Personal exposure to air pollutants during everyday activities of hybrid office workers in the UK

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SUMMARY
Hybrid working and a change in transport behaviour raise the question of what are the new patterns of personal exposure to indoor air pollution during commuting and typical daily activities. This pilot study discusses the results from IAQ monitoring during long commute transects by train and car and during working remotely from home and in the office. The aim is to investigate exposure patterns to air pollutants and identify spot events of high exposure. The initial results present the NO_2 exposure in relation to the duration of commuting and workday. The findings discuss air quality-related risks to hybrid workers' health due to cumulative, long-term exposure. The paper concludes that often, people's workplace is not the main cause of exposure. Building design, neighbourhood, and town planning are necessary to provide good outdoor and indoor air quality both at home and office.

KEYWORDS
Indoor Air Pollution; Hybrid working; Exposure Timeline; Air Quality; Urban planning

1 INTRODUCTION
The recent COVID-19 pandemic has changed working patterns worldwide with remote working and flexible hours. In many cases, a hybrid working approach between office and work from home has been favoured by employees and employers alike (Umishio *et al.*, 2022). This has raised concerns about the indoor environmental quality as residential space and furniture have been repurposed as workspace. However, the heating and ventilation systems and control remained the same. Dwellings are likely to have reduced ventilation rates (Pietrogrande *et al.*, 2021) in comparison with regulation requirements for office buildings, leading potentially to higher exposure to air pollutants (Roh *et al.*, 2021) with marked health impacts (i.e., respiratory diseases). Existing literature has investigated the home-office indoor air quality and relevant health connections. However, it has not addressed the air pollution exposure during commuting yet. A study on commuting conducted before the pandemic suggests that commuting can cause elevated stress, anxiety, exhaustion and even hypertension (Norgate *et al.*, 2020), but environmental aspects of commuting were not addressed. This study looks at personal exposure to air pollutants during commuting (train and car) and work (office and home) for the newly emerging hybrid office workers.

2 MATERIALS/METHODS
This pilot study collected data with a wearable air pollution sensor (Plume Labs, 2021). PM_1, $PM_{2.5}$, PM_{10} and NO_2 were measured at 1-minute intervals during commuting (by train and car) to Lancaster University from different parts of the UK and working time (office and home). This is a first attempt to study air pollution transects across densely populated (and heavy traffic) areas in this part of the UK. The NO_2 exposure rate (μg/sec) was calculated assuming

6L/min personal minute ventilation rate (Carroll, 2007) during work-stay hours (08:00 to 19:00) and 12L/min (Zuurbier *et al.*, 2009; Tang and Niemeier, 2020) during commuting (~3 hrs train trip and ~6 hrs drive). This paper reports results from three train journeys and four car journeys in the UK between November to January 2022. Work-stay data were collected for five days in an open plan office space at LICA building, Lancaster University, and three days from a home office. This paper only discusses NO_2 measurements. Nonetheless, according to EPA and EC (EC, 2008; US EPA, 2022) air quality standards, all monitored pollutants remained within an acceptable range (i.e. hourly and daily average thresholds). The analysis mainly used R (R Core Team, 2021) Tidyverse (Wickham *et al.*, 2019) packages.

3 RESULTS AND DISCUSSION

The two figures summarise the main results about NO_2 exposure between two modes of transport (car – train, Figure 1) and two places of work (home – office, Figure 2). It should be noted that the NO_2 exposure (y-axis) in the travel related graph (Figure 1) has a different scale than the work-related graph (Figure 2).

