

Adopting Clean Fuels and Technologies on School Buses

Pollution and Health Impacts in Children

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Abstract

Rationale: More than 25 million American children breathe polluted air on diesel school buses. Emission reduction policies exist, but the health impacts to individual children have not been evaluated.

Methods: Using a natural experiment, we characterized the exposures and health of 275 school bus riders before, during, and after the adoption of clean technologies and fuels between 2005 and 2009. Air pollution was measured during 597 trips on 188 school buses. Repeated measures of exhaled nitric oxide (F_{ENO}), lung function (FEV₁, FVC), and absenteeism were also collected monthly (1,768 visits). Mixed-effects models longitudinally related the adoption of diesel oxidation catalysts (DOCs), closed crankcase ventilation systems (CCVs), ultralow-sulfur diesel (ULSD), or biodiesel with exposures and health.

Measurements and Main Results: Fine and ultrafine particle concentrations were 10–50% lower on buses using ULSD, DOCs,

and/or CCVs. ULSD adoption was also associated with reduced F_{ENO} (−16% [95% confidence interval (CI), −21 to −10%]), greater changes in FVC and FEV₁ (0.02 [95% CI, 0.003 to 0.05] and 0.01 [95% CI, −0.006 to 0.03] L/yr, respectively), and lower absenteeism (−8% [95% CI, −16.0 to −0.7%]), with stronger associations among patients with asthma. DOCs, and to a lesser extent CCVs, also were associated with improved F_{ENO}, FVC growth, and absenteeism, but these findings were primarily restricted to patients with persistent asthma and were often sensitive to control for ULSD. No health benefits were noted for biodiesel. Extrapolating to the U.S. population, changed fuel/technologies likely reduced absenteeism by more than 14 million/yr.

Conclusions: National and local diesel policies appear to have reduced children's exposures and improved health.

Keywords: particulate matter; air pollution; asthma; absenteeism; lung function

Traffic-related air pollution may adversely affect children's respiratory health (1–11). Little is known, however, about the health effects of commuting to school, especially aboard diesel-powered school buses. As more than 25 million American

children commute via school bus (12) and experience elevated pollution levels on these buses (13–19), commuting is a major contributor to children's exposures to traffic-related air pollutants (14, 20–22).

To limit exposures to diesel exhaust and to protect health, the U.S. Environmental Protection Agency (USEPA) created a voluntary retrofit initiative to help states install clean air technologies on vehicles. Clean air technologies such as

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At a Glance Commentary

Scientific Knowledge on the

Subject: Exposures to traffic-related air pollution at home and school have been repeatedly linked to adverse respiratory health in children. Children also experience elevated pollution levels on diesel-powered school buses, yet little is known about the resultant health effects or the level of protection offered by clean air technologies and fuels on school buses.

What This Study Adds to the

Field: The findings from this natural experiment suggest that when children ride buses with clean air technologies and/or fuels, they experience lower exposures to air pollution, less pulmonary inflammation, more rapid lung growth over time, and reduced absenteeism than when they are on buses without these technologies and fuels. These improvements were often strongest among children with asthma, suggesting that cleaner buses may be especially important to protecting the health of our most vulnerable students. Given that more than 25 million American children commute to school each day via school bus, these findings have clear policy implications for protecting the health of school children.

diesel oxidation catalysts (DOCs) and crankcase ventilation systems (CCVs) are used to reduce tailpipe and engine emissions, respectively. These technologies, which can be adopted on older buses and are commonly installed on newer buses, are estimated to reduce particulate emissions and onboard concentrations by 20 to 50% (23–28). The USEPA also required that refineries produce ultralow-sulfur diesel (ULSD) starting in 2006 under the Highway Diesel Fuel Sulfur Control Requirements. ULSD and biodiesel are projected to reduce particle generation by approximately 10–30% and to enhance the operation of clean air technologies (23, 29). Although these initiatives have been estimated to prevent approximately 20,000 hospitalizations and 3.3 million days of lost productivity (30), no study has directly assessed the health impacts of these policies on individual children.

We investigated the impacts of clean air technologies and fuels on air pollution levels in school buses and on pulmonary health in a cohort of elementary school children. Associations were explored using a natural experiment in which we monitored in-bus air pollution concentrations and markers of health before, during, and after the staggered adoption of clean air technologies and fuels. Early results of this study have been previously reported as abstracts (31–33), and one published article (16).

