Original Research

Is active travel a breath of fresh air? Examining children’s exposure to air pollution during the school commute

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ABSTRACT

The aim of this study was to assess how children’s personal exposure to fine particulate matter (PM_{2.5}) during the school commute is influenced by mode of travel and neighborhood environment in a mid-sized Canadian city. A total of 101 commutes to and from school were tracked using a GPS, and personal exposure to PM_{2.5} along commute routes was assessed by spatially-referencing the monitored exposure levels with time-synchronized GPS data. Students who walked to and from school were exposed to lower PM_{2.5} concentrations than those in cars or riding the school bus. There was also a significant difference in mean PM_{2.5} concentrations by the built environment, with children who walked to school in suburban neighborhoods experiencing higher personal concentrations than children in urban neighborhoods. To reduce children’s daily exposure to air pollutants, neighborhoods should be designed to maximize the number of children who are able to walk between home and school.

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1. Background

Public health professionals and researchers widely promote ‘active travel’ modes such as walking or bicycling as healthier alternatives to motorized forms of transportation, especially personal automobiles (Buttazzoni et al., 2018). Active travel to school is regularly encouraged as part of a physical activity strategy for combating the growing problem of childhood obesity in many countries, as it is well-documented that children who walk to school benefit from higher physical activity levels than those who are driven (Cooper et al., 2005, Tucker et al., 2009, Brown et al., 2017). Nevertheless, little is known about how the choice of travelling to and from school by walking or biking versus being driven in a car or bus can affect children’s exposure to health-damaging air pollutants.

Children are more susceptible than adults to the adverse health effects of air pollution due to greater physiological sensitivity to air pollutants, higher respiration rates, and more time spent outdoors (Committee on Environmental Health 2004, Hricko, 2006). Particulate matter (PM) is a heterogeneous mixture of solid and liquid suspended particles conventionally measured by aerodynamics diame-
ter (i.e., PM$_{10}$ with diameter less than 10 μm (or microns), PM$_{2.5}$ less than 2.5 μm) (Liang, 2013). Particulate matter less than 2.5 μm in aerodynamic diameter (PM$_{2.5}$) specifically has been found to aggravate asthma (Liu et al., 2009). Regardless of the size or the chemical properties of particulate matter (Wilson et al., 2005), the World Health Organization states that there is no zero-effect threshold for particulates and health risks are present at any level (World Health Organization 2005). The elevated levels of air pollutants found in road transport microenvironments (i.e., sites that can be treated as homogeneous in terms of pollution concentrations) (Borrego et al., 2007), especially the school bus (Sabin et al., 2005, Adar et al., 2008), occurring during the school commute may represent a significant portion of the child’s daily exposure. The school commute is of particular interest as it is usually consistent between days in both transport mode and designated route, but is often amenable to change. Accordingly, if research evidence indicates that certain travel modes or environmental characteristics contribute to significantly higher levels of children’s exposure to harmful pollutants, then behavioral or environmental interventions may be identified to reduce exposure and thereby minimize potential damages to children’s health.

As part of the Spatio-Temporal Exposure and Activity Monitoring (STEAM) project which examines environmental influences on children’s mobility and health-related behaviors (Tillmann et al., 2018, Sadler et al., 2016, Mitchell et al., 2016, Loebach and Gilliland, 2016) the aim of this study was to empirically assess how children’s personal exposure to PM$_{2.5}$ during the school commute is influenced by mode of travel (i.e., walk, bus, or personal automobile) and neighborhood built environment (i.e., urban versus suburban), in London, Ontario, Canada. This study adds to the literature on pollution exposure, active travel, and children’s health by using an innovative combination of observational tools, including portable high resolution PM$_{2.5}$ monitors, GPS devices, and self-report activity diaries, to establish an empirical understanding of children’s exposure to PM$_{2.5}$ during the school commute. This study will also provide recommendations for further study and suggest potential interventions for mitigating the burden of PM$_{2.5}$ exposure.

