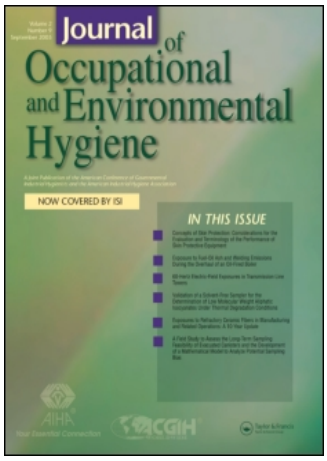

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://oeh.informaworld.com/soeh/title~content=t713657996

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To cite this Article: Borak, Jonathan and Sirianni, Greg , 'Studies of Self-Pollution in Diesel School Buses: Methodological Issues', Journal of Occupational and Environmental Hygiene, 4:9, 660 - 668
To link to this article: DOI: 10.1080/15459620701501578
URL: http://dx.doi.org/10.1080/15459620701501578

Journal of Occupational and Environmental Hygiene, 4: 660–668
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459620701501578

Studies of Self-Pollution in Diesel School Buses: Methodological Issues

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Considerable interest has focused on levels of exhaust emissions in the cabins of diesel-powered school buses and their possible adverse health effects. Significantly different policy and engineering issues would be raised if compelling evidence found that in-cabin contamination was due to self-pollution from bus emissions, rather than ambient pollution, neighboring vehicles, and/or re-entrained road dust. We identified 19 reports from 11 studies that measured diesel exhaust particulate in the cabins of 58 school bus of various type. Studies were evaluated in light of their experimental design, their data quality, and their capacity to quantify self-pollution. Only one study had a true experimental design, comparing the same buses with and without emission controls, while four others used intentional tracers to quantify tailpipe and/or crankcase emissions. Although definitive data are still lacking, these studies suggest that currently available control technologies can nearly eliminate particulate self-pollution inside diesel school buses.

Keywords diesel, diesel emissions, diesel exhaust, exposure assessment, school bus, tracer

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INTRODUCTION

Considerable attention has focused on the possible adverse health effects of exposure to diesel exhaust emissions. Concerns have spanned a wide range of scenarios and exposure levels, from relatively common, low-level ambient exposures[1–3] to the much higher levels found in certain occupational settings, such as underground mines.[4–6] One particular set of diesel-related concerns has involved the levels of exhaust emissions likely to be encountered during everyday vehicular transport and the health effects that such exposures might cause. Especially keen interest has focused on exposures encountered in the cabins of diesel-powered school buses, a specialized environment simultaneously posing ambient exposures to passengers and occupational exposure to drivers.

The nature of occupational exposures impacting bus drivers and other professional drivers has been a subject of worldwide study. In Sweden, bus drivers were exposed to higher levels of NO_2 and PM_{10} than were taxi drivers but less than short-haul truck drivers.[7]

In Copenhagen, bus drivers had higher levels of urinary 1-hydroxypyrene and mutagenicity than did mail carriers.[8] In Paris and Bordeaux, bus drivers were exposed to levels of NO_2, CO, and lead that were higher than background and exceeded ambient standards but not occupational exposure limits.[9] In Bangkok, bus drivers had increased exposures to benzene and lead.[10]

Other studies have associated risks of cancer with employment as a bus driver[11,12] or, more generally, as a professional driver.[13–16] But because these exposures are not unique to diesel exhaust emissions and because at least some of the drivers included in the studies drove vehicles that were not diesel-powered,[7,8] such reports provide only incomplete information about the exposures and hazards specific to diesel buses.

More recent studies have specifically considered pollutant levels inside diesel school buses under a variety of operating conditions. These reports have generated considerable interest and media attention reflecting, in part, concerns that children are potentially more susceptible to the adverse effects of air pollutants and that many children are transported daily in diesel-powered school buses. But, as discussed below, these studies generally included only small numbers of buses of differing types and vintages, and study conditions (e.g., traffic patterns, background exposure levels, window position) differed across studies. In addition, some studies were published outside the traditional peer-reviewed literature and provided fewer methodological details and less data than might otherwise have been expected. Thus, it has been difficult to compare or aggregate study findings.

Despite such limitations in studies, it is apparent that air quality inside school bus cabins varies directly with ambient pollution levels, air quality is worse in urban and rush-hour traffic than in light rural traffic, and pollutant levels inside buses generally exceed those measured outside. Accumulating

evidence indicates that newer school buses are cleaner than older ones, and school buses with retrofit emission controls are cleaner than those without controls.

On the other hand, a number of important questions remain unanswered, such as the relative contributions of different sources of diesel particulate matter and their routes of entry into bus cabins. Significantly different policy issues would be raised and engineering needs identified if there was compelling evidence that the primary source of contamination was specifically self-pollution from bus tailpipe exhaust or crankcase road-draft-tube emissions, rather than ambient pollution, exhaust from neighboring vehicles, and/or re-entrained road dust.

The following review was undertaken to understand the nature and limitations of these accumulated studies on diesel exhaust exposures in school bus cabins. One objective was to compile the studies, because some are not readily retrievable from standard scientific reference databases (e.g., PubMed, Toxline). A second objective was to evaluate the studies with respect to their methodological adequacy and their capacity to evaluate and quantify self-pollution of diesel school buses.

