyamide tube and released by a valve located at the head region of the passenger seat. Consequently, the experimental design allowes to imitate a smoker sitting on the passenger seat.

Two remotely controllable fans (Model: Master BML 4800) were installed inside the car cabin to quickly remove the harmful tobacco smoke from the car and garage. Two outer-placed fans (Model: TTV 4500 HP) were installed on both sides of the front window (driver´s side and passenger´s side) at 113 cm height. They were positioned 20 cm in front of the window edges and did not overlap with the hood or front screen of the car. The fans can imitate an airflow capable of mimicking a vehicle during its motion. For this study, only the fan on the smoker´s side was used and turned on at the highest power level, creating an airstream of 25.1 to 25.8 km/h measured at a distance of 5 cm with a handheld anemometer (Voltcraft PL-130 AN). The airstream speed at a distance of one meter was 15.9 to 17.4 km/h.

Tobacco products. 3R4F reference cigarettes (3R4F)[19], Marlboro red (MR), and Marlboro gold (MG) were used (Table 1). Marlboro cigarettes are products of Phillip Morris International[20].

Smoking protocol. A single cigarette at a time was remotely ignited. After cigarette ignition, two initiation puffs were taken with a time interval of 1 s (s). Over the course of 4.5 min in total, additional 8 puffs were taken (1 puff every 30 s). Each puff lasted for 3 s and had a volume of 40 ml. After 10 puffs, the cigarette was automatically expelled and extinguished in a water bath.

Before igniting the next cigarette, the car cabin was ventilated for at least 5 min using the integrated fans. The researcher could open the tailgate of the car, step out of the garage, and remotely turn on the fans.

Measuring system. The LAS measured the PM concentration every 6 s through a mobile tube placed on the driver's seat. The mobile tube was positioned 70 cm next to the burning cigarette. The passenger´s window was 105 cm beside the mobile tube, while the driver´s window was located at a distance of 65 cm. The LAS can measure particles from 0.25 to 32 µm[17]. It automatically differentiates particles according to their size into categories PM_{10}, $PM_{2.5}$, and PM_1. Positioning a specialized sensor next to the mobile tube enabled the operator to acquire exact temperature and relative humidity (RH) data during the PM measurements [17].

Measuring conditions. Measurements were conducted under seven different ventilation conditions. For all investigated conditions (except condition no. 1) applied: The onboard ventilation was turned on power level 2/4. Fresh air entered the vehicle through a large duct at the front of the car and was directed towards the windshield by the onboard ventilation system. The recirculation mode was not in use. Only the passenger side window was opened. The outer-placed fan on the passenger side window has three power levels. Only the highest power level (3/3) was used (15.9–17.4 km/h at one meter distance) under C3, C5, and C7 to simulate the airflow of a driving car.

C1: Windows closed, car ventilation turned off, outside fan turned off.
C2: Window 10 cm opened.
C3: Window 10 cm opened with the outside fan turned on at highest power level (3/3).
C4: Window half-opened.
C5: Window half-opened with the outside fan turned on at highest power level (3/3).
C6: Window fully opened.
C7: Window fully opened with the outside fan turned on at highest power level (3/3).

Data processing and analysis. PM measurements were divided into three phases:

1: PM measurement started after the vehicle cabin has been ventilated for at least 5 min.
2: PM was measured between cigarette ignition and extinguishment (4.5 min).
3: PM was measured for 5.5 additional min after the cigarette had been extinguished.

The statistics software GraphPad Prism version 6 (GraphPad Software, La Jolla, California, USA) was used to evaluate and compare the generated data of all 7 test conditions. To check Gaussian distribution, the following tests were performed: Shapiro–Wilk, D`Agostino-Pearson, and Kolmogorov–Smirnov test (passed). One-way analysis of variance (ANOVA) with Tukey's multiple comparison test was used to analyze the level of significance ($p = 0.05$). The mean concentrations (C_{mean}) of PM after 4.5 min and 10 min were evaluated from data sets containing 101 measurements per cigarette. For each ventilation condition, 24 cigarettes were smoked, therefore, each condition was replicated 24 times. The same data sets were also used to analyze peak emissions of PM at exactly 4.5 min (46th measurement) and 10 min (101st measurement). The baseline PM exposure before cigarette ignition was calculated using the time interval between the end of the 3rd phase and beginning of the 1st phase.

Results

Before cigarette ignition, PM_{10}, $PM_{2.5}$, and PM_1 accounted for an average baseline PM exposure of 16.6 ± 3.4 µg/m^3, 15.1 ± 3.4 µg/m^3, and 14.1 ± 3.6 µg/m^3, respectively.

Tables 2 and 3 show the mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 values of all tested tobacco products after 4.5 and 10 min, respectively. C_{mean} of PM_{10} after 4.5 min was between 87.6 to 1218 µg/m^3, while PM_{10} after

	3R4F reference (mg)	Marlboro red (mg)	Marlboro gold (mg)
Tar	9.4	10	6
Nicotine	0.73	0.8	0.5
Carbon monoxide	12	10	7

Table 1. Content of cigarettes [18,20,21].

