Knibbs, Luke D. and deDear, Richard (2010) *Exposure to ultrafine particles and PM2.5 in four Sydney transport modes.* Atmospheric Environment, 44(26). pp. 3224-3227.

Short Communication

Exposure to ultrafine particles and $PM_{2.5}$ in four Sydney transport modes

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Abstract

Concentrations of ultrafine (<0.1µm) particles (UFPs) and $PM_{2.5}$ (<2.5µm) were measured whilst commuting along a similar route by train, bus, ferry and automobile in Sydney, Australia. One trip on each transport mode was undertaken during both morning and evening peak hours throughout a working week, for a total of 40 trips. Analyses comprised one-way ANOVA to compare overall (i.e. all trips combined) geometric mean concentrations of both particle fractions measured across transport modes, and assessment of both the correlation between wind speed and individual trip means of UFPs and $PM_{2.5}$, and the correlation between the two particle fractions. Overall geometric mean concentrations of UFPs and $PM_{2.5}$ ranged from 2.8 (train) to 8.4 (bus) × 10^4 particles cm^{-3} and 22.6 (automobile) to 29.6 (bus) µg m^{-3}, respectively, and a statistically significant difference (p <0.001) between modes was found for both particle fractions. Individual trip geometric mean concentrations were between 9.7 × 10^3 (train) and 2.2 × 10^5 (bus) particles cm^{-3} and 9.5 (train) to 78.7 (train) µg m^{-3}. Estimated commuter exposures were variable, and the highest return trip mean $PM_{2.5}$ exposure occurred in the ferry mode, whilst the highest UFP exposure occurred during bus trips. The correlation between fractions was generally poor, and in keeping with the duality of particle mass and number emissions in vehicle-dominated urban areas. Wind speed was negatively correlated with, and a generally poor determinant of, UFP and $PM_{2.5}$ concentrations, suggesting a more significant role for other factors in determining commuter exposure.

Keywords: Commuter; Exposure; Transport; Ultrafine Particles; $PM_{2.5}$

1. Introduction

Acute and chronic human health effects can occur following exposure to particulate matter. However, the degree to which observed effects can be ascribed to varying concentrations of $PM_{2.5}$ (aerodynamic diameter <2.5µm) and ultrafine particles (UFPs, aerodynamic diameter <0.1µm) is not well understood. $PM_{2.5}$ is measured in terms of mass concentration, whilst ultrafine particles (UFPs), given their insignificant mass, are measured in terms of number concentration. Increases in both metrics are reported to be associated with various negative health effects (Wichmann and Peters, 2000). Commuters are potentially exposed to elevated levels of particulates, as people are often most proximate to concentrated vehicle emissions during transit. Whilst studies of the nature of in-transit exposures to both $PM_{2.5}$ and UFPs have become an increasingly prominent feature of the literature in recent years, the global database of exposure levels and their determinant factors them remains relatively small. As such, this pilot study aimed to quantify $PM_{2.5}$ and UFP concentrations and commuter exposure during transit in four common transport modes in Sydney, Australia's most populous city (approximately 4.4 million residents). Additionally, we sought to assess: (a) whether mean concentrations of both particulate fractions differed significantly between transport modes, (b) the correlation between the two particle fractions, and (c) the role of wind speed as a determinant of in-transit UFP and $PM_{2.5}$ concentrations (Alm et al., 1999; Adams et al., 2001; Briggs et al., 2008).

2. Methods

2.1 Study Location and Design

Four popular transport modes were selected: train, bus, automobile and ferry. A short route of approximately 4km that linked North Sydney (north of Sydney Harbour) and Wynyard (CBD, south of Sydney Harbour) rail stations via the Sydney Harbour Bridge was selected for the train, bus and automobile. The route selected for the ferry linked McMahons Point and Circular Quay wharves. The bus, car and train modes shared a nearly identical route, notwithstanding the train passing through a short tunnelled section not present on the car and bus routes. The ferry route was as close as practical to that of the other modes, as figure 1 shows. All non-ferry modes traversed the Sydney Harbour Bridge, which carries approximately 160 000 vehicles day^{-1} (NSW RTA, 2010).

