Environmental Research 235 (2023) 116681

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

# Exposure to secondhand and thirdhand smoke in private vehicles: Measurements in air and dust samples

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ARTICLE INFO

Handling Editor: Jose L Domingo

*Keywords:*
Tobacco smoke pollution
Thirdhand smoke
Airborne nicotine
Dust
Tobacco-specific nitrosamines
Automobile

ABSTRACT

*Background:* This study aimed to estimate airborne nicotine concentrations and nicotine, cotinine, and tobacco-specific nitrosamines (TSNAs) in settled dust from private cars in Spain and the UK.
*Methods:* We measured vapor-phase nicotine concentrations in a convenience sample of 45 private cars from Spain (N = 30) and the UK (N = 15) in 2017–2018. We recruited non-smoking drivers (n = 20), smoking drivers who do not smoke inside the car (n = 15), and smoking drivers who smoke inside (n = 10). Nicotine, cotinine, and three TSNAs (NNK, NNN, NNA) were also measured in settled dust in a random subsample (n = 20). We computed medians and interquartile ranges (IQR) of secondhand smoke (SHS) and thirdhand smoke (THS) compounds according to the drivers' profile.
*Results:* 24-h samples yielded median airborne nicotine concentrations below the limit of quantification (LOQ) (IQR: <LOQ - <LOQ) in non-smokers' cars, 0.23 $\mu g/m^3$ (IQR:0.18–0.45) in cars of smokers not smoking inside, and 3.53 $\mu g/m^3$, (IQR:1.74–6.38) in cars of smokers smoking inside ($p < 0.001$). Nicotine concentrations measured only while travelling increased to 21.44 $\mu g/m^3$ (IQR:6.60–86.15) in cars of smokers smoking inside. THS concentrations were higher in all cars of smokers, and specially in cars of drivers smoking inside (nicotine: 38.9 μg/g (IQR:19.3–105.7); NNK: 28.5 ng/g (IQR:26.6–70.2); NNN: 23.7 ng/g (IQR:14.3–55.3)), THS concentrations being up to six times those in non-smokers' cars.
*Conclusions:* All cars of smokers had measurable SHS and THS pollution, the exposure levels markedly higher in vehicles of drivers where smoking took place. Our results evidence the need for policies to prohibit smoking in

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https://doi.org/10.1016/j.envres.2023.116681
Received 16 June 2023; Received in revised form 13 July 2023; Accepted 14 July 2023
Available online 18 July 2023

vehicles, but also urge for more comprehensive strategies aiming towards the elimination of tobacco consumption.

## 1. Introduction

Secondhand smoke (SHS) is responsible for a high burden of preventable morbidity and mortality among non-smokers (Carreras et al., 2019). The health risks for those exposed to SHS in cars are much higher than in other indoor areas. Although exposure periods are generally short, SHS concentrations in cars rapidly increase when someone smokes (Sly et al., 2007), and exposures are more intense given the confined and enclosed space of automobiles (Jones et al., 2009). Moreover, earlier studies in cars have found considerable concentrations of fine particulate matter ($PM_{2.5}$) and airborne nicotine regardless of the ventilation conditions (Semple et al., 2012; Sendzik et al., 2009; Fortmann et al., 2010).

Passengers travelling in a smoker's car are not only exposed to SHS when smoking occurs in their presence, but also to thirdhand smoke (THS). THS is a serious health risk for non-smokers and, especially, for children (Sleiman et al., 2010). THS originates from the deposition of tobacco smoke SHS compounds on surfaces (Jacob et al., 2017). Nicotine deposited on particles can react with atmospheric trace gases releasing carcinogenic tobacco-specific nitrosamines (TSNAs) (Sleiman et al., 2010; Petrick et al., 2011). THS pollutants may persist for several weeks to months after smoking occurred (Matt et al., 2011, 2016) and can be resuspended or re-emitted to the air and inhaled (Fortmann et al., 2010).