Condition	Tobacco products	C_{mean} PM_{10} [µg/m³]	C_{mean} $PM_{2.5}$ [µg/m³]	C_{mean} PM_1 [µg/m³]
C1	3R4F	A: 1218 ± 299.9	A: 1198 ± 296.5	A: 959.7 ± 283.6
		B: 2261 ± 396.8	B: 2217 ± 395.2	B: 1442 ± 201
C1	MR	A: 920.8 ± 173.3	A: 908.7 ± 169.5	A: 751.3 ± 105.8
		B: 1415 ± 252	B: 1396 ± 245.6	B: 1076 ± 138.7
C1	MG	A: 859.8 ± 259.3	A: 846.1 ± 252.9	A: 696.8 ± 165.4
		B: 1601 ± 546.3	B: 1576 ± 530.9	B: 1192 ± 271.8
C2	3R4F	A: 108.7 ± 16.5	A: 108.1 ± 16.4	A: 104.9 ± 15.6
		B: 144.1 ± 32.2	B: 143.7 ± 32.1	B: 137.4 ± 29.5
C2	MR	A: 107.8 ± 18.7	A: 106.1 ± 18.2	A: 101.9 ± 16.8
		B: 147.6 ± 29.6	B: 146.7 ± 29.1	B: 139.1 ± 26.2
C2	MG	A: 87.6 ± 13.6	A: 86.8 ± 13.5	A: 84.3 ± 12.7
		B: 106.5 ± 16	B: 106.3 ± 15.8	B: 103 ± 14.8
C3	3R4F	A: 164.2 ± 12.6	A: 162.7 ± 13	A: 156.3 ± 12.5
		B: 234.9 ± 20.9	B: 233.6 ± 20.5	B: 221.1 ± 18.1
C3	MR	A: 153 ± 9.6	A: 150 ± 9.1	A: 142.4 ± 8.4
		B: 235.4 ± 20.5	B: 231.1 ± 18.7	B: 214.9 ± 16
C3	MG	A: 119.1 ± 13.7	A: 117.9 ± 14	A: 114.1 ± 12.9
		B: 170.8 ± 21	B: 170 ± 20.8	B: 163.2 ± 18.9
C4	3R4F	A: 123.4 ± 16.3	A: 122.7 ± 16.2	A: 118.5 ± 15.6
		B: 165.2 ± 42.5	B: 164.5 ± 42.4	B: 157.7 ± 39.2
C4	MR	A: 121.2 ± 21.1	A: 120.5 ± 20.8	A: 115.7 ± 18.5
		B: 155.8 ± 37	B: 155.1 ± 36.5	B: 147.7 ± 32.4
C4	MG	A: 109.6 ± 16.4	A: 109.3 ± 16.3	A: 106.5 ± 15.5
		B: 152.5 ± 31.6	B: 152.1 ± 31.6	B: 146.9 ± 29.6
C5	3R4F	A: 152.7 ± 11.2	A: 150.9 ± 11.2	A: 145.1 ± 10.3
		B: 205.7 ± 20.8	B: 204.2 ± 20.7	B: 193.1 ± 18.3
C5	MR	A: 136.4 ± 12.3	A: 134.4 ± 12.3	A: 128.8 ± 11.4
		B: 192.4 ± 21.6	B: 190.6 ± 21.1	B: 180.1 ± 19.1
C5	MG	A: 118.1 ± 11.5	A: 116.3 ± 11.5	A: 112.5 ± 11.1
		B: 161.3 ± 19.2	B: 159.3 ± 19.2	B: 152.5 ± 17.9
C6	3R4F	A: 268.4 ± 24.5	A: 266.2 ± 23.7	A: 251.2 ± 19.7
		B: 340.4 ± 61.5	B: 338.6 ± 60.9	B: 314.6 ± 52.5
C6	MR	A: 219.8 ± 33.4	A: 218.9 ± 33.2	A: 209.1 ± 30.1
		B: 259.7 ± 42.7	B: 258.5 ± 42.6	B: 244.9 ± 38.3
C6	MG	A: 213.2 ± 21.9	A: 212.4 ± 21.6	A: 204.3 ± 19.4
		B: 258 ± 28.4	B: 256.3 ± 28.5	B: 244.8 ± 25.9
C7	3R4F	A: 129.9 ± 18	A: 127.4 ± 17.7	A: 122.3 ± 16.5
		B: 168 ± 27.1	B: 165.2 ± 26.5	B: 157 ± 24.1
C7	MR	A: 100.9 ± 10.6	A: 99.4 ± 10.2	A: 95.6 ± 9.6
		B: 149.2 ± 9.7	B: 147.6 ± 9	B: 140.6 ± 8.1
C7	MG	A: 95.8 ± 16	A: 93.8 ± 15.9	A: 90.1 ± 14.8
		B: 127.7 ± 24.8	B: 126.2 ± 24.6	B: 120.8 ± 22.6

Table 2. Mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 after 4.5 min, and peak emissions at 4.5 min. 3R4F, 3R4F reference cigarette; MR, Marlboro red; MG, Marlboro gold; A, Mean concentration after a specific time interval; B, Peak emissions at a specific time; PM, Particulate matter; C, Condition; C1, Windows closed, car ventilation off, outside fan off; C2, Window 10 cm opened, car ventilation on; C3, Window 10 cm opened, car ventilation on, outside fan turned on at highest power level; C4, Window half-opened, car ventilation on; C5, Window half-opened, car ventilation on, outside fan turned on at highest power level; C6, Window fully opened, car ventilation on; C7, Window fully opened, car ventilation on, outside fan turned on at highest power level.

