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Evaluation of the heterogeneity of air pollution exposure in mobility tracks: a focus on Paris public transport network lines and personal cars.

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Contents

List of acronyms

AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
BC	Black Carbon
COPD	Chronic Obstructive Pulmonary Disease
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DALY	Disability-adjusted life years
GPS	Global Positioning System
LEZ	Low Emission Zone
MET	Metabolic Equivalent of Task
NO_2	Nitrogen Dioxide
O_3	Ozone
PPB	Particles per Billion
PPM	Particles per Million
$P.M._{2.5}$	Particulate Matter 2.5
$P.M._{10}$	Particulate Matter 10
RATP	*Régie autonome des transports parisiens*
SO_2	Sulphur Dioxide
TRAP	Traffic-Related Air Pollution
YLD	Years of Healthy Life Lost to Disability
WHO	World Health Organization

Abstract

Introduction: Air pollution, primarily from traffic, is a major health risk linked to asthma, stroke, dementia, and diabetes. Despite Europeans spending a significant time commuting, exposure during this period is under-researched. This study assesses exposure to nitrogen dioxide, carbon monoxide, and black carbon in the metro, RER, buses, trams, and cars in the Grand Paris area using MobiliSense data. **Method:** Data was collected from May 2018 to March 2022 from 289 participants in Grand Paris. Participants wore sensors for 6 days, including a GPS, accelerometer, BC monitor, and a gases monitor. Mixed-effects models accounted for season, day type, temperature, humidity, and rush hour. **Results:** The study analyzed 1123 metro trips across 14 lines, 455 RER trips across 5 lines, 325 bus trips, 116 tram trips, and 1799 car trips categorized by Euro Standard and Crit'Air. Participants in line 13 were exposed to the highest NO_2 9.28 ppb (95% CI 4.95, 13.62) more than Line 5, participants in line 7 were exposed to the highest CO 0.30 ppm (95% CI 0.07, 0.52) more than Line 6, and participants in line 13 were exposed to the highest BC 4.16 mg/m^3 (95% CI 2.44, 6.79) more than Line 6. Individual exposure in RER E had higher CO levels of 0.18 ppm (95% CI 0.03, 0.33) than in RER D, and exposure in RER A had higher BC levels of 4.87 mg/m^3 (95% CI 1.82, 7.91) than in RER D. Crit'Air 2 cars had 1.37 mg/m^3 (95% CI 0.31, 2.43) higher BC levels than level 1. **Conclusion**: Paris commuters are exposed to air pollution, especially on metro lines 7, 8, and 13. Stricter Euro Standard 7 emission tests should be required. The Crit'Air system offers a better framework for lowering exposure to air pollution.

Keywords: air pollution, transportation, traffic, GPS, environmental.

Titre : Évaluation de l'hétérogénéité de l'exposition à la pollution de l'air dans les parcours de mobilité individuels : focus sur les lignes du réseau de transport public parisien et les véhicules personnels.

Résumé

Introduction : La pollution de l'air, principalement due à la circulation, est un risque sanitaire majeur lié à l'asthme, aux accidents vasculaires cérébraux, à la démence et au diabète. Bien que les Européens passent beaucoup de temps à se déplacer, l'exposition pendant cette période n'est pas suffisamment étudiée. Cette étude évalue l'exposition au dioxyde d'azote, au monoxyde de carbone et au carbone noir dans le métro, le RER, les bus, les tramways et les voitures dans le Grand Paris en utilisant les données MobiliSense. **Méthode :** Les données ont été collectées de mai 2018 à mars 2022 auprès de 289 participants du Grand Paris. Les participants ont porté des capteurs pendant 6 jours, notamment un GPS, un accéléromètre, un moniteur BC et un moniteur de gaz. Les modèles à effets mixtes ont pris en compte la saison, le type de jour, la température, l'humidité et l'heure de pointe. **Résultats :** L'étude a analysé 1123 trajets en métro sur 14 lignes, 455 trajets en RER sur 5 lignes, 325 trajets en bus, 116 trajets en tramway et 1799 trajets en voiture classés par Euro Standard et Crit'Air. Les participants de la ligne 13 ont été exposés au NO2 le plus élevé 9,28 ppb (95% CI 4,95, 13,62) plus que la ligne 5, les participants de la ligne 7 ont été exposés au CO le plus élevé 0,30 ppm (95% CI 0,07, 0,52) plus que la ligne 6, et les participants de la ligne 13 ont été exposés au BC le plus élevé 4,16 mg/m³ (95% CI 2,44, 6,79) plus que la ligne 6. L'exposition individuelle dans le RER E présentait des niveaux de CO plus élevés de 0,18 ppm (IC à 95 % 0,03, 0,33) que dans le RER D, et l'exposition dans le RER A présentait des niveaux de BC plus élevés de 4,87 mg/m³ (IC à 95 % 1,82, 7,91) que dans le RER D. Les voitures Crit'Air 2 présentaient des niveaux de BC plus élevés de 1,37 mg/m³ (IC à 95 % 0,31, 2,43) que le niveau 1. **Conclusion :** Les banlieusards parisiens sont exposés à la pollution atmosphérique, en particulier sur les lignes de métro 7, 8 et 13. Des tests d'émission Euro Standard 7 plus stricts devraient être exigés. Le système Crit'Air offre un meilleur cadre pour réduire l'exposition à la pollution de l'air.

1. Introduction

Beginning with the Industrial Revolution there has been a steady and constant rise in air pollution, mainly due to traffic-related activities, like public transportation, cars, or aircraft emissions (1). In recent years there has been an interest in investigating the health impacts of air pollution, as well as the environmental impacts, like haze, eutrophication, crop damage, or ozone depletion, and the relationship with climate change, to create policies to protect human health, the environment and, reduce global emissions as well as support alternative transportation (2).

1.1 Effects of air pollution on human health

According to the World Health Organization (WHO) (2) in the year 2019, 99% of the global population lived in an area that surpassed the air pollution guidelines that include the pollutants of PM, O_3, NO_2, SO_2, and CO_2, and 4.2 million deaths are attributable to ambient (outdoor) air pollution. Air pollution is the fourth leading risk factor of death. The main causes were 37% due to ischemic heart disease and stroke, 18% and 23% of deaths were due to chronic obstructive pulmonary disease and acute lower respiratory infections, and 11% of deaths were due to cancer within the respiratory tract (2). Vulnerable populations such as children, pregnant or older people, as well as those with a lower socioeconomic status, or with preexisting health conditions, are more affected by air pollution (1).

According to the 2019 Global Burden of Disease study, air pollution contributes to 213 million disability-adjusted life years (DALYs) (3). Within the 27 European Union member states (4) in the year 2020, exposure above the WHO guidelines to fine particulate matter resulted in 238,000 premature deaths; exposure to nitrogen dioxide (NO_2) led to 49,000 premature deaths and 24,000 premature deaths due to ozone (O_3) exposure.

In France, 55.6 years lived in disability (YLDs) per 100,000 inhabitants are due to having a chronic obstructive pulmonary disease (COPD) attributable to $PM_{2.5}$ in adults over 25 years old, 37.3 YLDs per 100,000 inhabitants (adults over 35 years old) experienced diabetes mellitus type 2 attributable to NO_2 exposure, and 16 hospital admissions by 100,000 inhabitants for respiratory disease in adult over 65 years old were attributed to O_3 (4).

Studies on the health effects of air pollution have been rising especially in the North American and European context. A systematic review and meta-analysis (5) from 2022 evaluated the evidence between traffic-related air pollution (TRAP) and health outcomes. The studies that were included investigated health effects in the adult population (cardiometabolic, or respiratory effects and mortality). The evidence on the effects of exposure to air pollutants was moderate to high for asthma onset, and low for other respiratory outcomes like chronic obstructive pulmonary disease, ischemic heart disease, diabetes, and stroke. Lastly, there was a high confidence level in the data that established the relationship between traffic-related air pollution and mortality (5).

A cohort study in China found a positive association of $PM_{2.5}$ and its components with increased blood pressure in males, aging people, and those residing in most exposed urban areas (6). In contrast with these results, a study in a low-pollution city in Ontario, Canada found that even the recommended safe levels of NO_2 were associated with total carotid plaque area (7). In the French context, a study in the south region of NO_2, $PM_{10,}$ and O_3 explored the incidence of cardiac dyspnea and, concluded that there was a significant association between short-term exposure and cardiac dyspnea (8).