2. Methods
2.1. Active versus ambient monitoring of exposure

To properly assess personal exposure to any environmental toxicant, it is essential to know where individuals spend their time. While most government agencies report pollution exposure for the entire population of a region using a small number of fixed-site ambient monitors, our initial tests of personal PM$_{2.5}$ exposure outside our sample urban school supported the findings of previous research indicating that levels of exposure can vary dramatically over a very short distance, depending on how close one is to the major sources (Boogaard et al., 2009, Li et al., 2009). The top line of the graph in Fig. 1 illustrates personal PM$_{2.5}$ exposure for an individual standing in the school parking lot during the morning drop-off before school, and the bottom line shows PM$_{2.5}$ exposure for someone standing in a grassy field behind the school. The former is only 50 m away from a busy four-lane arterial road (over 30,000 vehicles per day), while the latter is 250 m away. As expected, the individual in the parking lot is exposed to much higher levels due to close proximity to the road; additionally, the periodic spikes of increased exposure coincided with school buses entering the parking lot then turning off their engines while students disembark. This preliminary test justified our decision to adopt a new geographical approach for ‘actively’ monitoring pollution exposure directly in the micro-environments which children inhabit.

Personal PM$_{2.5}$ exposure for each participant in this study was recorded with a personal DataRAM pDR1500 aerosol monitor (Thermo-Scientific, Waltham, Massachusetts, USA). All of the pDR1500 units were calibrated daily with each other, and any apparent noise lied generally within the manufacturer’s guidelines of ±5 μg/m$^3$.

2.2. Study design

This spatial ecological study measured children’s direct personal exposure to PM$_{2.5}$ during the school commute for a sample of 36 students using a real-time monitoring device (DataRAM monitor, model PDR-1500) which has been used in other research (e.g., (Wang et al., 2016, Ouidir et al., 2015, Kumar et al., 2015, Gilliland et al., 2018)). The pDR-1500 is a fully integrated, active sampling, real-time aerosol monitor/data logger with aerodynamic sizing and post-gravimetric validation of data. The study examined variation in mean personal PM$_{2.5}$ concentrations and total PM$_{2.5}$ exposure load on children per journey, in relation to different transport modes. The study region encompassed commuter sheds around one urban and one suburban elementary school in London, Ontario, a mid-sized Canadian City of 383,822 people in 2016. These schools were selected from two distinct areas of the city to allow for examination of exposure variations by the built environment (Race et al., 2017). Fig. 2 maps the built forms and land uses within each neighborhood, along with a 1600 m buffer (i.e., Euclidean distance) around each school to highlight the approximate cut-off distance beyond which children are provided school bus service at schools in this
school board (Larsen et al., 2009). In the middle of the regular school year (February 2010; winter season in Canada), 36 volunteer children aged 10–13 years (18 from each school) were selected based upon their home location and mode of transport to school to maximize spatial and behavioral variability. Prior to recruitment and data collection, study approval was obtained from the research ethics boards (Western University and London District Catholic School Board), and informed written consent was obtained from participants and their parents.

2.3. Data collection

Children’s direct personal exposure to PM$_{2.5}$ was measured at 10-s intervals during the school commute. Participating students were portable personal PM$_{2.5}$ monitors for four school days (Tuesday–Friday) and one weekend day (Saturday). To prevent tampering, the pollution monitors were housed in a lightweight camera case. The input tube was taped to the shoulder strap and the inlet positioned as near to the child’s breathing zone as possible. The following weekly maintenance standard operating procedures were followed: (1) teflon filter replaced with fibreglass filter, (2) physically cleaned for dust or particles, (3) unit was calibrated using the zeroing filter, (4) flow rate was checked to ensure 1.52 L/min, and (5) instruments were all brought together and ran simultaneously for several hours. PM$_{2.5}$ monitors were worn in combination with portable GPS devices (VGPS 900, Visiontaec Instrument Inc.) recording latitude and longitude at 1-s intervals, thereby allowing for a time-synchronized location of each pollution measurement. The precise commute time, route, and speed were delineated by examining the daily ‘trail’ of GPS points between home and school within a geographic information system (ArcGIS 10; ESRI, Redlands, CA). Participants completed questionnaires to identify demographic characteristics, the normal mode of travel to and from school, and any health issues such as asthma, in addition to elucidating some confounding variables such as the presence of a smoker or pet in the home. Student activity diaries were consulted to clear any ambiguity in determining the transport mode.