Methods

Population and Design

We sampled 307 school bus riders (6–12 yr) attending a public elementary school in the Seattle and Tahoma, Washington, school districts (see Figure E1 in the online supplement). Children were monitored monthly (2005–2009) while the Puget Sound Clean Air Agency (PSCAA) incentivized clean air technology installation and a fuel change occurred under USEPA rules. Children were unaware of the technology and fuel of their buses, resulting in a blinded natural experiment with the collection of exposure and health measurements before, during, and after the staggered implementation of interventions. Children with asthma were preferentially recruited for power and as a sensitive subpopulation (34). Children in smoking households, on buses with fewer than 50 seats, taking oral corticosteroids, or missing information were excluded, resulting in a sample of 275. All protocols were approved by our institutional review board and written guardian consent and child assent were obtained.

Bus Characteristics

Children's buses were identified on the basis of information from the district transportation departments and later confirmed by school administrators and study technicians. When children rode more than one bus, we used their primary bus for our analyses. Bus characteristics, including age, mileage, technologies, and fuels, were compiled from the PSCAA, school transportation departments, and annual inspection. Adoption of clean air technologies and fuels was also tracked continuously with a focus on DOCs, CCVs, ULSD, and a biodiesel mixture (approximately 20%). Although we had also been interested in diesel

particulate filters (DPFs), these were used only temporarily on five buses, so we had insufficient information for our models.

Air Pollution

We collected measurements inside 188 buses ("in cabin") during 597 regular commutes greater than 10 minutes. Fine ($PM_{2.5}$) and ultrafine (UFP) particulate matter were measured with a $pDR-1200$ equipped with a cyclone preseparator (Thermo Scientific, Waltham, MA) and P-TRAK 8525 (TSI, Shoreview, MN), respectively. A PAS2000CE (EcoChem Analytics, League City, TX) was also used to capture particle-bound polycyclic aromatic hydrocarbons (pb-PAHs) as well as the black carbon content of the particles. During most trips, pollution was also measured inside a gasoline hybrid electric car traveling before the bus with open windows ("on road"). Differences between the bus and road reflect the pollution from the bus itself ("self-pollution") as has been validated by chemical tracer research (35). Ambient pollution measurements were also obtained from the PSCAA.

Pulmonary Health

Lung function and exhaled nitric oxide ($FeNO$) were measured monthly at school by technicians unaware of the children's bus characteristics. Measurements were collected at fixed times on school day mornings and afternoons, in accordance with standard procedures (36). $FeNO$ and room nitric oxide were collected with an offline collection kit (Sievers, Boulder, CO). Children exhaled into 1.5-liter aluminized Mylar balloons at a constant pressure of 12 cm H_2O to prevent contamination by nasal nitric oxide and to normalize expiratory flow rates. $FeNO$ samples were collected in triplicate and analyzed within 4 hours with an NOA 280i (Sievers), using the median value for our analysis. FEV_1 and FVC were measured with a MicroDL spirometer (Micro Medical, Lewiston, ME). Self-reported absenteeism in the previous month was supplemented with technician-collected records on absenteeism on the day of health testing.

General health, including asthma symptoms and recent illness, was ascertained by technician-administered questionnaires. Asthma status was assessed annually by doctor diagnosis or symptoms of wheezing or whistling in chest, wheezing after exercise, or a dry cough at night over the previous year based on validated questions

from the International Study of Asthma and Allergies in Childhood (ISAAC) survey (37). Asthma severity was defined as persistent asthma (on controller medication), intermittent asthma (not on controller medication), and nonasthmatic.

Covariates

Self-reported demographics (race, sex, parental education) and medical history were collected at an annual health screening. Height and weight were obtained during monthly examinations, concurrent with collection of pulmonary health endpoints. Meteorology (relative humidity and temperature) and flu prevalence data were obtained from the University of Washington Atmospheric Sciences Department and the U.S. Influenza-Like Illness Surveillance Network, respectively. School and home locations were classified as near a major roadway, using ArcGIS (ESRI, Redlands, CA), if they were within 100 m of an interstate or U.S. highway or within 50 m of a state or county highway.

Statistical Analysis

Descriptive statistics were generated using repeated-measures analysis of variance models. Exploratory analyses then compared pollution and health between buses that never or always had certain technologies/fuels as well as within buses before and after a switch. Pollutant and FeNO levels were log-transformed due to right-skewed distributions and investigated using multivariable mixed-effects models to account for correlation between repeated measures. Two-stage growth models with random intercepts and slopes were used for spirometry measures (38, 39). Risk differences for being absent within the past month were modeled with a mixed-effects log binomial regression. In-bus pollution models adjusted for ambient $\text{PM}_{2.5}$, weather (wind speed, temperature, relative humidity), bus characteristics (manufacturer, mileage, year, engine position, make, and model, bus base), and trip covariates (stops, duration, window usage, time of day, on-road pollution events). Health models were adjusted for age, race, sex, asthma, temperature, relative humidity, ambient $\text{PM}_{2.5}$, district flu prevalence, and seasonality. For FeNO and spirometry, height, weight, and cold/flu were also included. School air nitric oxide and day of week were included in FeNO models. Nonlinear relationships were assessed in R version 3.02 (www.r-project.org)

and modeled with splines (flu prevalence) whereas other analyses used SAS version 9.3 (SAS Institute, Cary, NC). Models were run first with individual technologies and fuels and then with all technologies and fuels to separate the independent associations with pollutants and health. We further explored the impacts of DOC, CCV, and biodiesel among buses after the national switch to ULSD to assess the added benefit of nonrequired clean air interventions.

