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Impact of School Location on Children's Air Pollution Exposure

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Abstract

The role of school location in children's air pollution exposure and ability to actively commute is a growing policy issue. Well-documented health impacts associated with near-roadway exposures have led school districts to consider school sites in cleaner air quality environments requiring school bus transportation. We analyze children's traffic-related air pollution exposure across an average Detroit school day to assess whether the benefits of reduced air pollution exposure at cleaner school sites are eroded by the need to transport students by bus or private vehicle. We simulated two school attendance scenarios using modeled hourly pollutant concentrations over the school day to understand how air pollution exposure may vary by school location and commute mode. We found that busing children from a high-traffic neighborhood to a school 19 km away in a low-traffic environment resulted in average daily exposures 2 to 3 times higher than children walking to a local school. Health benefits of siting schools away from high-volume roadways may be diminished by pollution exposure during bus commutes. School districts cannot simply select sites with low levels of air pollution, but must carefully analyze tradeoffs between location, transportation, and pollution exposure.

Keywords

school siting; school travel; air pollution; near-roadway exposures

Introduction

Decisions about the location of new schools are often contentious as schools seek to balance land, construction, and future school transport costs with community desires and concerns. In recent years, the conversation surrounding school siting decisions has increasingly focused on student health. There is a growing interest in how school location impacts children's air pollution exposure and the ability of children to be physically active by walking and biking to school.

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A multitude of health-related considerations influence, and often complicate, school siting decisions. Tenets of smart growth and compact development encourage districts to locate schools in “walkable” locations, often near dense road networks. Public health professionals promote opportunities for physical activity through active modes of school travel, while also emphasizing the importance of minimizing near-roadway exposure to air pollution and traffic danger from high-volume roadways. From a health exposures perspective, siting schools away from high-volume roads within a walkable distance for children is ideal; however, for many communities, this option is often not available. Ultimately, these decisions require tradeoffs by school facility planners, school boards, and parents alike.

We add clarity to these complexities by asking a critical policy question: How is children’s traffic-related air pollution exposure affected by some of the tradeoffs that districts face in school siting and assignment decisions? Specifically, what are the exposure-related implications of busing children farther distances to school in order to avoid poor air quality environments?

In this paper, we first describe school siting in the context of American planning and the shift to health-based concerns related to school siting and assignment policy and summarize the threats to children’s health posed by traffic-related air pollution exposure. We then present findings from our own simulation of two school siting scenarios and discuss the implications of our results for planning practice.

Our analysis involves a simulation of two hypothetical school assignment scenarios. We used data from Detroit, Michigan to estimate modeled traffic-related air pollution exposure for a synthetic sample of children living near high-volume roadways who walk to a nearby school in a high-traffic area as well as their exposure if they were to be bused or driven to a more distant school located in a low-traffic, “cleaner” air environment. We compared average daily exposures for these two scenarios to examine how school siting policies focused on locating schools away from high-volume roads might impact children’s daily exposure to air pollution. Finally, we explored how pollution exposure can be mitigated through various strategies such as idle reduction policies and clean school bus fleets.

We found that busing children to a distant school in a “cleaner” air quality site did not reduce pollution exposures for children who would otherwise walk to the local school. Mitigation strategies impacted results differently, with the use of clean bus technology having the greatest reductions in exposure for children busing longer distances to the “clean” school while HVAC strategies had modest reductions for children attending the local school. Our findings challenge the assumption that locating schools away from high-volume roadways will necessarily avoid exposure to air pollution for students. If locating schools away from roadways requires substantial school bus travel, the policy may not achieve the goal of reducing children’s exposure to traffic-related air pollutants.

Background: School siting decisions and air pollution exposure

School siting decisions

Schools are critical, and costly, infrastructure investments. After highways, K–12 public schools represent the largest public building sector in the U.S., accounting for nearly one-quarter of all state and local infrastructure investments (Filardo, 2016). From 1994 to 2013, states and school districts invested an average of $49 billion per year[1] from their capital budgets for new school construction and capital projects to improve existing schools (Filardo, 2016).

Planning practice has long acknowledged the important role of schools within communities. American planner and sociologist Clarence Perry, known most notably for his comprehensive planning model of the "neighborhood unit," advocated for the design of self-contained neighborhoods with the school placed at the center (Brownlow, 1929). Building standards and minimum acreage guidelines were introduced and revised beginning in the 1920s through the 1950s, and school architecture similarly saw transformations over this period (see McDonald, 2010 for a review). In the 1950s and 60s, school siting decisionmaking largely shifted from the realm of planners to that of school districts. When deciding where to build or "site" new schools, districts seek to balance many factors: costs of land, building, and transport; accessibility to current and future student populations; community desires; and state regulations (e.g. minimum acreage requirements).

In recent decades, school siting decisions have engaged debates on "sprawl," or widespread low-density suburbanization, as school districts have increasingly decided to abandon aging urban schools and instead build large educational complexes in rural or exurban locations (Norton, 2007). Changes in school assignment policy have also been a catalyst for discussion surrounding school siting decisions. Unlike neighborhood school models that assign students to schools based on where parents live, school choice systems allow families to choose where to enroll their child through magnet and charter programs or through open enrollment—the most popular form of school choice—which allows students to attend a public school of their choice inside or outside of the district in which they live. While many such programs were created to limit race- and socioeconomic-based segregation, research indicates that states are increasingly seeing that this is not always the case (Bell, 2009; Cookson et al., 2018). While school assignment policies continue to be an important consideration for school policy moreover, our discussion favors a focus on land use decisions, as they are most pertinent to planning practice and have long-term implications for school travel.

The location of a school impacts myriad aspects of the lives of children who attend it as well as those who reside nearby. School siting affects public sector costs, modal decisions, local employment opportunities, and availability of educational and extracurricular activities. Researchers have catalogued powerful rationales for new approaches to school siting, including economic savings to school districts, transportation infrastructure needs, and improved child health outcomes (Miles, Adelaja, & Wyckoff, 2011). Health outcomes have

[1] 2014 dollars

traditionally consisted of exposure to traffic danger around schools. A significant number of motor vehicle collisions involving school-aged children occur during school-related travel (Warsh, Rothman, Slater, Steverango, & Howard, 2009). A 2015 study found that collisions are more likely to happen on highways, interstates, and arterial roads and in places with traffic-generating land uses than on local roads and places with greater sidewalk connectivity (Yu, 2015).