10 min was between 68,7 and 1697 µg/m³. C_{mean} of $PM_{2.5}$ after 4.5 and 10 min ranged from 86.8 to 1198 µg/m³ and from 68.2 to 1659 µg/m³, respectively. C_{mean} of PM_1 after 4.5 min was between 84.3 and 959.7 µg/m³, while PM_1 after 10 min ranged from 66.1 to 1263 µg/m³. Additionally, Tables 2 and 3 contain data about the PM peaks at 4.5 and 10 min. Peaks are the average of single measurement values at a given time per condition. Peaks of PM_{10} at 4.5 min were between 106.5 and 2261 µg/m³, while PM_{10} peaks at 10 min were between 14.6 and 2185 µg/m³. Peaks of $PM_{2.5}$ at 4.5 and 10 min ranged from 106.3 to 2217 µg/m³ and from 14.5 to 2146 µg/

Condition	Tobacco products	C_{mean} PM_{10} [μg/m^3]	C_{mean} $PM_{2.5}$ [μg/m^3]	C_{mean} PM_1 [μg/m^3]
C1	3R4F	A: 1697 ± 386.7	A: 1659 ± 374.3	A: 1263 ± 260.1
		B: 2016 ± 121.7	B: 1971 ± 119.7	B: 1409 ± 85.4
C1	MR	A: 1512 ± 232.6	A: 1488 ± 225.8	A: 1075 ± 108.9
		B: 2185 ± 348.2	B: 2146 ± 336.7	B: 1421 ± 137.8
C1	MG	A: 1272 ± 217.7	A: 1253 ± 211.4	A: 964 ± 116.2
		B: 1641 ± 275.7	B: 1617 ± 268.2	B: 1190 ± 130.3
C2	3R4F	A: 79.7 ± 10.5	A: 79.3 ± 10.5	A: 76.8 ± 9.9
		B: 19.1 ± 3.5	B: 19 ± 3.5	B: 18.4 ± 3.5
C2	MR	A: 83.6 ± 13.6	A: 82.6 ± 13.2	A: 78.7 ± 12
		B: 20.4 ± 4.6	B: 20 ± 4.4	B: 19 ± 4.2
C2	MG	A: 68.7 ± 8	A: 68.2 ± 7.9	A: 66.1 ± 7.4
		B: 23.8 ± 1.7	B: 23.7 ± 1.6	B: 23.1 ± 1.5
C3	3R4F	A: 139 ± 6.6	A: 137.9 ± 6.5	A: 131.9 ± 6.1
		B: 42 ± 3.9	B: 41.4 ± 3.3	B: 40.1 ± 2.9
C3	MR	A: 134.1 ± 8.5	A: 131.6 ± 8.4	A: 123.9 ± 7.8
		B: 39.4 ± 3.8	B: 37.8 ± 3.5	B: 35.5 ± 3.1
C3	MG	A: 99.6 ± 8.9	A: 98.7 ± 9	A: 95.1 ± 8.5
		B: 28.4 ± 4.5	B: 27.9 ± 4.4	B: 26.9 ± 4.4
C4	3R4F	A: 88.5 ± 13	A: 87.9 ± 12.9	A: 84.6 ± 12.5
		B: 14.6 ± 3.2	B: 14.5 ± 3.1	B: 13.5 ± 3.2
C4	MR	A: 93.5 ± 18	A: 93 ± 17.8	A: 88.9 ± 16
		B: 19.6 ± 3.2	B: 19.5 ± 3.2	B: 18.7 ± 2.9
C4	MG	A: 83.9 ± 12.1	A: 83.6 ± 12.1	A: 81.1 ± 11.3
		B: 17.9 ± 2	B: 17.8 ± 2	B: 17.5 ± 1.9
C5	3R4F	A: 120.1 ± 8.1	A: 118.7 ± 8.1	A: 113.8 ± 7.5
		B: 38.8 ± 4.7	B: 38.24 ± 4.7	B: 37 ± 4.4
C5	MR	A: 109.9 ± 8.8	A: 108.2 ± 8.9	A: 103.1 ± 8.2
		B: 37.55 ± 4.1	B: 36 ± 3.5	B: 34.2 ± 3.5
C5	MG	A: 94.3 ± 5.8	A: 92.8 ± 5.7	A: 89.5 ± 5.2
		B: 35.6 ± 3	B: 34.7 ± 2.6	B: 33.5 ± 2.4
C6	3R4F	A: 196.2 ± 23.4	A: 194.7 ± 22.7	A: 183.8 ± 19.8
		B: 34.2 ± 4.3	B: 34.1 ± 4.4	B: 33 ± 4.6
C6	MR	A: 159 ± 23.3	A: 158.3 ± 23.2	A: 150.9 ± 21.3
		B: 25.3 ± 4.6	B: 25.16 ± 4.5	B: 24.4 ± 4.3
C6	MG	A: 155.2 ± 15.5	A: 154.4 ± 15.3	A: 148.1 ± 13.9
		B: 21.1 ± 3.8	B: 21 ± 3.7	B: 20.1 ± 3.5
C7	3R4F	A: 99.4 ± 13.5	A: 97.5 ± 13.3	A: 93.3 ± 12.5
		B: 27.4 ± 4.2	B: 26.8 ± 3.9	B: 25.3 ± 3.7
C7	MR	A: 83.6 ± 7.5	A: 82.1 ± 7	A: 78.5 ± 6.5
		B: 24.5 ± 4.5	B: 23.2 ± 3.4	B: 21.9 ± 3.2
C7	MG	A: 73.7 ± 11	A: 72 ± 11.2	A: 68.9 ± 10.5
		B: 20.2 ± 3.7	B: 19 ± 3.2	B: 17.9 ± 3.1