We tested for effect modification by asthma status and confirmed the robustness of our results to control for parental education, school/home roadway proximity, district, and additional time trends. We also explored sensitivity to classifying asthma on the basis of doctor diagnosis, restricting to children riding the same bus at least 75% of the time, control for or exclusion of buses with a DPF, and using fixed-effects models. Finally, we estimated preventable absences if all American school bus riders exclusively rode buses with clean air technologies and fuels. These calculations assumed that 54.6% of 54,876,000 school children ride buses (12), that 9.3% of these children have asthma (40), and that, of the children with asthma, 25% have persistent asthma (41).

Results

Study Participants

A total of 275 bus riders provided 3,223 observations with an average of 6 (range, 1–19) repeat visits over 4 years. These children were predominantly white and from college-educated families (Table 1). The mean age was 9.5 years. More than half (54%) were asthmatic, and the majority (85%) were not taking controller medication. Higher FeNO levels, more frequent absenteeism, and lower baseline lung function were observed among children with asthma compared with healthy children.

Buses Serving Study Population

During our 4-year study the adoption of clean air technologies and fuels increased over time (Figure 1). Across all buses serving our study population, approximately half had DOCs and ULSD and 35% had CCVs in the first year whereas greater than 90% had these technologies and fuels in the final year. This resulted in the majority of students always riding buses with DOCs (69%) and ULSD (81%) and

fewer always riding buses with CCV (34%) and biodiesel (7%). Between 15 and 37% of students rode buses with and without clean air technologies and/or fuels, allowing for within-subject comparisons (Table 1 and Table E1). In general, there was little correlation between the various technologies and fuels, with the exception of DOC and ULSD, which had a correlation of approximately 0.5.

Measured Pollution Levels on Monitored Buses

Among the 597 trips on 188 buses with air pollution monitoring, the average mileage was 65,100 (SD, 58,700) and bus body year was 2002 (SD, 5) (Table 2). The average trip had a duration of 40 minutes (SD, 17 min) with 27 riders (SD, 14). Mean ($\pm$ SD) in-cabin $\text{PM}_{2.5}$ concentrations ($20 \pm 18 \mu\text{g}/\text{m}^3$) were approximately three times higher than ambient levels ($7 \pm 5 \mu\text{g}/\text{m}^3$) and 1.5 times higher than roadway levels ($13 \pm 12 \mu\text{g}/\text{m}^3$). Mean in-cabin UFP levels (21 ± 12 thousand/ cm^3) were lower than on the surrounding roadways (29 ± 20 thousand/ cm^3). Average pb-PAH concentrations were also lower inside bus cabins ($101 \pm 70 \text{ ng}/\text{m}^3$) than on surrounding roadways ($125 \pm 88 \text{ ng}/\text{m}^3$).

In multivariable models, we found strong evidence of lower in-cabin $\text{PM}_{2.5}$ concentrations with clean air technology use but weaker evidence for fuel types (Figure 2). DOCs and CCVs were associated with 26% (95% CI, –42 to –6%) and 40% (95% CI, –48 to –30%) lower in-cabin $\text{PM}_{2.5}$ concentrations, respectively. In contrast, UFPs were lowest with DOCs (–43%; 95% CI, –53 to –31%) and ULSD (–47%; 95% CI, –58 to –34%) with weaker reductions for CCVs and no associations with biodiesel. For pb-PAH concentrations, there were consistent increases with DOCs, CCVs, and ULSD. Only biodiesel was associated with lower in-cabin pb-PAH concentrations (–40%; 95% CI, –49 to –28%). Findings were similar for self-pollution concentrations and models adjusted for other technologies and fuels (results not shown).