Referencing the respiratory health effects, the UK Biobank cohort study evaluated the commuting pattern and residential levels of NO_2 with lung cancer risk, concluding that those who travel by public transportation, compared to those traveling by car, also had a higher level of residential NO_2 and had an increased lung cancer risk with possible multiplicative interaction (9). A positive association was found between air and noise pollution and the incidence of chronic obstructive pulmonary disease (10) and of air pollution specifically of NO_2 with the development of adult asthma (11).

A cohort study (12) in the older Mexican American community, in the Sacramento Valley, United States of America established that separately air and noise pollution affects cognitive impairment. A land use regression model for the annual levels of $PM_{2.5}$, NO_2, and O_3 showed an increase in the hazard of cognitive impairment and dementia, with higher effects when individuals were co-exposed to traffic-related noise, suggesting an independent and synergistic association between air and noise pollution and cognitive impairment.

These results were confirmed by a study in Ruhr, Germany that measured air pollution, and concluded that higher levels of air pollutants and high noise exposure are comparable to 1 year of aging (13).

The limitations of the Chinese, the Ontario, the UK biobank, the Mexican American cohort, and the German studies are using models that could underestimate or overestimate the level of exposure to pollutants. There are no consistent results between air pollution and health outcomes; this is why a new comprehensive analysis that uses real-time reports of air pollution during transportation with GPS is needed.

1.2 Mobility and the measurement of air pollution

The interest in environmental exposure and its effects on health has created innovative ways to measure the exposure, the previous studies mostly work with land use regression, calculating the exposure at the neighborhood level with geolocation but people move to different environments beyond the neighborhood which could lead to a change in the levels of exposure the solution could be GPS and tracking people's trajectories (14).

A study in Barcelona, Spain compared neighborhood level measurements to GPS measurements of air and noise pollution in the senior community, finding that for $PM_{2.5}$ there was a 6% discrepancy between the measurements, the change was too small for NO_2 and PM_{10}, in the context of Barcelona neighborhood-level measures are underrepresenting real exposures. The lack of evident changes could be due to the population being over 65 years old, and the layout of the city producing a smaller distance to the activity spaces, suggesting that GPS measurements may only be needed in the population groups that spend more time outside of the residential area (15).

However, a study in Shenzhen, China found that the neighborhood-based method underestimates exposures to CO, NO_2, and $PM_{2.5}$, and overestimates for O_3. Ignoring mobility could lead to a 33% underestimation of relative risk. The data used was from the cell towers that would handle the wireless communication rather than the individual live location and indoor pollution was not considered (14).

A French study in the Ile de France compared questionnaire-based location and GPS data. Their results showed that most participants had the GPS data with 85.5% accuracy from their reported location, making both appropriate research methods. Even though subgroups of individuals like unemployed people are less likely to have a structured routine and spend more time in other places that were not reported. Another advantage was that GPS data also considers the commute to different places. The problem with GPS measurements is missing data due to human error as forgetting to wear the device, charge the device, or signal problems, meaning a supplementary dairy should be added (16).

In that sense, GPS-based sensors allow objective data of activity and travel behaviors avoiding misclassification and estimation errors making it easier to account for the mobility indicators of space, time, movement scope, and their attributes, fragmentation of activities producing a more accurate exposure avoiding the residential effect fallacy bias (17).

1.3 Air pollution in public transport modes

Regarding commuting, a systematic review of Asian studies on the exposure to air pollutants during transport modes (car, bus, subway, and walking); concluded that bus use had the most significant exposure to air pollution attributable partly to traffic and the fuel type. The lowest exposure concentration to air pollutants is found in transportation modes with better air ventilation and air tightness. The use of multiple devices for the recollection of pollutants has resulted in challenges in the comparability of measurements. Light scattering techniques have been the primary method of choice for utilizing instruments (18).

Researchers should employ instruments that have undergone validation and testing to ensure their accuracy, precision, and reliability in the measurement of pollutants. Standardizing measurements across various studies can facilitate comparison and aggregation of data. Furthermore, it is important to establish uniformity in the measurement and documentation to improve comparability (18).

A study of the underground network of Philadelphia in Pennsylvania, United States of America, found that stations' $PM_{2.5}$ levels were 5.1 times higher than aboveground street levels, the variability across stations could be attributed to the designs, air conditioning systems, or ventilation systems, the number of commuters and location, newness of the station. PM concentrations were higher during peak hours compared to off-peak hours, train frequency increases the number of particles. What may give the greatest variability is due to the composition of the wheels, brake systems, ventilation levels, and outdoor pollution levels (19).

Another study in Beijing, China concluded that the subway had the highest air pollution at the entrance, followed by the transfer tunnels, and the cabins. They also found that over-ground concentrations were higher than underground concentrations (20). These results were confirmed by a Shanghai, China study where those who travel by car with the windows closed inhaled less amounts of $PM_{2.5}$ and cyclists the highest (21).

As a confirmation, a study from Greater Cairo, Egypt, studied differences in pollutant exposure in 4 transportation modes and found that cars with recirculation had the least amount of $PM_{2.5}$ followed by walking, cars with windows open, microbuses with windows open, and cycling. However, the study didn't evaluate the individual health impacts of repeated exposure to this concentration (22).

A study in Mumbai, India found that office workers inhaled 25-30% of their daily dose of PM and gases during the commute. The study was done during the summer, suggesting that the windows were down in cars and buses, increasing the amount of PM due to background pollution (23).

In the European context, people spend 5-8% of their time commuting. A study from Lisbon, Portugal investigated the amount of pollutants in different transportation modes, reporting the least amount of $PM_{2.5}$ in buses, followed by bicycles, cars, and metro. It's important to note that the bus has recirculating air conditioner, and the metro is powered by electricity. The inhalation of black carbon was the lowest in the buses followed by cycling, metro, and car. There was also a higher rate of PM_{10} inhalation in the metro system, with cars having the lowest for both $PM_{2.5}$ and PM_{10} but having the highest emission per commuter. Due to the advances in technology, these results may not be generalizable to other contexts with older systems of transportation (24).

Another study of undergrad students from Istanbul, Turkey exploring the exposure to air pollutants discovered that the exposure to black carbon was six times higher during the commute than at the home levels. However, it was with a low number of participants and during spring, black carbon measurements can vary during the season (25).

A study done in Paris, France using the MobiliSense data, as well as this study, explored the inhalation of black carbon during public and private transportation use, the highest concentration was in the metro likely due to the diameter of the particles and the inefficacy of the filters. And the lowest in the tram probably because it's completely electric but within proximity to the roads (26).

In contrast, a Swedish study in Stockholm explains that only 22% of the variability in exposure to black carbon can be attributed to transportation mode. Traveling by bus was found to have the highest levels, and it's the same if traveling by car, walking, or cycling. The exposure levels were lower than the regular level of other cities outside of Sweden, the bicycle lanes are between trees but the sidewalk is next to traffic, and the study didn't take into account the windows and car filters (27).

A preliminary study in Paris, France did repeated measurements of the levels of $PM_{2.5}$ in the metro and RER system at the end of the platform of each line and found that the highest levels were in line 5, RER A, line 9, line 2, line 7, line 7bis, line 13 and line 8, these results have not been validated yet (28).

1.4 Air pollution on private transport modes

In regards to the different types of fuel a study compares the air pollution inside electric and diesel-powered trains resulting in passenger cars of diesel trains compared with electric trains were for ultrafine 35-fold, black carbon 6-fold, NO_x 8-fold, NO_2 3-fold, $PM_{2.5}$ 2-fold. The trains that were measured were from the 1980s making it difficult to extrapolate to other models and didn't have enough data to account for ventilation systems or seasonal changes (29).

Traveling by car has a different burden than other transportation modes. A systematic review analyzed the levels of air pollution in taxicabs the results varied depending on the country CO levels in Iran were 5 times greater on average than in France, and $PM_{2.5}$ levels in China were almost 4 times higher than in the US. The levels of particle pollutants were higher inside the taxi than in the background, and gas pollutants were 3 times higher than when traveling by metro. There are too few studies with a small sample to be able to generalize the results (30).

A recent study from Leicester, UK found that average NO_2 concentrations were 1.1 to 2.6 times higher in the vehicle cabin compared to the active commute, O_3 concentrations were also higher but concentrations vary in the literature due to differences in test conditions, vehicle relative humidity, meteorology, fleet mix, fuel type, the study area and route (31).

In Paris, a study compared the presence of ultra-fine particles and black carbon before and after the COVID-19 lockdowns in taxi cars, resulting in a decrease of 32% in vehicle concentrations of ultra-fine particles and 31% for black carbon, which may be due to the changes in traffic congestion, the study did not control for atmospheric pollution (32).

1.5 Problematic

Even as more studies are being published on the effects and causes of air pollution, there is a need for more evidence for the exposure in microenvironments such as during the commute, the studies that measure the levels of air pollution in different transportation modes don't show consensus in the data, depending on the region the data was collected the results vary widely as shown in this introduction.