Table 3. Mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 after 10 min, and peak emissions at 10 min. 3R4F, 3R4F reference cigarette; MR, Marlboro red; MG, Marlboro gold; A, Mean concentration after a specific time interval; B, Peak emissions at a specific time; PM, Particulate matter; C, Condition; C1, Windows closed, car ventilation off, outside fan off; C2, Window 10 cm opened, car ventilation on; C3, Window 10 cm opened, car ventilation on, outside fan turned on at highest power level; C4, Window half-opened, car ventilation on; C5, Window half-opened, car ventilation on, outside fan turned on at highest power level; C6, Window fully opened, car ventilation on; C7, Window fully opened, car ventilation on, outside fan turned on at highest power level.

m^3, respectively. PM_1 peaks at 4.5 min were between 103 and 1442 μg/m^3, while peaks at 10 min ranged from 13.5 to 1421 μg/m^3. The percentage changes between measured PM concentrations are found as Supplementary Table S1 online. Only same tobacco products are compared (e.g., MR with MR) under different ventilation conditions (C1–C7). Tobacco products smoked under C1 showed drastically increased PM concentrations compared to C2 to C7 ($p < 0.0001$). For example, $PM_{2.5}$ concentrations of MR under C7 after 4.5 and 10 min were 99.4 and 82.1 μg/m^3, respectively. On the contrary, $PM_{2.5}$ of MR under C1 after 4.5 and 10 min was 908.7 to 1488 μg/m^3, respectively. After extinguishing the cigarette, PM mean values continued to rise under C1 (3R4F: 31.6–39.3%, MR: 43.1–64.2%, MG: 38.3–48.1%) because PM concentrations decrease slower under conditions without ventilation compared to conditions with ventilation. PM C_{mean} of C2 to C7 decreased after 10 min compared to 4.5 min (3R4F: − 15.2 to − 28.6%, MR: − 12.3 to − 27.8%, MG: − 16.3 to − 27.5%). PM mean values of ventilated conditions (C2–C7) after 4.5 and 10 min were more than 90% lower than under C1 (see Supplementary Table S1 online). The lowest PM concentrations were measured under C2 (Tables 2, 3). $PM_{2.5}$ C_{mean} of MG under C2 after 4.5 and 10 min was 106.1 and 82.6 μg/m^3, respectively, while $PM_{2.5}$ peaks at 4.5 and 10 min, respectively, accounted for 106.3 and 23.7 μg/m^3.

After 4.5 and 10 min, C2 to C7 showed no significant differences ($p > 0.05$) among each other in most cases. All exceptions can be found as Supplementary Table S2 online.

PM peaks at 4.5 and 10 min gained extremely high levels for all tested tobacco products under C1. PM peaks of C2 to C7 at 4.5 and 10 min were 77.2 to 99.3% lower than under C1. C1 showed significant differences ($p < 0.0001$) compared to C2 to C7 at 4.5 and 10 min. All PM peaks at 4.5 and 10 min with significant differences are listed as Supplementary Table S2 online.

Figures 1 and 2 illustrate the different PM emissions after 4.5 and 10 min, respectively, at conditions C1 to C7.

The distribution patterns of different particle size fractions for each condition (C1–C7) are displayed in Fig. 3. The lowest portion of PM_1 (71–76%) had C1, while no other condition had higher values of $PM_{2.5-1}$ (23–27%). PM_1 for C2 to C7 ranged from 92 to 96%, while $PM_{2.5-1}$ accounted for 3 to 6%. C1 to C7 showed low levels of $PM_{10-2.5}$, ranging from 0.4 to 2.4%.

During the experiments, the measured relative air humidity was between 33 and 52%, while the temperature was between 12.6 and 16.7 °C.

Discussion

Airborne PM poses high risks to human health[23]. Cigarettes produce toxic PM emissions, thereby harming not only the smoker but also surrounding individuals. Especially, smoking in an enclosed space, such as a car cabin, increase PM concentrations substantially. Frequently, children and adolescents become innocent victims of toxic SHS[24]. Narbi-Burza et al. conducted a study in the USA investigating parental smoke-free policies in cars. The study showed that 48% of smoking parents routinely expose their children to SHS in vehicles[25].

The experimental setup and design allowed us to conduct this study entirely remote from a safe distance of at least five meters avoiding exposition to toxic SHS. Thanks to the unique and ethically acceptable measuring platform, the researcher could conduct the investigations without exposing himself or others to SHS.