Considering air quality at schools

Air pollution exposure at schools is a growing concern in the school siting literature. Whether due to formal guidance or community pressures, school districts have increasingly had to consider local air quality as a factor in school siting decisions as the body of evidence linking numerous health issues in children to air pollution near school facilities continues to grow.

According to a recent investigation by the Center for Public Integrity and The Center for Investigative Reporting, about 1 in every 11 U.S. public schools (or 8,000 schools serving roughly 4.4 million students) lies within 500 feet of highways, truck routes, and other roads with heavy traffic (defined as those with daily traffic of at least 30,000 vehicles or with a minimum of 10,000 vehicles but at least 500 trucks) (Hopkins, 2017). A 2007 study found that more than 30% of public schools in nine large U.S. Metropolitan Statistical Areas were located within 400 meters of an Interstate or highway (Appatova, Ryan, LeMasters, & Grinshpun, 2008).

Researchers continue to shed light on the risks of near road air pollution exposure to children’s health, such as stunted lung development (Gauderman et al., 2007), worsening asthma (Delfino, Kleeman, Gillen, Wu, & Nickerson, 2015), and increased risk of cancer (International Agency for Research on Cancer, 2012). Concerns over such health risks led the State of California to pass Senate Bill 352 in 2003, which restricts new development of elementary and secondary schools within 500 feet of a high volume roadway, defined as having traffic in excess of 50,000 vehicles in a rural area and 100,000 vehicles in an urban area (Escutia, 2003).

Disparities in school-related air pollution exposure are notably drawn along racial and socioeconomic lines. In a 2018 nationwide study of geographic and social disparities in exposure to air neurotoxicants at nearly 85,000 U.S. public schools, researchers found that black, Hispanic, and low-income students are most likely to be exposed to harmful toxins at school; black children comprise 16% of all US public school students, yet more than a quarter of them attend schools most affected by air pollution while of white children (52% of the public school system), only 28% of those attend the highest risk schools, and this disparity remained even when the urban-rural divide is accounted for (Grineski & Collins, 2018).

The U.S. Environmental Protection Agency (EPA) does not have the statutory authority to control school siting decisions directly, however, the agency released voluntary school siting guidelines followed by best practices for reducing pollution exposure at near-road schools (EPA, 2015; EPA., 2011). Some states offer school siting guidance similar to EPA, focusing on reduction rather than avoidance; however, researchers have pointed out that full implementation of EPA's air pollution guidelines could be time- and cost-prohibitive for many local school districts (Gaffron & Niemeier, 2015).

School districts that do strive to adhere to the guidance of locating schools away from heavy-traffic roadways, especially in urban areas where land is often scarce, are often faced with the prospect of school sites that are far and disconnected from students' neighborhoods and accessible only by motorized transport modes. In urban areas especially, where land away from high-volume roads is scarce, this can often mean that children are placed at distant schools requiring long bus rides (or car rides) and making active travel impossible. These challenges are perhaps evidenced by the fact that nearly one in five schools that opened from 2014–2015 was built nearby a busy road —which is a higher percentage than even the overall rate of schools sited near such roads (Hopkins, 2017).

Traffic-related air pollution and health outcomes

Children are particularly vulnerable to health risks associated with air pollution. Their heightened susceptibility is due to processes of continued lung growth and development, incomplete metabolic systems, immature immune systems, high rates of infection with respiratory pathogens, and particular activity patterns (e.g. time outdoors) that exacerbate exposure to air pollution (EPA, 2011; World Health Organization, 2005).

There is a growing literature on the adverse health effects of short and/or long-term exposure to traffic-related air pollution for children. Research using longitudinal data that follows children over time has concluded that air pollution may not only trigger and exacerbate asthma symptoms, but also contribute to the development of asthma in children in the long-term (Anderson, Favarato, & Atkinson, 2013) and living close to busy roads appears to be an independent risk factor for the onset of childhood asthma (Health Effects Institute, 2010). Studies have shown neurotoxic effects of air pollution related to impaired cognitive development (Porta et al., 2015) and evidence suggests a link to the etiology of mental disorders including generalized anxiety and depression (Brunst et al., 2019). Air pollution is also linked to a significant decline in cognition (Zhang, Chen, & Zhang, 2018) as well as increased behavioral incidents and school absences (Heissel, Persico, & Simon, 2019).

Key pollutants that have been identified as highly elevated in near-road environments, and linked to adverse health effects identified for near-road populations, include particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), and contaminants known as mobile source air toxics, such as benzene and other volatile organic compounds (VOCs) (Karner, Eisinger, & Niemeier, 2010).

Exposures across microenvironments

Personal exposure to high concentrations of air pollutants are a function of both indoor and outdoor air quality and the time spent in various microenvironments, and evidence suggests that as much as 29% of indoor air concentrations result from outdoor sources (Habre et al., 2013). In examining the daily pollution exposure of school children, researchers can assess several microenvironments in which children spend time throughout a given day, such as at home, their commute to school, and at school.

School commutes may comprise a small percentage of a child's waking hours, but this time can contribute to a large fraction of a child's total exposures due to elevated pollutant concentrations in roadway environments (Behrentz et al., 2005; Dons, Int Panis, Van Poppel, Theunis, & Wets, 2012). Researchers have examined exposures during school bus commutes in particular, and found that children's in-transit exposure to vehicle-related pollutants is significantly higher than ambient air concentrations (Behrentz et al., 2005; Wargo, Brown, Cullen, Addiss, & Alderman, 2002). Researchers in California used real-time measurements of pollutant concentrations in school buses in the Los Angeles Unified School District and found that bused children were exposed to significantly higher concentrations of vehicle-related pollutants than ambient air concentrations and frequently higher concentrations than those measured on the roadway (Sabin et al., 2005). On-board concentrations of vehicle-related pollutants were significantly higher on urban routes compared to the rural/suburban route, indicative of surrounding traffic density. This study also examined bus (un)loading and wait time at the bus stop and found that these scenarios made relatively insignificant contributions to children's exposure compared to bus commutes.

