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Research Article

Effects of the Emissions of Vehicles Ahead on In-Car Exposure to Traffic-Related Air Pollutants: A Multiple Statistical Analysis Approach

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Traffic-related air pollutants inside vehicle cabins are often extremely high compared to background pollution concentrations. The study of the determinants of these concentrations is particularly important for professional drivers and commuters who spend long periods in vehicles. This study is aimed at identifying and quantifying the effect of several exposure determinants on carbon monoxide (CO), equivalent black carbon (eBC), two particulate matter (PM) fractions ($PM_{0.3-1}$ and $PM_{1-2.5}$), and ultrafine particle (UFP) concentrations inside a passenger car cabin. The novelty of this work consists in examining the effects of the emissions of the first vehicle ahead (henceforth called "leading vehicle") on pollutant concentrations inside the cabin of the following vehicle (i.e., the car that was equipped with the air monitoring devices), with particular emphasis on the role of the leading vehicle characteristics (e.g., emission reduction technologies). The real-time instrumentation was placed inside the cabin of a petrol passenger car, which was driven by the same operator two times per day on the same route in real driving conditions. The in-cabin ventilation settings were set as follows: windows closed, air conditioning and recirculation modes off, and the fanned ventilation system on. The measurements were conducted over a total of 10 weekdays during two different seasons (i.e., summer and autumn). A video camera fixed to the windscreen was used to retrieve information about traffic conditions and leading vehicle characteristics through careful video analysis. The associations among pollutant concentrations and their potential determinants were evaluated using generalized estimating equation univariate and multiple models. The results confirmed the significant impact of several well-known determinants such as seasonality, microclimatic parameters, traffic jam situations, and route characteristics. Moreover, the outcomes shed light on the key role of leading vehicle emissions as determinant factors of the pollutant concentrations inside car cabins. Indeed, in the tested cabin ventilation conditions, it was demonstrated that in-cabin pollutant concentrations were significantly higher with leading vehicles ahead (from +14.6% to +67.5%) compared to empty road conditions, even though the introduction of newer technologies with better emissions reduction helped mitigate their effect. Additionally, diesel-fuelled leading vehicles compared to petrol-fuelled leading vehicles were impactful on in-cabin CO (−7.2%) and eBC (+45.3%) concentrations. An important effect (+30.4%) on in-vehicle $PM_{1-2.5}$

concentrations was found with heavy-duty compared to light-duty leading vehicles. Finally, this research pointed out that road-scale factors are more important determinant factors of in-cabin concentrations than local pollution and meteorological conditions.

Keywords: car environment; emission standard levels; exposure predictors; in-vehicle air quality; multiple analysis; vehicular traffic exhausts

1. Introduction

In terms of air pollution, special interest should be focused on human exposure to traffic-related air pollutants (TRAPs), which are a complex mixture of gases and particles that can be emitted from exhausts (i.e., tailpipe emissions) and non-exhaust sources (e.g., resuspension of dust, the wear of brakes and tyres, and evaporative emissions of fuel) that are known as nontailpipe emissions [1, 2]. Among the emitted substances, carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_x), particulate matter (PM), and mobile source air toxics such as formaldehyde and acetaldehyde are the most important. Each of these pollutants, along with secondary by-products such as ozone (O_3) and secondary aerosols, can cause adverse effects on health and the environment [2]. In this regard, a recent systematic review and meta-analysis found that long-term exposure to TRAPs was associated with adverse health outcomes related to all-cause, circulatory, ischemic heart disease, and lung cancer mortality in adults; asthma onset in children and adults; and acute lower respiratory infections in children [3]. More specifically, a 1 mg/m^3 increase in the mean CO concentration (at lag 1 day) was associated with a 0.91% (95% confidence interval [CI]: 0.32–1.50) raise in daily total mortality [4]. Moreover, a study focused on short-term effects of CO demonstrated that the pooled relative risk for myocardial infarction was 1.052 (95% CI: 1.017–1.089) per 1 mg/m^3 increase in ambient CO concentration [5]. Among NO_x, the air pollutant chemical species of most interest for human health is nitrogen dioxide (NO_2). A systematic review showed a positive association between long-term exposure to NO_2 and nonaccidental mortality reporting a meta-analytic effect estimate of relative risk equal to 1.02 (95% CI: 1.01–1.04) per 10 μg/m^3 NO_2, assuming a linear relationship [6]. NO_2, along with nonmethane volatile organic compounds (VOCs), are the precursors that contribute most to the formation of oxidation species, among which O_3. The review conducted by Huangfu and Atkinson reported that the association between exposure to O_3 in the warm season (using peak O_3 metrics) and nonaccidental mortality was 1.01 (95% CI: 1.00–1.02) per 10 μg/m^3 increase, assuming a linear relationship [6]. Also, PM particles emitted from traffic are of toxicological concern. Focusing on short-term exposure, a study found positive associations between both PM_{10} and $PM_{2.5}$ and all-cause nonaccidental mortality reporting a meta-analytic effects estimate of risk ratio (RR) = 1.0041 (95% CI: 1.0034–1.0049) and RR = 1.0065 (96% CI: 1.0044–1.0086) per 10 μg/m^3 increase in PM_{10} and $PM_{2.5}$ concentrations [7]. Regarding long-term exposure, a systematic review reported that the combined RRs for all nonaccidental mortality were 1.04 (95% CI: 1.03–1.06) and 1.08 (95% CI: 1.06–1.09) per 10 μg/m^3 increase in PM_{10} and $PM_{2.5}$, respectively [8]. Moreover, these two pollutants were also positively associated with cardiovascular, respiratory, and cerebrovascular mortality [7]. Black carbon is a component of PM. Between the various sources, it can be produced by incomplete combustion of fossil fuels. A review of the literature performed by WHO found that both short- and long-term exposures to black carbon were linked to cardiovascular health effects and premature mortality [9]. In the last decades, a growing number of studies have dealt with the health effects of exposure to ultrafine particles (UFPs). However, the evidence about health effects strictly correlated to UFPs was insufficient. Among those at least partially independent of other pollutants, several studies reported associations between short-term exposure to UFPs and pulmonary and systemic inflammation, changing autonomic tone, and increasing arterial blood pressure [10].