METHODS

Reports of studies evaluating exhaust particulate matter emissions inside diesel school bus cabins were identified by searching scientific reference databases (e.g., Medline), web searches using popular search engines, reviewing references cited in identified sources, and by direct contact with researchers in the field. Reports were included if they described studies performed in the United States and contained quantitative measurements of at least one diesel exhaust component. It was also necessary that study reports be available to interested readers; the sponsors of otherwise unpublished research agreed to make study reports available on websites or by email. If several reports presented the same or related data derived from the same study, they were grouped together and regarded as comprising a single, cumulative study.

The key characteristics of each study and the methods used for exposure monitoring were abstracted in table form to facilitate comparisons. More detailed summaries of these studies and reports are available as supplemental online material. The methodological adequacy of individual studies to document school bus self-pollution was evaluated in light of the following concerns:

Experimental design. Studies were categorized as experimental or observational. The presence of recognized and unrecognized influences that might have biased study findings (e.g., confounding) were noted, as was the appropriateness and apparent adequacy of efforts made to avoid or address such bias.

Tracer study methods. Methods used to study exhaust and crankcase emissions were reviewed, with particular emphasis on potential sources of bias and their capacity to quantify school bus self-pollution.

Data quality. Studies were evaluated to determine whether the precision and accuracy of analytical methods had been appropriately evaluated and addressed in the reports. A second concern was the completeness of the data reported and its consistency within and across reports. A third concern was whether conclusions were based on complete or selected subsets of study data.

RESULTS

The Studies

We identified 19 reports from 11 studies that measured diesel exhaust particulate matter in school bus cabins.[17–35] As detailed in Table I, those studies included 58 school

TABLE I. Characteristics of School Bus Studies

	No. of Buses				Background		
Study and Source	**Conventional**	**Retrofit**	**Clean**	**CNG**	**Lead Car**	**Monitor**	**Wind**
NRDC[17]	4				✓		
Fairfax County[18]	11[A]			1			
EHHI[19]	2			1			
Anchorage[21]	4						✓
Fitz[20]	1[B]	[B]					✓
Borak et al.[22]	2		1			✓	
Fitz et al.[23–27]	4[C]	1		1		✓	✓
EnSIGHT[28,29]	1				✓	✓	✓
Hammond[30,31]	4	8	2			✓[D]	
Clean Air Task Force[32]	4	4		1	✓		
Washington[33–35]	1	1			✓		

[A] One of 11 buses used diesel to idle and CNG while moving.
[B] A single bus was tested without and then retrofitted with various emission controls.
[C] Two typical diesel buses and two high emitting diesel buses.
[D] Ambient particle count at one of the major roadways.

buses: 35 conventional buses (typically, yellow school buses using traditional diesel fuel and without emission control systems); 14 retrofit buses (conventional school buses with retrofit emission control systems); one conventional bus tested with and without retrofitted emission controls; three clean technology school buses; four CNG buses; and one bus that used both diesel and compressed natural gas (CNG).

The identified reports each included measurements of at least one of six markers of diesel exhaust-associated particles: black carbon (BC); elemental carbon (EC); $PM_{2.5}$; PM_{10}; size-specific particle count (PC); particle-bound polycyclic aromatic hydrocarbons PAHs (PPB-PAH). Table II presents the various particle exposure metrics used in each of the 11 studies. Nine of the 11 studies provided detailed exposure data, often including data for individual bus runs. Most also provided summary statistics (e.g., range of data, range of means, or means ± standard deviations), corresponding to individual buses or specific bus runs or operating conditions.

Table III presents representative measurements, either the range of individual values or the range of means, for five measures of particulate matter reported in those nine studies. Sampling times were greater than 1 hour in 10 studies, and 20–30 minutes in the eleventh.[33–35]

In addition to measuring diesel exhaust components, four studies used an intentional marker to quantify entry of diesel exhaust into school bus cabins. In two studies,[20,23–26] a tracer gas (sulfur hexafluoride; SF_6) was injected into the bus exhaust system, and gaseous SF_6 was measured inside the bus. In a third study[28,29] an organic iridium compound (tris[norbornadiene] iridium[III] acetylacetonate) was added to the diesel fuel; following combustion, the iridium is incorporated into carbon-based particles emitted in engine exhaust. Levels of iridium were measured in $PM_{2.5}$ samples collected on filters. The fourth study[33–35] used dual tracers; iridium was added to the diesel fuel and measured as above, while a fully deuterated alkane (normal hexatriaconntane, n-$C_{36}D_{74}$) was added to the engine lubricating oil and measured in $PM_{2.5}$ samples collected on filters.

All 11 studies were undertaken to determine the levels of diesel exhaust-related pollutants inside school buses, but only four specifically aimed to measure self-pollution. An important objective of the Fitz et al. SF_6 tracer studies "was to quantify self-pollution . . . the percentage of a bus's own exhaust that can be found inside its cabin."[24,p.3736] The primary objective of the EnSIGHT iridium tracer study was to evaluate the potential exposure of bus riders to "diesel particulate matter emitted by the diesel engine powering the school bus."[28,p.22] The Ireson et al. dual-tracer study was "conducted to evaluate methods for quantifying in-cabin source contributions,"[33–35,p.1] while the purpose of the Clean Air Task Force study "was to investigate the causes of school bus self-pollution and to test the effectiveness of emissions reduction devices."[32,p.2]

The other studies did not focus on the specific sources of pollutants inside buses, although two compared diesel versus CNG buses and two others compared buses with differing emission control systems. The Fairfax County, study[18] measured EC and PM_{10} as time-weighted-averages during typical bus routes. EHHI[19] determined near-real-time values of BC, $PM_{2.5}$, and PM_{10} during typical bus routes and stressed comparisons between levels in moving versus idling buses. The Anchorage, Alaska, study[21] measured real time $PM_{2.5}$ levels on three typical bus routes.