To mimic the typical activities of commuters, CBD inbound (North Sydney to Wynyard) trips were undertaken between 7 and 9am, whilst CBD outbound (Wynyard to North Sydney) trips were performed between 4 and 6pm. One trip was taken on each mode during these two periods over five consecutive weekdays from 27/09/2004 to 01/10/2004, and 40 trips were completed during the week. The order in which trips were taken was randomised. Data was collected only whilst aboard each transport mode. Average train and car trips took 7 minutes, with bus and ferry trips taking 9 and 12 minutes, respectively.

The automobile utilised was a 1998 model Mitsubishi Magna sedan. The automobile was powered by regular unleaded petrol. Ferries and some buses were powered by diesel fuel; other buses relied on compressed natural gas. All trains were powered by electricity delivered by overhead lines.

During all measurements, the automobile's air conditioner was on and set to cool the cabin, the lowest fan speed setting was selected and recirculation was not in operation. The vehicle was not equipped with a cabin air filter. The ventilation system in use on trains and buses (i.e. natural or mechanical) was noted by the investigator. All ferries were naturally ventilated.

Wind speed measurements recorded at one minute intervals by the Fort Denison Automatic Weather Station, located approximately 1.5km east of the study route mid-point, were obtained from the Australian Bureau of Meteorology. Figure 1 shows the location of the weather station. Wind direction observations corresponding to the study period were unavailable. The sampling week was free of precipitation, with the exception of 01/10/04 when occasional light rain fell during the morning and evening sampling periods.

→Figure 1 to be inserted here.

Figure 1. Overview of the study area and routes. The bus and automobile route is shown in purple. The train route is shown in yellow and pink, with the pink segment indicating the approximate position of the underground portion. The ferry route is shown in red. The figure was produced using the Google Earth™ mapping utility.

2.2 Instrumentation

A TSI 3007 condensation particle counter (CPC) was used to measure total particle number concentration in the range 10nm (50% detection threshold) to >1000nm; although the overwhelming majority of particle counts recorded in urban areas are expected to fall within the UFP size range (Morawska et al., 2008). The unit is capable of detecting particle concentrations up to 1×10^5 p cm^{-3}. Following the measurement campaign, we compared simultaneous measurements of a TSI 3022A CPC (capable of measuring up to 1×10^7 p cm^{-3}) and TSI 3007 in order to develop a correction factor applicable to situations where the 3007's maximum concentration threshold was exceeded. In agreement with the findings of Westerdahl et al. (2005) for an analogous experiment, we found that 3007 readings up to ~3×10^5 p cm^{-3} could be converted with reasonable confidence to the corresponding 3022A reading (~9×10^5 p cm^{-3}).

A TSI 8520 DustTrak that had been calibrated by the manufacturer prior to the measurement campaign was equipped with a 2.5 µm inlet. This instrument typically overestimates the true mass of particles in fuel combustion aerosols (Jamriska et al., 2004). However, even without correction the relative concentrations between or within the locations measured are retained.

The zero reading of both units and the flow rate of the DustTrak was checked prior to each measurement session. Sampling intervals were set to one second. The investigator placed both instruments inside a foam-lined bag from which the sample inlets protruded. During trips on the train, bus and ferry modes, the bag was held on the investigator's lap when they were seated, whilst the bag was held at the approximate height of a seated passenger's breathing zone when the investigator was standing. During all automobile trips, the bag was placed on the front passenger's seat, which was otherwise unoccupied.

2.3 Analyses

Both UFP and $PM_{2.5}$ data obtained in all transport modes were skewed to the right. Accordingly, the data underwent logarithmic transformation, and normal scores plots produced subsequent to this process indicated approximate normality of all data. Arithmetic (i.e. pre-transformation) and geometric overall and individual trip mean particle concentrations were calculated. The Pearson Correlation Coefficient (*r*) between $PM_{2.5}$ and UFP geometric trip means for a given mode, in addition to that between trip mean wind speed and both aforementioned particle metrics, was then determined. To assess whether statistically significant differences existed between modes in the overall geometric means of one second measurements of both UFPs and $PM_{2.5}$, homoscedascity was confirmed using Levene's Test prior to the application of one-way ANOVA. In all analyses, the 5% level was taken to represent statistical significance.