Previous studies have investigated the effect of ventilation conditions on PM concentration inside a car cabin using human smokers[25–31]. Although it guaranteed a simple and realistic research setup, it also exposed at least the smoker to SHS. Furthermore, the puff volume of human smokers varies and depends on the smokers' lung volume and smoking habits. That affects the exhaled PM emissions[33]. The AETSE of our experimental setup used equal puff volumes that eliminate the influence of human smoking behavior on PM exposure[16,34]. This study limitation can also be considered as advantage as standardized and comparable data is generated independently from the individual human smoker. Another technical limitation of the study was that particles of size < 0.25 μm could not be detected by the laser aerosol spectrometer (LAS) Grimm Model 11 R. Therefore, a small portion of fine particles (< 1 μm) and ultra-fine particles (< 0.1 μm) is not included in the data. Nevertheless, the majority of emitted PM_1 is included in the analysis as the mass median diameter of mainstream cigarette smoke is 0.38 μm[35]. Since particularly ultra-fine particles are the source of many adverse health effects it would be useful to expand the technical equipment of the TAPaC measuring platform[36].

In general, the study systematically focused on seven different ventilation conditions, opening no more than one window (passenger's side) at once. Stop and go during real driving generates an inconstant and variable airstream that might result in incomparable PM data. Therefore, one powerful ventilator was used to simulate a constant and reproducible airstream. The setup in a garage allowed us to eliminate all exterior wind drifts that could otherwise have affected our investigations. Moreover, the garage had the advantage of small fluctuations in temperature.

PM concentrations under test condition C1 (windows closed, car ventilation off, fan off) remained extremely high, even after the cigarette was extinguished. The unventilated condition of C1 did not allow PM to escape from the vehicle, resulting in sustained high PM values. $PM_{2.5}$ of Marlboro Gold under C1 after 10 min was 13.5% lower than Marlboro Red. Braun et al. showed 36% lower $PM_{2.5}$ values of Marlboro Gold compared to Marlboro Red in an enclosed space of 2.88 m^3 [37]. This difference is most probably caused by the larger interior volume of the car (3.709 m^3). The over 90-fold increase of PM_{10}, $PM_{2.5}$, and PM_1 under C1 compared to baseline measurements was expectable, as previous studies have already shown extremely high concentrations of PM in confined spaces[37–39]. Measured PM concentrations of C2 to C7 compared to C1 were significantly lower (see Supplementary Table S2 online). The results are in line with a study conducted by Müller et al. that measured PM emissions of cigarettes smoked in a telephone booth. They showed 90% less $PM_{2.5}$ under open-door ventilation in comparison to a closed telephone booth[40]. Our study came to comparable results after 10 min, showing ≥ 87.7% fewer $PM_{2.5}$ at conditions C2 to C7 compared to C1 (see Supplementary Table S1 online).

Although different cigarette types were used, only a minority displayed significant differences under conditions with an opened window (C2 to C7) (see Supplementary Table S2 online). Nonetheless, different PM values can be seen comparing the reference cigarette, Marlboro Red, and Marlboro Gold under each test condition. With lower nicotine and tar content, Marlboro Gold presented with generally lower PM emissions than Marlboro Red and the reference cigarette (Figs. 1, 2). That is in line with Braun et al. showing that the PM emissions of cigarettes vary depending on their content and filter size[37].