Effects of personal exposure to high concentrations of air pollutants are a function of outdoor concentrations, indoor concentrations, and the time that one spends in various microenvironments (Gaffron & Niemeier, 2015; Habre et al., 2013). A modeling approach that looks at exposures across microenvironments is common across exposures literature. Our study facilitates a comparison of exposures, assigned by time-weighted concentrations across microenvironments, based on school assignment policy.

We contribute to planning literature related to health exposures by examining children's air pollution exposures in light of important variation in air pollution exposure level across microenvironments of the school day. We use a unique dataset that captures spatial and temporal variability of traffic-related air pollution. Our approach examines what happens to children's exposures when school siting and attendance policies favor distant schools in cleaner environments, and whether these policies might achieve their aims of reducing children's air pollution exposure.

Detroit as a case site

We examine our research questions in the setting of Detroit, Michigan for two main reasons. First, we utilize a unique dataset of temporally- and spatially-resolved estimates of traffic-related air pollutant concentrations from a modeling approach that accounts for relative contributions of mobile and stationary sources. The model was developed through the EPA-funded Near-road Exposures and Effects of Urban Air Pollutants Study (NEXUS), from 2010–2012, which investigated respiratory health impacts of exposure to traffic-related air pollutants for children with asthma living in Detroit.

Second, Detroit is located in a region with a relatively high percentage of schools that are at a heightened risk for air neurotoxicant exposures. In a 2018 national-level study of geographic and social disparities in exposure to air neurotoxicants at public schools, researchers found that U.S. EPA Region 5, containing Detroit (Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin), has the third highest levels of air neurotoxicants, with 16% of schools being "high risk," and that students attending these "high risk" public schools are significantly more likely to be eligible for free or reduced lunch, and to be Hispanic, black, or Asian Pacific Islander (Grineski & Collins, 2018). An earlier study of school-based air pollution exposure across all 3,660 public schools in the state of Michigan found that 63% of schools were located in the top 20% of areas with pollution from industrial sources (Mohai, Kweon, Lee, & Ard, 2011). These authors similarly found important implications regarding exposure by race and ethnicity: 44% of all white students in Michigan attend schools located in the top 10% of the most polluted locations while 82% percent and 62% percent of African American and Hispanic students, respectively, attend schools in the most polluted zones.

The nature of this case study of course is that it is limited in its generalizability. Detroit is historically acknowledged for its auto-dominant urban fabric and contains neighborhoods with high exposure to pollution from roadways; the richness of our dataset makes this context an excellent place to examine our research questions. Results from our simulation are useful to policy debates playing out in regions of the U.S. with significant air quality issues, like Detroit. Further research should explore similar questions about exposures related to school siting decisions in different environmental contexts.

Methods

We simulated school day traffic-related air pollution exposures for a synthetic sample of children living in a high-traffic environment under two school assignment scenarios: attendance at 1) a local school in the high-traffic environment or 2) a distant school in a low-traffic environment. We focus our analysis on near-roadway pollution because background conditions are similar across scenarios. Travel modes modeled were walk mode for the local school and private vehicle and school bus modes for the distant school. These scenarios reflect school assignment and modal decisions faced by school districts and families as air quality near schools has been an issue with growing attention.

We generated shortest path home-to-school commuting routes to two hypothetical school locations for a randomly selected synthetic sample of students in Detroit. We estimated daily exposures for six pollutants (benzene, CO, NOx, total $PM_{2.5}$ mass, and its components such as elemental carbon [EC] and organic carbon [OC]) across five phases of an average school day (morning commute, unloading at school, in-school, loading after school, and afternoon commute). We also estimated potential impacts of three relevant mitigation strategies: adopting clean bus technology, improving school HVAC filtration systems, and idle reduction policies.

Site selection, sample creation, and route generation

We selected our two school sites by assessing 2010 average hourly pollutant concentrations of NOx and $PM_{2.5}$ for 107 Detroit schools using data from the NEXUS study (Isakov et al., 2014; Vette et al., 2013). The NEXUS study examined the relationship between near-roadway exposures to air pollutants and respiratory outcomes in a cohort of asthmatic children living near major roadways in Detroit. We chose two existing school sites with very different air quality environments: a “local” school in a high-traffic environment within 152.4 meters (or 500 feet) of a major roadway (defined as roads with >90,000 total vehicles/day of annual average daily traffic) and a “distant” school in a low-traffic, cleaner air quality site. Our final site selection used hypothetical school sites offset from their actual locations by about 0.5 km to mask school locations.

The selected local school had the highest impact from traffic emissions on air quality of all schools in the NEXUS study. The distant school selected was the closest location to the local school site where air quality impacts from traffic were 50 percent or lower than at the local school. Thus, this distant school represents the closest alternative school with a “clean” environment for children attending the local school. This scenario replicates a choice faced by many school districts in which there are few options for school sites that are not near arterials or high-volume roads. The distant school site is located 19 km northwest of the local school site (26 km via the shortest-path network).

To generate a synthetic sample of children living within walking distance of the ‘local’ school in the high-traffic environment, we randomly selected 300 residential parcels within 3.2 km (2 miles) Euclidean distance of the local school. We used residential parcels as our sampling unit to replicate likely distance to school patterns. We then excluded any parcels whose shortest path walking route to school exceeded 3.2 km as national data shows that 94% of students who walk to school have trips under this distance (author’s analysis of the 2009 National Household Travel Survey). The final sample size was 179 synthetic students.