To study the functional characteristics of aethalometers, Borak et al.[22] compared side-by-side measurements of EC

TABLE II. Exposure Metrics and Instrumentation Concerns

Study and Source	BC	EC	$PM_{2.5}$	PM_{10}	PC	PB-PAH	Tracer	Accuracy/ Precision	Calibration
NRDC[17]	✓		✓						
Fairfax County[18]		✓		✓					✓
EHHI[19]	✓		✓	✓					
Anchorage[21]			✓						✓
Fitz[20]					✓[A]	✓	SF_6	✓	✓
Borak et al.[22]	✓	✓						✓	✓
Fitz et al.[23–27]	✓		✓	✓	✓[B]	✓	SF_6	✓	✓
EnSIGHT[28,29]			✓				Iridium	✓	✓
Hammond[30,31]					✓[C]			✓	✓
Clean Air Task Force[32]	✓		✓		✓[D]	✓	✓	✓	
Washington[33–35]	✓	✓	✓		✓[E]	✓	Iridium	✓	
							n-$C_{36}D_{74}$	✓	

Notes: BC = black carbon; EC = elemental carbon; PC = particle count; PPB-PAH = particle-bound polycyclic aromatic hydrocarbons.

[A] => 0.003 μm.
[B] = 0.03–0.8 μm, 0.3–0.5 μm; 0.3–10 μm.
[C] = <2.5 μm.
[D] = 0.01–1.0 μm.
[E] = ultrafine.

TABLE III. Representative Measurements of Particulate Matter in Nine School Bus Studies

Study and Source	BC ($\mu g/m^3$)	EC ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	PC (#/cm^3)	PB-PAH (ng/m^3)
Fairfax County[18]		<LOD[A]			
Anchorage[21]			7–149 (range)		
Fitz[20]				29,700–46,300 (range) (Particles: >0.003 μm)	9–43 (range)
Borak et al.[22]	1.0–1.2 (range of means)	≤1.6 (range of means)			
Fitz et al.[23–27]	2.5–19 (range of means)		13–60 (range of means)	19–276 (range of means) (Particles: 0.3–0.5 μm)	14–400 (range of means)
EnSIGHT[28,29]			39–128 (range)		
Hammond[30,31]				17,316 – 54,541 (range of means) (Particles: <2.5 μm)	
Clean Air Task Force[32]	0.4–2.8 (range of means)		22–76 (range of means)	13,000–53,000 (range of means) (Particles: 0.01–1.0 μm)	19–56 (range of means)
Washington[33–35]	0.67–1.82 (range of means)		5.1–28.4 (range of means)	23,011–27,288 (range of means) (Particles: "ultrafine")	70–74 (range of means)

Notes: BC = black carbon; EC = elemental carbon; PC = particle count; PPB-PAH = particle-bound polycyclic aromatic hydrocarbons.
[A]LOD: Limit of detection ranged from 4.1–4.9 $\mu g/m^3$ depending on sampling duration.

and BC in conventional and clean diesel buses driving and idling on a rural test track. Fitz[20] used SF_6 to measure the effectiveness of school bus emission control equipment. The Natural Resources Defense Council (NRDC)[17] compared BC levels inside a bus vs. in a lead car, and Hammond et al.[30,31] compared $PM_{2.5}$ levels in conventional, retrofitted and clean diesel buses.

Experimental Design

Of the 11 studies, only the Clean Air Task Force Study[32] was designed as a formal experiment; individual buses were tested and compared with and without retrofit emission controls. The other 10 were mainly observational; each included data from multiple buses of different type driven at differing times on different days. In some studies, bus routes and traffic patterns varied from day to day with buses operated under significantly different conditions. The presence of so many uncontrolled variables raises concerns about potential biases and limits the ability to compare data between studies and aggregate data across studies.

Various sources of potential confounding were noted in the reports. Background air pollutant levels, for example varied within and between studies. Eight of 11 studies determined background ambient levels (Table I). In four studies, background was measured with instruments placed in a lead vehicle, whereas five studies cited data obtained from fixed-site air pollution monitors. As expected, studies that monitored pollutant levels along actual bus routes found that urban routes had significantly higher background levels than rural routes.[23,24]

Some studies monitored in-cabin pollutants under mainly low background conditions; three studies were conducted on rural bus routes,[19–21] two used residential bus routes,[32–35] described as "largely free of diesel traffic,"[32,p.2] and a fifth took place on a rural test track.[22] By contrast, other studies were specifically conducted under high background conditions. One used "typical" Los Angeles bus routes,[28] and a second used bus routes in highly urbanized settings to study "realistic high-end exposures."[23–25]

Background air pollutant levels also varied by time of day. Hammond et al.[30,31] reported fine particle counts that were more than twofold higher during morning than afternoon runs, whereas equally larger diurnal $PM_{2.5}$ differences (but in the opposite direction) were noted in the Anchorage study.[21] Table IV illustrates the differing levels of exposure observed at different times of day (morning vs. afternoon) in three studies.