There is no consensus on how mobility should be measured, which pollutants need to be represented in each transport mode, and the variables that should be considered to be able to compare between transport modes. Let alone, an explanation for the variability in exposure in different lines of the same transport modes or depending on car types.

Based on the literature review, the decision for which pollutants should be measured relies on the tracks that will be evaluated what is predicted that will be produced, as well as methodological and economical constraints. To benefit this study the analysis will be done on black carbon, NO_2, and CO.

This study has as a goal to explain the variability in public and private transportation modes, which is why the following chapters are divided between public transport including the metro, the RER, the bus, and the tram following private transportation meaning cars that are divided by the Euro Standard or the Crit'Air categorization.

1.6 Objectives

Explore how the intra-variability of public and private transportation modes affect air pollution exposure during mobility tracks.

- Evaluate the variability of individual exposure to air pollution in the public transportation network of Paris among the metro, RER, bus, and tram.
- Asses the variability of individual exposure to air pollution according to Euro Standard and Crit'Air systems in personal vehicles.

1.7 Main contribution of the student to the study

This study was executed with the MobiliSense dataset. The data had already been collected from May 2018 to March 2022 and preprocessed. The student selected the relevant information for the project, including the air pollution measurements and the transportation data, as well as the dates and times of each trip to be able to create other necessary variables. Proceeded to clean the data, at that point, it became evident that there had been a few issues in the processing of the data so the student corrected the errors, the data management is detailed in the methodology section. Important data was not processed, subsequently, the student investigated and collected that data from open-source materials on the Internet. After the data cleaning and data management the student proceeded to do the statistical modeling, concluding with the writing of this thesis and the scientific article.

2. Methods

2.1 Study population: MobiliSense study

Data for this study come from the MobiliSense sensor-based study. The MobiliSense study was conducted in the Grand Paris metropolitan area, France, from May 2018 to October 2020. The second wave started in March 2020 but was delayed due to the COVID-19 pandemic and lasted until March 2022.

To ensure diversity in neighborhood conditions from the Grand Paris area, participants in the study were recruited through a two-stage stratified random sampling technique. The neighborhood sampling stage involved the random selection of local neighborhoods in the first and last quartiles of road traffic density within each quartile of area income. In the second stage, dwelling units in each pre-selected neighborhood were randomly selected in the 2013 and 2014 censuses by the National Institute of Statistics and Economic Studies. Overall, 31,970 dwellings were selected from 234 neighborhoods (33).

The inclusion and exclusion criteria for the study are detailed elsewhere (33). In brief, the eligible participants had to be non-smoking adults from non-smoking households, living in the Grand Paris, France, and aged 30–64 years on January 1, 2016. Postal invitations to participate in the study were sent twice to the residents of the pre-selected dwellings, resulting in the recruitment of 289 participants. The sample was slightly biased toward older French citizens, married with higher education. Self-employed people and people with stable and unstable jobs were more likely to consent than unemployed.

Research assistants guided participants through a standard computerized questionnaire on the following: sociodemographic characteristics of the individual and neighborhood, resources for transport (driving license, motorized and non-motorized vehicle ownership, access to parking, public transport pass, etc.), for those that use private motorized transport the characteristics of the vehicle, were also recorded. At the end of the sensor-based assessment, participants were asked to answer a postquestionnaire during a phone call about their travel itinerary over the specific days when the sensors were worn (33).

2.2 Ethical statement

The sampling and data collection protocol was approved by the National Council for Statistical Information. The MobiliSense project also received the appropriate allowances from the French Data Protection Authority and the Ethical Committee of Inserm.

2.3 Sensors

2.3.1 GPS and accelerometers

Participants were followed with sensors over 6 days (thus encompassing week and weekend days). Over these days, they alternated between different configurations of sensors. On all days, participants carried a GPS receiver and an accelerometer. Participants carried every day two of the three following monitors: a monitor of black carbon concentration, a wearable monitor for gases and particles, and a monitor for sound pressure. Participants wore all devices from wake-up to bedtime. They were instructed to not deviate from their usual routine during the data collection

2.3.2 Outcome: Air pollution measurement.

Participants wore the AE51 Aethalometer (AethLabs, San Francisco, California, USA) on days 1, 2, 3, and 4 for measuring concentrations of black carbon. Measurements were taken every 10 seconds.

On days 1, 2, 5, and 6, participants carried the Personal Air Quality Monitor, PAQM 520 (Atmospheric Sensors, Bedfordshire, United Kingdom), which measures concentrations of gases (O_3, NO_2, NO, and CO) and particles. The measurement of gases is averaged over 10 seconds epochs. Participants were instructed to place the air pollution monitors as close as possible to them when they did not wear them.

2.3.3 Exposure: Transport and spatial information

GPS data was uploaded into the TripBuilder application where they were automatically analyzed. Based on GPS data, these algorithms identify the places visited by participants and the trips between the locations.

The pre-processed GPS tracks and imputed information on the nature of visited places and the transport modes in each trip stage were shown in the web mapping interface of the TripBuilder application. The final output over 6 days comprises (among other information) the cleaned GPS tracks; the location of, arrival time to and departure time from each visited place; and the location and time of each point of change of mode during trips.

2.3.3.1 Public transportation

First, public transport was classified into modalities: metro, RER, bus, and tram. Followed by the lines taken into each mode, for the metro, there are 16 lines, the RER has 5 lines, the bus has almost 350 lines and the tram has 13 lines.

2.3.3.2 Private transportation

For each trip stage with a personal motorized vehicle, the ID of the automobile was collected, which can be matched to relevant characteristics, including the brand, the model, and various motorization and emission characteristics, including, the mileage, the year of registration, the motor size, the fuel type, the horsepower, the level of CO_2 emissions and its environmental classification.

Furthermore, the cars were divided into Euro Standard which is the European Union classification of vehicles according to the year of production. The Crit'Air system which is exclusively French utilizes the Euro Standard and fuel type to regulate the low emission zones (LEZ).

The Euro standard regulation categorizes vehicles from 1 to 6 according to the year of production: cars older than 1992 have a 0, before 1996 is a 1, before 2000 is 2, before 2005 is 3, before 2009 is a 4, before 2014 is 5, and lastly, after 2014 is a 6.

Cars were divided by the Crit'Air category according to the modifications that entered into effect on July 2023 that divide the motorized vehicles from 0 or green to 5.

- 0 or green for all vehicles powered by hydrogen or that are electric.
- Crit'Air 1 is for gasoline cars with a Euro Standard of 5 or 6, non-rechargeable hybrids with a Euro Standard of 5 or 6, or if the car is powered by gas or is a plug-in hybrid.
- Crit'Air 2 is for diesel cars with a Euro Standard of 5 or 6, gasoline cars with a Euro Standard of 4, or non-rechargeable hybrids with a Euro Standard of 2, 3, or 4.
- Crit'Air 3 is for diesel cars with a Euro Standard of 4 or gasoline cars with a Euro Standard of 2 or 3.
- Crit'Air 4 is for diesel cars with a Euro Standard of 3.
- Crit'Air 5 for diesel cars with a Euro Standard of 2.
- Non-Classifiable for all cars with Euro Standard 1 or 0.

2.4 Covariables

i. Temperature: measured with the PAQM 520 the participant wore as the mean temperature of each trip.

ii. Relative humidity: measured with the PAQM 520 the participant wore as the mean relative humidity of each trip.

iii. Season: categorized as spring from March 20th to June 20th, summer from 21st of June to 22nd of September, fall from September 23rd to December 20th and winter from December 21st to march 19th.

iv. Workday vs weekend. Monday through Friday as workdays and Saturday and Sunday as weekends.

v. Rush hour: defined as from 07:00 to 09:30 and 17:00 to 20:30.

vi. Socioeconomic level of the individual: recorded in the MobiliSense survey, classified as low (less than 1600), middle (between 1600-2300), and high (more than 2300).

vii. Socioeconomic level at the residential level: based on data from the National Institute of Statistics and Economic Studies and the communal divisions. Divided into low (less than 22358), middle low (between 22358 to 26942), middle high (between 26942 and 31117), and high (more than 3117)

viii. Automatized versus non-automatized lines: Automatize lines 1, 4, and 14 and the rest as non-automatized as reported by the RATP.

ix. Rolling stock: Rubber tires for lines 1, 4, 6, 11, and 14 or steel wheels for lines 2, 3, 5, 7, 8, 9, 10, 12, and 13 as reported by the RATP.