This research was focalized on the study of in-vehicle CO, equivalent black carbon (eBC), two fine PM fractions ($PM_{0.3-1}$ and $PM_{1-2.5}$, i.e., particles with aerodynamic diameter between 0.3–1 μm and 1–2.5 μm, respectively) and UFPs (i.e., particles with aerodynamic diameter less than 0.1 μm) concentrations. Indoor environments also include motor vehicle cabins [11–13] that can be considered a significant source of exposure to TRAPs [14–19]. Therefore, the study of human exposure inside them is extremely important, especially focusing on both professional drivers and commuters, spending their entire work shift (typically about 8 h/day) and 1–2 h/day (often during high traffic level conditions) inside vehicle cabins, respectively [20]. It is well known that CO emissions from vehicle exhausts were significantly reduced in the last decades [21]. Nevertheless, several studies measured that CO concentrations were greater than 5 ppm inside vehicle cabins in Chinese, Iranian, and Indian urban environments [22–24]. Moreover, high CO concentrations were more frequent when driving at congested road segments [25]. Further, the concentrations of black carbon, often used as a tracer for diesel vehicle emissions, have been associated with several possible health outcomes [26–30]. Moreover, in spite of the small percentage of time (6%–8% of the day) usually spent by the general population in traffic environments [31], this part of the day can substantially contribute to the total daily exposure to PM and black carbon [32–35]. Indeed, transport environments were characterized by higher black carbon concentrations (2–5 times) compared to those measured at home, and the highest concentrations were observed inside car and bus cabins [34]. In this regard, traveling by car often results in higher exposure to black carbon and UFPs compared to other modes of transport (i.e., bicycle and bus) and walking [36, 37]. Vehicle cabin environments are also typically characterized by high variability in fine PM and UFPs with concentrations up to two orders of magnitude greater than the urban background concentrations [38, 39]. The choice to focus on the above-mentioned PM fractions is explained by the fact that $PM_{2.5}$ is the most important fraction to represent health risks, corresponding to the "high-risk respirable convention" as defined in ISO 7708:1995 and has a pivotal role in indoor air quality studies because it includes the near totality of combustion-generated particles and secondary PM deriving from chemical reactions either outdoors or indoors. In this context, the splitting between $PM_{0.3-1}$ and $PM_{1-2.5}$ can help to discriminate between exhaust versus nonexhaust PM [40]. On the other hand, the measurement of UFP concentrations allows the identification of freshly emitted and "short living" particles, which is crucial for studies of indoor environments characterized by combustion sources, which explains also why ISO 16000-42 (measurement of the particle number concentration by condensation particle counters) was recently published in 2023 [41, 42].

The present study precisely aimed at identifying and quantifying the effect of several exposure determinants on TRAP concentrations inside a passenger car cabin. To reach this goal, two dedicated measurement campaigns were performed, attempting to control many other possible determinant factors such as cabin ventilation settings, roads traveled, and time of the day. The novelty of this work arose from the results of a recent literature review [25]. Specifically, it lies in examining the effects of the emissions of the first vehicle ahead (hereafter called "leading vehicle") on TRAP concentrations inside the cabin of the following vehicle (i.e., the car that was equipped with the monitoring instruments—henceforth called "study vehicle"). Special emphasis was given to the leading vehicle characteristics (e.g., emission standard level and fuel type).

2. Materials and Methods

2.1. Study Design. We conducted this study along the roads connecting the provinces of Como and Varese, two medium-sized cities (about 84,200 and 80,000 inhabitants, respectively) located in the northern part of Italy. The measurements were carried out on the same route (about 55 km long, average travel time: about 80 min) from Cuveglio (a town in Varese Province) (45°54′13.9″ N; 8°43′44.9″ E) to Como (45°48′36.9″ N; 9°05′10.1″ E). The route was planned a priori to incorporate several types of roads (i.e., rural roads, extraurban bypass roads, extraurban roads that connected two cities, and urban roads) (Figure S1). Based on this, the route was divided into four sections.

Experimental data were collected during two different periods called "summer" (from 17th to 21st of June 2019) and "autumn" (from 30th of September to 4th of October 2019) campaigns. The measurements were performed over five consecutive weekdays per monitoring campaign during two specific periods that included morning and late afternoon rush hours: approximately from 8:00 to 9:30 am, the "outward trip" from Cuveglio to Como, and approximately from 5:00 to 6:30 pm, the "return-trip" from Como to Cuveglio. There were no rain events during the monitoring days.

The study vehicle was a petrol-fueled 2017 Kia RIO passenger car. Its emission standard level corresponded to "Euro 6" [43]. The in-cabin ventilation settings were set as follows: windows closed, air conditioning off, recirculation fan off, and the fanned ventilation system on. This ventilation set-up, together with windows open, was associated with the highest exposures among car drivers [44]. The study vehicle was driven by the same operator without other passengers to avoid any driver behavior effects [45]. Moreover, during regular driving conditions, the driver maintained a distance of at least 10 m from the leading vehicle (respecting the Highway Code safe distance requirements). In reality, this distance was shorter when the vehicles were traveling in a queue (e.g., during traffic light stops or traffic jam situations).

2.2. In-Vehicle Air Quality Monitoring. The TRAP concentrations were measured using the following direct-reading instruments:

- CO (parts per million): electrochemical sensor (model T15v, Langan Products Inc., San Francisco, CA, United States);
- eBC (micrograms per cubic meter): microaethalometer (model AE51, AethLabs, San Francisco, CA, United States);
- $PM_{0.3-1}$ and $PM_{1-2.5}$ (particle per cubic centimeter): optical particle counter (OPC) (model Handheld 3016 IAQ, Lighthouse Worldwide Solutions, Fremont, CA, United States);
- UFPs (particle per cubic centimeter): miniature diffusion size classifier (DiSCmini, Matter Aerosol AG, Wohlen AG, Swiss).

These portable devices have been used in previous studies for data collection in traffic environments [18, 19, 46–50]. The quality assurance and quality control (QA/QC) procedures are described here. Regarding the CO passive electrochemical sensor, zeroing and calibrating operations were carried out before and after the measurement campaigns in glove bags at 20°C, using a climatic cabinet and two certified standard gas mixtures containing < 0.5 and 10.3 ppm of CO in air. All particle instruments were calibrated by factory-supplied services within 1 year before the end of the survey. To measure the background concentrations, the instruments were placed and left in the cabin of the study vehicle at least 10 min before and after the sampling trips. Moreover, the zeroing control was carried out using a HEPA zero filter (rated at 99.96% removal efficiency for 0.45 μm particles) that was placed on the inlet of both fine PM and UFP instruments and by checking that the particle number concentration dropped to < 100 particles/cm^3. More details about the measurement devices are reported in the Supporting Information (Text S1).