In the last decades, some countries and sub-national regions have implemented legislation in private motor vehicles banning smoking where minors are passengers (e.g., Canada, the UK or Italy) (Semple et al., 2022). Likewise, positive attitudes towards this restriction have increased among the general population, including smokers and non-smokers (Martínez-Sánchez et al., 2014; Díez-Izquierdo et al., 2016). Even so, in most countries in Europe, as in Spain, smoking inside private motor vehicles is still not regulated. Studies assessing the magnitude of SHS and THS exposure in cars are very scarce and almost all of them have been conducted in the US. This study aimed to estimate airborne nicotine concentrations and nicotine, cotinine, and TSNAs in dust from private cars in Spain and the UK.

## 2. Materials and methods

This is a cross-sectional study framed within the TackSHS project (Fernández et al., 2020). Between April 2017 and August 2018, we recruited a convenience sample of drivers from Spain and the UK. A total of 45 drivers were enrolled: 20 non-smoking drivers (10 from Spain and 10 from the UK), 15 smoking drivers who do not smoke inside the car (10 from Spain and 5 from the UK), and 10 who smoke inside (all from Spain). Participants had to drive their cars for at least 30 min on their typical working day and give written informed consent to participate in the study.

We measured vapor-phase nicotine concentrations with passive samplers for 24 h (Hammond et al., 1987). Samplers were assembled from 37-mm diameter plastic cassettes that contained a filter treated with sodium bisulfate. In each car, we hung for 24 h two samplers on the rearview mirror or at the headrest of the front passenger seat. Participants were told to open one of the samplers only while driving and, otherwise, close the sampler. The remaining sampler was left open for the whole 24-h sampling period. Nicotine filters were collected by the investigators and shipped to the Public Health Agency of Barcelona laboratory to be analyzed by gas chromatography-mass spectrometry. This analytical procedure is accredited by ISO-17025 and had a limit of quantification (LOQ) of 5 ng per filter which is equal to 0.059 $\mu g/m^3$ for samples taken for 24 h, and from 0.110 to 4 $\mu g/m^3$ for samples taken only while travelling, depending on the time filters had been exposed. We computed time-weighted average nicotine concentrations (in $\mu g/m^3$) by dividing the nicotine extracted from the filter by the empirically established airflow rate through the filter of $2.4 \times 10^{-5}$ $m^3$/min (Hammond et al., 1987) and the time (in minutes) the sampler had been hang up.

Among the 30 participants from Spain, we measured THS exposure in a subsample of 20 cars (4 owned by non-smokers, 8 by smokers who do not smoke inside the car, and 8 by smokers who smoke inside the car). Dust samples were taken for 10 min, after removing nicotine samplers past the 24-h SHS sampling, from the front seats, rear seats, floor mats, carpet, gearshift area, and dashboard using a conventional vacuum cleaner. Dust was captured in the recipient of the vacuum cleaner and then transferred to a plastic zipper bag. All bags were properly coded and stored at ambient temperature and away from direct light. After each sampling, to avoid contamination between samples, the parts of the vacuum cleaner in contact with dust were cleaned following a systematic procedure using water and soap in a first step and ethanol in a second step. The collected samples were sent to the Pere Virgili Health Research Institute laboratory for the determination of nicotine (μg/g), cotinine (μg/g), and TSNAs (N′-nitrosonornicotine [NNN], 4-(Methylnitrosoamino)-1-(3-pyridyl)-1-butanone [NNK], and 4-(Methylnitrosoamino)-1-(3-pyridyl)-1-butanol [NNA]) concentrations (ng/g). THS toxicants were extracted by using a modified QuEChERS (Quick, Easy, Cheap, Effective, Rugged and Safe) extraction with Z-Sep as clean-up sorbent and determined by ultra-high performance liquid chromatography coupled to triple quadrupole mass spectrometry. LOQ ranged from 0.1 to 12 ng per g of dust.