Air quality model

We modeled hourly pollutant concentrations along roadways and at our hypothetical school sites for each day in 2010 in the study area using the Research-LINE (R-LINE) dispersion model version 2.0 (Isakov et al., 2014; Snyder et al., 2013). R-LINE is a research grade model designed to model near-road conditions. The model simulates dispersion of pollution from vehicular traffic on roadways, as line sources, accounting for weather conditions. Pollutants modeled include CO, NOx, total $PM_{2.5}$ mass, and its components such as elemental carbon (EC) and organic carbon (OC), along with benzene to represent a key mobile source air toxic. The spatial resolution of R-LINE is flexible, i.e., the model can be configured to predict concentrations at any receptor locations on demand with respect to the location of the source. For this study, we instrumented the receptors along the various commute paths from home to the school.

Emissions from mobile sources, i.e. traffic, are modeled using road network geometries, traffic volumes, fleet mixes, and pollutant-specific emission factors in combination with meteorological inputs (Snyder et al., 2014). We collected roadway information from the Federal Highway Administration’s Freight Analysis Framework (FAF3), which contains primary and secondary roadways and includes data on vehicle speed, vehicle type, and annual average daily traffic (AADT) for all vehicles, including passenger and commercial vehicles (Federal Highway Administration, 2012). Since FAF3 does not provide temporally-resolved traffic activity data, we used temporal allocation factors from EPA’s National Emission Inventory to allocate AADT to hourly levels. We combined this hourly resolved traffic volume data with MOtor Vehicle Emission Simulator (MOVES 2010b) emission factor tables by matching vehicle speed, vehicle type, and road type in order to calculate link-specific emissions which served as inputs for the R-LINE dispersion model.

Physical dispersion of traffic-related line source pollution is modeled using hourly meteorological data for the year 2010 from National Weather Service station (Detroit City Airport located at 42.4092 N and 83.0099 W) data processed through AERMET, the meteorological pre-processor. Pollutant concentrations estimated by R-LINE only include the contributions from the roadway sources. Further information about R-LINE can be found in Isakov et al. (2014) and Snyder et al. (2014).

Exposure estimation

Children move through various microenvironments over the course of the day, with each setting uniquely contributing to overall pollution exposure. We are interested in how travel mode and school location impact pollution exposure and therefore focus on exposure from 7am to 4pm since our variables of interest do not impact exposures after returning home from school and at night. During this time period, children pass through five microenvironments: 1) morning commute, 2) unloading at school, 3) school, 4) loading at school, and 5) afternoon commute. For each student and each of the three travel mode/school assignment scenarios, we calculated time spent in the microenvironment and pollution concentrations. From this, we determine the time-weighted exposure for each child, for each pollutant, and each mode/school scenario. The following describes the approach to estimating pollutant exposures for each micro-environment.

Morning and Afternoon Commute—To calculate pollution exposure during the school commute, we calculated the route, used R-LINE to estimate pollution levels along each route segment, and applied in-cabin infiltration factors to school bus and private vehicle modes. Exposure estimates were calculated for each route segment, by time of day and by day of year and then averaged across the school year for each child in the synthetic sample.

We generated home-to-school commuting routes in ArcGIS for each child for three scenarios: walk to the local school, school bus to the distant school, and private vehicle to the distant school. The shortest path algorithm in ArcGIS was used for both the walk mode and private automobile. Restrictions based on roadway type were used in order to ensure that children’s walking routes did not follow along interstates and on/off ramps. We produced walking routes only for when students attend the local school, as walking to a school approximately 19 km from home is impractical. To generate school bus routes, we applied the traveling salesman algorithm in ArcGIS Network Analyst extension, which finds the shortest route that passes through each of a set of points once and only once.

Each route between a student’s home and school consisted of a set of nodes and links; nodes were located at directional changes in the route, and the links connect these nodes. We used the modeled traffic-related air pollution concentration (which varies by time of day, day of year, and road link) at the midpoint of each link and weighted these estimates by the time spent on each link of the path in order to calculate the time-weighted exposure along each route (see Figure 1).

Time spent on each link was calculated using average speeds based on the roadway functional class (FC) and mode. For walking mode, we used an average speed of 2.7 mph based on previous studies on median walking speed for children ages 5–13 (McDonald, 2008). For motorized modes, we developed average speeds by FC for school buses and private autos based on Department of Transportation literature and verified our approach with posted speed limits on Google Maps. For example, FC 4 roads, which are considered minor arterials because they connect and distribute traffic between neighborhoods, were assigned a speed of 35 mph for private autos and 30 mph for school buses.

In-cabin filtration factors were applied to modelled concentration levels for both motorized modes. An infiltration multiplier of 3.5 was used for the bus in-cabin exposure for all pollutants (Zhu & Zhang, 2014). For auto in-cabin exposure, we used infiltration factors of 0.71 ($PM_{2.5}$, EC, and OC), 0.8 (NOx), 1.0 (CO), and 3.0 (Benzene) (Dionisio, Baxter, & Chang, 2014).

School—To model exposure at school, we used the pollution concentrations from R-LINE at the school locations. Hourly estimates from 8am to 3pm were averaged to produce a representative concentration. Time spent at school was calculated for each child as the time between drop-off at school in the morning and pick-up in the afternoon. A 30-minute period of this time was allocated to "outdoor time" for recess. For the remainder of in-school time, we used the mid-level infiltration factors reported in McCarthy et al. (2013), where researchers assessed infiltration factors in three different schools by measuring indoor and outdoor concentrations. For $PM_{2.5}$, EC, and OC, we used an infiltration factor of 0.259. For NOx, CO, and Benzene, we used an infiltration factor of 1.0.

Loading, Unloading at School—Research has shown that idling at schools can lead to increased pollution levels during drop off and pick up periods (Behrentz et al., 2005; Sabin et al., 2005). Children's exposure to these areas depends on school-specific design factors, e.g. location of walk, school bus, and private vehicle access routes to the school. We assumed that all children, irrespective of mode, had to pass through the loading zone. To model pollutant exposures in these zones, we applied a scaling factor of 10.0 (as reported in Zhu & Zhang, 2014). Little empirical data exists to estimate the average time spent in the loading zone; we therefore assumed a duration of 5 minutes for both the unloading and loading periods.

Total Exposure from 7am to 4pm—We then summed the time-weighted exposures for all five phases of the day, or microenvironments, to calculate the average school day exposures for each child, in each mode/school attendance scenario for all study pollutants for the months of the Detroit Schools academic year (Equation 1).