Exhaled Nitric Oxide

Strong and statistically significant associations were identified between FeNO and ULSD use in fully adjusted models (Figure 3). Among the whole cohort, ULSD was associated with 16% (95% CI, –21 to –10%) lower FeNO levels. These

Table 1. Characteristics of Bus-Riding Elementary School Children Monitored between 2005 and 2009 during the Adoption of Clean Air Technologies and Fuels

	All	No Asthma	Intermittent Asthma	Persistent Asthma
Number of children	275 (100%)	126 (46%)	126 (46%)	23 (8%)
Number of samples	3,223 (100%)	1,590 (49%)	1,326 (41%)	307 (10%)
Baseline age, yr				
6–8	90 (33%)	34 (27%)	47 (37%)	9 (39%)
9–10	127 (46%)	65 (52%)	52 (41%)	10 (43%)
11–12	58 (21%)	27 (21%)	27 (21%)	4 (17%)
Female	124 (45%)	57 (45%)	58 (46%)	9 (39%)
Race				
Asian	25 (9%)	11 (9%)	13 (10%)	1 (4%)
Black	23 (8%)	4 (3%)	18 (14%)	1 (4%)
Other	19 (7%)	5 (4%)	9 (7%)	5 (22%)
White	203 (74%)	105 (83%)	83 (66%)	15 (65%)
Parental education				
College	33 (12%)	8 (6%)	22 (17%)	3 (13%)
Some college	35 (13%)	16 (13%)	16 (13%)	3 (13%)
College	88 (32%)	45 (36%)	32 (25%)	11 (48%)
College	105 (38%)	54 (43%)	45 (36%)	6 (26%)
School district				
Tahoma	89 (32%)	39 (31%)	39 (31%)	11 (48%)
Seattle	186 (68%)	87 (69%)	87 (69%)	12 (52%)
Height, m	1.4 (0.1)	1.4 (0.1)	1.4 (0.1)	1.4 (0.2)
Weight, kg	35.2 (11.0)	34.2 (9.1)	36.2 (12.1)	34.6 (14.1)
Outcomes				
F _{ENO} , ppb	12.1 (1.9)	10.0 (1.6)	14.2 (2.0)	14.3 (2.3)
FEV ₁ , L				
Baseline	1.73 (0.4)	1.78 (0.36)	1.69 (0.42)	1.67 (0.47)
Δ per year	0.13 (0.49)	0.15 (0.4)	0.14 (0.51)	0.01 (0.77)
FVC, L				
Baseline	2.09 (0.48)	2.13 (0.45)	2.06 (0.49)	2.09 (0.54)
Δ per year	0.17 (0.54)	0.2 (0.38)	0.2 (0.57)	−0.06 (0.94)
MMEF, cl/s				
Baseline	167.0 (56.1)	176.2 (52.5)	160.5 (58.2)	152.3 (58.2)
Δ per year	14.5 (121.1)	14.4 (113.5)	14.8 (125.7)	12.9 (141.4)
Missed school days per month	0.35 (0.25)	0.32 (0.25)	0.35 (0.26)	0.40 (0.24)
Interventions				
DOC				
Never	36 (13%)	19 (15%)	15 (15%)	2 (9%)
Sometimes	48 (17%)	23 (18%)	18 (18%)	7 (30%)
Always	191 (69%)	84 (67%)	93 (67%)	14 (61%)
CCV				
Never	81 (29%)	37 (29%)	36 (29%)	8 (35%)
Sometimes	101 (37%)	52 (41%)	41 (33%)	8 (35%)
Always	93 (34%)	37 (29%)	49 (39%)	7 (30%)
ULSD				
Never	13 (5%)	8 (6%)	5 (4%)	0 (0%)
Sometimes	40 (15%)	18 (14%)	15 (12%)	7 (30%)
Always	222 (81%)	100 (79%)	106 (84%)	16 (70%)
Biodiesel				
Never	183 (67%)	90 (71%)	77 (61%)	16 (70%)
Sometimes	72 (26%)	32 (25%)	38 (30%)	2 (9%)
Always	20 (7%)	4 (3%)	11 (9%)	5 (22%)

Definition of abbreviations: CCV = crankcase ventilation system; DOC = diesel oxidation catalyst; F_{ENO} = fraction of exhaled nitric oxide; MMEF = maximal midexpiratory flow; ULSD = ultralow-sulfur diesel. Data are given as n (%) or mean (SD).

associations were strongest among children with asthma: 31% (95% CI, −39 to −21%), 20% (95% CI, −28 to −12%), and 6% (95% CI, −14 to 2%) lower levels among children with persistent asthma, intermittent asthma, and no asthma,

respectively. These associations were robust to control for other technologies and fuels (results not shown).

For children with persistent asthma, lower F_{ENO} levels were observed for children riding buses with DOCs (−12%;

95% CI, −23 to −0.4%) or CCVs (−14%; 95% CI, −24 to −4%) compared with buses without these technologies.