After the travel sampling period, participants filled out a self-reported form with socio-demographic information, tobacco consumption patterns, and other characteristics of the car journeys.

We calculated medians and interquartile ranges (IQR) of the SHS and THS compounds. Differences in medians according to the participant's tobacco consumption were compared using the non-parametric Kruskal Wallis test. All analyses were conducted using STATA v15.

The TackSHS project was approved by the Clinical Research Ethics Committee of the Bellvitge University Hospital (PR341/15). This specific study was approved by local Ethics Committees in Spain (2016/6725/I) and the UK (CERB/2017/3/1421). The study protocol was registered on ClinicalTrials.gov (ID: NCT03150186).

## 3. Results

This study analyzed tobacco smoke pollution in 45 cars, 30 from Spain and 15 from the UK. Half the drivers were women, the median age was 41 years old, and 71.1% had completed university studies. Of the ten drivers who smoked inside the car, four allowed smoking with no restrictions, and six allowed smoking only under certain circumstances (i.e. when children are not in the car, with the windows open, only when driving alone, etc.) (Table 1).

Air nicotine samples taken for 24-h measurements yield median

**Table 1**
Characteristics of the sample, according to the driver's tobacco consumption. TackSHS project (2017–2018).

| | TOTAL (n = 45) | Cars of non-smokers (n = 20) | Cars of smokers who do not smoke inside (n = 15) | Cars of smokers who smoke inside (n = 10) | |
|---|---|---|---|---|---|
| | % (n) | % (n) | % (n) | % (n) | p-value[a] |
| **Country** | | | | | |
| Spain | 66.7 (30) | 50.0 (10) | 66.7 (10) | 10 (100.0) | 0.024 |
| UK | 33.3 (15) | 50.0 (10) | 33.3 (5) | 0 (0.0) | |
| **Sex** | | | | | |
| Male | 48.9 (22) | 50.0 (10) | 66.7 (10) | 20.0 (2) | 0.073 |
| Female | 51.1 (23) | 50.0 (10) | 33.3 (5) | 80.0 (8) | |
| **Educational attainment** | | | | | |
| Primary studies or lower | 6.7 (1) | 0.0 (0) | 6.7 (1) | 0.0 (0) | 0.540 |
| Secondary studies | 26.7 (12) | 20.0 (4) | 33.3 (5) | 30.0 (3) | |
| University studies | 71.1 (32) | 80.0 (16) | 60.0 (9) | 70.0 (7) | |
| **Age (years)** | | | | | |
| Median (IQR) | 41 (33–51) | 39.5 (33.5–51.5) | 39 (29–49) | 43 (36–53) | 0.463 |
| **Car volume**[b] | | | | | |
| Large | 31.8 (13) | 31.6 (6) | 38.5 (5) | 22.2 (2) | 0.344 |
| Medium | 34.2 (14) | 21.1 (4) | 38.5 (5) | 55.6 (5) | |
| Small | 34.2 (14) | 47.4 (9) | 23.1 (3) | 22.2 (2) | |
| **Total journeys time (minutes)** | | | | | |
| Median (IQR) | 86 (68–117) | 94.5 (72–118.5) | 86 (75–104) | 75 (50–155) | 0.880 |
| **Restrictions** | | | | | |
| Not allowed | 68.9 (31) | 100.0 (20) | 73.3 (11) | 0.0 (0) | <0.001 |
| Allowed with restrictions[c] | 20.0 (9) | 0.0 (0) | 26.7 (3) | 60.0 (6) | |
| Allowed with no restrictions | 11.1 (5) | 0.0 (0) | 6.7 (1) | 40.0 (4) | |

**IQR**: Interquartile Range.
[a] Chi-squared or Kuskal Wallis test, as appropriate.
[b] Missing values: 8.9%.
[c] Smoking only allowed under certain circumstances: when children are not in the car, with the windows open, or only when driving alone.