Limitations of Exposure Estimation Approach

Our approach has some important limitations. Pollutant concentrations estimated by the R-LINE dispersion model only include the contributions from roadway sources as we assume that background pollution levels for both schools are similar. Of course, there are exceptions to this based on the location of nearby polluting facilities, for example.

We do not account for the fact that active transportation may increase exposure during a trip due to increased inhalation rates associated with an increase in physical exertion (de Nazelle et al., 2012). Increased vulnerability of children to inhaled air pollution exposure is one of the motivating factors of our analysis; however, calculating the dose or other inhalation metric could be misleading since susceptibility to air pollution varies by numerous individual-level factors; many assumptions would be required to do so and these assumptions would yield substantially more uncertainty in the assessment. For an overview of an approach that accounts for inhalation rates see Adams, Yiannakoulias, & Kanaroglou, 2016.

We make some assumptions about a child's behavior throughout the day. We chose to use the shortest path approach for route creation even though research has found that students do not always take the shortest path to reach school (Buliung, Larsen, Faulkner, & Stone, 2013). A typical school day in Detroit is 8am-3pm; however, we modeled a child's day from 7am to 4pm to account for the time spent commuting to and from school. For children with shorter commute times, the difference in time was assumed spent at school to avoid inflating the influence of residential exposure differences in this assessment. We recognize that it is likely that children with shorter commutes would rather leave home later, thus spending less time at school; however, for the sake of comparison, we assume that all children leave from home and return to home at the same time.

We also acknowledge the importance of exposure at a child's home even though this study examines only exposure related to the school day. While the influence of residential air quality on a child's life is likely most significant, school-related exposures are not negligible and are critical to the school siting conversation. We limit our examination to time spent away from home during a school day (e.g. commute and time at school) as we assume that parents have slightly greater flexibility in choosing how their child will commute to school, compared to where their home is located.

Testing mitigation strategies

We modeled three different pollution mitigation strategies to examine their potential roles in alleviating pollution exposure. These strategies include 1) switching from diesel to clean bus technology, 2) improving or updating HVAC (air filtration) at schools, and 3) implementing a no-idling policy at school pick-up and drop-off areas. To approximate the effect of clean bus technology, the in-cabin infiltration factors from Zhu & Zhang (2014) were adjusted from mid- to low-bound infiltration estimates (from 3.5 for all pollutants to 1.0 for all pollutants). These factors are multiplicative in nature and reflect the amount of ambient air pollution that infiltrates the bus. Similarly, we used the low-bound infiltration estimate from McCarthy et al. (2013) for in-school exposure to examine the effects of improved HVAC systems on in-school exposure; factors for $PM_{2.5}$, EC, and OC were adjusted from 0.259 to 0.028 and factors for NOx, CO, and Benzene remained at 1.0. In addition to indoor and outdoor sources of pollution, the most important determinant of indoor air quality are the design and operation of the ventilation system to limit the accumulation of pollutants and humidity (National Research Council, 2006).

Finally, to test the potential impact of a no-idling policy at school, we simply removed the scaling factor of 10.0 that was previously applied in the loading and unloading microenvironments to compare exposures in a standard idling zone to a zone in which both buses and automobiles were restricted from idling. By using infiltration and scaling factors established in the literature, we are able to explore how exposure might change in light of certain varying factors. These three scenarios facilitate a means of sensitivity testing by allowing us to examine how the model responds to changing parameters on in-cabin bus infiltration, school building infiltration, and presence of idling vehicles.

Results

Characteristics of each modeled pollutant are available in the Appendix. Our results suggest that busing children substantial distances to a school site with cleaner air does not reduce their daily air pollution exposure. In fact, our simulation found that busing children from a high-traffic neighborhood to a distant school in a low-traffic environment 19 km away is associated with average daily exposures ranging from 2 to 3 times higher than if those children were to walk to the local school, as illustrated in Table 1. These disparities were statistically significant across all six pollutants ($p<0.001$). For example, $PM_{2.5}$ exposure during the study day was estimated at 0.33 $\mu g/m^3$ for walking to the local school in the high-traffic area but was 2.5 times higher on average if students were bussed to the school in the clean air environment.

Compared to walking to the local school, driving in a private vehicle to the distant school generated lower exposures for all pollutants except Benzene. For example, driving children to the distant school was associated with a $PM_{2.5}$ exposure of 0.21$\mu g/m^3$ or approximately two-thirds the estimate for walking to the local school. For EC, average exposure for driving children to the distant school was just over half the estimate for walking to the local school (0.47 $\mu g/m^3$ and 0.83 $\mu g/m^3$ respectively). Driving children long distances to school, however, imposes significant time and logistical burdens on families and would impact local congestion levels and increase regional air pollution. In practice, public provision of school buses would generally be required even if some families opted to drive. Driving also removes an opportunity for physical activity, i.e. walking to school, and previous research has shown the physical activity benefits to outweigh most pollution exposure (Woodcock et al., 2009).

Contribution of microenvironments

Air quality at the school site directly influences in-school exposures and this influence can be seen independent of commute mode. Across all pollutants, modeled pollution levels are on average two times higher at the school in the high-traffic area compared to those at the distant school (as seen in Table 1). While in-school duration is very similar for students walking to school in the high-traffic setting compared to those being bused to the low-traffic setting (8.1 hours versus 8.0 hours respectively), in-school exposure accounts for 28–57% of daily levels at the former and only 5–15% at the latter.

Variation in exposure for each attendance scenario depends on the commute mode. While the commute is a relatively small portion of students' days (ranging from 6–10% in this study), exposure levels in these commuting microenvironments are quite high relative to other microenvironments of the school day. This is especially true for children who ride the bus to the distant school, as evident in Figure 2. When attending the distant school, for example, the average morning bus commute is 6% of the child's day, yet accounts for 53%

of daily exposure on average across all six pollutants. The average morning car commute to the distant school is 3% of the day and accounts for 31% of daily exposure. For students walking to the local school, the morning commute is 5% of the day and accounts for 19% of total exposure.