As indicated in previous research [19], the data were collected using a high-resolution measurement time (i.e., 10-s averaged) to capture very fast changes in traffic conditions. The instruments were placed inside the pockets of a "car seat organizer" that was positioned in front of the passenger seat's backrest (Figure 1). Tygon tubes were used to locate the sampling inlets of the fine PM and UFP sampling devices at the height of a seated passenger's head. Regarding the eBC instrument, a polyurethane sampling tube, approximately 15 cm long, designed to dissipate electrostatic discharge from air passing through the tube was used. Since the sampling probes were located in proximity to the subject (within 3 m), the "individual exposure'" was evaluated [51]. The differences with the "personal exposure" (in the proximity of the breathing zone, the 30 cm hemispheric radius extending in front of the face) [52] are reported in a dedicated publication and are summarized in the Supporting Information (Text S2) [51].

Additionally, in-vehicle air temperature (in-vehicle T, degree Celsius) and relative humidity (in-vehicle RH, percentage) were measured by using a data logger with integrated sensor (Hobo U12, Onset Computer Corporation, Bourne, MA, United States; Accuracy $T = \pm 0.35°C$; $RH = \pm 2.5\%$).

2.3. Traffic Variables and Leading Vehicle Characteristics. A video camera (model Dash Cam 45, Garmin Ltd., Olathe, KS, United States) was fixed to the windscreen to record the view in front of the study vehicle. The video camera embedded a global navigation satellite system receiver, and it also showed the exact location (GPS coordinates; Garmin GPS receivers are typically accurate to within 10 m) and the instantaneous driving speed of the study vehicle. Both the monitoring devices and the video camera clocks were synchronized before each test. The video recordings were carefully watched by an operator to extract information about real-time traffic variables. In this regard, variables related to road characteristics and traffic conditions were retrieved, specifically:

- changing points between the different road types (i.e., rural roads, extraurban bypass roads, extraurban roads that connected two cities, and urban roads);
- traffic jam situations (i.e., when the speed of the study vehicle was lower than 40 km/h and there was more than one leading vehicle in front of it; these criteria were arbitrarily chosen);
- stops at traffic lights.

Moreover, the characteristics of the leading vehicles were also retrieved, in particular:

- presence (i.e., a leading vehicle was detected in front of the study vehicle) or absence (i.e., empty road conditions: no leading vehicle in front of the study vehicle);
- type (i.e., light- or heavy-duty) [53, 54];
- fuel type (i.e., petrol, diesel, hybrid, petrol, and compressed natural gas-CNG dual fuel, petrol);
- European emission standard level [43].

The detailed procedures to obtain and process data concerning the characteristics of the leading vehicles were

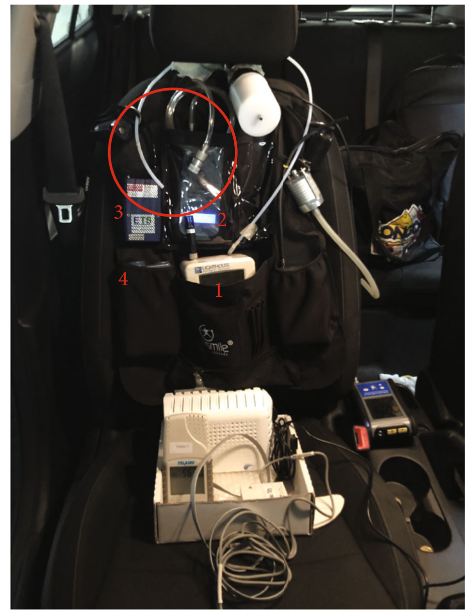

Figure 1: Location of the instruments. The devices considered in the present research are indicated with numbers: (1) optical particle counter (PM fractions), (2) diffusion size classifier miniature (UFPs), (3) aethalometer (eBC), and (4) passive electrochemical sensor (CO). The circle indicates the position of eBC, fine PM, and UFP sampling inlets. Before conducting the measurements, several tests were performed to verify that the tubes would not significantly affect the results. The tests showed that the relative instrument errors with the tubes versus without the tubes were < 10% (on average) for all particle size fractions of interest (< 2.5 μm).

already presented in a previous publication and are reported in the Supporting Information (Text S3) [19]. It is important to note that, in a few cases, the information concerning both fuel types and European emission standard levels was not available from the public Italian vehicle registration database. This occurred especially for passenger cars and trucks belonging to private companies or coming from other countries.

2.4. Environmental Variables. Since the exposure to TRAPs inside vehicle cabins varied according to ambient factors (i.e., ambient air pollution and meteorological variables) [25, 55], even those variables were considered in the statistical analysis. Specifically, CO hourly mean (parts per million), NO_2 hourly mean (parts per billion), PM_{10} daily mean (micrograms per cubic meter), $PM_{2.5}$ daily mean (micrograms per cubic meter), ambient T (degree Celsius), ambient RH (percentage), wind direction (degree), and wind velocity (meters per second) (since the measurements were performed during dry weather conditions, the rainfall data were not examined) were inserted in the models as ambient pollutant concentrations and meteorological variables, respectively. All these data were retrieved from fixed air quality and meteorological monitoring stations managed by the regional environmental protection agency (ARPA Lombardia), which were chosen based on two criteria: (1) proximity to the monitoring route and (2) data availability.

Especially, when feasible, it was tried to build the database combining data from the two types of fixed stations (i.e., air quality and meteorological) to every single section of the route (see Section 2.1). The selected fixed monitoring stations are indicated on the map that is reported in the Supporting Information (Figure S1).

2.5. Data Cleaning. In total, $N = 10,435$ data observations were collected. Since the missing values were less than 5% of the total values and were missing completely at random (problems occurred with the analyzers), the listwise deletion (i.e., elimination of an entire case if it has missing data on any of the measured pollutant variables) was applied [56, 57]. Accordingly, $N = 10,030$ observations were then included in the statistical analysis.

2.6. Statistical Analysis. Data were evaluated by standard descriptive statistics. Frequencies and percentages were calculated for categorical variables. Continuous data were expressed as mean ± SD, median and interquartile range (25th–75th percentile), and minimum and maximum value. The generalized estimating equation (GEE) models were applied to evaluate average changes in in-vehicle TRAP concentrations over time (dependent variables) associated with the leading vehicles, their characteristics, and boundary conditions (e.g., road types and traffic situations) (independent variables) accounting for trip variables (covariates) such as ambient pollutant concentrations and meteorological variables. The GEE method focuses on average changes in response over time and the impact of covariates on these changes and is appropriate for repeated measures. The method models the mean response as a linear function of covariates of interest via a transformation or link function. An identity link function was used as the response variables are continuous. In addition, to account for variation in the correlation between repeated measures, GEE allows the specification of the correlation structure. We chose an exchangeable correlation structure based on the quasi-information criterion (QIC), as the same correlation is assumed for all measurements on the same trip variable, irrespective of their timing. The first step was the identification of specific determinant factors (independent variables) per in-vehicle TRAP (dependent continuous variable) through a separate GEE univariate. Since the TRAP data distribution was not normal, they were log-transformed to correct skewness. The potential determinant factors were chosen based on the results yielded from a recent review of the literature [25]. Due to the small sample size of both the outdated emission standard levels (from Euro 0 to Euro 3) and the dual-fuelled leading vehicles (petrol&CNG and hybrid) (see Table 1 in the next section), these categories were merged and analyzed as a single category in the respective categorical variable. The continuous and categorical covariates included in the univariate models are presented in Table 2.