2.5 Data management

The MobiliSense dataset is spatiotemporal data, there was an error for 220 trips of 64 participants where the trip stages were not properly divided into the different lines of a transport mode, for this analysis it was important to have independent trip stages of the metro and RER lines. To achieve this an algorithm was built on R software.

For each of the 64 participants the accelerometry data was recovered, and then using R an algorithm was created to identify within the start and stop times of the concerned trips, those moments where the metabolic equivalent of task (MET) rate was higher than 1 for over a minute and a half. This metric signifies that the person was walking and was probably transferring from one metro/RER line to another. The algorithm eliminated the first and last two minutes of the trip under the logic that if a person needs to transfer stations they wouldn’t do it for a single stop.

If the algorithm came up with several timeframes or no changes in the accelerometry data only for those trips with the help of the RATP webpage, the start station, end station, and start time were inserted. In the case, the algorithm gave several alternatives the closest to the RATP suggested route was selected. When the algorithm came with no solution, the filter of the first and last two minutes was removed, and if a solution was proposed and confirmed by the RATP page it was selected. If there was no solution the suggested route was selected.

Once all the transfer times were selected for all the participants, this was used to calculate the new correct start and stop times of each of the trip stages. The start time of the transfer was the end time for the first route, and then the next route would have the start time as the end of the transfer. The pollution data was re-calculated with the new start and stop times so that each trip stage would have its corresponding pollution data.

For the car model, the following variables were created: 1) the categorization of the engine size according to the number of cylinders, 2) the age of the car based on the year of production, with 2020 as the current year because that was when the last of the data for the project was collected, 3) the kilometers per year based on the French average and the age of the car, and 4) the fuel type: divided between gasoline, diesel and a category of alternative fuel that encompasses all the other types of fuel. The data was managed based on the Euro Standard and Crit'Air classifications.

2.6 Statistical analysis

Each mobility track was analyzed and compared to other tracks within the same transport mode, meaning the data collected from the metro system is divided into the 16 metro lines that exist in Paris, these were compared against each other, and the RER was the comparison of the 5 lines, the bus and the tram were taken as a whole. A variable called trip duration was calculated between the start and stop time to be used as weights for the model.

The statistical analysis was done with the statistical software of Rstudio 4.2. The models were performed with the Lmer package for its mixed effects models (34). First, a descriptive statistical analysis between the pollutants and covariables was performed. Then a basic analysis was performed and the outliers in each transport mode were eliminated.

After data management, a multilevel linear regression model for each transportation mode was created. A random intercept at the participant level was added. The covariables of temperature, relative humidity, workday, season, rush hour, income level of the individual and the neighborhood, rolling stock, and automatization were tested in a forward analysis. The best model was selected according to the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) measurements. The model included weight based on the duration of the trip. The final model consists of the following covariables: temperature, relative humidity, workday, rush hour, and season. Temporal autoregression at level 1 was also tested but following the AIC and BIC measurements, the model without it was better.

This first model was for the metro, then the same method was applied to all public transport categories: RER using the lines as categorical values, followed by the bus and tram. For consistency, the same model was selected across transportation modes.

In total 1801 car trips were recorded but for the models, the selection was based on the availability for the Euro Standard and Crit'Air classification, with 1799 trips. The model in cars was done first according to the Euro Standard classification and after with the Crit'Air classification, the same covariates as in public transport were selected.

A separate model was constructed to see if the car characteristics could explain the levels of exposure to air pollution, the tested additional covariables were: brand, age, mileage, mileage per year, engine size, and fuel type. The best model was selected based on AIC and BIC measurements. The best model only included age and brand, but for the final model engine and fuel type were also included for their implication in the production of pollution. A model was created with only the car characteristics and then the Euro Standard classification and Crit'Air were added to each model removing the variables that could cause multicollinearity, age was removed from the Euro Standard model, as for the Crit'Air model the variables that were removed were age and fuel type.

3. Results

3.1 Descriptive statistics of the sample

The results of the descriptive statistics are summarized in Table 1 showing the average pollution in each transportation mode. The dataset was compromised for the metro, 1123 trips were recorded across 14 lines, no trips were recorded for line 3bis, and for line 7bis only 3 trips were registered and eliminated due to the size not being representative. During metro trips, the mean of NO_2 measured by the captors was 19.41 ppb, the mean of CO was 0.63 ppm and the mean of BC was 4.67 mg/m^3.

For the RER across the 5 lines, 455 trips were collected the average of the measured pollutants was 17.87 ppb for NO_2, 0.56 ppm for CO, and 4.85 mg/m^3 for BC. The bus recorded 325 trips; the average pollutants recorded in the trip stage were 23.03 ppb for NO_2, CO 0.72 ppm, and 2.94 mg/m^3 for BC. The tram recorded 116 trips the average each trip stage recorded was of NO_2 18.45 ppb, CO was 0.54 ppm, and BC was 1.79 mg/m^3. In the case of the metro and RER, the least polluted was selected as the reference for the models.

The cars were classified by their Euro Standard with a total of 1801. The oldest cars in the sample are Euro Standard 3 with 242 trips, followed by 282 in Euro Standard 4, 512 trips for Euro Standard 5, and 765 for Euro Standard 6. No cars with Euro Standard 1 or 2 were recorded in the sample. The levels of air pollutants measured by the captors as a whole were 13.17 ppm for NO_2, 0.86 ppb for CO, and 2.95 mg/m^3 for black carbon.

Following Crit'Air the sample size is 1799 trips with average exposure to air pollutants of NO$_2$ of 13.23 ppm, 0.85 ppb for CO, and 2.95 mg/m^3 for black carbon. There are no cars with a 0 classification, 539 trips recorded in Crit'Air 1, 841 in Crit'Air 2, 274 in Crit'Air 3, and 145 in Crit'Air 4.

Table 1. Descriptive table of pollution in mobility tracks divided into mobility type.

Mobility Type		**No. of trips**	**Mean of NO$_2$ (ppm)**	**Mean of CO (ppb)**	**Mean of BC (mg/m^3)**
Metro		***1123***	**19.41**	**0.63**	**4.67**
	Line 1	168	21.25 ↑	0.67 ↑	4.62
	Line 2	70	18.00	0.67 ↑	4.44
	Line 3	101	21.50 ↑	0.62	3.79
	Line 4	114	17.36	0.63	4.42
	Line 5	67	13.79	0.48	6.22 ↑
	Line 6	76	17.83	0.43	2.46
	Line 7	67	18.20	0.93 ↑	4.65
	Line 8	114	20.32 ↑	0.74 ↑	5.61 ↑
	Line 9	85	16.84	0.62	4.97 ↑
	Line 10	50	24.89 ↑	0.69 ↑	3.20
	Line 11	11	19.45 ↑	0.76 ↑	3.90
	Line 12	66	17.93	0.59	4.20
	Line 13	77	24.76 ↑	0.68 ↑	7.11 ↑
	Line 14	57	20.24 ↑	0.42	4.57
RER		***455***	**17.87**	**0.56**	**4.85**
	RER A	181	17.60	0.56	6.76 ↑
	RER B	119	19.06 ↑	0.61 ↑	4.28
	RER C	54	19.71 ↑	0.58 ↑	2.23
	RER D	38	13.66	0.43	2.39
	RER E	63	18.62 ↑	0.57 ↑	2.76
Bus		***325***	**23.03**	**0.72**	**2.94**
Tram		***116***	**18.45**	**0.54**	**1.79**
Cars	**Euro Standard**	***1801***	**13.17**	**0.86**	**2.95**
	3 (2001, 2005)	242	14.94 ↑	0.78	3.72 ↑
	4 (2006, 2010)	282	14.49 ↑	0.84	3.56 ↑

	5 (2011, 2014)	512	12.19	0.94 ↑	2.76
	6 (>2014)	765	12.83	0.84	2.63
Cars	**Crit'Air**	***1799***	**13.23**	**0.85**	**2.95**
	1 (Euro S. 5/6, gasoline)	539	12.59	0.80	2.28
	2 (Euro S. 4, gasoline/Euro S. 5/6, diesel)	841	13.12	0.94 ↑	3.06 ↑
	3 (Euro S. 2/3, gasoline/Euro S. 4, diesel)	274	13.45 ↑	0.79	3.22 ↑
	4 (Euro S. 3, diesel)	145	15.24 ↑	0.73	4.24 ↑

3.2 Individual exposure to air pollution in public transport. Intramobility analysis.

In Table 2, there is a summary of the first model that considers the transportation modes as a whole with the tram as the reference. For the pollutant of $NO_{2,}$ there was an association with the bus as those that traveled by bus were exposed to 4.56 ppm (95% CI 1.57, 7.54) in comparison to those that used the tram, on the opposite those that used a car were exposed to -4.67 ppm (95% CI -7.55, -1.79) less than the one that used the tram.