For the pollutant CO, for example, total commuting time accounts for 23% of daily exposures for students walking to the local school, 43% for driving to the distant school, and 79% for busing to the distant school. Because exposure during the commute is correlated with time spent in the mode (e.g. on the school bus), the distance between the two schools affects these results. The longer students must travel to reach a school located in a clean air quality environment, the more the commute offsets the potential benefits of a cleaner school site.

Mitigation strategies: Clean Bus, Improved HVAC, no-idling

For students who must bus to a distant school, riding on a “clean bus” could reduce average daily pollutant exposure by more than half for all six pollutants ($p<0.001$) as seen in Table 2. However, riding a clean bus to a distant school does not consistently reduce air pollution exposure compared with walking to a local school in a poor air quality environment. Improved HVAC systems at the local school in heavy-diesel/heavy-traffic yielded moderate decreases of about 20% for the three pollutants modeled, EC, OC, and $PM_{2.5}$ ($p<0.001$), which is also seen in Table 2.

Impacts of implementing a no-idling policy can be seen in Table 3. We found that the greatest potential reductions in average daily exposure occurred for the walkers, with reductions ranging from 19 to 34% across all six pollutants. Reductions for children being driven in a car ranged from 7 to 26%. The most modest exposure reductions of a no-idling policy were associated with the bus mode, with potential reductions of about 5–6%.

Discussion

In our simulation of two school attendance scenarios using contrasting school sites, we found that for all pollutants studied, children who were bussed to a more distant school in a “cleaner” air quality environment experienced greater daily exposure to traffic-related air pollution than if they were to walk to their local school in a “dirtier” air quality environment. For all pollutants except benzene, driving children to a more distant school in a private auto was associated with lower daily exposures than if they were to walk to the local school.

Adverse impacts of long school bus commutes could be mitigated by significant investments in clean school bus fleets. We found that switching to a clean bus for commutes to the distant school reduced average daily air pollution exposure by more than half for all pollutants (though even with the clean buses, exposures for most pollutants were comparable to those when children walked to the local school). But the costs for upgrading school bus fleets can be substantial; the estimated cost of a 2019 model year diesel bus is $83,500 compared to $92,400 for a propane bus and $113,500 for a compressed natural gas bus (NC.gov, 2017). Greater capital costs make this an incremental solution for most school districts.

Mitigation measures have seen success in some states. For example, Southern California's air agency earmarked settlements from polluting companies to partially cover the cost of HVAC-based filtration systems at about 80 schools near freeways and other pollution sources. In February 2018, the Texas Commission on Environmental Quality announced $6.2 million in funding for school districts to purchase alternative fuel school buses or retrofit existing diesel buses as part of the Texas Emissions Reduction Plan's "Clean School Bus Program"

Conclusion: Evaluating tradeoffs in school siting policy

Our research evaluates the potential implications of a health-based school siting decision that places schools away from high-volume roadways. School districts must evaluate significant factors like land and building costs, accessibility to current and future student populations (especially in light of increasing school choice), community desires, and state regulations alongside more recent concerns regarding student health outcomes related to active travel to school and the school's local air quality environment. As districts attempt to navigate these tradeoffs, approaches for quantitatively comparing the risks of elevated air pollution exposures with the benefits of active transport are needed to guide school siting decisions.

We simulated two school attendance scenarios to evaluate the impact of school siting and commute mode on students' school day exposure to traffic-related air pollution. We calculated average school day exposure to six pollutants for children who live in a high-traffic neighborhood and 1) walk to the local school situated near a major roadway in a high-traffic environment and 2) take a school bus or private auto to a school situated at a setback from major roads, away from high traffic volume. We account for variation in pollution levels across time of day, day of year, and across microenvironments of the school day.

We found that for all pollutants studied, children who were bussed to a school farther from home in a cleaner air quality environment did not experience reductions in daily exposure to traffic-related air pollution. School siting and attendance policies favoring distant schools in cleaner air quality environments can fail to achieve their aims of reducing air pollution exposure for children who rely on busing and require significant investment of public funds in long-term school bus service.

While school districts will continue to face the uncertainties associated with school siting decisions, school facility planners and school boards should be willing to question the assumption that locating schools away from high-volume roadways will necessarily reduce children's traffic-related air pollution exposure. Instead, when proposed school sites require long commutes, the air pollution exposure amassed from school bus commutes can offset the desired benefits of reduced exposures at the school location. Mitigation measures offer school districts opportunities for near-term, proactive strategies to curb students' air pollution exposure during the school day.

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Appendix:

$$Ei = \sum_{j}^{J} C_{ij} * \frac{T_{ij}}{T} \qquad \text{Equation 1.}$$

where E_i is the time-weighted exposure for child i over the specified time period (school day, 7am-4pm); C_{ij} is the pollutant concentration in microenvironment j; T_{ij} is the time child i spends in microenvironment j; T is the total time in the modeled day of 9 hours; and J is the total number of microenvironments that child i moves through during the school day.

Table A1.

Summary characteristics of pollutants by school attendance scenario and microenvironment

	Mean daily concentration (μg/m^3)†					
	benzene	**CO**	**NOx**	**$PM_{2.5}$**	**OC**	**EC**
Walk to Local School						
AM Commute	0.022	14	4.7	0.17	0.057	0.085
Unload at School	0.12	79	27	0.97	0.33	0.49
In-School	0.0051	3.3	1.1	0.012	0.0039	0.0058
Load at School	0.055	35	11	0.38	0.12	0.20
PM Commute	0.014	8.6	2.5	0.091	0.028	0.047
Bus to Distant School						
AM Commute	0.13	89	24	0.92	0.36	0.41
Unload at School	0.061	41	11	0.48	0.18	0.20
In-School	0.0027	1.8	0.44	0.0059	0.0022	0.0025
Load at School	0.029	20	4.5	0.19	0.068	0.084
PM Commute	0.084	58	13	0.49	0.17	0.23
Drive to Distant School						
AM Commute	0.16	37	7.7	0.27	0.10	0.12
Unload at School	0.061	41	11	0.48	0.18	0.20
In-School	0.0027	1.8	0.44	0.0059	0.0020	0.0025
Load at School	0.029	20	4.5	0.19	0.068	0.084

	Mean daily concentration (μg/m^3)†					
	benzene	**CO**	**NOx**	**$PM_{2.5}$**	**OC**	**EC**
PM Commute	0.11	26	4.7	0.15	0.054	0.069

†All scenarios include vehicle idling.