Variables that were associated with statistically significant changes of in-vehicle TRAP concentrations in the univariate analysis were included in the multiple models. The final set of covariates for each TRAP was selected after the preliminary inspection of fit in the model and kept in the final models only when significant. The results were presented as the percentage change (delta% [Δ%]) in in-vehicle TRAP concentrations related to each predictor (i.e., a statistically significant determinant factor found in the multiple analysis), the relative 95% CI, and the p value. The Δ% was calculated using the following formula: $\Delta\% = [\exp(\beta) - 1] * 100$. A positive coefficient reveals that as the value of the independent variable increases (when it is continuous) or moves from the reference category to another one (if it is categorical), the mean of the dependent variable (i.e., the pollutant concentrations) also tends to increase. A negative coefficient suggests that as the independent variable increases, the dependent variable tends to decrease.

All analyses were performed with the statistical software SAS software (Version 9.4; SAS Institute Inc., Cary, North Carolina, Unitec States, https://www.sas.com). Statistical significance was considered when $p < 0.05$.

3. Results and Discussion

3.1. In-Cabin TRAP Concentrations. The in-cabin TRAP concentrations measured during the monitoring campaigns are summarized in Table 3. The summaries of the single campaigns (summer and winter) data are reported in the Supporting Information (Tables S1 and S2, respectively).

First of all, it is important to underline that the in-cabin pollutant concentrations are generally difficult to compare among the various studies, mainly because of the different experimental designs in terms of (i) monitoring period (e.g., seasonality and time of day), (ii) traffic conditions, and (iii) vehicle characteristics (in particular the ventilation settings) [25]. Nevertheless, several comparisons among the central tendency of the data collected in this study and other similar research are here reported. Regarding CO, the mean in-vehicle concentration measured in this study (1.5 ppm) was slightly higher than the mean concentrations observed in previous studies performed in several different traffic environments. Specifically, Kaur and Nieuwenhuijsen found 1.1 ppm inside passenger cars and 1.05 ppm inside taxicabs in the urban area of London [58]. Still, inside taxis, Hachem et al. reported a mean concentration of 0.42 ppm in the urban and suburban areas of Paris [55]. A lower mean concentration (1.3 ppm) was observed also inside a car on a main trunk road in Newcastle [24]. At last, Flachsbart and Ott reported a mean of 0.5 ppm inside a motor vehicle on a major arterial highway in the San Francisco Peninsula [59]. However, several other studies showed higher in-vehicle CO concentrations with respect to the present work. Firstly, a study performed by Spinazzè et al. on a very busy road in the urban area of Milan indicated a median in-car concentration of 2.45 ppm [60]. In addition, another research observed a mean concentration of 5.6 ppm inside a car in commercial and residential areas of Mumbai (India) [24]. At last, de Nazelle et al. found an in-vehicle CO mean of 7.3 ppm on a typical commuting route in the urban area of Barcelona [37]. Regarding eBC, the same study found a mean in-cabin concentration (16.7 $\mu g/m^3$) higher than our

Table 1: Frequency of the observations per category of the categorical variables.

Variable	Category	*n* (%)
Campaign	Summer	4565 (45.5)
	Autumn	5465 (54.5)
Day	1	1959 (19.5)
	2	1889 (18.9)
	3	2049 (20.4)
	4	2060 (20.5)
	5	2073 (20.7)
Roundtrip	Outward	4579 (45.6)
	Return trip	5451 (54.4)
Road types	EU city connection	3919 (39.1)
	EU bypass	2908 (29.0)
	Rural	1483 (14.8)
	Urban	1720 (17.1)
Traffic jam	No	7079 (70.6)
	Yes	2951 (29.4)
Stop at traffic light	No	9170 (91.4)
	Yes	860 (8.6)
Leading vehicle	No (absence)	1671 (16.7)
	Yes (presence)	8359 (83.3)
Leading vehicle types	Absence	1671 (16.7)
	Heavy-duty	468 (4.7)
	Light-duty	7634 (76.1)
	No data	257 (2.5)
Leading vehicle emission standard level	Absence	1671 (16.7)
	Euro 0	19 (0.2)
	Euro 1	9 (0.1)
	Euro 2	152 (1.5)
	Euro 3	734 (7.3)
	Euro 4	2149 (21.4)
	Euro 5	2376 (23.7)
	Euro 6	2468 (24.6)
	No data	452 (4.5)
Leading vehicle fuel type	Absence	1671 (16.7)
	Diesel	3700 (36.9)
	Hybrid	163 (1.6)
	No data	490 (4.9)
	Petrol	3856 (38.4)
	Petrol&CNG	150 (1.5)

Note: The category "no data" means that no information about the emission standard levels and fuel types was retrievable from the public Italian vehicle registration database.

work (7.3 $\mu g/m^3$) [37]. Conversely, lower concentrations were measured in both electric and diesel-fuelled taxis in central London (3.6 and 6.8 $\mu g/m^3$, respectively) [61]. Moreover, the median concentration (4.9 $\mu g/m^3$) observed in our study was lower than the median concentration measured in several types of passenger cars (5.9 $\mu g/m^3$) on central and peripheral roads of Milan [18]. Concerning fine PM inside car cabins, the mean $PM_{0.3-1}$ concentration observed in this study (39 particles/cm^3) was lower than that (63 particles/cm^3) collected in a similar study carried out in northern Italy in 2019 [19]. On the contrary, the mean $PM_{1-2.5}$ concentrations showed an opposite behavior (0.27 vs. 0.21 particles/cm^3) [19]. Although those two studies were characterized by similar investigation approaches, a few dissimilarities in terms of in-cabin TRAP concentrations may be attributable to the different monitoring trips. Moreover, in the present work, the mean values were calculated whether with leading vehicles ahead or not, whereas in the other publication, the means were computed with leading vehicles ahead only [19]. Regarding UFPs, the mean in-vehicle concentration measured in this study (23,713 particles/cm^3) was lower than those monitored inside passenger cars along (1) a main road in Basel, (2) on a typical commuting route in Barcelona (31,784 and 117,600 particles/cm^3, respectively), and (3) in-taxis in the urban and suburban areas of Paris (29,700 particles/cm^3) [48, 55]. On the other hand, our result was higher than the mean in-car concentrations measured in two different studies performed in the urban and peripheral areas of Como (9158 and 16,142 particles/cm^3, respectively) [19, 49]. Finally, the UFP median in-cabin concentration (13,404 particles/cm^3) was about four times lower than the median in-car concentration (54,000 particles/cm^3) measured in the urban area of Milan [60, 62]. As previously specified, the differences may be mainly related to several in-cabin exposure determinants, in particular ventilation settings, traffic conditions, self-pollution, and seasonality [25]. The descriptive statistics of the other continuous variables are reported in the Supporting Information (Tables S3, S4, and S5).