Associations with CCVs, but not DOCs, were robust to control for other technologies and fuels but they were not

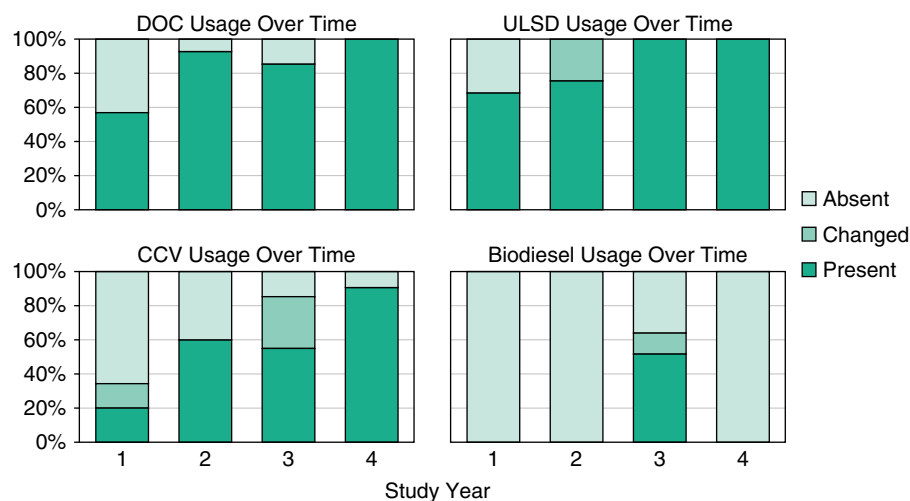


Figure 1. Clean air technologies and fuels over the 4-year study (defined as absent all year, changed during the year, or present all year). CCV = crankcase ventilation system; DOC = diesel oxidation catalyst; ULSD = ultralow-sulfur diesel.

found among other children. Biodiesel was unassociated with FE_{NO} .

Pulmonary Function

Among all children, rates of change were 0.17 L/yr for FVC and 0.13 L/yr for FEV_1 . After control for other factors, we observed 0.02 (95% CI, 0.003–0.05) and 0.02 (95% CI, 0.001–0.04) L/yr faster rates of change in FVC among children riding buses with ULSD and DOCs, respectively (Figure 4). These associations with FVC were generally robust to control for other technologies and fuels as well as stratification by school year among

children without asthma (results not shown). Suggestive increases in FEV_1 over time were also found among all children for ULSD (0.01 L/yr; 95% CI, –0.006 to 0.03) and DOC (0.01 L/yr; 95% CI, –0.008 to 0.03) use, due primarily to associations with children without asthma and those with mild asthma. Lower changes in FEV_1 were observed with DOCs, ULSD, and biodiesel among those with persistent asthma. Although these associations were generally robust to control for multiple interventions, they had wide confidence intervals and could not be distinguished from no association.

Table 2. Characteristics of Monitored School Buses and Trips

	All Buses		Buses That Switched Technologies/Fuels	
	Buses	Trips	Buses	Trips
n	188	597	62	292
Clean air technologies*				
Diesel oxidative catalyst	165 (88%)	510 (85%)	18 (29%)	93 (32%)
Crankcase ventilation	134 (71%)	376 (63%)	36 (58%)	177 (61%)
Diesel particulate filter	5 (3%)	10 (2%)	0 (0%)	0 (0%)
Clean air fuels*				
Ultralow-sulfur diesel	183 (97%)	549 (92%)	18 (29%)	93 (32%)
Biodiesel	59 (31%)	152 (25%)	28 (45%)	138 (47%)
Mileage, in thousands	65.7 (57.4)	65.1 (58.7)	70.1 (54.5)	71.3 (58.9)
Body year	2002 (5.2)	2002 (5.0)	2002 (4.7)	2002 (4.7)
Seating capacity	72 (4.4)	72 (4.5)	73 (4.0)	73 (4.1)
Opacity, %	4 (7.3)	5 (9.8)	5 (7.9)	5 (9.6)

Data are given as n (%) or mean (SD).

*Bus results reported if bus ever had the technology or fuel. Trip data reflect the conditions during the monitoring event.

Absenteeism

Children missed an average of 3.1 school days over 9 months (2.9 for children without asthma, 3.6 for children with persistent asthma). Among all children, there was an 8% (95% CI, –16 to –1%) lower risk of being absent in the previous month when riding a bus with ULSD as compared with other buses (Figure 5). Similar findings were observed for DOC use: a 6% (95% CI, –11 to –0.2%) reduction in the risk of absenteeism over the past month. These associations were largest among children with asthma, especially those receiving controller therapy. Although associations with ULSD were robust to control for other technologies and fuels, associations with DOCs were diminished by control for ULSD (results not shown). On the basis of these findings, we estimate that the switch to ULSD resulted in 14 million fewer absences per year across the United States.