Wind and weather conditions also varied over the course of a day, thus influencing study findings; for example, Fitz et al. found "little or no wind during the morning runs"[23,p.34] (mean: 0.4 m/sec; range: 0.19–1.1) but "significant wind speeds"[23,p.34] during afternoon runs (mean: 3.6 m/sec; range: 2.4–4.7). Wind speeds <2 m/sec ("calm weather,"[36,p.240]

TABLE IV. Effects of Time-of-Day and Window Position on In-Cabin Pollutant Levels: Means (and Ranges) of Measured Levels

Operating Conditions	BC ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	PC (#/cm^3)	PB-PAH (ng/m^3)
		Anchorage[A]		
Route 11, windows closed		AM: 7; PM: 21		
Route 33, windows closed		AM: 24; PM: 48		
Route 708, windows open		AM: 83; PM: 149		
		Hammond[B]		
AM, Conventional			46,098 (37,825–54,541)	
PM ,Conventional			23,027 (20,311–25,708)	
AM, Diesel oxidative catalyst			36,017 (31,597–42,579)	
PM, Diesel oxidative catalyst			18,630 (17,316–20,455)	
			(Particles <2.5 μm)	
		Fitz et al.[C]		
AM, Windows closed, urban	10.0 (2.5–19)	(13–56)	113 (51–235)	198 (64–400)
PM, Windows open, urban	5.2 (2.9–9.1)	(36–60)	96 (19–276)	96 (33–147)
PM, Windows open, rural	2.7 (0.9–4.8)	(18–57)	159 (29–253)	36 (14–66)
			(Particles 0.3–0.5 μm)	

Notes: BC = black carbon; PC = particle count; PPB-PAH = particle-bound polycyclic aromatic hydrocarbons.
[A] Ref. 21.
[B] Refs. 30,31.
[C] Refs. 23–27.

"very light wind,"[37,p.43] cause less dispersion of exhaust emissions than do winds >3 m/sec ("windy weather"[36,p.240]), and Fitz et al. concluded that wind played a "likely significant role"[23,p.36] in differences noted between buses tested at different times and on different days. Likewise, the Clean Air Task Force found that entry of diesel particules was "dependent on the wind direction."[32,p.22]

Several studies were designed to specifically minimize such biases. The Clean Air Task Force tested buses on relatively diesel-free routes so that "confounding . . . was minimized by a general absence of external source influences."[32,p.10] Fitz used a largely rural route "in order to lessen the impact of local emissions."[20,p.4] Borak et al. performed testing on a rural test track to avoid "confounding effects of other nearby vehicles."[22,p.267]

By contrast, other studies specifically emphasized the effects of confounding due to emissions from nearby vehicles, which they documented as important sources of in-cabin pollution. The significant impact of nearby "smoky" vehicles was described by NRDC,[17] EHHI,[19] Fitz,[20] and Fitz et al.[23–26]

Fitz et al.[23,24] were inconsistent with respect to potential bias. On the one hand, they acknowledged the risks of confounding due to differing bus routes, traffic density, time of day, and window position: "It is axiomatic in any scientific investigation that one would like to control all but one variable at a time in order to elucidate the effects of the remaining changed variable (e.g. fuel type)."[23,p.44]

But on the other hand, their study design did not adequately address those concerns and their results likely reflect substantial confounding bias. One example (discussed above) was their observation that differing wind conditions significantly affected in-cabin pollutant levels. It also seems probable that their evaluation of the effects of window position were significantly confounded. Windows-closed runs were conducted during morning rush hours, when ambient levels were high and average wind speeds were low, while windows-open runs were conducted under the opposite conditions during afternoons. It does not seem possible to distinguish the effects of window position from differing wind and ambient particle levels.

Tracer Study Methods

The tracer studies employed three different methods. Fitz[20] and Fitz et al.[23–26] injected SF_6 from a pressurized cylinder into the bus exhaust system about 15 cm from the terminal end of the exhaust pipe and measured SF_6 levels inside the bus by means of an electron capture detection analyzer. Tracer flow rates were not constant, but varied "between runs and even within runs."[23,p.97]

One study[20] noted that the SF_6 cylinder leaked during several runs. Although SF_6 flow rates were measured during runs, actual levels of SF_6 in bus exhaust were not directly measured. Instead, exhaust concentrations were calculated from median SF_6 flow rates and exhaust flow rates that were estimated, rather than measured, using the average performance characteristics of typical diesel engines. The emission characteristics of individual buses were not determined by chassis dynamometer testing or otherwise, so a quantitative relationship between tracer concentrations and emissions can not be determined.

Because SF_6 flow rates were adjusted during runs for unspecified reasons and were uncoupled from exhaust flow rates, and because concentrations of SF_6 in exhaust emissions

were estimated for "typical" engines not the buses actually being tested, the study findings must be interpreted cautiously. Moreover, while SF_6 can be used to characterize the volume and rate of gaseous tailpipe emissions, it does not track particulate matter; reported SF_6 results would be unchanged even if tailpipe exhaust emissions were particle-free. Accordingly, the ability to use this marker to quantify emissions of diesel particles is limited.

In the EnSIGHT study,[28,29] an organic iridium compound added to diesel fuel became incorporated into carbon-based particles and was emitted in engine exhaust. Fine particulate matter ($PM_{2.5}$) was collected using high-flow rate samplers; particulate mass was measured gravimetrically, and iridium mass was measured by instrumental neutron activation analysis (INAA).[38] First, $PM_{2.5}$ was collected in the bus cabin during runs over "typical school bus routes" and the levels of particulate matter and iridium were determined. Then, after on-road sampling was completed, the particulate:iridium mass ratio was determined in the exhaust of the same bus during dynamometer testing. The quantity of diesel particulate from exhaust emissions that entered the cabin during on-road testing was calculated from the amount of iridium measured inside the cabin and the particulate:iridium mass ratio determined during the dynamometer tests.