3.2. Measurement Trip Characteristics. Characteristics of the categorical covariates in terms of the frequency of the observations are described in Table 1.

From Table 1, the frequency of the observations was similar between the categories of the variables "campaign," "day," and "roundtrip." Regarding the variable "road types," the extraurban roads showed higher percentages, probably because they are longer than both urban and rural roads. As expected, traffic congestion and vehicle stop situations were characterized by lower observations than normal traffic conditions (less than 30% and 10%, respectively). The number of observations, in which a leading vehicle was ahead, was higher (more than 80%) than with the study vehicle in empty road conditions. Moreover, about 76% of the leading vehicles were light-duty. At last, most of them were petrol- and diesel-fuelled (38.4% and 36.9%, respectively) and were characterized by Euro 4, 5, and 6 emission standard levels (21.4%, 23.7%, and 24.6%, respectively). As previously specified, the categories Euro 0, 1, 2, and 3; hybrid; and petrol&CNG were considered as single categories in the pertaining categorical variable. Other information about the number of leading vehicles encountered per categorical variable and the features of each roundtrip in terms of number of observations, trip duration, and number of leading

Table 2: Continuous and categorical covariates included in the univariate models.

Continuous covariates	
In-vehicle air temperature (in-vehicle T)	Degree Celsius
In-vehicle relative humidity (in-vehicle RH)	Percentage
Vehicle speed	Kilometers per hour
Ambient $PM_{2.5}$[a]	Micrograms per cubic meter
Ambient PM_{10}[a]	Micrograms per cubic meter
CO[a]	Parts per million
NO_2[a]	Parts per billion
Ambient T[b]	Degree Celsius
Ambient RH[b]	Percentage
Wind direction[b]	Degree
Wind velocity[b]	Meters per second
Categorical covariates	
Campaign	Summer-reference vs. autumn
Day	Day 1-reference vs. Day 2, Day 3, Day 4, Day 5
Roundtrip	Outward-reference vs. return-trip
Leading vehicle	No (absence)-reference vs. yes (presence)
Types of leading vehicles	Light-duty-reference vs. absence and heavy-duty
Emission standard levels of the leading vehicles	Euro 0, 1, 2, and 3-reference vs. Euro 4, Euro 5, Euro 6
Fuel types of the leading vehicles	Petrol-reference vs. absence, diesel, petrol&CNG+hybrid
Traffic jam	No-reference vs. yes
Traffic light stops	No-reference vs. yes
Road types	Rural-reference vs. extraurban (EU) city connection, EU bypass, urban

[a]Data from fixed air quality monitoring stations.
[b]Data from fixed meteorological monitoring stations.

vehicles is reported in the Supporting Information (Tables S6 and S7). It is important to notice that due to operational problems with the monitoring equipment, the outward trip of the second day of the summer campaign consisted of a much smaller number of observations than the other monitoring days.

3.3. Determinant Factors Affecting In-Vehicle Exposure to TRAPs Identified Through GEE Models. The present study identified several determinant factors of in-cabin exposure to TRAPs. Most of them were linked to the leading vehicles and their characteristics, whereas the other determinants were associated with monitoring seasons, road characteristics, and in-vehicle and meteorological variables (Table 4).

The results of the GEE univariate and multiple models of the in-cabin TRAP concentrations are reported in Supporting Information from Tables S8–S22.

3.3.1. In-Vehicle Exposure to TRAPs: Determinant Factors Related to Leading Vehicle Characteristics. The identified determinant factors associated to the leading vehicles and their characteristics are summarized in Figure 2.

Obtained results revealed that the leading vehicles played a crucial role in explaining the variability of in-cabin TRAP concentrations. The strongest effect was detected for in-cabin eBC concentrations (+67.5%), even though also CO, $PM_{0.3-1}$, $PM_{1-2.5}$, and UFP concentrations showed important increases (ranging from +14.6% to +30.6%) with leading vehicles ahead. As also highlighted in a literature review, to date, only a few studies have focused on the leading vehicle effects on in-cabin TRAP concentrations [25]. Nevertheless, a more recent publication found that following a heavy emitter increased in-vehicle NO_2 concentrations (with a percentage change of 2.1%), but no statistically significant results were observed for in-cabin $PM_{2.5}$, probably because they tested different ventilation settings compared to the present study [63]. Except for the one just mentioned, other researches have only assumed that high in-cabin TRAP concentrations could be explained by high-emitting vehicles ahead without quantifying the effect. For instance, Joodatnia, Kumar, and Robins observed that short-term increases of UFPs were correlated to the proximity of leading vehicles, and Kadiyala and Kumar explained that high and medium in-bus UFP concentrations were apparently determined by leading vehicles exhaust emissions [64, 65]. The results obtained from the multiple analyses also showed statistically significant associations with several leading vehicle characteristics. Firstly, the fuel type was another important predictor of in-cabin CO and eBC concentrations. In particular, the in-cabin CO and eBC concentrations were, respectively, lower (−7.2%) and greater (+45.3%) with diesel-fuelled leading vehicles with respect to petrol-fuelled ones (Table 4 and Figure 2). It is well known that CO is a by-product of incomplete combustion of carbonaceous fuels, especially from

Table 3: Descriptive statistics for CO, eBC, fine PM fractions, and UFP concentrations monitored in the study vehicle ($n = 10{,}030$).