Sensitivity of Results

Associations between clean air technologies and fuels with each of the health endpoints were qualitatively robust to further adjustment for parental education, school/home proximity to major roads, district, and additional time trends. Our findings were also insensitive to use of doctor-diagnosed asthma, restricting to children riding the same bus at least 75% of the time, excluding or controlling for buses with a DPF, and modeling using fixed effects. Restriction to only those buses using ULSD suggested independent improvements with DOCs for absenteeism among children with severe asthma and changes in FVC over time, although little change was observed with FEV_1 or FE_{NO} after this restriction (results not shown).

Discussion

In this natural experiment, we documented lower in-vehicle exposures and improved pulmonary health of children with the adoption of clean air technologies and fuels on school buses. $PM_{2.5}$ concentrations were 25–40% lower on buses with DOCs and CCVs, and UFP levels were 40–50% lower on buses with DOCs and ULSD. In health analyses, we found that ULSD was most consistently associated with beneficial effects with evidence of less pulmonary inflammation, faster lung growth, and lower risks of school absenteeism. These

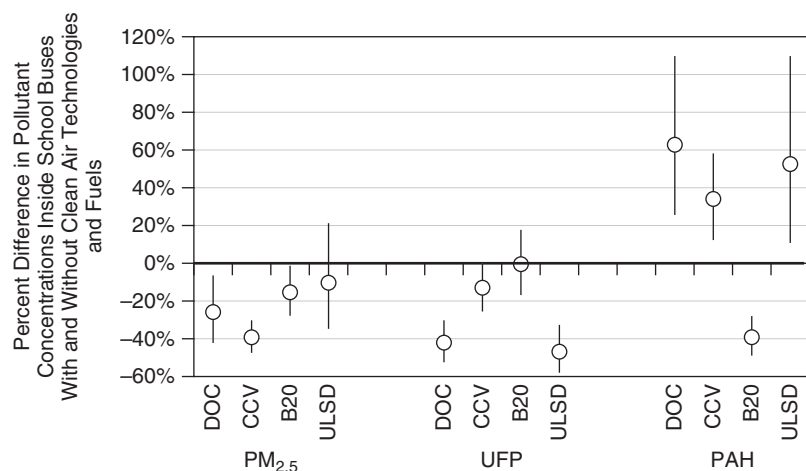


Figure 2. Associations of clean air technologies and fuels with air pollution concentrations inside school buses after control for ambient weather and pollutants, bus characteristics, and trip features. Models were adjusted for ambient wind speed, temperature, relative humidity, ambient PM_{2.5}, noted pollution events, trip duration, number of stops, open windows, time of day, bus base, year bus was built, mileage, engine make and model, body make, and random intercept for each bus. These contrasts include data from different buses and those that switched technologies. B20 = biodiesel; CCV = crankcase ventilation system; DOC = diesel oxidative catalyst; PAH = polycyclic aromatic hydrocarbons; PM_{2.5} = fine particulate matter, $\leq 2.5\text{-}\mu\text{m}$ diameter; UFP = ultrafine particulate matter; ULSD = ultralow-sulfur diesel.

results were robust to control for other technologies and fuels and were often largest among children with asthma, especially those with persistent asthma. DOCs, and to a lesser extent CCVs, also were associated with better health, but these findings were primarily restricted to those with persistent asthma and were often sensitive to control for ULSD. Overall, we found that adopting certain clean air

technologies and fuels reduced in-vehicle particulate exposures and likely improved respiratory health.

To our knowledge, no prior studies have examined the individual-level health impacts of clean air technologies and fuels, although one school district-level analysis suggested that a school bus emission reduction program was associated with decreased incidence of bronchitis, asthma,

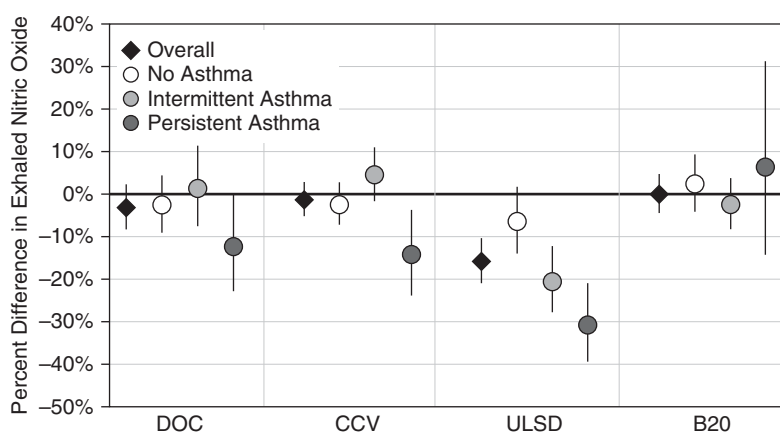


Figure 3. Adjusted associations (percent difference, 95% confidence interval) between levels of exhaled nitric oxide and clean air technologies and fuels among all students and by asthma status. Models were adjusted for age, sex, race/ethnicity, height, asthma status, ambient temperature, relative humidity, fine particulate matter ($\leq 2.5\text{-}\mu\text{m}$ diameter), room nitric oxide, district flu prevalence, individual report of a cold or flu, within-school year time trend, time of day, and random subject effect. B20 = biodiesel; CCV = crankcase ventilation system; DOC = diesel oxidative catalyst; ULSD = ultralow-sulfur diesel.