To compare with directly measured personal PM$_{2.5}$ concentrations for each participant, mean ambient PM$_{2.5}$ concentrations for the city as a whole were determined by averaging hourly measurements from the single Ministry of Environment Ontario site located in London, Ontario from 7 a.m.–9 a.m. and 3 p.m.–5 p.m. on school days.

2.4. Data analysis

All data were imported into GIS for manipulation and analysis. Individual PM$_{2.5}$ measurements were given spatial coordinates by matching times on both the GPS and the pDR1500s, which were both synchronized with the atomic clock. Routes to and from school in each neighborhood were identified in the GIS and were attributed according to the mode of travel and PM$_{2.5}$ measurements. Mean PM$_{2.5}$ was then tabulated for each route. Mean values represent the average of all PM$_{2.5}$ measurements recorded for each journey; however, the mean PM$_{2.5}$ values for bus riders consider only the bussed portion of their school journey and not the partial journey between home and bus stop (AM) or bus stop and home (PM). Total PM$_{2.5}$ load for each journey was calculated by multiplying the mean PM$_{2.5}$ exposure ($\mu g/m^3$) by the duration of the journey (minutes) and by the estimated ventilation rate or inhaled volume per minute ($m^3/min$) of the child (Davies and Whyatt, 2014).

Mean ventilation rates were estimated to be 0.0198 m$^3$/min for children walking and 0.00789 m$^3$/min for children riding in an automobile or bus, based upon previously determined mean ventilation rates of children aged 10–13 years while walking at 4 km/h and the same at rest (e.g. sitting) (Ondrak and McMurray, 2006). Total load does not represent the actual deposited dose as some particles will inevitably be exhaled. To focus only on exposure during journeys to and from school, routes that involved extended stops were excluded from total load calculations. Routes were also excluded from the analysis if any equipment appeared to be malfunctioning (e.g., data missing or deemed unreliable). Routes with less than 6 measurements (n=14;signifying less than 1 min of measured concentrations) were also eliminated from analysis.

The Shapiro–Wilk test for normality and Bartlett’s test for homogeneity of variances were performed using the statistical software R (R Development Core Team 2011).
Mean PM$_{2.5}$ measurements for the commuting routes were compared using ANOVA and $t$-tests with significance level set at 0.05 in Excel (Microsoft 2007). Tukey's honest significance post-hoc test was employed in R (R Development Core Team 2011) to determine which mean exposures by transport mode and by neighborhood type are different from one another after a significant ANOVA result.

### 3. Results

Spatially-referenced pollution data was successfully recorded for a total of 101 out of 252 possible journeys (40%): 15 routes (6%) were missing due to the student being absent from school, and 136 routes (54%) were excluded from the analyses due to missing or unreliable data suggesting mechanical error of the GPS ($n = 34$) or PM$_{2.5}$ monitor ($n = 102$). The mean journey PM$_{2.5}$ concentration of 10 µg/m$^3$ was significantly greater than the concurrently-measured mean ambient concentration of 3.7 µg/m$^3$ (two-tailed paired $t$-test, $p < 0.001$) at the Ministry of Environment Ontario's station in London.

An example route (Fig. 3) demonstrates the high resolution of recorded data as well as the difference that microenvironments can have on PM$_{2.5}$ concentrations over short time periods. The student’s exposure level drops slightly after the school day ends, jumps sharply as she enters the parking lot, and remains relatively high during the school bus ride. After disembarking the bus, exposure levels drop significantly and decline to lowest levels after returning home; all of the concentrations, except inside the dwelling, are above ambient levels for the city.

A Shapiro–Wilk test for normality found significant deviations from normality in all three transport modes, drive, bus, and walk ($p < 0.001$ in all cases) for measured PM$_{2.5}$ concentrations. A Bartlett test for homogeneity of variances found significantly different variances between the three transport microenvironments ($p < 0.001$). As both the normality and equal variance assumptions were violated, ANOVA results must be interpreted with caution. Modified $t$-tests that account for heteroscedasticity were consequently employed.