Although this approach provides a seemingly precise measure of exhaust-related self-pollution, it suffers from several potential methodological limitations. The addition of metals to lubricating oil can enhance the oxidation of soot, thereby reducing diesel particle emissions,[39] and it is not known whether iridium at the levels used in this study has such effects. The fact that particle emissions in this study were similar to those described in other studies where iridium was not added to the fuel[40–42] suggests that any such effect of iridium would have been small. Another limitation is that the sampling method allows only for determination of cumulative and time-weighted average exposures; the iridium tracer method provides no information about fluctuations occurring during bus operations.

The Ireson et al. dual-tracer studies[33–35] added organic iridium to diesel fuel, as just described, plus a deuterated alkane (n-$C_{36}D_{74}$) that was added to the lubricating oil. Using high-flow rate samplers, $PM_{2.5}$ was collected on collocated Teflon and quartz filters. Particulate mass on Teflon filters was measured gravimetrically, and iridium mass was determined by INAA. A punch from each quartz filter was analyzed for EC and organic carbon (OC) by thermal optical reflectance,[43] and the remaining filter sample was analyzed for the deuterated alkane tracer by gas chromatography/mass spectrometry.[44]

In addition, $PM_{2.5}$ samples of tailpipe emissions and crankcase emissions were separately collected for each of three separate bus runs and analyzed as above. The ratio of iridium to d-alkane in tailpipe emissions was more than 1000-fold greater than in crankcase emissions, indicating that the dual-tracer method could reasonably distinguish between those two sources. The particulate:iridium mass ratio and the particulate:d-alkane mass ratio were then calculated and used to estimate the quantities of tailpipe and crankcase emissions entering the bus cabin during on-road testing.

The dual-tracer method seems able to differentiate and quantify two important sources of school bus self-pollution, tailpipe, and crankcase. The importance of this advance is emphasized by findings of the Clean Air Task Force,[32] which did not use tracers but compared the same buses with and without various retrofit emission control devices. That study found that use of diesel particulate exhaust filters plus ultra-low sulfur diesel virtually eliminated self-pollution by ultra-fine particles and BC, while installation of a closed-crankcase filtration device (which reroutes crankcase emissions into the engine intake manifold) eliminated $PM_{2.5}$ self-pollution but did not affect levels of ultra-fine particles or BC. These findings are illustrated in Table V, which presents four measures of in-cabin particulate matter for a single bus operating under seven different configurations of fuel, tail-pipe, and crankcase emission controls. Neither SF_6 nor iridium alone is able to differentiate and quantify the contributions of both tail-pipe and crankcase emissions.

Data Quality

Six of the 11 studies described assessments of the accuracy and/or precision of the monitoring instruments used and eight

TABLE V. Representative Findings of Clean Air Task Force Study

Bus #56 Configuration[A]	BC ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	PC (#/cm^3)[B]	PB-PAH (ng/m^3)
Conventional	2.0	50	50,724	
ULSD	2.5	76	53,040	25
DOC	2.8	52	38,091	41
DOC and Spiracle	2.8	22	30,969	56
Spiracle and ULSD	2.6	36	26,927	34
DPF and ULSD	0.7	45	15,445	
DPF, ULSD, and Spiracle	1.1	43	13,029	19

[A] Bus configurations: DOC = diesel oxidation catalyst and convention fuel; DPF = diesel particulate filter; Spiracle = closed-crankcase filtration device; ULSD = ultra-low sulfur diesel fuel.
[B] Particles 0.01–1.0 μm.

TABLE VI. Precision Measures Based on Results from Paired Instruments

Pollutant	Instrument	Coefficient of Variation (%)	Correlation
PC (0.3–0.5 μm)	OPC Clilmet	7	.70
PB-PAH	Ecochem		
$PM_{2.5}$	PAS 2000	14	.65
BC	DustTrak	23	.54
	Aethalometer	52	.18

Notes: Adapted from "Characterizing the Range of Children's Pollutant Exposure During School Bus Commutes, by Fitz et al. (2003).[23]
PC = particle count, BC = black carbon, PPB-PAH = particle-bound polycyclic aromatic hydrocarbons.

detailed the calibration of pumps and instruments (Table II). Precision was generally high for all instruments except the aethalometer, for which precision was low. The most extensive testing was reported by Fitz et al.,[23] who initially conducted 17 comparisons of paired instruments (Table VI). The aethalometer had the largest coefficient of variation (52%) and smallest correlation between instruments (0.18), indicating that imprecision was not likely due to simple bias but to random instrumental error. Unlike the other instruments, aethalometer precision did not improve as exposure levels increased.[23] Four of five studies that used Aethalometers disregarded their apparent inaccuracy.[17,19,23–26,32] Despite documenting their erratic performance, Fitz et al. wrongly asserted that such findings "only apply to analyses which used paired instruments."[23,p.81]

Two reports presented incomplete study data. NRDC[17] provided only limited detailed data for one of four buses and essentially no data for the other three. EHHI conducted "eight runs of diesel buses . . . per day for 4 days,"[19,p.36] but reported BC and $PM_{2.5}$ data for lesser numbers of runs, varying from 22 to 28. Neither report discussed the missing data. The other studies provided detailed and seemingly complete data.

