Journal of Exposure Analysis and Environmental Epidemiology (2005) 15, 377–387

www.nature.com/jea

Characterizing the range of children's air pollutant exposure during school bus commutes

LISA D. SABIN,[a] EDUARDO BEHRENTZ,[a] ARTHUR M. WINER,[a,b] SEONG JEONG,[a] DENNIS R. FITZ,[c] DAVID V. PANKRATZ,[c] STEVEN D. COLOME[d] AND SCOTT A. FRUIN[e]

[a]*Environmental Science and Engineering Program, UCLA School of Public Health, 650 Charles E. Young Drive, South, Los Angeles, California 90095-1772, USA*
[b]*Department of Environmental Health Sciences, UCLA School of Public Health, University of California, Los Angeles, California 90095-1772, USA*
[c]*College of Engineering, Center for Environmental Research and Technology, University of California, Riverside, California 92507, USA*
[d]*Integrated Environmental Sciences, 5319 University Drive #430, Irvine, California 92612, USA*
[e]*California Air Resources Board, Research Division, Sacramento, California 95814, USA*

Real-time and integrated measurements of gaseous and particulate pollutants were conducted inside five conventional diesel school buses, a diesel bus with a particulate trap, and a bus powered by compressed natural gas (CNG) to determine the range of children's exposures during school bus commutes and conditions leading to high exposures. Measurements were made during 24 morning and afternoon commutes on two Los Angeles Unified School District bus routes from South to West Los Angeles, with seven additional runs on a rural/suburban route, and three runs to test the effect of window position. For these commutes, the mean concentrations of diesel vehicle-related pollutants ranged from 0.9 to 19 $\mu g/m^3$ for black carbon, 23 to 400 ng/m^3 for particle-bound polycyclic aromatic hydrocarbon (PB-PAH), and 64 to 220 $\mu g/m^3$ for NO_2. Concentrations of benzene and formaldehyde ranged from 0.1 to 11 $\mu g/m^3$ and 0.3 to 5 $\mu g/m^3$, respectively. The highest real-time concentrations of black carbon, PB-PAH and NO_2 inside the buses were 52 $\mu g/m^3$, 2000 ng/m^3, and 370 $\mu g/m^3$, respectively. These pollutants were significantly higher inside conventional diesel buses compared to the CNG bus, although formaldehyde concentrations were higher inside the CNG bus. Mean black carbon, PB-PAH, benzene and formaldehyde concentrations were higher when the windows were closed, compared with partially open, in part, due to intrusion of the bus's own exhaust into the bus cabin, as demonstrated through the use of a tracer gas added to each bus's exhaust. These same pollutants tended to be higher on urban routes compared to the rural/suburban route, and substantially higher inside the bus cabins compared to ambient measurements. Mean concentrations of pollutants with substantial secondary formation, such as $PM_{2.5}$, showed smaller differences between open and closed window conditions and between bus routes. Type of bus, traffic congestion levels, and encounters with other diesel vehicles contributed to high exposure variability between runs.
Journal of Exposure Analysis and Environmental Epidemiology (2005) **15,** 377–387. doi:10.1038/sj.jea.7500414; published online 8 December 2004

Keywords: *diesel, bus, children, exposure, air pollutant, black carbon.*

Introduction

Although ambient air pollution contributes to adverse health effects, exposure to the highest concentrations of many air contaminants occurs in other microenvironments, such as vehicles. Roadways and sidewalks have been shown to exhibit the highest outdoor concentrations for many air pollutants and elevated concentrations of elemental carbon and polycyclic aromatic hydrocarbons (PAH) have been recorded in tunnels and on heavily traveled roadways (Benner et al., 1989; Venkataraman et al., 1994; Kirchstetter and Harley, 1999). In-vehicle concentrations have been shown to be higher than those measured at fixed site monitors and in some cases higher than those measured along roadways (Shikiya et al., 1989; Ptak and Fallon, 1994; Lawryk and Weisel, 1995; Rodes et al., 1998; Alm et al., 1999). However, although a number of studies have investigated exposure to air pollutants inside vehicles, the majority of these focused on passenger cars and pollutants predominantly emitted by them (carbon monoxide and volatile organic compounds), and few focused on diesel-related pollutants such as particulate matter (PM), particle-bound PAH (PB-PAH) or black carbon.