Biography

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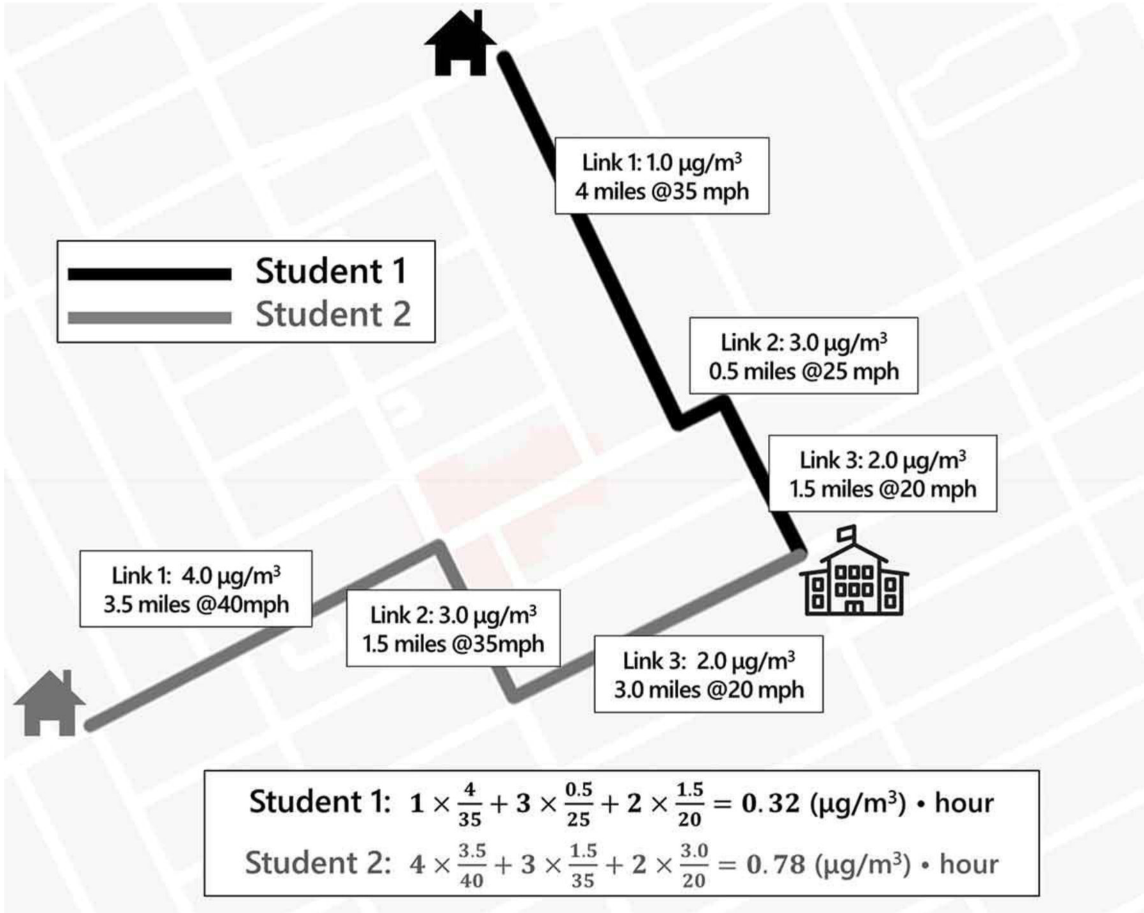

Figure 1.
Illustration of exposure estimation along routes for AM and PM commutes. Average pollution concentrations along each link, accounting for time of day, are weighted by the time spent traveling on each link (which is calculated using distance of each link and velocity pertaining to the relevant mode)