In-cabin TRAPs	Min.	25th perc.	Mean	SD	Median	75th perc.	Max
CO (ppm)	0.2	1.1	1.5	0.7	1.5	1.9	9.1
eBC ($\mu g/m^3$)	0.2	2.8	7.3	8.6	4.9	8.3	145
$PM_{0.3-1}$ (particles/cm^3)	1.8	22	39	22	37	51	176
$PM_{1-2.5}$ (particles/cm^3)	0.01	0.16	0.27	0.15	0.24	0.38	1.5
UFPs (particles/cm^3)	365	8.6×10^3	2.4×10^4	4.9×10^4	1.3×10^4	2.3×10^4	1.0×10^6

Abbreviations: 25th perc. = 25th percentile; 75th perc. = 75th percentile; Max = maximum; Min = minimum; SD = standard deviation.

petrol-fuelled motor vehicles that represent a major source of CO [66]. Regarding eBC, previous studies found that eBC emissions from diesel vehicles were up to seven times greater than those from petrol vehicles [67, 68]. Among the leading vehicle features, emission reduction technologies were identified as a noteworthy determinant of in-cabin exposure. Both in-cabin eBC and $PM_{0.3-1}$ concentrations showed statistically significant decreases (up to about −47% and −19%, respectively) when leading vehicles were characterized by the latest emission standard levels (i.e., Euro 4, 5, and 6) compared to Euro 0, 1, 2, and 3 vehicles. In this regard, significant reductions of the in-cabin concentrations with both Euro 5 and 6 leading vehicles were observed. Also, in a recent publication, on the contrary, nonsignificant differences were reported comparing Euro 4 with older leading vehicles [19]. Regarding in-cabin CO concentrations, significantly lower concentrations were detected with both Euro 5 and 6 compared to the Euro 0–3 leading vehicles (about −20% and −17.5%, respectively). According to a study dedicated to exhaust emissions from pre-Euro to Euro 4 vehicles, the CO-measured values were progressively and significantly lowered from older to newer petrol passenger cars. In particular, the median concentrations were 0.95%, 0.29%, 0.13%, 0.03%, and 0.02% for pre-Euro, Euro 1, 2, 3, and 4 vehicles, respectively. That study did not observe statistically significant differences for diesel-fuelled passenger cars, taxis, and light goods [21]. This finding may explain why in the present study, in which petrol and diesel cars were considered together, nonsignificant reductions were found between Euro 4 and Euro 0–3 leading vehicles. Concerning in-cabin UFP concentrations, the GEE model results showed a statistically significant reduction (about −29%) with Euro 5 compared to Euro 0–3 leading vehicles. Another research indicated that the greatest decreases were found for Euro 5 leading vehicles compared to those equipped with previous generation emission reduction technologies [19]. In relation to $PM_{1-2.5}$ concentrations, a statistically significant reduction was observed with Euro 6 with respect to Euro 0–3 leading vehicles (−12.5%). In this regard, a recent study observed that the median in-cabin $PM_{1-2.5}$ concentrations were statistically lower comparing Euro 6 with Euro 0–3 leading vehicles (both analyzing petrol- and diesel-fuelled leading vehicles) [19]. Lastly, the GEE model results showed that the in-cabin $PM_{1-2.5}$ concentrations were statistically greater (about +30%) with heavy-duty compared to light-duty leading vehicles. This association may be related to both tailpipe emissions of heavy-duty leading vehicles and the resuspension of pavement and soil dust during their passage [69].

3.3.2. In-Vehicle Exposure to TRAPs: Other Identified Determinant Factors. Among the identified predictors, several well-known determinant factors of in-cabin TRAP concentrations were found (Figure 3).

First, a strong effect of the season on CO concentrations was observed. As expected, the in-cabin concentrations were higher during the autumn than during the summer. A similar finding was observed in a previous study, in which the ambient T explained 11% of in-vehicle CO concentration variability [58]. However, in the present study, it was calculated that the in-vehicle CO concentrations increased by about 5% with each 1°C increase of the in-vehicle T. This result was in contrast with previous studies dedicated to exposure to TRAPs inside vehicles. For instance, research performed in public transport buses observed high concentrations of CO (> 35 ppm) with low (< 4.4°C) to medium indoor T (from 4.4°C to 22.2°C) [70]. Nevertheless, in this work, the explanation of the positive association between in-cabin CO and in-cabin T should be looked for in other predictors. Indeed, as revealed by the model results, the in-vehicle CO concentrations were significantly greater on both urban and EU city connection roads. These roads were traveled at the end part of the morning (outward trip—on urban roads) and in the middle part of the afternoon (return trip—on EU city connection roads) monitoring trips, when the T was higher than the other sections of the trip (e.g., in-vehicle T was 6.5°C—on average—higher on urban roads than on rural roads during the summer campaign). Therefore, it can be assumed that indoor T was not a predictor of in-cabin CO exposure, but rather it was an inherent feature of this study. Moreover, the GEE model results showed positive and significant associations between in-cabin CO concentrations and both traffic jam situations (+5.8%) and traffic light stops (+6.7%). In these regards, it has been widely demonstrated that an increase in traffic intensity is an important factor affecting CO concentrations inside vehicles [58, 71–74]. However, these traffic situations are typically characterized by high CO exhaust emissions due to vehicle engines running at low revolutions per minute and frequent stop-and-go events [75]. Curiously, CO concentrations were lower (about −12%) when running on EU bypass roads (vs. EU city connection roads), whereas both eBC and UFP concentrations (about +37%) were significantly greater. A possible explanation was probably related to more traffic

Table 4: Summary of the determinants identified through multiple regression using GEE models relating to in-cabin TRAP concentrations. The Δ% with the corresponding 95% confidence interval and p value (< 0.05 [one asterisk], < 0.01 [double asterisks], < 0.005 [triple asterisks], and < 0.0001 [quadruple asterisks]) were reported.