Fig. 4 reveals that children who walked had the lowest mean personal exposure concentrations (8.6 µg/m$^3$); however, there was no statistically significant difference between transport modes (bus: 10.1 µg/m$^3$; car: 9.6 µg/m$^3$). When children’s commutes had both a bus component and walking component – which is the case for all bussed students unless they are picked up directly in front of their house – the bus component (10.4 µg/m$^3$) had significantly higher mean personal exposure than the walking component (8.6 µg/m$^3$), using a paired two-tailed $t$-test in both actual measurements ($p = 0.004$). The exposure levels were similar ($p = 0.97$) between those who walked to and from school (8.7 µg/m$^3$) and those who walked to and from the bus (8.6 µg/m$^3$), so the latter journeys were added to the
pool of walking events for calculating mean exposure for walkers.

Children who walked in the suburban neighborhood had significantly higher measured PM$_{2.5}$ concentrations than those who walked in the urban neighborhood (Fig. 5). There was no statistically significant difference for those who drove or took the bus in either neighborhood.

As can be seen in Fig. 6, the mean total load of PM$_{2.5}$ of children who travelled by walking (0.66 μg) and driving (0.40 μg) are both significantly lower than those taking the bus (1.52 μg) ($p < 0.001$). As the total PM$_{2.5}$ load is also influenced by time exposed, it is not surprising that the average duration of the bus commute (15.5 min) was longer than the average commute by automobile (5.5 min) and by walking (6.6 min). The majority of total load of PM$_{2.5}$ during the bus commute occurs while in the vehicle; however, as can be seen by the top portion of the stacked bar in the middle of Fig. 6, the walking portion of the commute consists of a considerable fraction of the total load due to higher ventilation rates of walkers versus bus riders.

4. Discussion and recommendations

This study ‘actively’ assesses children’s exposure to harmful pollutants (i.e., PM$_{2.5}$) in their everyday environments using personal pollution monitoring and GPS tracking. A key finding of this study is that mean personal exposure PM$_{2.5}$ concentrations for sample children during the school commute were significantly higher than concurrently measured ambient concentrations at the city’s sole monitoring station (located 1 km from the urban school and 7.5 km from the suburban school). The findings emphasize the inadequacy of using a single fixed-site monitor to characterize pollution exposure across a large territory. It could be argued that reliance on such dramatic underestimations of pollution exposure for the development of health protection tools related to air quality (e.g., Air Quality Health Index) could put vulnerable children, such as those with asthma, bronchitis, or cardiovascular disease, at heightened risk for health complications due to poor air quality. As it not economically feasible for governments to significantly increase the number of monitoring stations within a city, it is recommended that further innovative studies of exposure be undertaken to develop and validate better models for predicting exposure variation within different environments, particularly those inhabited by children.

Although it appeared that mean PM$_{2.5}$ exposure was lowest among those who walked to and from school and higher among those who were driven by bus and car, the differences in mean exposure by transport mode were not statistically significant (Fig. 4, left). On the other hand, when children’s commutes had both a bus and walking component (the majority of bussing cases), the bus component did have significantly higher mean personal exposure than the walking component (Fig. 4, right). Previous studies in other locales have found that students who commute by school bus are exposed to the highest PM$_{2.5}$ concentrations (McNabola et al., 2008). These collective findings suggest that riding the bus can increase children’s exposure to fine particulate matter, and may, therefore, exacerbate symptoms among children who are already vulnerable with asthma or other respiratory ailments. However, this result should be interpreted with caution as certain conditions such as driving with windows open/closed and weather conditions could influence the results (e.g., this study was conducted in winter, when average temperature was consistently below freezing during morning [−3.8 C mean, −6.6 C min, −2.1 C max] and afternoon [−2.1 C mean, −5.7 C min, 0.5 C max] for afternoon commute) (Chaney et al., 2017, DeGaetano and Doherty, 2004). Nevertheless, school buses should not be considered an unhealthy transportation option for those who live too far to walk to school, as they serve to reduce the number of vehicles on the road, resulting in decreased overall air pollution levels. The most effective intervention for reducing pollution exposure for children who ride the bus would be for school boards to retire any
old diesel school buses and to invest in new buses that produce less self-polluting PM$_{2.5}$, including those that run on compressed natural gas or hybrid electric vehicles; at the very least, existing school buses should be retrofitted with better air filtration systems and devices to control pollution emissions. It is also worth exploring the possibility of reducing the number of bus stops on certain routes and spacing them further apart to reduce stopping/starting and the opening/closing of doors which may allow air pollutants to enter the cabin; this strategy can save fuel costs and also means that some children will get the added health benefit of increased physical activity by walking further to the bus stop. School board decision-makers and municipal planners should work together to ensure that schools are strategically located and neighborhoods carefully designed to maximize the number of children who are able to comfortably walk between home and school.