For CO no associations were found in the level of exposure during the use of public transportation. For BC the people who used the metro were exposed to 3.76 mg/m^3 (95% 1.49, 6.04) more than the participants who used the tram, while the exposure of those who used the RER was 2.79 mg/m^3 (95% CI 0.46, 5.11) in comparison to the tram, the participants that used the car were exposed to 2.59 mg/m^3 (95% CI 0.32, 4.86) in respect to the tram. For the pollutant of NO_2 and CO there were 2362 observations and for BC there were 1082.

Table 2. Level of exposure to air pollution in public transportation.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
Trans	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
Tram	*Reference*		*Reference*		*Reference*	
Metro	-0.91	(-3.76, 1.93)	-0.05	(-0.68, 0.58)	3.76	(1.49, 6.04)
RER	-1.57	(-4.43, 1.29)	0.06	(-0.57, 0.69)	2.79	(0.46, 5.11)
Bus	4.56	(1.57, 7.54)	0.21	(-0.46, 0.87)	1.82	(-0.58, 4.23)
Cars	-4.67	(-7.55, -1.79)	0.54	(-0.09, 1.18)	2.59	(0.32, 4.86)
Random effect						
σ^2	782.41		38.36		185.46	
τ_{00}	393.84		11.08		5.61	
ICC	0.33		0.22		0.03	
Marginal R^2/ Conditional R^2						
	0.014/0.344		0.003/0.227		0.007/0.036	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration. Observations: 2362 for NO_2 and CO; 1082 for BC.

3.2.1 Metro

Table 3. Levels of exposure to air pollution in the metro lines.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
Metro	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
1	6.19	(2.44, 9.94)	0.19	(0.08, 0.31)	3.53	(1.83, 5.22)
2	3.56	(-0.65, 7.78)	0.17	(0.03, 0.32)	1.80	(-0.34, 3.95)
3	6.77	(2.54, 11.00)	0.15	(0.01, 0.29)	1.44	(-0.63, 3.52)
4	3.91	(0.11, 7.71)	0.14	(0.01, 0.27)	0.83	(-1.31, 2.96)
5	*Reference*		0.03	(-0.12, 0.18)	3.15	(0.89, 5.41)
6	5.64	(1.65, 9.63)	*Reference*		*Reference*	
7	6.86	(0.50, 13.22)	0.30	(0.07, 0.52)	2.55	(-0.18, 5.27)
8	5.99	(2.20, 9.87)	0.19	(0.06, 0.31)	3.57	(1.83, 5.31)
9	6.19	(2.29, 10.08)	0.17	(0.04, 0.30)	3.56	(1.70, 5.42)
10	7.61	(3.00, 12.22)	0.19	(0.03, 0.34)	2.07	(-0.26, 4.39)
11	5.07	(-1.74, 11.87)	0.24	(-0.01, 0.49)	1.04	(-2.27, 4.36)
12	3.09	(-1.21, 7.31)	0.18	(0.04, 0.32)	2.04	(0.04, 4.05)
13	9.28	(4.95, 13.62)	0.18	(0.03, 0.32)	4.61	(2.44, 6.79)
14	5.42	(0.32, 10.52)	0.03	(-0.41, 0.21)	2.87	(0.25, 5.48)
Random effect						
σ^2	415.62		0.64		64.75	
τ_{00}	23.55		0.02		3.72	
ICC	0.05		0.03		0.05	
Marginal R^2/ Conditional R^2						
	0.030/0.082		0.022/0.053		0.046/0.098	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration. Observations: 506 for NO_2 and CO; 248 for BC.

The least polluted lines were selected as the reference for each pollutant. For the pollutant of NO_2, metro line 5 was the reference, the results are displayed in Table 3. The associated lines are the following: participants are exposed to an increase of 6.19 ppb (95% CI 2.44, 9.44) in exposure to NO_2 in comparison to line 5. The participants that traveled in line 3 had an increased exposure of 6.77 ppb (95% CI 2.54, 11.00) than those in line 5. In comparison to the reference when using line 4 the exposure was of 3.91 ppb (95% CI 0.11, 7.11). Participants were exposed to 5.64 ppb (95% CI 1.65-9.63) more than the reference when using line 6; while in line 7 the excess of exposure was 6.86 ppb (95% CI 0.50, 13.22) in comparison to line 5. Those who travel in line 8 were exposed to 5.99 ppb (95% CI 2.20, 9.78) than those in line 5, and those in line 9 had an increase of 6.19 ppb (95% CI 2.29, 10.08) more than the ones in line 5.

Compared to line 5, the participants that used line 10 had an exposure of 7.61 ppb (95% CI 3.00, 12.22), while in line 13 the exposure was 9.28 ppb (95% CI 4.95-13.62) in comparison to metro line 5; lastly, for metro 14, the exposure increased by 5.42 ppb (95% CI 0.32, 10.52) against the reference. The variance of 23.55 showed a moderate variability in the levels of NO_2 due to the participants, while the residual variance of 415.62 showed high within-participant variability but the ICC of 5% explanation by the differences of the participants. The fixed effect explained 3% of the variance in the levels of NO_2, the total variance explained by the models is 0.0082. There were 506 observations of individual exposure to NO_2 in the metro lines.

For the pollutant CO, metro line 6 was the reference as it exposed the participants to the lowest levels of pollution, for the analysis the lines associated are the following: The participants that used line 1 had an increase in exposure of 0.19 ppm (95% CI 0.08, 0.31) against line 6, those that use line 2 had an exposure of 0.17 ppm (95% CI 0.03, 0.32), the ones that traveled by line 3 were exposed to 0.15 ppm (95% CI 0.01, 0.29), and in line 4 0.14 ppm (95% CI 0.01, 0.27) in comparison to the reference. As compared to line 6 the participants that used line 7 had an exposure of 0.30 ppm (95% CI 0.07, 0.52), while the ones that used line 8 were exposed to 0.19 ppm (95% CI 0.06, 0.31), in line 9 they were exposed to 0.17 ppm (95% CI 0.03, 0.34) more than the reference.

The study participants who took line 10 had 0.19 ppm (95% CI 0.03, 0.34) more exposure in comparison to line 6, while those who used line 12 were exposed to 0.18 ppm (95% CI 0.04, 0.32) more than those that use line 6, while the people that traveled in line 13 had an exposure of 0.18 ppm (95% CI 0.03, 0.32) in comparison to line 6. The variance of the random effect was low at 0.02, as well as the residual variance was 0.64, with an ICC of 3% explaining the variability of CO due to differences in the participants. The fixed effects explained 2.2% of the variability in the levels of CO, while the total variance explained is 0.053. There were 506 observations of individual exposure to CO in the metro lines.

Lastly, for black carbon the lines that show association using line 6 as the reference were: the participants that used line 1 with an increase of 3.53 mg/m^3 (95% CI 1.83, 5.22) in exposure in comparison to line 6, while for those that use line 5, the exposure increased to 3.15 mg/m^3 (95% CI 0.89, 5.41), the participants that traveled in line 8 showed exposure of 3.57 mg/m^3 (95% CI 1.83, 5.31) in comparison to line 6.

The people that used line 9 had a raise of exposure of 3.56 mg/m^3 (95% CI 1.70, 5.24) against the reference, while if line 12 was the one used the exposure was of 2.04 mg/m^3 (95% CI 0.04, 4.05) in comparison to metro line 6. The participants that traveled in line 13 had an exposure of 4.16 mg/m^3 (95% CI 2.44, 6.79) in comparison to the reference and finally, line 14 had an exposure of 2.87 mg/m^3 (95% CI 0.25, 5.48) in comparison to line 6. The variance was 3.72, while the residual variance was moderate at 64.75 and the interclass correlation coefficient of 5% of the variability of black carbon was due to differences in the participants. The fixed effects explain 4.6% of the variance in BC, while the total was 0.098. There were 248 observations of individual exposure to black carbon in the metro lines.

3.2.2 RER

Table 4. Level of exposure to air pollution in the RER lines.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
RER	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
A	0.92	(-3.00, 4.83)	0.12	(-0.00, 0.25)	4.87	(1.82, 7.91)
B	2.50	(-1.24, 6.24)	0.10	(-0.02, 0.21)	3.25	(-0.04, 6.55)
C	3.00	(-1.53, 7.54)	0.04	(-0.10, 0.19)	0.27	(-4.32, 4.85)
D	*Reference*		*Reference*		*Reference*	
E	1.90	(-2.85, 6.65)	0.18	(0.03, 0.33)	2.07	(-1.46, 5.61)
Random effect						
σ^2	552.27		0.51		155.40	
τ_{00}	18.05		0.02		2.72	
ICC	0.03		0.04		0.02	
Marginal R^2/ Conditional R^2						
	0.025/0.056		0.020/0.058		0.017/0.034	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration. Observations: 235 for NO_2 and CO; 97 for BC.