concentrations below the LOQ (IQR: <LOQ - <LOQ) in non-smokers' cars (n = 20), 0.23 μg/m$^3$ (IQR:0.18–0.45) in cars of smokers who do not smoke inside (n = 15), and 3.53 μg/m$^3$ (IQR:1.74–6.38) in cars of smokers who smoke inside (n = 10) (p < 0.001). Air nicotine samples measured only while driving yielded markedly higher median concentrations in cars of smokers who smoke inside (21.44 μg/m$^3$ (IQR:6.60–86.15)) than in cars of smokers who do not smoke inside (<LOQ (IQR: <LOQ-4.01)) and of non-smokers (<LOQ (IQR:< LOQ - <LOQ)) (p < 0.001) (Table 2). We found no significant differences by country (data not shown in Tables).

Table 2 also shows nicotine, cotinine, and TSNAs levels, as measures of THS, in the dust of 20 cars (all from Spain). We found higher concentrations of all THS compounds in cars of smokers, and particularly in cars where drivers reported smoking inside, THS concentrations being up to six times those in non-smokers' cars. Median nicotine concentrations in dust gradually increased by type of driver: 7.2 μg/g (IQR:6.7–10.6) in non-smokers' cars (n = 4), 20.5 μg/g (IQR:8.9–42.8) in cars of smokers who do not smoke inside (n = 8), and 38.9 μg/g (IQR:19.3–105.7) in cars of smokers who smoke inside (n = 8) (p = 0.014). Relative to non-smokers' cars, cars of smokers who smoke inside

**Table 2**
Airborne nicotine concentration (μg/m$^3$) and nicotine (μg/g), cotinine (μg/g), NNN, NNA and NNK concentrations (ng/g) in dust of cars, according to the driver's tobacco consumption. TackSHS project (2017–2018).

| | Cars of non-smokers | | Cars of smokers who do not smoke inside | | Cars of smokers who smoke inside | | |
|---|---|---|---|---|---|---|---|
| | Median (IQR) | Min-Max | Median (IQR) | Min-Max | Median (IQR) | Min-Max | p-value[a] |
| **SHS measures**[b] | (N = 20) | | (N = 15) | | (N = 10) | | |
| Nicotine (μg/m$^3$) (24-h sampling)[c] | <LOQ (<LOQ - <LOQ) | <LOQ-0.16 | 0.23 (0.18–0.45) | 0.19–1.35 | 3.53 (1.74–6.38) | 0.26–67.24 | <0.001 |
| Nicotine (μg/m$^3$) (only while travelling)[d] | <LOQ (<LOQ - <LOQ) | <LOQ-4.60 | <LOQ (<LOQ-4.01) | <LOQ-10.80 | 21.44 (6.60–86.15) | 2.29–322.57 | <0.001 |
| **THS measures**[e] | (N = 4) | | (N = 8) | | (N = 8) | | |
| Nicotine (μg/g) | 7.2 (6.7–10.6) | 6.6–13.5 | 20.5 (8.9–42.8) | 1.9–47.2 | 38.9 (19.3–105.7) | 13.7–217.8 | 0.014 |
| Cotinine (μg/g) | 1.4 (0.5–2.2) | 0.3–2.3 | 1.4 (1.0–1.8) | 0.7–3.7 | 2.9 (2.5–6.1) | 1.6–12.7 | 0.020 |
| NNN (ng/g) | 3.9 (1.6–6.7) | 0.8–8.0 | 7.3 (2.8–12.1) | <LOQ -15.1 | 23.7 (14.3–55.3) | 7.8–138.6 | 0.005 |
| NNA (ng/g) | 27.6 (22.7–33.0) | 19.5–36.7 | 33.3 (25.3–60.9) | 15.8–97.3 | 61.4 (52.8–76.5) | 32.7–177.8 | 0.030 |
| NNK (ng/g) | 15.2 (8.0–22.2) | 6.2–23.7 | 15.8 (12.1–20.5) | 8.2–25.1 | 28.5 (26.6–70.2) | 21.9–200.4 | 0.002 |