Despite reporting extensive data, Fitz et al.[24] relied on an incomplete set of selected data to justify a key conclusion, i.e., that SF_6 levels inside bus cabins were more closely related to BC than $PM_{2.5}$.[23] That conclusion derived from a comparison of the correlation coefficients calculated between SF_6 and BC and between SF_6 and $PM_{2.5}$ respectively. However, the correlations each reflected data from only two of the five diesel buses (and not even the same two buses for each); data from the other three buses were disregarded because the corresponding correlations were not statistically significant. The authors attributed such lack of significance to "insufficient data points,"[24,p.3741] but data insufficiency was not otherwise noted in their reports and large amounts of aethalometer (BC) and DustTrak ($PM_{2.5}$) data should have been available.

Two alternative explanations seem possible: either correlations between SF_6 and both BC and $PM_{2.5}$ were not significant for the majority of bus runs, or the SF_6 tracer system was not consistently adequate. (In an earlier study, Fitz reported that SF_6 levels "did not show any significant degree of correlation"[20,p.10] with particulate or PB-PAH levels.) In either event, the study conclusion was based on a selected subset of data, rather than the full database, and should be viewed with caution.

Finally, it should be noted that (a) the three tracer methods have generally been used in only a small number of buses and over a limited number of bus runs;[28,29,33–35] (b) reports present anecdotal evidence of equipment leaks and mechanical failures during tracer testing;[20,25,33–35] (c) similar tracer methods yielded inconsistent results between studies;[20,23] and (d) even the most extensive reported tracer tests resulted in apparently "insufficient data points"[24,p.3740] to sustain quantitative analyses. These observations emphasize the preliminary nature of the reported tracer methods.

DISCUSSION

It is generally accepted that levels of fine particulates inside the cabins of operating school buses are often higher than background levels, but the primary source of contamination remains uncertain. Importantly, different policy and engineering issues would be raised if compelling evidence indicated that contamination was due mainly to self-pollution from exhaust or crankcase emissions rather than ambient pollution, exhaust from neighboring vehicles, and/or re-entrained road dust. Until recently, the available literature has not adequately addressed this concern.

Only one of the reviewed studies[32] was designed as a true experiment, comparing pollutant levels in specific buses, each operating under a variety of emission-control conditions. The others were essentially phenomenological, collecting and presenting compilations of data from buses operating under more or less real-world conditions. A number of studies provided incomplete data, and some did not determine the accuracy and precision of their analytical instruments, whereas others ignored analytical limitations; still others failed to control for significant sources of confounding.

Such limitations are not entirely surprising. The early studies (e.g., NRDC,[17] EHHI,[19] Anchorage[21]) were exploratory in nature, seeking to determine whether elevated levels of diesel-related pollutants were present inside school bus cabins; the actual sources of contamination were not of primary concern. Accordingly, their methodological limitations can be largely excused, although presentation of only selected data limits the ability to generalize their findings. Nevertheless, those studies correctly identified a number of thematic concerns and stimulated a number of subsequent, more rigorous assessments.

Four more recent studies aimed to measure self-pollution with tracers but reached seemingly opposite conclusions. Because of differences in the presentations of their findings,

however, head-to-head comparisons are not possible. Fitz[20] found no correlation between levels of SF_6 tracer and other pollutants measured in bus cabins. Fitz et al.[23–27] described a strong relationship between SF_6 and BC, estimating that "up to 0.3% of the air inside the cabin was from the bus's own exhaust."[24,p.3745] EnSIGHT[28,29] used iridium to show that exhaust emissions contributed a very small fraction of in-cabin particulate, estimating that self-pollution explained less than 2.5% of the diesel particulate levels estimated by others on the basis of BC and EC measurements. Ireson et al.,[33–35] using iridium to label diesel fuel and a deuterated alkane to label engine oil, reported that crankcase emissions were the major source of in-cabin particulate, up to tenfold more than tailpipe emissions.

As related findings, Ireson et al. also reported that crankcase emissions consisted mainly of OC and contained the majority of particle-related PAHs, whereas tailpipe emissions were dominated by EC.[34] The latter findings are largely consistent with the results of nontracer studies by the Clean Air Task Force, which reported that crankcase rather than tailpipe emissions were "the principal source of cabin $PM_{2.5}$ pollution" in school buses.[32,p.64]

Unfortunately, such findings are not consistent with the reported results of the SF_6 studies.[23–27] Such disagreement may be related to methodological concerns discussed above. The SF_6 studies did not adequately control for potential confounding, exposure estimates were made using relatively simplified calculations that ignored the performance characteristics of the buses actually tested, and some conclusions were based on only subsets of data. On the other hand, the EnSight[28] and Ireson et al. studies[33–35] considered only three buses in total, and the latter study is currently available only as extended abstracts; thus, their results must be today viewed as preliminary.

Although definitive data are still lacking, this evolving body of studies provides increasing understanding of the nature of exposures in the cabins of diesel school buses. Most importantly, it seems likely that currently available control technologies, notably particulate exhaust filters and closed-crankcase filtration devices, can nearly eliminate particulate self-pollution. If so, then presumably such controls would also eliminate the majority of self-pollution exposures to toxic and carcinogenic compounds, e.g., particle-bound PAHs and nitro-PAHs. However, to be fully confident in these predictions, it will require further testing of sufficient numbers of buses and increasing variety of fuel and engine configurations as well as reconciliation of the apparent differences between the various tracer methodologies.

ACKNOWLEDGMENTS

Financial support was provided by International Truck and Engine Corporation, which did not participate in the design of this study or in the collection, management, analysis or interpretation of the data. Preparation and editing of the manuscript were performed solely by the authors.