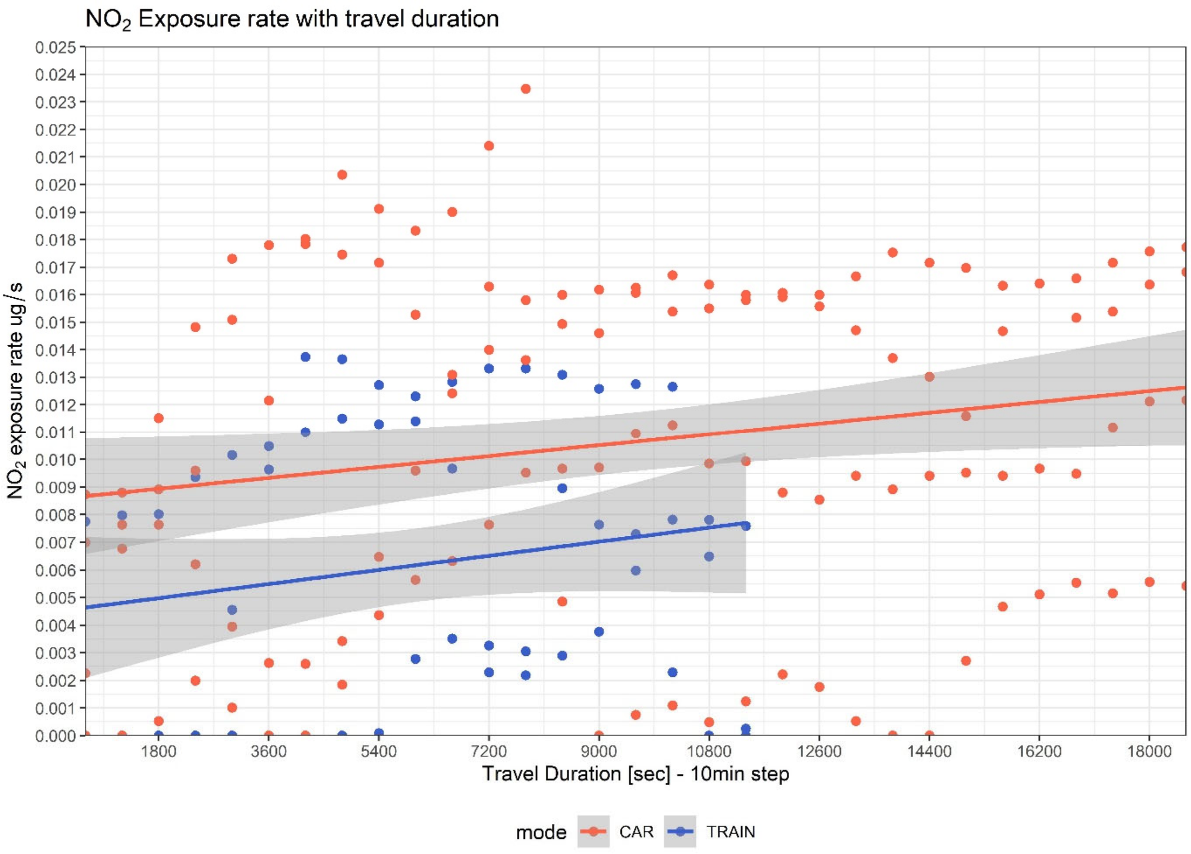

Figure 1. Comparison of the NO_2 exposure rate (μg/s) with travel duration (s) for car (red) and train (blue) journeys during commute to office.

The NO_2 measurements from both car and train as a mode of transport suggest an increasing trend of exposure in relation to the duration of travel. The car passengers were subjected to higher NO_2 concentrations than the train passengers as their journeys were longer. This result supports previously published studies that showed a similar trend (Chertok *et al.*, 2004). It has also been observed that exposure in the car was higher during peak hour traffic outside large cities as expected. Weather conditions have not been taken into consideration. The increasing exposure with the duration of travel also indicates the impact of the vehicles themselves on the air quality in the passenger cabins. During the monitoring periods, all pollutant concentration levels have remained within the good to acceptable ("moderate") range.

The NO_2 exposure shown in Figure 2 for the workplace shows a similar increasing trend with the increasing duration at work. NO_2 levels in the office were distinctly higher on some days than others. Days with higher NO_2 in the office were usually Mondays which, according to recorded office occupancy, were one of the busiest days in the office and nearby parking. While the presence of people in the office does not directly impact the NO_2 concentrations, it could indicate that the increased traffic on the university campus and the nearby dual carriage road and motorway could affect the air quality and exposure levels within the office space.