and pneumonia (42). Our findings suggest that the benefits of school bus emission reductions are also experienced at the child level. We identified sizeable improvements in absenteeism for children riding buses with ULSD that are comparable to 50–70% of the reductions observed for children living in nonsmoking homes as compared with homes with smokers (43). With 25 million children riding buses to school (12), we estimate that switching to ULSD resulted in 14 million fewer absences per year in the United States. Such reductions in absenteeism may translate to improved grades and health for the students (15, 16) as well as less missed work and lost productivity for their caregivers. Although results were strongest with ULSD, we also found evidence of reduced absenteeism among children with severe asthma and increased FVC over time with DOC usage even when restricted to buses using ULSD. This suggests that there may be additional benefit to clean air technologies independent of any changes in fuel.

Clean air technologies and fuels were not only associated with health benefits but also with reductions in on-board pollution. Both DOC and CCVs showed significant reductions in PM_{2.5} and UFPs. This is generally consistent with previous in-vehicle studies, which found reductions of 25–60% for PM_{2.5} and 5–70% for UFPs (17, 25, 27, 28). Reductions in UFPs, and to a lesser extent PM_{2.5}, with ULSD are also consistent with an earlier in-cabin study using ULSD in combination with DPF (17). Interestingly, our findings of comparatively larger reductions in PM_{2.5} with CCVs and larger reductions in UFPs with DOCs are supported by previous research demonstrating that in-cabin PM_{2.5} concentrations are primarily due to crankcase emissions and that UFPs primarily originate from the tailpipe (35, 44). Although we have previously demonstrated distinct patterning of pb-PAHs from PM_{2.5} and UFPs in school buses (45), the observed increase in pb-PAHs with DOCs, CCVs, and ULSD is unexpected given that past research has generally shown reductions with clean air technologies and fuels (17, 46–48). Unfortunately, we have little explanation for these findings. One hypothesis is that a shift in the distribution of PAHs between the gaseous and particle phase may have led to measurement artifact because enhanced

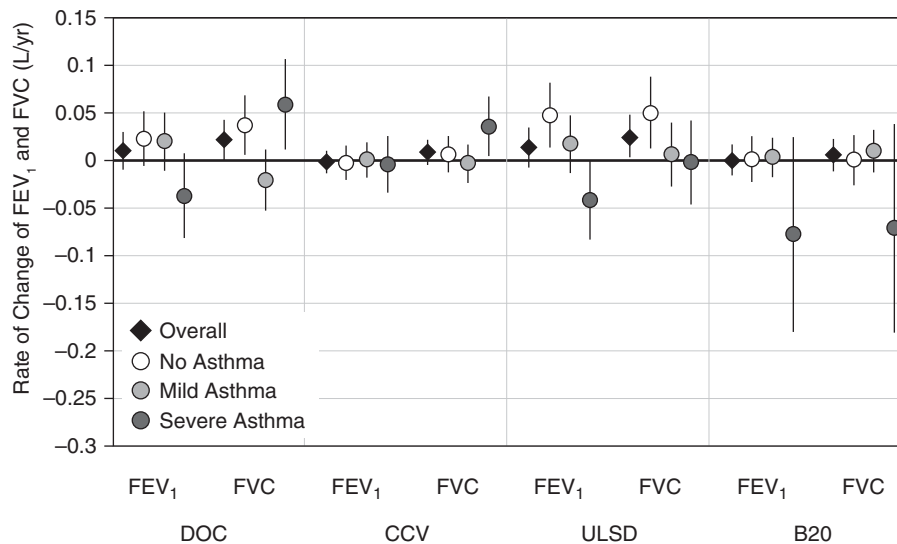


Figure 4. Adjusted associations (percent difference, 95% confidence interval) between rate of change in lung function over time and clean air technologies and fuels among all students and by asthma status. Models were adjusted for age, sex, race/ethnicity, height, weight, asthma status, ambient temperature, relative humidity, fine particulate matter ($\leq 2.5\text{-}\mu\text{m}$ diameter), district flu prevalence, individual report of a cold or flu, within-school year time trend, and random subject effect. B20 = biodiesel; CCV = crankcase ventilation system; DOC = diesel oxidative catalyst; ULSD = ultralow-sulfur diesel.

nitro-PAH formation and nucleation can occur with clean air technologies (46, 49, 50).