REFERENCES

1. **Cass, G.R., and H.A. Gray:** Regional emissions and atmospheric concentrations of diesel engine particulate matter: Los Angeles as a case study. In *Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects*. Cambridge, Mass.: Health Effects Institute, 1995. pp. 125–138.
2. **Air Resources Board:** *Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant. Appendix III Executive Summary.* Sacramento, Calif.: California Environmental Protection Agency, 1998.
3. **U.S. Environmental Protection Agency (USEPA):** *Health Assessment Document for Diesel Engine Exhaust (EPA/600/8-90/057F)*. Washington, D.C.: USEPA, 2002.
4. **Haney, R.:** Diesel particulate exposures in underground mines. *Mining Eng*. 2:173–176 (1992).
5. **Cohen, H.J., J. Borak, T. Hall, G. Sirianni, and S. Chemerynski:** Exposure of miners to diesel exhaust particulates in underground nonmetal mines. *Am. Ind. Hyg. Assoc. J.* 63:651–658 (2002).
6. "Diesel Particulate Exposure of Underground Metal and Nonmetal Miners;" Final Rule. *Fed. Reg.* 70:32868–32968 (2005).
7. **Lewne, M., G. Nise, M.L. Lind, and P. Gustavsson:** Exposure to particles and nitrogen dioxide among taxi, bus and lorry drivers. *Int. Arch. Occup. Environ. Health* 79:220–226 (2006).
8. **Hansen, A.M., H. Wallin, M.-L. Binderup, et al.:** Urinary 1-hydroxypyrene and mutagenicity in bus drivers and mail carriers exposed to urban air pollution in Denmark. *Mutat. Res.* 557:7–17 (2004).
9. **Limasset, J.C., F. Diebold, and G. Hubert:** Exposition des conducteurs de bus urbains aux polluants de la circulation automobile (Assessment of bus drivers' exposure to the pollutants of urban traffic). *Sci. Total Environ.* 134:39–49 (1993).
10. **Muttamara, S., S.T. Leong, M. Arayasiri, and P. Laortanakul:** Benzene and lead exposure assessment among occupational bus drivers in Bangkok traffic. *J. Environ. Sci. (China)* 16:61–66 (2004).
11. **Soll-Johanning, H., E. Bach, and S.S. Jensen:** Lung and bladder cancer among Danish urban bus drivers and tramway employees: a nested case-control study. *Occup. Med. (London)* 53:25–33 (2003).
12. **Jakobssen, R., P. Gustavsson, and I. Lundberg:** Increased risk of lung cancer among male professional drivers in urban but not rural areas of Sweden. *Occup. Environ. Med.* 54:189–193 (1997).
13. **Burns, P.B., and G.M. Swanson:** The occupational cancer incidence surveillance study (OCISS): Risk of lung cancer by usual occupation and industry in the Detroit Metropolitan Area. *Am. J. Ind. Med.* 19:655–671 (1991).
14. **Guberan, E., M. Usel, L. Raymond, J. Bolay, G. Fioretta, and J. Puissant:** Increased risk for lung cancer and for cancer of the gastrointestinal tract among Geneva professional drivers. *Br. J. Ind. Med.* 49:337–344 (1992).
15. **Hansen, J., O. Raaschou-Nielsen, and J.H. Olsen:** Increased risk of lung cancer among different types of professional drivers in Denmark. *Occup. Environ. Med.* 55:115–118 (1998).
16. **Steenland, N.K., D.T. Silverman, and R.W. Hornung:** Case-control study of lung cancer and truck driving in the Teamsters Union. *Am. J. Publ. Health* 80:670–674 (1990).
17. **Solomon, G.M., T.R. Campbell, G.R. Feuer, J. Masters, A. Samkian, and K.A. Paul:** *No Breathing in the Aisles. Diesel Exhaust Inside School Buses*. New York: Natural Resources Defense Council (NRDC), 2001.
18. **O'Neill, D.:** *A Representative Sample of Fairfax County Public Schools Buses Found to be Free of Significant Diesel Exhaust*. [Online] Available at: http://www.fcps.k12.va.us/fts/safety-security/publications/busexhaustreport.pdf (Accessed 8/11/06).