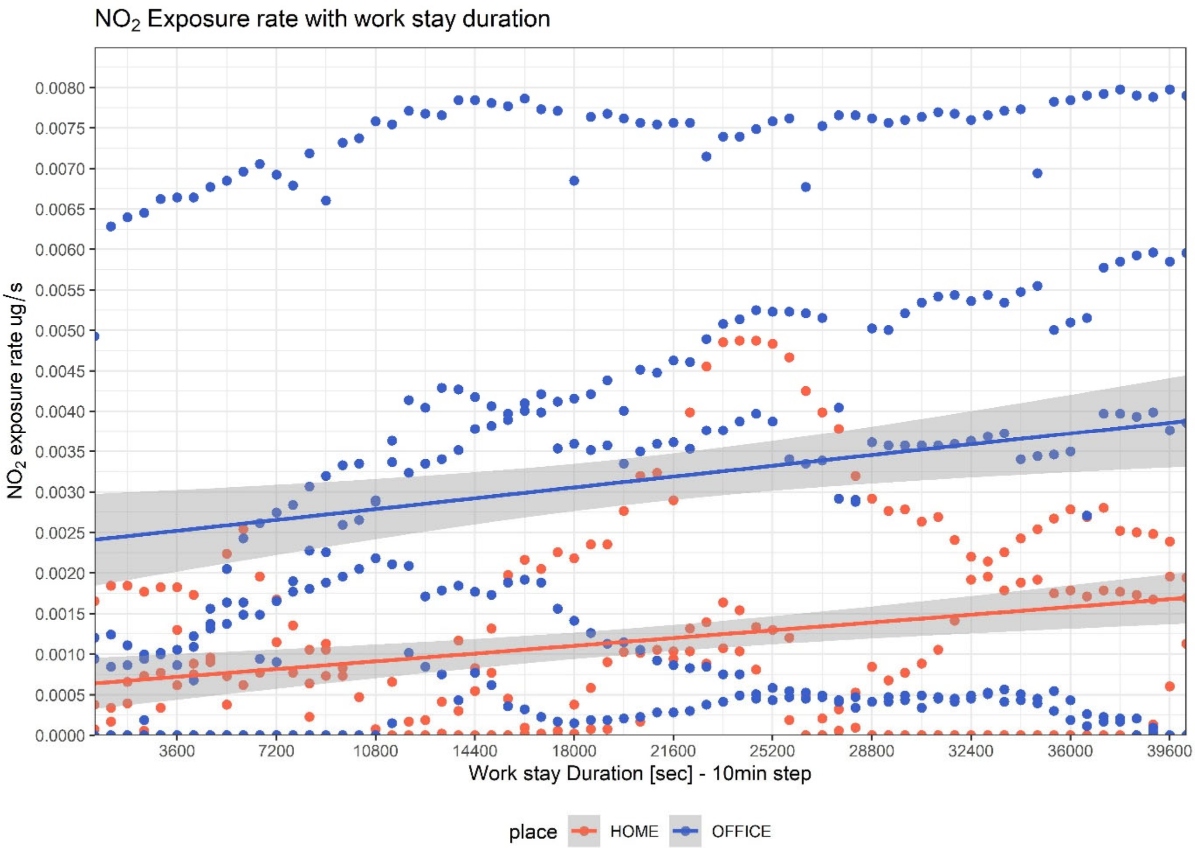

Figure 2. Comparison of the NO_2 exposure rate (µg/s) with travel duration (s) for work from home (red) and in an open plan office (blue).