3. Results

Figure 2 shows overall geometric mean concentrations of $PM_{2.5}$ and UFP for each transport mode, in addition to maximum and minimum trip geometric means. Overall in-transit concentrations of $PM_{2.5}$ were broadly comparable across modes, with geometric means of 27.3 (AM = 35.8), 29.6 (AM = 33.4), 22.6 (AM = 27.3) and 28.0 (AM = 58.3) µg m^{-3} measured in the train, bus, automobile and ferry modes, respectively. The ratio of the maximum to minimum mean was therefore 1.3 (AM = 2.1). Single trip geometric mean concentrations ranged from 9.5 to 78.7 µg m^{-3} (max:min = 8.3), with both values recorded inside trains. Arithmetic means ranged from 10 to 151.8 µg m^{-3} (max:min = 15.2), and were recorded in the train and ferry modes, respectively. Overall geometric mean UFP concentrations were 2.8 (AM = 4.6), 8.4 (AM = 10.5), 7.5 (AM = 8.9) and 3.7 (AM = 5.5) × 10^4 particles cm^{-3} for the train, bus, automobile and ferry modes, respectively. Trip geometric mean UFP concentrations ranged from 9.7 (AM = 10.0) × 10^3 to 2.2 (AM = 2.6) × 10^5 particles cm^{-3}, and these values were recorded in the train and bus modes, respectively.

The ANOVA performed indicated that statistically significant differences were present in overall geometric mean concentrations of both $PM_{2.5}$ ($p < 0.001$) and UFPs ($p < 0.001$) between the four transport modes.

➔ Figure 2 to be inserted here

Figure 2. Overall (i.e. all trips) geometric mean concentrations of $PM_{2.5}$ and UFPs measured in each of the four transport modes. Upper and lower extent of error bars denote maximum and minimum individual trip geometric mean concentrations, respectively.

The correlation between trip geometric mean concentrations of $PM_{2.5}$ and UFPs was positive in all cases, albeit weak and not statistically significant for the bus, automobile and ferry modes, with respective r values of 0.49 ($p = 0.15$), 0.30 ($p = 0.39$) and 0.14 ($p = 0.72$). A statistically significant correlation ($p = 0.03$, $r = 0.69$) was present in the train mode data.

Mean wind speed during each trip varied between 4.8 and 39.5 km h^{-1} and the correlation between this variable and the corresponding trip geometric mean measurements of both particle fractions was negative in all cases. Results indicated generally poor correlations of no statistical significance between wind speed and UFP concentrations, with r values of -0.49 ($p = 0.18$), -0.20 ($p = 0.57$), -0.14 ($p = 0.68$) and -0.30 ($p = 0.39$) for the train, bus, automobile and ferry modes, respectively. Similarly, no statistically significant correlations existed between trip mean wind speed and $PM_{2.5}$ concentrations, although r values were generally slightly higher; -0.36 ($p = 0.35$), -0.52 ($p = 0.12$), -0.59 ($p = 0.07$) and -0.37 ($p = 0.28$) for the train, bus, automobile and ferry modes, respectively.

4. Discussion and Conclusions

4.1 Comparison Across Modes

Although ANOVA found statistically significant differences were present between overall geometric mean $PM_{2.5}$ concentrations measured in the four transport modes, the values were comparable. The non-ferry modes sharing of a largely common route and proximity to vehicle emissions (Boogaard et al., 2009) could partially explain their observed similarity. However, the concentration measured in the automobile was the lowest of all modes, and this may reflect the influence of ventilation, which is discussed further below. The geometric mean measured in the ferry was comparable to that of the other modes, suggesting that the ferry mode, which was itself the local source of particulates, did not result in higher commuter exposure levels. However, the arithmetic mean $PM_{2.5}$ concentration measured in the ferry mode was substantially above those measured in the other modes.

Overall geometric mean UFP concentrations exhibited statistically significant differences across the four modes, and were more variable than equivalent measurements of $PM_{2.5}$. Higher concentrations were recorded in the two on-road modes (bus and automobile), which is likely to have reflected the highly dynamic spatial and temporal characteristics of UFP concentrations in the roadway environment (Morawska et al., 2008).

Individual trip geometric mean concentrations of both particle fractions exhibited a greater range in the train, bus and ferry modes compared to the automobile. This was likely due to the greater diversity present in ventilation technologies (i.e. natural or mechanical) and/or the location of investigator in relation to ventilation delivery points during trips in the three non-automobile modes. By comparison, the automobile had a consistent ventilation setting and measurement location throughout the sampling period.