	In-cabin CO Δ% (95% CI)	**In-cabin eBC Δ% (95% CI)**	**In-cabin $PM_{0.3-1}$ Δ% (95% CI)**	**In-cabin $PM_{1-2.5}$ Δ% (95% CI)**	**In-cabin UFPs Δ% (95% CI)**
Campaign					
Autumn	130.6**** (87.4; 183.7)	—	—	—	—
Summer			Ref		
Leading vehicle					
Yes (presence)	20.1*** (9.0; 32.3)	67.5**** (27.1; 120.8)	21.7* (2.3; 44.8)	14.6* (3.4; 27.1)	30.6* (3.7; 64.5)
No (absence)			Ref		
Leading vehicle types					
Heavy-duty	—	—	—	30.4*** (10; 54.6)	—
Light-duty			Ref		
Leading vehicle emission standard level					
Euro 4	—	−32.9** (−49.6; −10.8)	−14* (−26.1; −0.1)	—	—
Euro 5	−20.5**** (−27.2; −13.2)	−39.4*** (−54.4; −19.5)	−13.9* (−25.2; −1.0)	—	−28.9* (−45.0; −8.0)
Euro 6	−17.4**** (−23.4; −11.0)	−46.7**** (−61.6; −26.0)	−18.7*** (−29.1; −6.9)	−12.5** (−20.4; −3.9)	—
Euro 0123			Ref		
Leading vehicle fuel type					
Diesel	−7.2** (−12.2; −1.9)	45.3**** (20.0; 75.9)	—	—	—
Petrol			Ref		
Traffic jam					
Yes	5.8*** (2.2; 9.5)	—	—	—	—
No			Ref		
Road types					
EU bypass	−11.8*** (−17.9; −5.3)	36.4* (6.7; 74.2)	—	—	37.7* (6.8; 77.5)
Rural	−26.2**** (−34.6; −16.6)	−28.5** (−43.2; −9.9)	−25.5*** (−38.4; −9.9)	−26.2**** (−35.7; −15.2)	−46.2**** (−60.1; −27.4)
Urban	13.9*** (4.9; 23.6)	20.8* (1.1; 44.3)	—	—	—
EU city connection			Ref		
Traffic light stops					
Yes	6.7*** (2.3; 11.3)	—	—	—	—
No			Ref		
In-cabin T	4.9**** (3.1; 6.8)	—	—	—	—
In-cabin RH	—	—	21.7* (2.3; 44.8)	—	2.6* (0.4; 4.9)
Sine of wind direction	—	—	—	8.3* (1.1; 16.1)	—

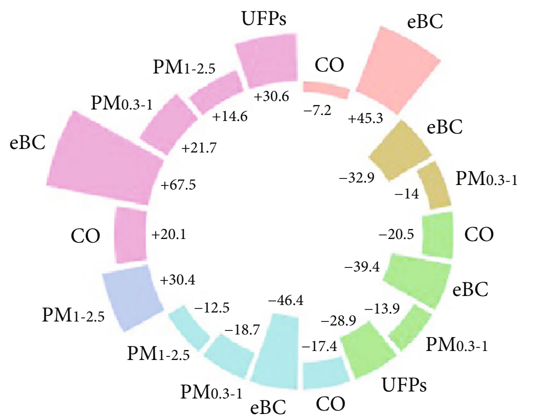

FIGURE 2: The graph reports the Δ% of in-cabin TRAP concentrations per predictor relating to the leading vehicles. Only the statistically significant results of the multiple regressions using GEE models are shown. Leading vehicles are abbreviated as "LVs."

jam situations and traffic light stops (determinant factors of in-cabin CO concentrations) on EU city connection roads. Regarding eBC and UFPs, greater in-cabin concentrations on EU bypass roads might be related to a greater number of high-emitting leading vehicles (diesel-fuelled, especially for in-cabin eBC concentrations). All monitored TRAPs showed significantly lower in-cabin concentrations when running on rural roads compared to EU city connection roads. This was expected because the ambient TRAP concentrations (especially eBC and UFPs) were generally the lowest on the rural roads [76]. Moreover, concerning eBC, it was already demonstrated that average in-vehicle exposure was lowest in rural areas but highest in urban areas [77]. By the way, as reported in Figure 3, also in this study, the results showed that in-cabin exposure to eBC was higher on urban roads with respect to EU city connection roads. A possible explanation was related to differences in traffic intensity [77] which may also have resulted in dissimilarities in the frequency of the leading vehicles on these road types: 17% for rural roads versus more than twice (35.7%) for urban roads (see Table S6 in the Supporting Information). The GEE model results also revealed that in-vehicle RH levels were significantly associated with increases in both in-cabin $PM_{0.3-1}$ (+21.7%) and UFPs (+2.6%) concentrations. As reported in the scientific literature, the increase in relative humidity from 10% to 90% led to greater particle number concentration (i.e., by a factor of 6), whereas the critical nucleus diameter decreased by approximately 30% [78]. Lastly, the results showed a positive statistically significant association between wind direction and in-cabin

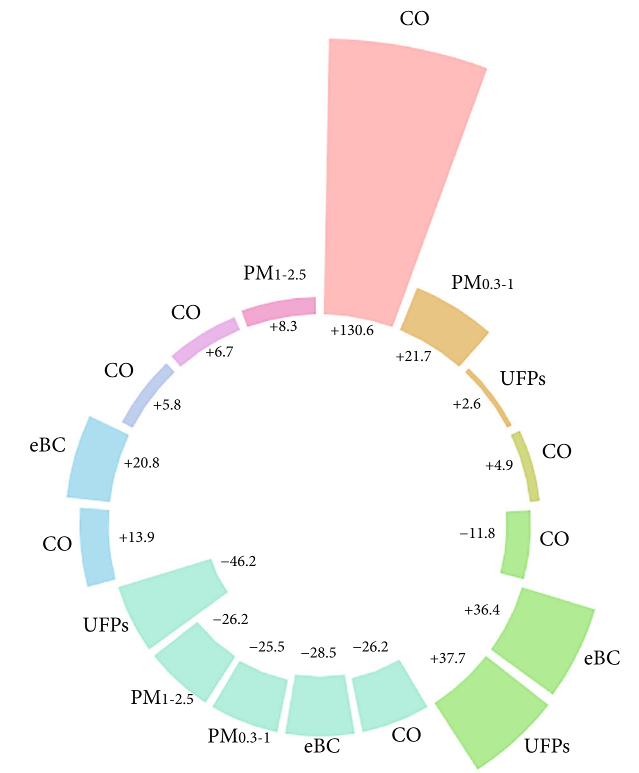

FIGURE 3: The graph reports the Δ% of in-cabin TRAP concentrations per predictor related to monitoring seasons, road characteristics, and in-vehicle and meteorological variables. Only the statistically significant results of the multiple regressions using GEE models are shown.

$PM_{1-2.5}$ concentrations (+8.3%), which contributed to high $PM_{2.5}$ concentration variation for both in-cabin and on-roadway commuting modes as demonstrated by previous research findings [79]. In particular, distinct patterns of exposure concentrations in different wind direction sectors were found in that study linked to pollution episodes that occurred when specific winds were prevailing. It is possible to suppose similar pollution events also in the present study, although it must be stated that this association is not easy to interpret.

3.4. Weakness and Strengths and Suggestions for Future. The main limitation of this study is related to the impossibility of quantifying the effect of the distance between the instrumented vehicle and the leading vehicles on in-cabin TRAP concentrations. That parameter may be acquired as reported, for instance, in two recent publications [80, 81]. However, in those cases, the leading vehicle was always the same and part of the study, whereas in our work the data were collected in real traffic conditions in which getting accurate distance values would have been too complicated. Therefore, we decided not to analyze that parameter. However, we believe that conducting measurements in real-world driving situations with a large variability in leading vehicle characteristics is a significant strength of our work. Anyway, as reported by Matthaios et al., increasing the distance between vehicles can lead to a reduction in in-vehicle exposure to TRAPs [63].