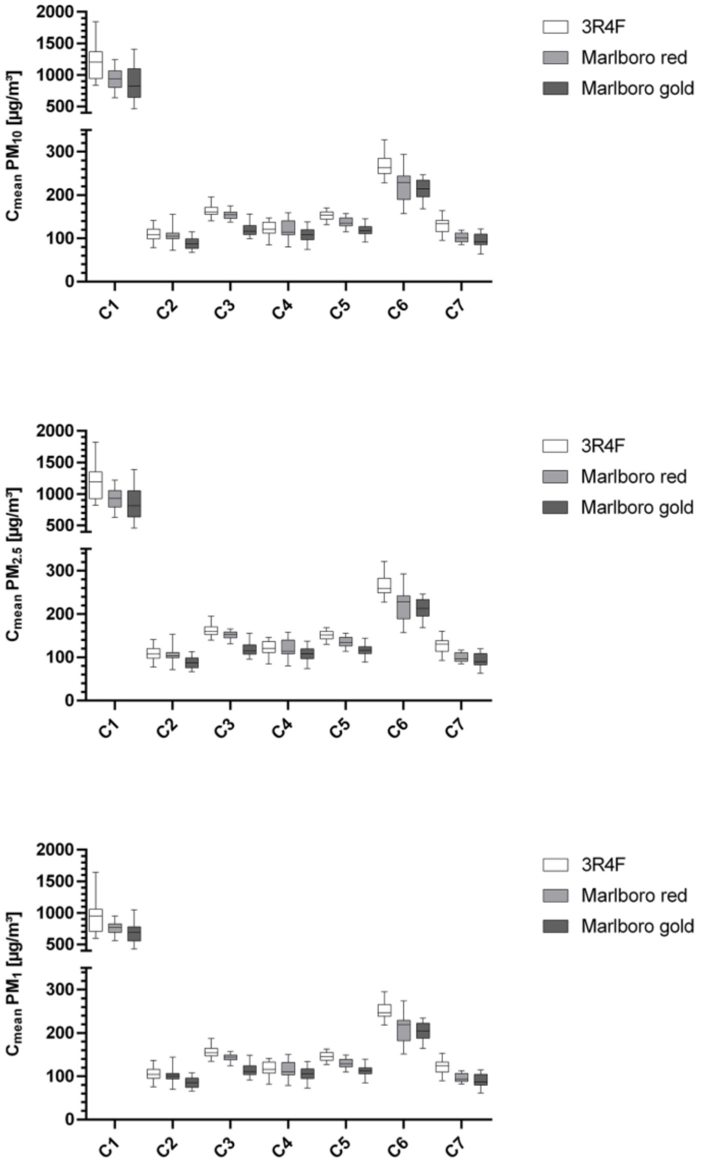


Figure 1. Boxplots (min to max whiskers) graphically display data of PM_{10}, $PM_{2.5}$, and PM_1 concentrations after 4.5 min. PM, Particulate matter, 3R4F, 3R4F reference cigarette; C, Condition; C1, Windows closed, car ventilation off, outside fan off; C2, Window 10 cm opened, car ventilation on; C3, Window 10 cm opened, car ventilation on, outside fan turned on at highest power level; C4, Window half-opened, car ventilation on; C5, Window half-opened, car ventilation on, outside fan turned on at highest power level; C6, Window fully opened, car ventilation on; C7, Window fully opened, car ventilation on, outside fan turned on at highest power level.

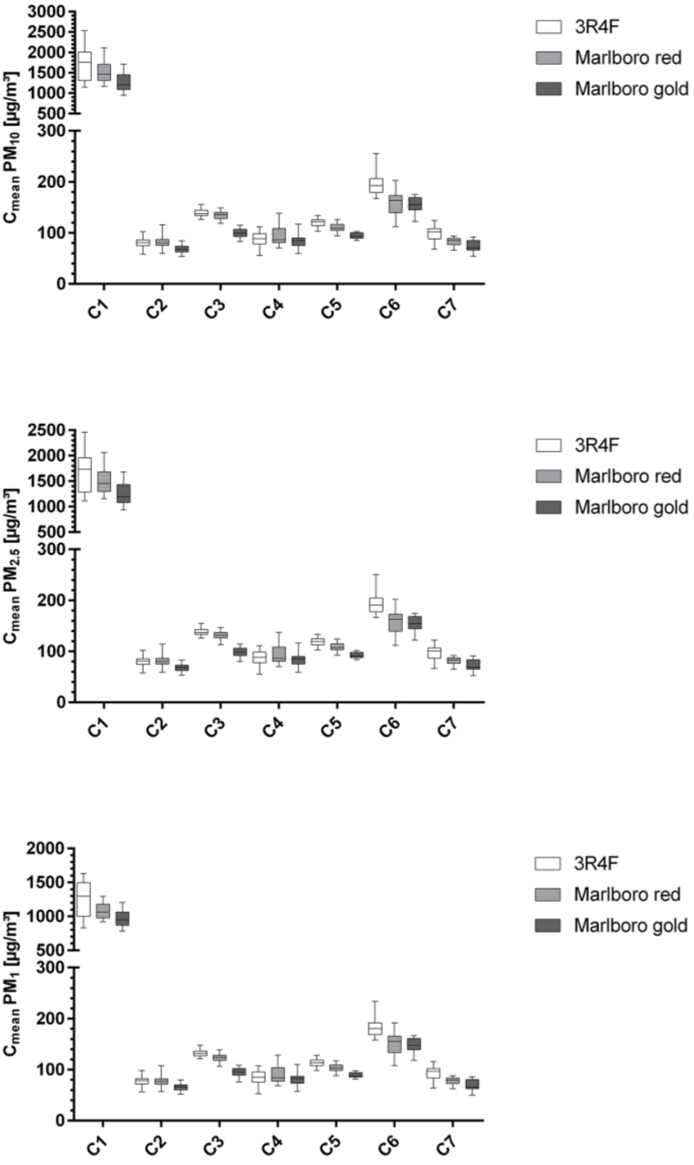
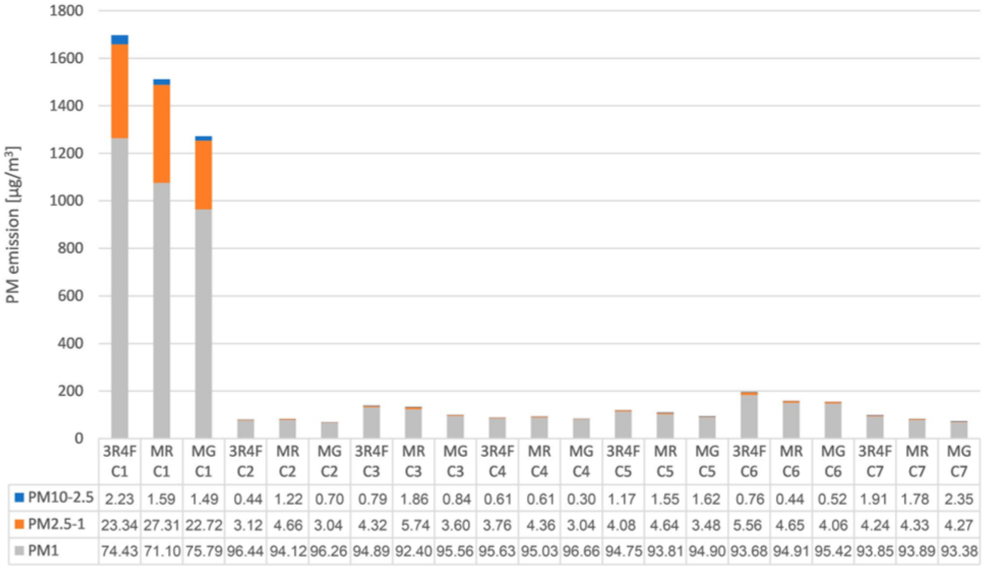