Given the small sample size, it is not possible to draw firm conclusions regarding the influence of ventilation parameters (i.e. air change rates and the effect of any cabin air filters) in the bus and train modes. However, for the purpose of highlighting the potential effect of ventilation, we note that 5 trips each were undertaken on mechanically and naturally ventilated buses, and these were distributed evenly throughout the sampling week. Geometric trip mean concentrations of $PM_{2.5}$ and UFPs ranged from 13.1 to 30.2 µg m^{-3} and 3.7 to 8.8 × 10^4 particles cm^{-3} in mechanically ventilated buses, and from 26.9 to 74.8 µg m^{-3} and 0.8 to 2.2 × 10^5 particles cm^{-3} in naturally ventilated buses. There was thus an approximately two-fold increase in geometric trip mean and overall $PM_{2.5}$ and UFP concentrations measured inside naturally ventilated buses compared to those in mechanically ventilated buses. This suggests that greater commuter protection from both particle fractions was afforded by newer, mechanically ventilated buses compared to the older naturally ventilated types, and agrees with the findings of Rim et al. (2008).

The two trips in naturally ventilated trains resulted in the two highest trip mean $PM_{2.5}$ and UFP concentrations measured in this mode. Assessment of the repeatability of the above observations and the extent to which they are attributable to ventilation rates (e.g. Knibbs et al., in press), filtration and factors such as exhaust re-entrainment (Behrentz et al., 2004) should be considered in further work.

4.2 Estimated Mean Commuter Exposure

Exposure estimates were calculated by multiplying the overall arithmetic mean concentration of the two particle fractions by double the mean trip time for each mode (i.e. a return trip). $PM_{2.5}$ exposure values are not presented due to the aforementioned limitations of the DustTrak; however, the highest mean exposure occurred for ferry occupants, and was 3.7 times greater than the lowest exposure, which occurred inside the automobile. Estimated UFP exposures were 1.1, 3.2, 2.1 and 2.2 × 10^4 particle hr cm^{-3} for the train, bus, automobile and ferry modes, respectively. Mean exposures to $PM_{2.5}$ and UFPs during brief return commuter trips clearly varied amongst the four travel modes, and investigation of the specific contribution of commuter exposures in-transit to total daily exposure, including assessment of longer trip times and different routes, is required in order to better appreciate potential health effects.

4.2 Correlation Between $PM_{2.5}$ and UFPs

Correlations observed between geometric trip mean concentrations of $PM_{2.5}$ and UFPs for the four modes were generally weak and not statistically significant. A lack of correlation between these two particle fractions is often reported, and reflects the inconsistency of many urban particle sources in terms of the relative strength of their mass and number emissions (Wichmann and Peters, 2000; Morawska et al., 2008). Our results are similar to those reported by Kaur et al. (2005) for pedestrians, and by Boogaard et al. (2009) for cyclists and vehicle occupants. This further reinforces the need to monitor both fractions in order to accurately assess commuter particulate exposure, irrespective of travel mode.

4.3 Influence of Wind Speed

Although no statistically significant correlations existed between trip mean wind speed and geometric trip mean concentrations of $PM_{2.5}$ and UFPs, some broad observations are noted; specifically, that correlations were negative in all cases, and that the correlation coefficient was almost always higher for $PM_{2.5}$ than for UFPs.

This is generally in agreement with results reported by Briggs et al. (2008) based on particulate measurements taken whilst walking and in an automobile on London roads. Wind speed has been reported by other studies to be negatively correlated with in-transit fine particle concentration (Alm et al., 1999; Adams et al., 2001), and its influence generally appears to be weak. The effects of other meteorological parameters, whilst likely to be relatively minor (Kaur et al., 2007), were not assessed in this study.

4.4 Conclusions

Mean commuter exposure to $PM_{2.5}$ and UFPs along a short route in Sydney varied with transport mode. The contributions to daily $PM_{2.5}$ and UFP exposure incurred during transit, including any subsequent negative health effects, should be assessed in detail in future work. The results further bolster the assertion that assessment of personal exposure to $PM_{2.5}$ and UFPs requires specific monitoring of both fractions, and that concentrations of one should not be used to infer those of the other. Wind speed was negatively correlated with both particle fractions, and other factors are likely to be of greater importance in determining commuter exposure. We also note that there exists a need for future studies to further differentiate the relative influence of meteorological, traffic, route and vehicle ventilation parameters, such that policy and mitigative measures are properly informed regarding the most salient determinants of commuter exposure to particulate matter.

Acknowledgement

Both authors were with the Division of Environmental and Life Sciences at Macquarie University, Sydney, when the study was undertaken.

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