As children are more susceptible to adverse health effects from air pollution (Lipsett, 1989; Wiley et al., 1991), potentially high pollutant exposures during school bus commutes are of concern, but few studies have attempted to characterize concentrations on board school buses. Solomon et al. (2001) investigated the concentrations of $PM_{2.5}$ and black carbon inside four diesel school buses in the Los Angeles area, including measurements inside and outside buses, and in a passenger car traveling ahead of the bus. They

1. Address all correspondence to: Prof. Arthur M. Winer, UCLA School of Public Health, 650 Charles E. Young Drive, South, Los Angeles, CA 90095-1772, USA. Tel.: +1-310-206-1278. Fax: +1-310-206-3358. E-mail: amwiner@ucla.edu
Received 16 March 2004; accepted 27 October 2004; published online 8 December 2004

reported levels of black carbon inside the bus increased when all windows were closed and decreased with windows open, and were higher in the back of the bus compared to the front. They concluded the level of black carbon in the back of a school bus with windows closed could be up to four times higher than in a passenger car ahead of the bus.

Wargo et al. (2002) reported concentrations of black carbon and $PM_{2.5}$ inside commuting diesel school buses in rural Connecticut were often 5–10 times higher than background concentrations. They found several important variables affected the concentrations of pollutants inside school buses, including bus ventilation via windows, bus idling behavior, and outdoor concentrations on bus routes. They also tested a school bus fueled with natural gas and observed 60–98% less black carbon on board than on diesel-powered buses.

In the present study, we investigated the range of exposures experienced by children during commutes on different types of school buses (e.g. conventional diesel, particle trap-outfitted diesel and natural gas) and bus routes, and identified factors leading to higher exposures.

Methodology

Study Design

Real-time and integrated concentrations of PM and gaseous pollutants were measured inside seven school buses across a wide range of commute conditions in the Los Angeles (LA) basin, with an emphasis on measurements during operations expected to lead to realistic high-end exposures. Concentrations reported here were measured in the rear of the bus cabin with the same set of instruments during all bus commutes, as we expected only small differences between the front and rear of the bus cabin (Fitz et al., 2003; Solomon et al., 2001). Instruments were secured inside the buses on plywood platforms strapped to the tops of the bus seats along the right side of each bus. Tests performed prior to the start of the study on emissions of formaldehyde from these plywood platforms found the platforms added no significant formaldehyde to bus cabin concentrations. Sampling probes were positioned at the height of the breathing zone of a child seated in the bus, approximately 1.2 m above the bus floor. Large diameter inlets were used for the interior sampling probes to minimize velocity changes and particle losses. Separate sampling systems were used for the gaseous and PM sampling trains. The instruments were powered with onboard 12-volt lead-acid storage batteries and an inverter. These batteries also provided ballast to represent the aggregate weight of children since for safety reasons, and because instruments and batteries occupied almost the entire seating area, no children were aboard any buses in this study.

Measurements were made on 31 bus commutes during April, May and June 2002 on seven school buses. For all bus commutes, the windows on the buses were closed during morning runs, while during the afternoon runs, windows were partially opened, to simulate conditions we observed on in-use school buses in the LA area. At bus stops along each route, the bus pulled up to the curb, opened the doors and waited for approximately 1 min before driving away to simulate the conditions of children loading or unloading from the bus. The exact routes and commute times of two urban Los Angeles Unified School District (LAUSD) school bus routes were followed, while a third route was selected to simulate rural/suburban driving conditions.

We also measured real-time ambient air concentrations of black carbon and PB-PAH before or after bus commutes either in West LA or at the first bus stop on a route in South LA. During the same period as the bus commutes, integrated benzene and formaldehyde ambient air concentrations were measured at the West LA South Coast Air Quality Management District (SCAQMD) monitoring site. For ambient concentrations of nitrogen dioxide (NO_2), we used the monitoring data collected by the SCAQMD at their Central LA and West LA sites, the two sites closest to our urban bus routes.

A day prior to the start of the commutes, the ventilation rate inside each bus was measured by releasing an SF_6 tracer gas inside the bus cabin. The concentration of the gas was monitored over time, both with windows open and closed, at bus speeds of 0, 32 and 64 km/h.