Figure 2. Boxplots (min to max whiskers) graphically display data of PM_{10}, $PM_{2.5}$, and PM_1 concentrations after 10 min. PM, Particulate matter, 3R4F, 3R4F reference cigarette, C, Condition; C1, Windows closed, car ventilation off, outside fan off; C2, Window 10 cm opened, car ventilation on; C3, Window 10 cm opened, car ventilation on, outside fan turned on at highest power level; C4, Window half-opened, car ventilation on; C5, Window half-opened, car ventilation on, outside fan turned on at highest power level; C6, Window fully opened, car ventilation on; C7, Window fully opened, car ventilation on, outside fan turned on at highest power level.



	3R4F C1	MR C1	MG C1	3R4F C2	MR C2	MG C2	3R4F C3	MR C3	MG C3	3R4F C4	MR C4	MG C4	3R4F C5	MR C5	MG C5	3R4F C6	MR C6	MG C6	3R4F C7	MR C7	MG C7
■ PM10-2.5	2.23	1.59	1.49	0.44	1.22	0.70	0.79	1.86	0.84	0.61	0.61	0.30	1.17	1.55	1.62	0.76	0.44	0.52	1.91	1.78	2.35
■ PM2.5-1	23.34	27.31	22.72	3.12	4.66	3.04	4.32	5.74	3.60	3.76	4.36	3.04	4.08	4.64	3.48	5.56	4.65	4.06	4.24	4.33	4.27
■ PM1	74.43	71.10	75.79	96.44	94.12	96.26	94.89	92.40	95.56	95.63	95.03	96.66	94.75	93.81	94.90	93.68	94.91	95.42	93.85	93.89	93.38

Figure 3. Distribution pattern of the mean concentrations (C_{mean}) after 10 min under different ventilation conditions. Percentage information of the PM fractions $PM_{10-2.5}$, $PM_{2.5-1}$, and PM_1 are rounded to two decimal places. PM, Particulate matter; 3R4F, 3R4F reference cigarette; MR, Marlboro red; MG, Marlboro gold; C, Condition; C1, Windows closed, car ventilation off, outside fan off; C2, Window 10 cm opened, car ventilation on; C3, Window 10 cm opened, car ventilation on, outside fan turned on at highest power level; C4, Window half-opened, car ventilation on; C5, Window half-opened, car ventilation on, outside fan turned on at highest power level; C6, Window fully opened, car ventilation on; C7, Window fully opened, car ventilation on, outside fan turned on at highest power level.

PM peaks at 4.5 and 10 min displayed similar percental changes as PM mean values (see Supplementary Table S1 online) because the cigarettes were extinguished after 4.5 min. Afterward, only PM of the remaining tobacco smoke was measured by the LAS. Thus, PM peaks were particularly high at 4.5 min and decreased markedly at 10 min measurements under C2 to C7.

PM_1 accounts for the majority (71–97%) of tobacco smoke, while $PM_{2.5-1}$ (3–27%) and $PM_{10-2.5}$ (0.3–2.4%) account for the remaining parts (Fig. 3). Combustion of tobacco products generates primarily fine particulate matter ($PM_{2.5}$)[41]. These extremely small particles are particularly dangerous for human health as they can be inhaled deeper into the lungs than coarse particles ($PM_{10-2.5}$), thereby causing more damage[14].

The variation of PM under conditions C2 to C7 is difficult to interpret and predict as many factors impact the interior PM concentrations. Ott et al. measured the air changes per hour in a car cabin. The study included multiple ventilation parameters (e.g., air conditioning, fan, speed, and degree of window opening) and showed that the air exchange per hour varies depending on the ventilation parameters[42]. Under real-life driving conditions, different speed levels affect the air inflow through the onboard ventilation system[43]. Future studies should install additional fans in front of the vehicle to investigate the impact of external airstream on PM elimination in a car cabin in more detail. In addition, a vehicle develops different interior and exterior pressure zones depending on the speed and other external factors. These pressure zones create variable air currents depending on how many windows are opened and to what degree[44].

In our previous establishment of the presently used platform, we already found an effect of in-vehicle ventilation on PM with closed windows and showed that directing the ventilation towards the windshield can reduce PM by 67.4 to 74.4% compared to no ventilation[17]. Here we extend these findings and show that opening the window by different degrees and usage of the ventilators resulted in an even further reduction of PM (see Supplementary Table S1 online). Another example that demonstrates the effectiveness of combining in-vehicle ventilation with window opening can be seen by comparing a study published in 2012 with our results. The study was conducted by Northcross et al. and measured the $PM_{2.5}$ emissions of three smoked cigarettes during 1 h inside a stationary vehicle. Although both front windows were opened during the investigations, the measured $PM_{2.5}$ concentration (746.1 µg/m³) was more than three times higher compared to C6 in our study[30]. The main difference between the two experimental setups was that in our investigation, under C2 to C7, the onboard ventilation system was turned on, thereby increasing the air exchange rate[42]. One more research paper with a similar study design was conducted by Sohn et al. who measured $PM_{2.5}$ of tobacco smoke inside a vehicle with three different window openings. $PM_{2.5}$ was measured in the back seat while the driver smoked a single cigarette in a driving vehicle. The average $PM_{2.5}$ concentrations during the smoking phase were substantially higher compared to C2 to C7 after 4.5 min in our study[28]. Nonetheless, both experiments exceeded the recommended WHO limits of PM by far[15].