The finding that ULSD and DOCs were most strongly and consistently associated with health suggests that UFPs may be a critical exposure on school buses. This is not surprising because UFPs are hypothesized to be especially toxic because of their high deposition in the lower airways, large surface areas to absorb chemicals/free radicals, lower removal by alveolar macrophages, and ability to initiate inflammation (51). Associations with FeNO , a marker of cytokine activity in the airways and alveoli (52), also suggest that lowered inflammation is a likely mechanism

through which decreased exposures may lead to improved health. Furthermore, our finding of greater health improvements among children with asthma is also consistent with UFPs because airway narrowing increases the deposition efficiency of UFP in the lungs (53).

The cohesiveness of our findings across several endpoints further supports the hypothesized benefits of clean air technologies and fuels on respiratory health. Our results are consistent with controlled exposure studies in animals and humans, which have reported increased inflammation after the inhalation of diesel exhaust (54–58). Given that ULSD, DOCs,

and CCVs were associated with lower particulate concentrations, our results are further supported by population-based studies of children that have linked higher particulate concentrations with higher FeNO (59, 60), slower lung growth (61, 62), asthma exacerbation (63), and school absenteeism (61, 64–66). Although all of our results were on the same order of magnitude as past research, our lung growth findings were somewhat larger than expected (61, 64–67). This may be partially attributable to the young age of this population or the high asthma prevalence because some, although not all, research has reported enhanced associations among this group (34).

This study has numerous strengths including its large size and repeated, individual-level health and in-vehicle air pollution measurements surrounding the adoption of clean air technologies and fuels. It is not, however, without limitations. One key limitation is the possibility for residual confounding by time because some technologies/fuels, like ULSD, were used only in the later years of the study. If our statistical models inadequately captured any temporal trends in health, then we could incorrectly attribute some of the observed changes in health to the bus technologies/fuels. Sensitivity analyses indicated that this was unlikely for FeNO and absenteeism as our models were robust to additional adjustment for time and there were no significant time trends among children who rode buses that did not change technologies or fuels. In contrast, FVC is more closely linked to time in this population. We allowed for different growth curves by age and age-adjusted height after accounting for differences between the sexes, ages, and asthma status. Within this age range, linear trends are expected and observed. If, however, accelerated growth due to puberty occurred among a small fraction of children, then the true associations with lung growth could be overestimated. Another limitation is that our absenteeism information was not verified by school records. Any misclassification would not likely be differential, however, because children were unaware of their bus characteristics. In addition, we supplemented self-reported absenteeism data with technician-recorded absenteeism of children during their monthly examinations to account for the inherent problem that absent children cannot report their absenteeism. Finally, although we

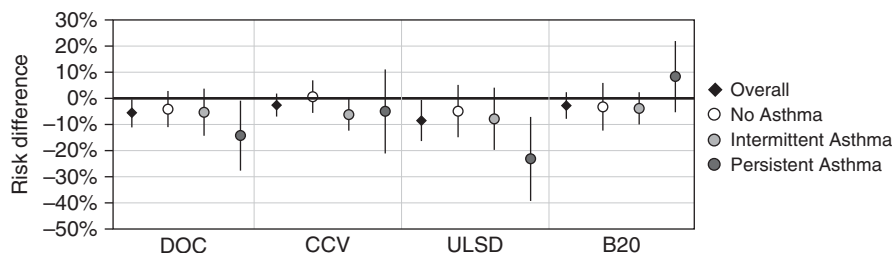


Figure 5. Adjusted associations (risk difference, 95% confidence interval) for any absenteeism in the past month as a function of clean air technologies and fuels among all students and by asthma status. Models were adjusted for age, sex, race/ethnicity, asthma status, ambient temperature, relative humidity, fine particulate matter ($\leq 2.5\text{-}\mu\text{m}$ diameter), district flu prevalence, within-school year time trend, and random subject effect. B20 = biodiesel; CCV = crankcase ventilation system; DOC = diesel oxidative catalyst; ULSD = ultralow-sulfur diesel.

a priori anticipated that children with asthma would be more sensitive to exposures, we cannot exclude the possibility that our findings of enhanced associations among those with persistent asthma were due to chance given the small sample size (23 children, 307 samples).

In summary, we used a natural experiment to examine associations between clear air technologies and fuels in school buses and children's health. Our results show that the national switch to ULSD fuel may have had a measurable positive public health impact on children riding diesel school buses. This benefit was likely especially important for children with asthma. Our results further

suggest that children with asthma may also have benefited from the nationwide voluntary school bus retrofit initiative and the adoption of DOCs and CCVs. Although the exact results varied by outcome, ULSD and DOCs were most consistently associated with both reduced pollutant concentrations and improved health, suggesting a role for UFPs in the health effects of diesel-powered school buses. ■

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