The home office has single-sided natural ventilation and it looks into a single lane street with local traffic. There are only three days of measurements (red) shown in Figure 2, but the peaks around 09:00 (3,600 sec) and 15:00 (25,200 sec) are likely attributed to school-run traffic to the nearby primary school, when there were small traffic jams every day caused from parking around the school, with many vehicles' engines idling. Due to cold weather, the home office window remained shut, but the trickle vent remained open. In the office space, windows are opened when possible and shut in the afternoon when people leave the office. The very low morning values (0 ug/s, blue points in Figure 2) were monitored on a Saturday when the number of people in the office was limited and sporadic, and the windows remained shut. It should also be noted that the monitored office building is on a campus with mixed-use and neighbouring residential student halls, which would explain traffic in the afternoon and at weekends.

4 DISCUSSIONS

The results suggest that exposure to NO_2 during commuting can play an important part in hybrid workers' personal exposure to air pollutants, especially during extended commuting times. Public transport and trains are likely to have better indoor air quality than cars mainly due to the cabin ventilation systems they use and the routes they follow. Often away from roads with heavy traffic. This is valid probably only for long commutes between cities as in this study and not within cities.

According to this pilot study's results, working from home and avoiding commuting is likely to expose office workers to lower air pollutants levels than working from the office or hybrid working. The observed exposure levels are expected to be exacerbated for transects across cities during hours with peak traffic. However, this suggests that people's workplaces might not be the main cause of exposure to air pollutants. It is well established that building design, neighbourhood, and town planning significantly impact outdoor and indoor air quality. New policy directions about active mobility and zero-emission public transport in cities are being developed to try to mitigate outdoor air pollution problems. Building design and neighbourhood planning should also carefully consider the possible effects of air quality on the energy efficiency of buildings, health and comfort of building occupants and active mobility users.

In addition, as the study design shows, there is a risk that hybrid working might lead many people to move out and/or further away from cities where office buildings are typically located. In some cases, that could lead to an increase in passenger kilometres travelled and an increase in the kilometres travelled by car instead of by public transport modes. This is a complex issue and a solution would require systemic changes in many aspects of city life and town planning. Affordability, quality of space (and time) and ecosystems, local amenities, community infrastructure and timescales are only some of the key aspects to consider across the scale.

The findings from a larger study have a number of potential applications in the field of public health, from estimating local health needs and policy to social marketing and supporting behaviour change in individuals around reducing car use and emissions. This is particularly timely as the UK moves forward from the COVID-19 pandemic and into a new hybrid way of working.

5 CONCLUSIONS

While the findings cannot be generalised, they suggest that personal exposure to air pollution for hybrid workers is higher in offices and that extended commuting periods are related to higher accumulative exposure to air pollutants. Further work should explore the impact of building design, neighbourhood and commute to personal exposure to air pollution with bigger sample size.

Limitations, validity and further work

This study focused on the commute between cities and not across busy intra-city transects. The sample size is limited and the initial results cannot be generalised and transferred to other than the studied home and office workspace. Consequently, the trends shown in the results are only an indication of a general trend in these observations and not an indication of any significance and magnitude of any relationships and correlations. The sample size and location of data collection will need to be expanded and addressed in further work.

Car air quality data were collected from an estate type vehicle with a diesel engine. The sensor was positioned in front of the gear lever, at the bottom of the centre console in the front of the vehicle, at the height of the driver's seat. The cabin air filters are periodically serviced as required. However, they have not been replaced with new ones at the beginning of the data collection. Climate control was turned on for heating, but air recirculation was turned off. Window opening and motorway service stops took place as and when needed during the transects (usually one 15-minute stop per trip). The longest part of the transect was travelled on dual carriage roads and motorways. Peak traffic hours outside large cities were avoided when possible.

The cabin of the train was almost empty, and the windows were shut down at all times. The monitored cabin was at the last coach of the train. Further work should collect observations from typical commute routes and other public transport and active mobility modes in cities.

Further work will look at the exposure during typical commute across a city and inter-city transects both by train and car for popular commuting routes. In terms of building air quality, ventilation parameters need to be considered, and buildings at different locations need to be studied, controlling for room size, occupancy behaviour, HVAC settings, and local weather conditions.

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