Although all cigarette types (3R4F, MR, MG) smoked under C1 presented with outstandingly high PM concentrations, the 3R4F reference cigarettes generated the highest emissions. PM_{10} after 10 min of cigarettes smoked under C1 was 38 times higher than the recommended WHO threshold, while $PM_{2.5}$ exceeded the threshold by factor 111. The lowest concentration of PM was measured under C2. After 10 min, PM_{10} and $PM_{2.5}$ exceeded the WHO threshold by factors 1.5 and 4.5, respectively. After 4.5 min, PM_{10} and $PM_{2.5}$ were 1.9 and 5.8 times higher than the WHO threshold[15] (Tables 2, 3). In summary, it is a given fact that under all conditions investigated in this study, dangerously high levels of PM from smoking cigarettes were present. Therefore, we recommend that regulators should focus on the role of tobacco smoking in cars.

Conclusion

This study underlines the danger of smoking in cars. It disproves the belief that vehicle ventilation can protect non-smoking passengers from SHS and concomitant PM and provides information about PM emissions under different ventilation conditions. Nonetheless, a drastic decrease of PM concentrations could be detected after opening one window by different degrees. The lowest PM concentrations were measured with the passenger´s window 10 cm opened, onboard vehicle ventilation turned on power level 2/4 and the fan turned off. It is the result of multiple ventilation parameters (fan speed, onboard ventilation, external pressure zones, degree of window opening) influencing the car´s air exchange per hour. However, once the window was opened the different degrees of window opening did not majorly impact the PM concentrations inside the vehicle cabin. This data points to the urgent need for legislation on tobacco use in the presence of children and pregnant women in vehicles.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

This article is part of the thesis by L.P. L.P., D.B., J.D., M.B., and D.A.G. have made a substantial contribution to the conception and design of the study. All experimental investigations and analyses were carried out by L.P. The manuscript was written by L.P. and critically reviewed by D.B., J.D., M.B., and D.A.G. All authors read and approved the final manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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8. Darstellung des eigenen Anteils

Lukas Pitten

Entwicklung des Konzepts:
Methodendesign, Ausformulierung der zentralen Fragestellung und Ausdifferenzierung diverserer Problemfelder, Versuchsaufbau, Hintergrundrecherche

Datenerhebung:
Durchführung der experimentellen Messungen

Auswertung:
Datenbearbeitung, Visualisierung, Interpretation und Diskussion der Daten

Anfertigung und Einreichung der Publikation.

Janis Dröge

Unterstützung bei wissenschaftlichen Fragestellungen.

Überprüfung des Manuskripts.

Dörthe Brüggmann

Unterstützung bei wissenschaftlichen Fragestellungen.

Überprüfung des Manuskripts.

Markus Braun

Unterstützung bei technischen und wissenschaftlichen Fragestellungen.

Überprüfung des Manuskripts.

David A. Groneberg

Unterstützung bei wissenschaftlichen Fragestellungen.

Überprüfung des Manuskripts.

9. Literaturverzeichnis

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11. Schriftliche Erklärung

Ich erkläre ehrenwörtlich, dass ich die dem Fachbereich Medizin der Johann Wolfgang Goethe-Universität Frankfurt am Main zur Promotionsprüfung eingereichte Dissertation mit dem Titel:

„Tobacco smoke-associated particulate matter emissions in a car cabin using the TAPaC platform”

im Institut für Arbeits-, Sozial- und Umweltmedizin unter Betreuung und Anleitung von Prof. Dr. med. David Groneberg mit Unterstützung durch Markus Braun ohne sonstige Hilfe selbst durchgeführt und bei der Abfassung der Arbeit keine anderen als die in der Dissertation angeführten Hilfsmittel benutzt habe. Darüber hinaus versichere ich, nicht die Hilfe einer kommerziellen Promotionsvermittlung in Anspruch genommen zu haben.

Ich habe bisher an keiner in- oder ausländischen Universität ein Gesuch um Zulassung zur Promotion eingereicht. Die vorliegende Arbeit wurde bisher nicht als Dissertation eingereicht.

Vorliegende Ergebnisse der Arbeit wurden in folgenden Publikationsorganen veröffentlicht:

1. Lukas Pitten, Dörthe Brüggmann, Janis Dröge, Markus Braun, David A. Groneberg, Journal of Occupational Medicine and Toxicology (2022)
   https://doi.org/10.1186/s12995-022-00359-x

2. Lukas Pitten, Dörthe Brüggmann, Janis Dröge, Markus Braun, David A. Groneberg, Scientific Reports 13, 8216 (2023)
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