On the other hand in Table 4, for the RER, after being adjusted by the covariables and setting RER D as the reference none of the lines showed associated differences in the level of NO_2, there is an associated difference between the levels of CO in RER D and RER E with the participants that used this one having an increase of 0.18 ppm (95% CI 0.03, 0.33) with a 4% of the variability being explained by the differences in participants, for black carbon the individual exposure on RER A was of 4.87 mg/m^3 (95% CI 1.82, 7.91) more than the exposure in RER D, 2% due to the participant variability.

3.3 Individual exposure to air pollution in private transport.

3.3.1 Euro Standard classification

No associations were found between the level of the Euro Standard of cars and the exposure to air pollutants, with the reference being Euro Standard 6 as the newest cars. There were 909 observations for NO_2 and CO and 382 for black carbon, as shown in Table 5.

Table 5. Levels of exposure to air pollution in the car according to Euro Standard.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
Euro Stan.	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
6 (>2014)	*Reference*		*Reference*		*Reference*	
5 (2011, 2014)	-0.88	(-3.27, 1.51)	0.04	(-0.10, 0.19)	0.10	(-1.01, 1.21)
4 (2006, 2010)	0.20	(-2.33, 2.72)	-0.04	(-0.20, 0.12)	0.75	(-0.78, 2.10)
3 (2001, 2005)	1.63	(-1.77, 5.03)	-0.12	(-0.32, 0.09)	0.86	(-0.72, 2.52)

Random effect			
σ^2	535.94	2.63	63.45
τ_{00}	23.82	0.08	3.78
ICC	0.04	0.03	0.06
Marginal R^2/ Conditional R^2			
	0.009/0.051	0.004/0.033	0.009/0.065

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration. Observations: 909 for NO_2 and CO; 382 for BC.

3.3.2 Crit'Air classification

When modeling individual exposure to air pollutants considering the Crit'Air system of cars, the reference was set to Crit'Air 1 as the category for the newest cars. Results showed 1.37 mg/m^3 (95% CI 0.31, 2.43) in the individual exposure to black carbon when participants commuted in Crit'Air 2 cars compared to those classified in Crit'Air 1, as seen in Table 6.

Table 6. Levels of exposure to air pollution in the car according to Crit'Air.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
Crit'Air	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
1 (Euro S. 5/6, gasoline)	*Reference*		*Reference*		*Reference*	
2 (Euro S. 4, gasoline/Euro S. 5/6, diesel)	0.75	(-1.57, 3.06)	0.09	(-0.05, 0.23)	1.37	(0.31, 2.43)
3 (Euro S. 2/3, gasoline/Euro S. 4, diesel)	1.60	(-1.60, 4.80)	-0.07	(-0.26, 0.13)	1.34	(-0.24, 2.93)
4 (Euro S. 3, diesel)	2.58	(-1.99, 7.16)	-0.18	(-0.45, 0.09)	1.88	(-0.05, 3.80)
Random effect						
σ^2	535.63		2.63		63.25	
τ_{00}	24.00		0.08		3.49	
ICC	0.04		0.03		0.05	
Marginal R^2/ Conditional R^2						
	0.009/0.051		0.005/0.033		0.014/0.065	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration. Observations: 909 for NO_2 and CO; 382 for BC.

3.3.3 Car characteristics

3.3.3.1 Euro Standard

In the model that evaluated the individual exposure to air pollutants considering the Euro Standard and the car characteristics presented in Table 7, no associations for NO_2 were found. For the pollutant of CO, the participants who had used an Audi car were exposed to 0.53 ppb (95% CI 0.02, 1.04) in comparison to those who used a Toyota car, and for BC, the participants that had a Peugeot car were exposed in the cabin to 2.92 mg/m^3 (95% CI 0.46, 5.39) more than the participants with a Toyota car and the ones with a Renault car were exposed to 2.91 mg/m^3 (95% CI 0.66, 5.17) in comparison to Toyota as the reference, and those that had a diesel-powered car were exposed to levels of 1.33 mg/m^3 (95% CI 0.19, 2.48) in black carbon in comparison to those that a gasoline car.

Table 7. Levels of exposure to air pollution due to car characteristics according to Euro Standard.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
Euro Standard						
6 (>2014)	*Reference*		*Reference*		*Reference*	
5 (2011, 2014)	-0.84	(-3.41, 1.72)	0.01	(-0.42, 0.71)	-0.35	(-1.51, 0.81)
4 (2006, 2010)	1.67	(-1.18, 4.52)	-0.08	(-0.15, 0.17)	0.68	(-0.83, 2.20)
3 (2001, 2005)	2.59	(-1.06, 6.24)	-0.07	(-0.25, 0.10)	1.15	(-0.59, 2.88)
Fuel type						
Gasoline	*Reference*		*Reference*		*Reference*	
Diesel	1.26	(-1.14, 3.67)	-0.02	(-0.13, 0.17)	1.33	(0.19, 2.48)
Alternative	0.24	(-6.50, 6.99)	-0.06	(-0.36, 0.47)	-0.13	(-3.05, 2.79)
Engine size						
Small	*Reference*		*Reference*		*Reference*	
Medium	0.19	(-2.03, 2.41)	-0.08	(-0.22, 0.06)	-0.40	(-1.62, 0.82)
Large	-1.83	(-8.95, 5.29)	-0.17	(-0.61, 0.26)	-1.67	(-5.92, 2.58)
Brands						
Toyota	*Reference*		*Reference*		*Reference*	
Audi	-2.64	(-10.85, 5.56)	0.53	(0.02, 1.04)	1.87	(-2.21, 5.96)
BMW	-1.00	(-9.07, 7.07)	0.47	(-0.04, 0.99)	2.91	(-2.62, 8.43)
Citroen	1.57	(-3.35, 6.50)	0.11	(-0.20, 0.42)	2.00	(-0.52, 4.53)
Dacia	6.22	(-1.41, 13.85)	-0.00	(-0.48, 0.47)	2.73	(-0.60, 6.06)
Fiat	4.25	(-3.18, 11.67)	0.27	(-0.19, 0.73)	2.49	(-0.72, 5.71)
Ford	-4.54	(-13.20, 4.12)	-0.09	(-0.62, 0.44)	1.37	(-2.37, 5.12)
Nissan	2.79	(-3.58, 9.16)	0.04	(-0.36, 0.43)	0.41	(-3.02, 3.83)
Other	1.09	(-3.52, 5.70)	0.14	(-0.15, 0.44)	1.66	(-0.89, 4.22)
Peugeot	1.05	(-3.75, 5.86)	0.10	(-0.20, 0.40)	2.92	(0.46, 5.39)
Renault	3.45	(-0.54, 7.44)	0.04	(-0.22, 0.29)	2.91	(0.66, 5.17)
Volkswagen	1.00	(-4.70, 6.69)	0.08	(-0.27, 0.43)	0.52	(-2.27, 3.31)
Random Effect						
σ^2	532.80		2.62		62.59	
τ_{00}	25.16		0.09		3.62	
ICC	0.05		0.03		0.05	
Marginal R^2/ Conditional R^2						
	0.016 / 0.060		0.007 / 0.039		0.027 / 0.080	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: Trip duration
Observations: 909 for NO_2 and CO; 382 for BC.

3.3.3.2 Crit'Air

The model that considers car characteristics and Crit'Air is in Table 8, where no associations were found for NO_2 and CO. But for black carbon, all the Crit'Air levels show association in comparison to Crit'Air 1 as the reference, for the participants that used a Crit'Air 2 car the individual exposure was 1.63 mg/m^3 (95% CI 0.39, 2.87) in comparison to Crit'Air 1, the ones that had a Crit'Air 3 car were exposed to 2.00 mg/m^3 (95% CI 0.23, 3.78) in comparison to the reference, as for Crit'Air 4 cars the exposure was of 2.49 mg/m^3 (95% CI 0.22, 4.75) in comparison to the people that use Crit'Air 1 cars. For the brands in comparison to the reference of Toyota, the participants that had a Peugeot car were exposed in the cabin to 2.88 mg/m^3 (95% CI 0.47, 5.29) in comparison to the participants that used Toyota cars, as for the people that used a Renault car the exposure to black carbon was of 2.71 mg/m^3 (95% CI 0.46, 4.96) in comparison to the people that used Toyota cars.