**NNN**: N′-nitrosonornicotine; **NNA**: 4-(Methylnitrosoamino)-1-(3-pyridyl)-1-butanol; **NNK**: 4-(Methylnitrosoamino)-1-(3-pyridyl)-1-butanone; **SHS**: secondhand smoke; **THS**: thirdhand smoke; **IQR**: interquartile range; **LOQ**: limit of quantification; **Min**: Minimum value; **Max**: Maximum value.
[a] Kruskal Wallis test.
[b] Measurements taken in cars in Spain (N = 30) and the UK (N = 15).
[c] Nicotine concentration obtained from the filters exposed during a 24-h period.
[d] Nicotine concentration obtained from the filters exposed only while travelling.
[e] Measurements taken in a subsample (N = 20) of cars in Spain.

had about two times higher NNK (28.5 ng/g; IQR:26.6–70.2 vs. 15.2 ng/g; IQR:8.0–22.2; $p = 0.002$) median concentrations, and six times higher NNN (23.7 ng/g; IQR:14.3–55.3 vs. 3.9 ng/g; IQR:1.6–6.7; $p = 0.005$) median concentrations.

## 4. Discussion

This study is the first to analyze a broad range of THS and SHS pollutants in cars from two European countries. It shows considerable differences in SHS and THS concentrations depending on the smoking profile of drivers, with much higher concentrations detected in cars of smokers who smoked inside the vehicle. Yet, measurable values of SHS and THS were also found in cars of smokers who do not allow smoking in the vehicle, indicating tobacco smoke contamination is pervasive.

Median airborne nicotine concentrations in cars of smokers who do not smoke inside were 0.23 μg/$m^3$, whereas in cars of drivers smoking inside, 3.5 μg/$m^3$. This 24-h average concentrations would be more than four times those found in homes with smokers (Henderson et al., 2023). Furthermore, nicotine concentrations were six times higher when assessing SHS exposure only while travelling, which is the actual exposure in car cabins for non-smoker passengers (21.4 μg/$m^3$). Airborne nicotine concentrations found during smoking car journeys far exceed those reported for typical indoor hospitality venues before the adoption of smoke-free policies in such venues (López et al., 2008). These results are in line with previous literature that shows SHS exposure is more intense in confined and enclosed space like automobiles (Jones et al., 2009). Of the comparable research measuring air nicotine in cars of smoking drivers, Jones et al., in 2009 also reported high median nicotine levels, being up to 12.5 μg/$m^3$ when four or more cigarettes were smoked inside the car (Jones et al., 2009).

THS in the microenvironment of a car becomes an added hazard for both smoking and non-smoking passengers, but especially for children (Ramirez et al., 2014). This study adds to the body of evidence demonstrating that cars of smokers are reservoirs of tobacco smoke pollutants (Park et al., 2018; Matt et al., 2013). Of special importance in terms of health risks due to their role in the pathogenesis of cancer (Sleiman et al., 2010; Ramirez et al., 2014) are the elevated concentrations of TSNAs we report in cars of smokers smoking inside. While THS markers were higher in cars of drivers who smoked inside, most of THS pollutants' concentrations did not differ much in cars of non-smokers and smokers who did not smoke inside. Still, our findings for non-smokers' cars should be interpreted with caution, as three of the cars had been purchased, between 9 months and 4 years before data collection, from drivers who smoked and THS can remain for prolonged periods on surfaces (Jacob et al., 2017).

Our results provide evidence that policies and legislative restrictions on in-vehicle smoking would be effective measures to reduce SHS and THS exposure in cars. Some countries, such as England and Scotland, have introduced smoking restrictions in cars with the main aim of protecting children (Semple et al., 2022) and have proven successful in curbing SHS exposures. (Laverty et al., 2020) THS pollutants, however, accumulate over time and constitute a perdurable source of exposure. Therefore, tobacco demand reduction measures should be strenghten to eliminate THS exposure in cars.