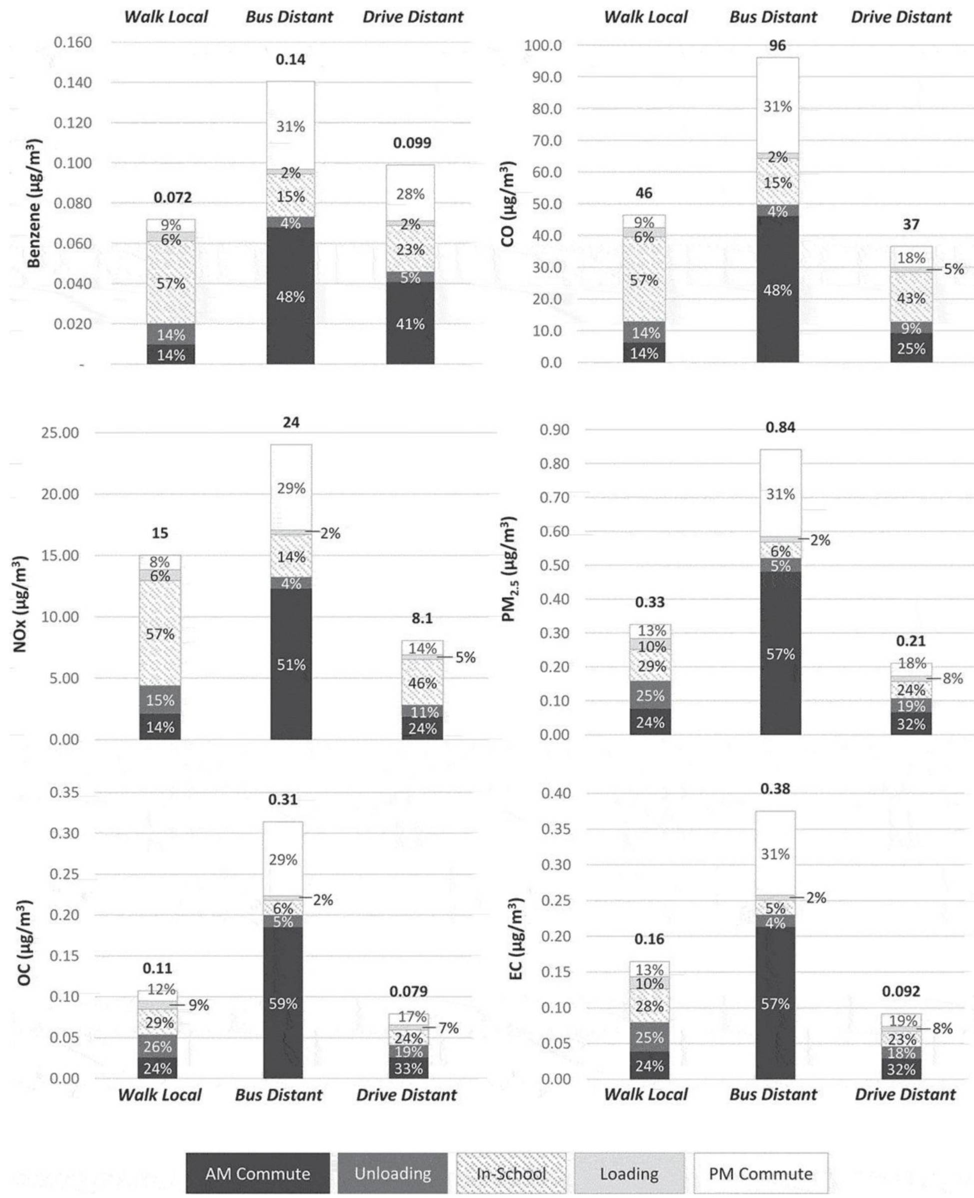

Figure 2.

Relative contributions of each microenvironment to average school day exposure, by school attendance scenario.Average time-weighted daily exposure by pollutant is totaled on top of each stacked bar. The relative contributions of each microenvironment are displayed as percentages within the stacked bars

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Table 1

Relative contributions of each microenvironment to average school day exposure, by school attendance scenario

Average time-weighted daily exposures for each pollutant are totaled in the bottom row of each Mode/School scenario block (in the row labeled "Total daily exposure, μg/m^3"). The relative contributions of each pollutant, by microenvironment, are displayed as percentages in the columns above each total.

School Attendance Scenario / Microenvironment (avg. hours spent)	benzene	CO	NOx	$PM_{2.5}$	OC	EC
Walk to Local School						
AM Commute (.46)	14%	14%	14%	24%	24%	24%
Unload at School (.08)	14%	14%	15%	25%	26%	25%
In-School (8.1)	57%	57%	57%	29%	29%	28%
Load at School (.08)	6%	6%	6%	10%	9%	10%
PM Commute (.46)	9%	9%	8%	13%	12%	13%
Total daily exposure, μg/m^3 (9.2)	0.072	46	15	0.33	0.11	0.16
Bus to Distant School						
AM Commute (.52)	48%	48%	51%	57%	59%	57%
Unload at School (.08)	4%	4%	4%	5%	5%	4%
In-School (8.0)	15%	15%	14%	6%	6%	5%
Load at School (.08)	2%	2%	2%	2%	2%	2%
PM Commute (.52)	31%	31%	29%	31%	29%	31%
Total daily exposure, μg/m^3 (9.2)	0.14	96	24	0.84	0.31	0.38
Drive to Distant School						
AM Commute (.25)	41%	25%	24%	32%	33%	32%
Unload at School (.08)	5%	9%	11%	19%	19%	18%
In-School (8.5)	23%	43%	46%	24%	24%	23%
Load at School (.08)	2%	5%	5%	8%	7%	8%
PM Commute (.25)	28%	18%	14%	18%	17%	19%
Total daily exposure, μg/m^3 (9.2)	0.099	37	8.1	0.21	0.079	0.092

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Table 2

Average school day exposure at baseline and with clean bus; improved HVAC strategies ($\mu g/m^3$)

Average time-weighted daily exposures by pollutant for the baseline walking and baseline bussing scenarios are displayed; to the right of each baseline are the average time-weighted daily exposures for the clean bus strategy and improved HVAC strategy, respectively, followed by the percentage change from baseline for each strategy.

	Standard Bus Distant Baseline	Clean Bus Distant	% change after clean bus	Walk Local Baseline	Walk Local Improved HVAC*	% change after improved HVAC*
benzene	0.14	0.062	−56%	0.072	--	--
CO	96	43	−56%	46	--	--
NOx	24	11	−56%	15	--	--
$PM_{2.5}$	0.84	0.32	−61%	0.33	0.26	−20%
OC	0.31	0.12	−62%	0.11	0.085	−21%
EC	0.38	0.14	−62%	0.16	0.13	−20%

*infiltration factors are fixed at 1.0 for CO, NO_X (100% infiltration), whereas no infiltration factors for benzene were available from the literature, and thus, not modeled here.

Table 3

Average school day exposure at baseline and with 'no-idling' strategies (μg/m^3)

Average time-weighted daily exposures by pollutant for the baseline walking, baseline bussing, and baseline driving scenarios are displayed along with the average time-weighted daily exposures for their respective no-idling scenarios. Percentage changes from baseline scenario to mitigation strategy scenario are also displayed.

	Walk Local Baseline	Walk local No-idle	% change for walk	Standard Bus Distant Baseline	Standard Bus Distant No-idle	% change for bus	Drive Distant Baseline	Drive Distant No-idle	% change for drive
Benzene	0.072	0.058	−19%	0.14	0.13	−5%	0.099	0.092	−7%
CO	46	37	−19%	96	91	−5%	37	32	−13%
NOx	15	12	−20%	24	23	−5%	8.1	6.9	−15%
$PM_{2.5}$	0.33	0.21	−34%	0.84	0.79	−7%	0.21	0.16	−26%
OC	0.11	0.071	−34%	0.31	0.29	−6%	0.079	0.059	−26%
EC	0.16	0.11	−34%	0.38	0.35	−6%	0.092	0.068	−26%