Table 8. Levels of exposure to air pollution due to car characteristics according to Crit'Air.

	NO_2 (ppm)		CO (ppb)		BC (mg/m^3)	
	Estimate	CI (95%)	Estimate	CI (95%)	Estimate	CI (95%)
Crit'Air						
1 (Euro S. 5/6, gasoline)	*Reference*		*Reference*		*Reference*	
2 (Euro S. 4, gasoline/Euro S. 5/6, diesel)	1.57	(-1.01, 4.16)	0.11	(-0.05, 0.26)	1.63	(0.39, 2.87)
3 (Euro S. 2/3, gasoline/Euro S. 4, diesel)	2.76	(-0.74, 6.26)	-0.04	(-0.25, 0.17)	2.00	(0.23, 3.78)
4 (Euro S. 3, diesel)	4.62	(-0.55, 9.79)	-0.12	(-0.43, 0.20)	2.49	(0.22, 4.75)
Engine size						
Small	*Reference*		*Reference*		*Reference*	
Medium	-0.03	(-1.95, 1.90)	-0.06	(-0.19, 0.06)	-0.46	(-1.61, 0.68)
Large	-1.65	(-8.55, 5.24)	-0.17	(-0.58, 0.24)	-1.47	(-5.65, 2.71)
Brands						
Toyota	*Reference*		*Reference*		*Reference*	
Audi	-2.74	(-10.75, 5.27)	0.47	(-0.02, 0.96)	1.80	(-2.15, 5.74)
BMW	-1.21	(-9.19, 6.78)	0.44	(-0.07, 0.94)	2.86	(-2.53, 8.24)
Citroen	1.53	(-3.22, 6.28)	0.07	(-0.22, 0.37)	1.93	(-0.56, 4.42)
Dacia	6.30	(-1.28, 13.88)	0.05	(-0.41, 0.51)	2.99	(-0.31, 6.30)
Fiat	4.16	(-3.14, 11.46)	0.26	(-0.18, 0.70)	2.60	(-0.56, 5.76)
Ford	-4.63	(-13.46, 4.19)	-0.08	(-0.61, 0.45)	1.47	(-2.37, 5.30)
Nissan	2.99	(-3.14, 9.13)	0.02	(-0.35, 0.40)	0.30	(-3.04, 3.64)
Other	1.03	(-3.44, 5.51)	0.08	(-0.20, 0.37)	1.45	(-1.13, 4.04)
Peugeot	1.15	(-3.42, 5.71)	0.07	(-0.21, 0.36)	2.88	(0.47, 5.29)
Renault	3.35	(-0.52, 7.21)	0.01	(-0.24, 0.25)	2.71	(0.46, 4.96)
Volkswagen	1.19	(-4.37, 6.75)	0.06	(-0.28, 0.40)	0.68	(-2.15, 3.50)
Random Effect						
σ^2	532.09		2.62		62.28	
τ_{00}	25.03		0.08		3.54	
ICC	0.04		0.03		0.05	
Marginal R^2/Conditional R^2						
	0.016 / 0.061		0.008 / 0.038		0.027 / 0.080	

Covariables: temperature, relative humidity, workday, rush hour, season. Weights: trip duration
Observations: 909 for NO_2 and CO; 382 for BC.

4. Discussion

The main aim of this study was to evaluate the differences in exposure in the transport modalities available in Paris, which included metro, RER, bus, tram, and private cars. Microenvironments and their exposure to air pollution during the commute are a new area of study (18). Most studies on air pollution evaluate it at the neighborhood level and attribute the different components to traffic-related pollution (14), some studies evaluate the exposure to air pollution during the commute by comparing different transportation systems, but this is the first study in Paris that explores differences in air pollution exposure in the metro or RER lines instead of evaluating the levels of pollution considering public transport type.

4.1 Public transport

Following the literature, (26) the tram is recognized to expose participants to the lowest levels of individual exposure to air pollution overall but in this particular study it was only confirmed for the pollutant of black carbon. The bus as a method of transportation was only associated with the levels of NO_2 but found no relation with the other pollutants which differs from the existing literature (18). The results from the tram and the bus could be due to a low sample size, underpowering the model.

The main source of black carbon in underground transportation modes is from the wear of metal due to friction between wheels and rails, the wear of the braking system, particle resuspension due to the movement of passengers and trains; and infiltration of particles from the outdoor air. Carbon monoxide primarily comes from indoor combustion activity and infiltration from outdoor vehicular exhaust emissions, the last one also being responsible for the NO_2 levels (35).

In the case of the metro, Airparif explains that the factors that affect the quality of the air are the size of the station, the depth of the station, the ventilation system, if the same station serves the metro and RER, how often the metro runs, and the age of the station (36). And that the levels of NO_2 in the metro stations tend to be lower than in outdoor air, particular matter being more prevalent because of the resuspension of the particles if the metro runs often or if it carries a high number of passengers and the braking system (36).

In collaboration with Ile de France Mobilites, Airparif published the levels of particulate matter in 44 stations, there is no geographical pattern that would explain the different levels of pollution (36). Following that trend, a news station France 5 also measured the levels of $PM_{2.5}$ at the exit of the tunnels of the metro stations and found the highest levels of pollutants are in metro line 5, RER A, lines 9, 2, 7, 8, 13 (28). Even if these studies start exploring the heterogeneity of air pollutants within the metro lines, these studies focus on PM and the station level, missing individual exposure during the trips. Measuring the real individual exposure during the whole trip (inside the metro cabin, at the station level, and in the transfer tunnels) the present study adds important information and awareness of the health risks due to environmental exposure during daily commuting.

The main results of this study showed that individuals were exposed to the highest levels of NO_2 and black carbon when commuting in line 13, the reason could be the amount of use the line has due to having a high number of passengers, the age of the structure and the length of the metro line (with 32 stations being the longest in Paris) (37). These results are in line with the study of air quality and social deprivation in four French metropolitan areas (38) that imputed this metro also serves the area of Seine-Saint-Denis an urban zone with poor air quality levels compared to the western Haut de Seine department. According to the same study, a positive relation between the levels of NO_2 and the proportion of immigrants was found to live in areas served by line 13 (38). For carbon monoxide, the levels of line 13 are on average with the other lines.

10 out of 14 lines exposed people to high values of carbon monoxide (between +0.17 or +0.19 ppb) compared to line 6. In contrast with other lines, metro line 7 registered a much higher level of exposure with +0.30 ppb of carbon monoxide compared to metro line 6. As it was for metro line 13, metro line 7 is also one of the longest lines in Paris (37). One explanation is that the territorial extension of the metro lines could contribute to the levels of carbon monoxide further studies need to be performed to confirm this theory. Metro lines 7 and 13 are the longest in Paris and have dividing branches at the end.

Metro lines 7, 8, and 13 have the same carriages MF 77 a steel wheel commissioned in 1977 (37). Metro lines 13 and 7 were refurbished completely and the fleet of line 8 is in the process. Those 3 lines show high levels of pollution beyond possible spatial inequalities in the areas the metro serves. One of the reasons for higher levels of pollution in metro lines 7, 8, and 13 in comparison to lines 5 or 6 could be the age of the fleet, the lack of maintenance, and the characteristics of the machinery (35). Metro lines 7 and 8 are planned to receive a new MF 19 fleet, after these changes a new study should examine if the levels of pollution will decrease with the update.

The least polluted line for NO_2 and CO is line 4, it could be due to the automatization of the line making it more efficient. Another reason can be due to the installation of platform screen doors. According to this, a previous study in Korea found that the doors decreased the levels of PM_{10} by 16% and $PM_{2.5}$ by 12% in the station (39).

A previous study using the MobiliSense data found high levels of black carbon in the metro. (26) The Paris metro has 2 types of rolling stock rubber tires that are in lines 1, 4, 6, 11, and 14 or the traditional steel wheel that is common worldwide for the rest of the lines, because of the friction of two steel parts and the possible use of friction-based brakes these could have slightly higher levels of black carbon and it is proven with the data from this study.

In this study, the participants who used steel wheel metro lines were exposed to more black carbon than the participants who used metro lines with rubber tires. Black carbon was associated only in lines 1 and 14, which have a lower level of black carbon than the steel wheel lines.

The idea to automatize the metro to reduce the amount of exposure to air pollution may have more implications; Paris metro lines 1, 4, and 14 are automatic and the people who took those lines had on average the same levels of exposure to air pollution that in other lines. It is important to mention that the automatization of these lines increased the frequency of the metro, which could be a factor to consider meaning that the automatization itself may reduce the level of pollution but because they are more frequent (automatic lines run every two minutes while the rest run in average every 3 to 4 minutes) they risk to expose individuals to the same levels of pollutants than non-automatic lines (37).