One of the main limitations of this study is convenience sampling, which does not guarantee representative samples. Still, this limitation does not hamper our objective of comparing SHS and THS exposure in cars with different profiles of drivers. Secondly, some travelling conditions that might affect SHS levels, such as windows being down or turning on the air conditioning, have not been analyzed. Although we recorded this information during fieldwork, the small sample size did not allow for considering these variables. Besides, previous studies have already demonstrated that car ventilation does not remove the exposure to SHS (Semple et al., 2012; Sendzik et al., 2009; Fortmann et al., 2010).

This is the first study in Europe monitoring SHS and THS exposure in private motor vehicles of smokers and non-smokers. Furthermore, SHS exposure and THS measures have been assessed using different objective environmental markers, which are specific and sensitive to tobacco smoke.

### 4.1. Conclusions

The extremely high SHS and THS concentrations reported in our study should prompt policymakers to consider urgent legislative measures banning smoking in vehicles with no restrictions. Importantly, these bans should come along with campaigns promoting smoke-free cars; and be implemented in the framework of more comprehensive tobacco control programs to protect effectively from tobacco smoke pollution exposure.

## Author contributions

**Xavier Continente**: Conceptualization, Investigation, Formal analysis, Writing – Original Draft, Visualization. **Elisabet Henderson**: Visualization, Validation, Writing – Original Draft. **Laura López-González**: Formal analysis, Visualization, Validation, Writing – Review & Editing. **Esteve Fernández**: Investigation, Writing – Review & Editing, Project Administration, Funding acquisition. **Olena Tigova**: Investigation, Writing – Review & Editing. **Sean Semple**: Investigation, Writing – Review & Editing. **Rachel O'Donnell**: Investigation, Writing – Review & Editing. **Ana Navas-Acien**: Visualization, Validation, Writing – Review & Editing. **Núria Cortés-Francisco**: Investigation, Writing – Review & Editing. **Noelia Ramírez**: Visualization, Validation, Writing – Review & Editing. **Ruaraidh Dobson**: Investigation, Writing – Review & Editing. **Maria José López**: Conceptualization, Writing – Review & Editing, Project Administration, Funding acquisition.

## Ethical considerations

The TackSHS project was approved by the Clinical Research Ethics Committee of the Bellvitge University Hospital (PR341/15). This specific study was approved by local Ethics Committees in Spain (2016/6725/I) and the UK (CERB/2017/3/1421). The study protocol was registered on ClinicalTrials.gov (ID: NCT03150186). All participants were informed about the aims, methods, and procedures undertaken in the study verbally and through an information sheet; and signed a written informed consent to take part in the study.

## Funding

This project has received funding from the European Union's Horizon 2020 research and innovation program [grant number 681040]; the Ministry of Universities and Research, Government of Catalonia [grant number 2021SGR00977 and 2021SGR00906]; and the Instituto de Salud Carlos III, co-financed by Fondo Europeo de Desarrollo Regional (FEDER) Unión Europea, "Una manera de hacer Europa" [the Miguel Servet contract CP19/00060].

## Disclaimer

This manuscript was developed by the TackSHS Project Consortium and does not necessarily reflect the views of the European Commission. The European Commission is not responsible for any use that may be made of the information that contains in this document.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Maria Jose Lopez and Esteve Fernandez reports financial support was provided by Horizon 2020 Research and Innovation Programme.

## Data availability

Data will be made available on request.

## Acknowledgements

We would like to thank to all participants their contribution to the study. We would also like to thank Francina Cortés for the design of pictograms of the graphical abstract. Esteve Fernández and Olena Tigova thanks the CERCA Programme for institutional support to IDIBELL.

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