Another limitation concerns the fact that only one type of ventilation setting and study vehicle type were tested, thus limiting the generalizability of the present research. Nevertheless, several researches were focused on in-cabin air quality during different ventilation conditions, and their results could be applied to the outcomes of the present study using appropriate models.

In the end, the COVID-19 outbreak in the Lombardy region of Italy during winter–spring 2020 caused the forced stop of the measurements, and, consequently, no data were collected in the winter season.

Overall, future studies need to be designed to test more ventilation settings, including air conditioning and recirculation systems, to verify their effects in protecting occupants from leading vehicle emissions. Additionally, it would also be important to perform the analysis of the differences between open windows and closed windows, mainly because car drivers can expect their greatest and lowest exposures when driving using those two ventilation settings, respectively [44]. Moreover, new measurements could be performed by means of an electric-powered study vehicle, reasonably eliminating any potential self-pollution [82]. Anyhow, our suggestion is to focus future research on measuring during the winter season, since the importance of seasonality mainly depends on in-vehicle concentrations of gaseous compounds [25]. In this respect, due to the lack of sufficiently accurate instrumentation in our laboratory, the present study was limited only to measuring the in-vehicle CO concentrations. Therefore, more efforts should be made to expand the range of gases, including also NO_2, VOCs (e.g., HC), and aldehydes.

The principal strength of this study lies in the capacity to obtain a substantial amount of information regarding the characteristics of leading vehicles (e.g., emission standard levels, fuel types, and vehicle-type categories). This is achieved through the utilisation of video analysis and the Italian public vehicle registration database, which has the effect of resolving some outstanding questions regarding the impact of leading vehicles on the air quality within vehicle cabins.

4. Conclusions

The original contribution of this article lies in the quantification of leading vehicle emission effects on in-cabin TRAP concentrations. Several important learning points were gained, including the following:

- In-cabin TRAP concentrations were significantly higher with leading vehicles ahead than during empty road conditions (from +14.6% to +67.5%);
- Euro 5 and 6 leading vehicles played a pivotal role in the decrease of in-cabin exposure to TRAPs with respect to older ones (from −12.5% to −46.7%);
- Diesel-fuelled leading vehicles as compared to petrol-fuelled leading vehicles showed significant impacts on in-cabin CO (−7.2%) and eBC (+45.3%) concentrations, respectively;
- Emissions coming from heavy-duty than light-duty leading vehicles revealed a strong effect (+30.4%) on in-cabin $PM_{1-2.5}$ concentrations.

Concluding, along with other well-known predictors mainly associated with route and traffic characteristics, the present study allowed to include the leading vehicle emissions among the most important determinant factors of exposure to TRAPs inside vehicle cabins, emphasizing their greater importance with respect to local pollution and meteorological conditions, except for rainfall effects that were not tested in this study. The emission reduction technologies were therefore important in decreasing not only the environmental pollutant concentrations but also the in-cabin TRAP concentrations.

Nomenclature

BC	black carbon
CNG	compressed natural gas
CO	carbon monoxide
eBC	equivalent black carbon
EU	extra-urban
GEE	generalized estimating equation
GPS	Global Positioning System
km/h	kilometers per hour
LV	leading vehicle
$\mu g/m^3$	micrograms per cubic meter
m/s	meters per second
OPC	optical particle counter
Particles/cm^3	number of particles per unit volume (cubic centimeter)
PM	particulate matter
$PM_{1-2.5}$	particulate matter with aerodynamic diameter between 1 and 2.5 μm
$PM_{0.3-1}$	particulate matter with aerodynamic diameter between 0.3 and 1 μm
PPB	parts per billion
PPM	parts per million
QIC	quasi-information criterion
RH	relative humidity
T	temperature
TRAPs	traffic-related air pollutants

UFPs ultrafine particles (particle matter with aerodynamic diameter < 0.1 μm)

Data Availability Statement

The in-vehicle exposure data used to support the findings of this study are included within the article and the Supporting Information file.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Supporting information included 1 figure, 3 texts, and 22 tables. Figure S1: the selected route. Text S1: the monitoring instruments. Text S2: differences between individual exposure and personal exposure. Text S3: procedures to obtain and process data concerning the leading vehicles. Table S1: descriptive statistics of the in-cabin TRAP concentrations—summer campaign. Table S2: descriptive statistics of the in-cabin TRAP concentrations—autumn campaign. Table S3: descriptive statistics for in-cabin T and RH, speed of the study vehicle, ambient pollutant concentrations, and meteorological variables—both campaigns. Table S4: descriptive statistics for in-cabin T and RH, speed of the study vehicle, ambient pollutant concentrations, and meteorological variables—summer campaign. Table S5: descriptive statistics for in-cabin T and RH, speed of the study vehicle, ambient pollutant concentrations, and meteorological variables—autumn campaign. Table S6: number of leading vehicles encountered per categorical variable. Table S7: characteristics of each roundtrip in terms of number of observations, duration of the trip, and number of leading vehicles. Table S8: in-cabin CO: summary of the results of the multiple regression using GEE models. Table S9: in-cabin CO: complete results of the univariate linear regression using GEE models. Table S10: in-cabin CO: complete results of the multiple linear regression using GEE models. Table S11: in-cabin eBC: summary of the results of the multiple regression using GEE models. Table S12: in-cabin eBC: complete results of the univariate linear regression using GEE models. Table S13: in-cabin eBC: complete results of the multiple linear regression using GEE models. Table S14: in-cabin $PM_{0.3-1}$: summary of the results of the multiple regression using GEE models. Table S15: in-cabin $PM_{0.3-1}$: complete results of the univariate linear regression using GEE models. Table S16: in-cabin $PM_{0.3-1}$: complete results of the multiple linear regression using GEE models. Table S17: in-cabin $PM_{1-2.5}$: summary of the results of the multiple regression using GEE models. Table S18: in-cabin $PM_{1-2.5}$: complete results of the univariate linear regression using GEE models. Table S19: in-cabin $PM_{1-2.5}$: complete results of the multiple linear regression using GEE models. Table S20: in-cabin UFPs: summary of the results of the multiple regression using GEE models. Table S21: in-cabin UFPs: complete results of the univariate linear regression using GEE models. Table S22: in-cabin UFPs: complete results of the multiple linear regression using GEE models.

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