The findings in this study provide further support for previous research which has repeatedly shown how pollution exposure can vary dramatically over very short distances (Greaves et al., 2008, Hertel et al., 2008, Thai et al., 2008). Pollution emissions from school buses and other motor vehicles have been shown to concentrate in areas around schools which have been designated for dropping off and picking up students, such as school parking lots. For example, previous research observed significantly higher PM$_{2.5}$ concentrations near the bus drop off zone compared to a control (Li et al., 2009). Our analysis indicated that PM$_{2.5}$ concentrations observed in the urban school parking lot were higher than inside the school, and nearly three times higher than concentrations in the field just 200 m away (Fig. 1). Accordingly, another recommended intervention to reduce children’s daily exposure to major sources of pollutants is to ensure that school site plans are (re)designed and policies introduced to maximize separation of the school building from all polluting vehicles on neighboring roads, parking lots, and drop-off/pick-up zones.

Statistically significant differences were found in mean PM$_{2.5}$ concentrations by school neighborhood type, as children who walked in the suburban environment experienced higher mean personal concentrations during the school commute than children who walked in the urban environment (Fig. 5). One possible explanation for the observed differences by neighborhood would be the potential impact of the Macdonald-Cartier Freeway, ‘Highway 401’, the busiest highway in Canada (Ministry of Transportation 2008), located within walking distance (1.5 km) from the suburban school, but 8.2 km away from the urban school. Despite the large difference in mean PM$_{2.5}$ exposure values, there was no statistically significant difference by neighborhood for those who were driven (by car or bus), possibly due to vehicle air filtration systems being similar regardless of neighborhood. Alternatively, consistent with the findings of previous studies (Li et al., 2009), our data illustrates how even minor differences in a child’s proximity to vehicles can have a considerable impact on their PM$_{2.5}$ exposure. It is recommended that additional studies adopt a similar methodology with some minor modifications to better isolate specific environmental characteristics that contribute to higher exposure levels.

To minimize the loss of sampling data, future investigations should follow the technical and regulatory considerations regarding lower cost sensor data performance, guidelines to ensure data quality, and ways for improving the consistency of measurements (Kumar et al., 2015, Judge and Wayland, 2014, Clements et al., 2017, Liu et al., 2019, Williams et al., 2014).

With a small sample population, it is not possible to infer exposure patterns for the wider youth population or potential health impacts resulting from exposure. Further experimental research which adopts our STEAM methodology with larger sample sizes in a wider diversity of built environments (e.g., urban cores, rural areas) and micro-environments (e.g., high vs low traffic streets, old versus new buses) is necessary for making conclusions at the population level. Additional research on short-term health impacts (e.g. asthma attacks) of increased exposure should also measure the intensity and/or rate of breathing among participants to determine the actual lung deposited dose of PM$_{2.5}$, and should have participants keep diaries related to poor respiratory symptoms and potential triggers.

The overall findings of this study indicate that both the choice of transport mode and the type of neighborhood built environment have an influence on children’s exposure to fine particulate matter during their school commute. Despite the limitations inherent in intensive studies with small sample sizes, the findings have important implications for future research, as well as the formation of behavioral, environmental, and policy interventions to promote children’s health. This study has revealed how the school commute can be a target for various mitigation strategies by city planners, transportation engineers, school boards, and parents aimed at reducing the burden of air pollution on children. The finding that mean PM$_{2.5}$ exposure was lowest among those who walked to and from school and higher among those who were driven should be of particular interest to public health professionals promoting active school travel (Buttazzoni et al., 2018). We can conclude that children’s health campaigns should promote active travel to school not only for the associated health benefits of increased physical activity, but also for its contribution to reducing exposure to air pollution: i.e., for the “breath of fresh air”.

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**Conflicts of interest**

None.
Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sste.2019.02.004.

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