For the RER, no associations were found for the levels of personal exposure to NO_2, for the levels of CO, RER E had higher levels of exposure than RER D, and for BC the association that was found was for RER A which had much higher levels of personal exposure of BC than RER D with 4.87 mg/m^3, this is accurate to the previous study from France 5 that reported that RER A had the highest number of $PM_{2.5}$ (28).

4.2 Private transport

Individual exposure to air pollution should be declining with the introduction of the newer and better Euro Standard criteria, but a different trend was found in this study. Euro Standard 6 is still higher than Euro Standard 2 for NO_2, while 3 and 5 are within limits, probably because of the need to reduce CO_2 emissions other pollutants have increased in compensation (40). In this study even if there is no association in the data, there was a decrease from Euro Standard 3 and 4, but an increase with Euro Standard 5 for NO_2 proving that the Euro Standard categorization does not reduce the levels of individual exposure to NO_2. There is evidence that NOx emissions in diesel cars have not decreased over the different euro standards but only for gasoline cars, meaning that low emission zones based on the Euro standard are less effective (41).

Because the Euro Standard only considers the year of manufacturing it could be that the trends are not decreasing when the sample is not divided by other factors like fuel. There is also an increase in the levels of CO following the Euro Standard which is the opposite of what should happen, with Euro Standard 3 and 4 producing less than 5 and 6. The trend of decreasing levels of BC has been respected, with each car with a new Euro Standard exposing the participants to less black carbon.

However, for the Crit'Air division even if no associations were found in the case of NO_2 there is a downward trend with the best category 1 producing less NO_2. For CO there is an upward trend that is the opposite of what was expected but the same as with the Euro Standard classification. An association between the classification of Crit'Air 2 and BC was found, however, it was higher than the no associated Crit'Air 3 and should be lower, with Crit'Air 4 as the lowest.

The division of Euro Standard and Crit'Air as categorization criteria was chosen because Crit'Air includes fuel type, meaning that perhaps there is a connection between the exposure of NO_2 and fuel and that is the reason the categories gave opposite results. For CO there are suggestions that the newer cars have worse filters and have less air tightness, resulting in higher levels of exposure in the cabin (42). The trends for CO and NO_2 are stable throughout the models in this study but not for black carbon indicating that there is probably another car characteristic that was not considered that could be influencing the personal exposure to the pollutant.

The models with car characteristics and the Euro Standard or Crit'Air follow the same tendencies previously explained, for NO_2 with Euro Standard 5 emitting less than Euro Standard 6, for CO Euro Standard 3 and 4 emitting less than 6. On the contrary, for BC Euro Standard 5 exposes the individuals to less black carbon than Euro Standard 6, probably the change is due to the adjustment of this model to fuel type. The same applies for Crit'Air in NO_2 the model also shows a descending trend, for CO the classification of 3 and 4 produce less than 1 and for BC the descending trend has an association for all the levels.

Even when factors like fuel type and engine size are considered, the Euro Standard fails to reduce the individual exposure to NO_2 in the cabin. Previous literature, (42) could be correct to suggest that in newer cars there is an infiltration of CO to the cabin regardless of the classification system and other variables. As for black carbon, there could be other variables that were not taken into consideration in this study that could explain the fluctuation in the models. Regardless a more complete categorization as Crit'Air is preferable to the Euro Standard.

In the car characteristics model, the levels of exposure to NO_2 increase with age, confirmed by, a study from the UK found a negative relationship between the age of the vehicle and the levels of NO_2 explaining that older vehicles are less leaky and have less air tightness(43). Even if there is no association larger engines produce less emissions than smaller engines, as confirmed by a study done on taxi drivers in Paris (42).

Regarding fuel type, in this study, the levels of in-cabin individual exposure to NO_2 and BC are higher than in cars that were gasoline-powered. A previous London-based study found that exposure to BC and NO_2 in taxi drivers would double if the car was diesel compared to an electric one, and gasoline was higher than diesel (44).

For the brands of the cars, there was an association for Audi, Renault, and Peugeot in comparison to the participants that used a Toyota car with different levels of pollution depending on the model, it is important to note that the sample of this study was deeply French, with an higher number of French-branded cars, meaning the sample would have higher statistical power to detect the changes in this brands, other brands have the same point estimate but because there were fewer cars the confidence interval widens making it less sensible. Even though the models presented in this study can be indicative of certain trends they cannot be considered as absolute because there are several characteristics of the vehicles that were not considered, as well as maintenance or the performance of the on the road.

4.3 Limitations

As previously mentioned during the data management section a small part of the data was not divided into trip stages. Even if the management and solution for this was at the best of the authors' and team's ability, it could have misclassified certain trips in the metro or RER. However, all possible checks were performed to guarantee the best selection of the solutions.

There was a small percentage of missing data for the car characteristics so open data was recollected to fill most of it, as the owner could have modified the cars or there are several models with slightly different characteristics misclassification could be possible, even if the data that was recollected was minimal and would not be statistically significant.

According to the literature (32), the levels of pollution inside the cabin are dependent on the windows of the car being open or closed, the heating or air conditioner being on, and if the air is recirculating, this data was not collected for MobiliSense and no proxies exist for this type of variable, as so nothing to mediate this effect was included in the models. Other data that could modify the exposure to pollution is the maintenance of the cars, and the road performance this data was not recorded in the MobiliSense study.

Another possible limitation is that the levels of exposure to air pollution in the different transportation modes are affected by the levels of pollution in the surrounding area (36), a further step of this study could be adjusting the models to the levels of atmospheric pollution recorded by Airparif for outdoor environments in each GPS point of the trip.

The MobiliSense study was divided into two waves, the first was used in this study but the data from the second one needed to be pre-processed by a research assistant, and due to time constraints it was not possible to include it in this study.

4.4 Recommendations

The Paris metro system is exposing people to air pollution, but the exposure is not equal because some lines have a higher level than others, one of the drivers of pollution in the metro system is the age of the carriages. The lines with the highest pollution in this study were lines 7, 8, and 13 which currently have the oldest carriages and the refurbishing may not be enough. It is expected that new carriages will be provided for lines 7, 8, 12, and 13 from 2027 to 2033 but the project has a one-year delay. In regards to line 13, in December of 2022 it was authorized to be the next line to be automated starting with the new MF19 in 2027 and then with the installation of screen doors and the conversion to fully automatic within 10 years, this study further proves that the lines need to be updated to reduce the individual exposure to air pollution.

Installing screen doors in all stations is an effective way to lower the levels of all pollutants not only the ones measured in this study, as well as continuing the automatization process. As previously mentioned, the levels of individual exposure to black carbon were lower in a rubber tire system. Further studies and health impact assessments should be done to evaluate if the transition to rubber tire systems is feasible and to assess the environmental, economic, and health effects that this transition could have.

In regards to exposure to pollutants during car trips, Europe is known to have a higher number of diesel cars this needs to be lower preferably with a conversion to vehicles with alternative fuels that don’t depend on fossils. The Euro Standard needs to consider requiring real driving emission tests and set more strict standards following the lead of China and the USA, not only for CO_2 but for several pollutants. An alternative like Crit’Air should be encouraged in other areas of Europe or another classification system that considers other factors besides the manufacturing year.

5. Conclusion

The residents of Paris have known for years that the public transport system is detrimental to their health and have asked for reforms, this has not happened due to a lack of scientific data. In the exploration of the inter-variability of Paris public transport network, this paper confirms these findings. To the author’s knowledge, this is the first scientific paper that complies real-life data and analyzes the levels of exposure in the different mobility tracks, putting in evidence an outdated system in need of change that only reinforces inequality.

In the case of private transport Europe has been the leading voice in decreasing emissions and fighting climate change, but in the regulation of passenger vehicles it has been failing and is getting outdistance by the USA, China, and Japan; it is time that Europe stops prioritizing diesel cars as it has for the last 20 years and enforces further regulation in the industry. In the case of Paris, the introduction of Crit’Air as a combination of fuel and Euro Standard is a great step forward, with the stricter low-emission zone regulations getting introduced this year hopefully this will translate into a significant decrease in emissions. Furthermore, the reduction in emission of vehicles should also decrease the in-cabin exposure to air pollution.

Regardless of the use of public or private means of transportation during the commute, the individual levels of exposure to air pollution are understudied for this microenvironment. The health implications of the exposure throughout the day including the commute could be detrimental. Additionally, the use of fossil fuels to power transportation and its effects on global warming are well reported, and the further use of these fuels will only aggravate the situation including the health problems associated with climate change.

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