19. **Wargo, J.:** *Children's Exposure to Diesel Exhaust on School Buses*. North Haven, Conn.: Environmental and Human Health, Inc., 2002. Available at http://www.ehhi.org/reports/diesel (Accessed 8/11/06).
20. **Fitz, D.:** *Evaluation of Emission Control Equipment in a School Bus Application (Final Report)*. Riverside, Calif.: College of Engineering-Center for Environmental Research and Technology, University of California, 2003. Available from jkovala@mail.donaldson.com.
21. **EHS-Alaska:** *School Bus Diesel Exhaust Sampling Report*. Available at www.asdk12.org/depts/transportation/safety.asp (Accessed 8/11/06).
22. **Borak, J., G. Sirianni, H.J. Cohen, S.M. Chemerynski, and R. Wheeler:** Comparison of NIOSH 5040 Method vs. aethalometer to monitor diesel particulate in school buses and work sites. *Am. Ind. Hyg. Assoc. J.* 64:260–268 (2002).
23. **Fitz, D.R., A.M. Winer, S. Colome, et al:** *Characterizing the Range of Children's Pollutant Exposure During School Bus Commutes*. Available at ftp://ftp.arb.ca.gov/carbis/research/schoolbus/report.pdf (Accessed 8/11/06).
24. **Behrentz, E., D.R. Fitz, D.V. Pankratz, et al.:** Measuring self-pollution in school buses using a tracer gas technique. *Atmos. Environ.* 38:3735–3746 (2004).
25. **Sabin, L.D., E. Behrentz, A.M. Winer, et al.:** Characterizing the range of children's air pollutant exposure during school bus commutes. *J. Expo. Anal. Environ. Epidemiol.* 15:377–387 (2005).
26. **Marshall, J.D., and E. Behrentz:** Vehicle self-pollution intake fraction: children's exposure to school bus emissions. *Environ. Sci. Technol.* 39:2559–2563 (2005).
27. **Behrentz, E., L.D. Sabin, A.M. Winer, et al.:** Relative importance of school bus-related microenvironments to children's pollutant exposure. *J. Air Waste Manage. Assoc.* 55:1418–1430 (2005).
28. **Ireson, R.G., M.D. Easter, M.L. Lakin, J.M. Ondov, N.N. Clark, and D.B. Wright:** Estimation of diesel particulate matter concentrations in a school bus using a fuel-based tracer—A sensitive and specific method for quantifying vehicle contributions. *Transport Res. Record: J. Transport. Res. Board* 1880:21–28 (2004).
29. **EnSIGHT:** *Estimated Concentrations of Diesel Particulates Inside a School Bus Based on Tracer Added to Its Fuel*. Available at http://www.greendieseltechnology.com/International%20Tracer%20Report%20final%209-1-03.pdf (Accessed 8/11/06).
30. **Hammond, D.M., M.M. Lalor, and S.L. Jones:** *On-Board Measurement of Particulates on School Buses with Diesel Bus Retrofits*. Birmingham, Ala.: Dept. of Civil and Environmental Engineering, University of Alabama at Birmingham, 2005.
31. **Hammond, D., M. Lalor, and S. Jones:** On-board measurement of particulates on school buses with diesel bus retrofits. In *84th Transportation Research Board Annual Meeting*. Washington, D.C.: Transportation Research Board, 2005.
32. **Hill, L.B., N.J. Zimmerman, and J. Gooch:** *A Multi-City Investigation of the Effectiveness of Retrofit Emissions Controls in Reducing Exposures to Particulate Matter in School Buses*. Available at http://www.catf.us/publications/view/82 (Accessed 8/11/06).
33. **Ireson, R.G., J.M. Ondov, B. Zielinska, et al:** Explicit quantification of in-cabin concentrations of school bus exhaust and crankcase emissions using intentional tracers (Ext. Abstract #100). In *Healthy Environments: Rebirth & Renewal (AWMA Annual Conference)*. Pittsburgh, PA: Air & Waste Management Association, 2006.
34. **Zielinska, B., D.E. Campbell, M. McDaniel, R. Ireson, et al:** Chemical characterization of diesel crankcase and tailpipe PM emissions, including a quantitative deuterated tracer for lubricating oil (Ext. Abstract #464). In *Healthy Environments: Rebirth & Renewal (AWMA's Annual Conference)*. Pittsburgh, Pa.: Air & Waste Management Association, 2006.
35. **Webber, W.L., M. Davey, T. Larson, R.G. Ireson, et al:** Comparing three approaches of estimating bus self-pollution—A pilot study (Ext. Abstract #313). In *Healthy Environments: Rebirth & Renewal (AWMA Annual Conference)*. Pittsburgh, Pa.: Air & Waste Management Association, 2006.
36. **Alm, S., M.J. Jantunen, and M. Vartianen:** Urban commuter exposure to particle matter and carbon monoxide inside an automobile. *J. Exp. Anal. Environ. Epidemiol.* 9:237–244 (1999).
37. **Pasquill, F.:** The estimation of the dispersion of wind-borne material. *Meteorol. Mag.* 90:33–49 (1961).
38. **Suarez, A.E., P.F. Caffrey, P.V. Borgoul, and J.M. Ondov:** Use of an iridium tracer to determine the size distribution of aerosol emitted from a fleet of diesel sanitation trucks. *Environ. Sci. Technol.* 32:1522–1529 (1998).
39. **Jung, H., D.B. Kittelson, and M.R. Zachariah:** The influence of engine lubricating oil on diesel nanoparticle emissions and kinetics of oxidation. *SAE Technical Paper Series* 2003-01-3179, 2003.
40. **LeTavec, C., J. Uihlein, J. Segal, and K. Vertin:** EC-Diesel Technology Validation Program Interim Report. *SAE Technical Paper Series* 2000-01-1854, 2000.
41. **LeTavec, C., J. Uihlein, K. Vertin, et al.:** Year-long evaluation of trucks and buses equipped with passive diesel particulate filters. *SAE Technical Paper Series* 2002-01-4333, 2002.
42. **Ullman, T.L., L.R. Smith, J.W. Anthony, et al.:** Comparison of exhaust emissions, including toxic air contaminants, from school buses in compressed natural gas, low emitting diesel, and conventional diesel engine configurations. *SAE Technical Paper Series* 2003-01-1381, 2003.
43. **Chow, J.C., J.G. Watson, L.C. Pritchett, W.R. Pierson, C.A. Frazier, and R.G. Purcell:** The DRI thermal/optical reflectance carbon analysis system: description, evaluation and applications in U.S. air quality studies. *Atmos. Environ.* 27A:1185–1201 (1993).
44. **Zielinska,B., J. Sagebiel, J.D. McDonald, K. Whitney, and D.R. Lawson:** Emission rates and comparative chemical composition from selected in-use diesel and gasoline-fueled vehicles. *J. Air Waste Manage. Assoc.* 54:1138–1150 (2004).