Buses and Fuels

Two local school districts provided the buses used in this study from their in-use fleet of approximately 150 buses (Table 1). Low-sulfur, Arco Emission Control Diesel fuel (ECD-1) was used in all diesel buses. Two conventional diesel buses were selected to be representative of California's in-use school bus fleet: 1993 (RE1) and 1998 (RE2) Thomas Saf-T-Liners. Three ''high emitter'' diesel buses were selected based on their age, the opinion of bus service personnel and snap and idle opacity tests: a 1985 Thomas Coach (HE1), and 1985 (HE2) and 1975 (HE3) Crown Supercoaches. To test a diesel bus equipped with a particle-trap catalyst (TO1), we selected a 1998 Thomas Saf-T-Liner equipped with a Johnson Matthey Continuously Regenerating Technology (CRT®) particulate filter. Finally, in order to compare children's exposure during commutes for a different bus fuel type, we tested a 2002 Thomas Saf-T-Liner operating on compressed natural gas (CNG).

Bus Routes

Urban school bus routes were selected from in-use routes at the LAUSD Brentwood Science Magnet School (BSMS), a K-5 facility. Typically, 85% of the children attending BSMS were transported to and from this school daily on 19 diesel school buses. The bus routes from this school provided a broad range of roadway type and traffic congestion

Table 1. Description of bus commutes, meteorological data and bus speeds during 34 runs.

Bus[a]	Bus description	Run date	Time of day	Route	Temperature (°C)	RH (%)	Mean wind speed[b] (m/s)	Mean commute speed (km/h)
HE1	1985 Thomas Coach Diesel	April 22, 2002	Afternoon	Rural/suburban	33	11	—	32
		April 23, 2002	Morning	Urban 1	25	43		18
			Afternoon	Urban 1	27	36		28
HE2	1985 Crown Supercoach Diesel	April 30, 2002	Afternoon	Rural/suburban	24	29	—	33
		May 1, 2002	Morning	Urban 1	20	46	0.56	20
			Afternoon	Urban 1	25	29	4.2	19
HE3	1975 Crown Supercoach Diesel	May 7, 2002	Afternoon	Rural/suburban	22	44		34
		May 8, 2002	Morning	Urban 1	22	48	0.28	22
			Morning	Window position test	23	43		43
			Afternoon	Urban 1	25	39	3.9	23
RE1	1998 Thomas Saf-T-Liner Diesel	May 13, 2002	Afternoon	Rural/suburban	37	10		37
		May 14, 2002	Morning	Urban 1	27	40	0.36	22
			Afternoon	Urban 1	27	36	3.6	28
		May 16, 2002	Morning	Urban 1	23	50	1.1	22
			Afternoon	Urban 1	24	44	2.4	20
RE2	1993 Thomas Saf-T-Liner Diesel	May 20, 2002	Afternoon	Rural/suburban	22	48		40
		May 21, 2002	Morning	Urban 1	23	41	0.36	–
			Afternoon	Urban 1	24	29	3.9	27
		May 22, 2002	Morning	Urban 1	22	43	0.36	25
			Afternoon	Urban 1	25	30	4.7	25
		May 29, 2002	Morning	Urban 2	25	50		20
			Afternoon	Urban 2	26	49	3.3	19
		May 30, 2002	Morning	Urban 2	25	53		21
			Afternoon	Urban 2	26	48	2.4	21
TO1	1998 Thomas Saf-T-Liner Diesel equipped with a Johnson Matthey CRT® particulate filter	June 4, 2002	Afternoon	Rural/suburban	33	29		40
		June 5, 2002	Morning	Urban 1	25	52	0.19	25
			Morning	Window position test	26	50		39
			Afternoon	Urban 1	28	46	3.9	24
		June 6, 2002	Morning	Urban 1	26	53	0.19	26
			Morning	Window position test	27	51		45
			Afternoon	Urban 1	27	50	2.8	22
CNG	2002 Thomas Saf-T-Liner CNG	June 11,2002	Afternoon	Rural/suburban	22	52		40
		June 12, 2002	Morning	Urban 1	24	50	0.31	24
			Afternoon	Urban 1	27	40	4.2	18

[a]HE = high emitter bus; RE = representative bus; TO = particle trap-outfitted bus; CNG = compressed natural gas bus.
[b]Wind speed data were not available for the RS and U2 bus routes.

scenarios. Caltrans annual average daily traffic count data from 1998 to 1999 were used to characterize the routes from BSMS in terms of expected traffic congestion levels.

The primary urban route (U1) used in this study was approximately 30 km long with five bus stops (Figure 1). In all, 40% of this route was on two of the most heavily congested freeways in the US, and 60% on surface streets ranging from single lane residential streets with little or no traffic to heavily congested, multilane surface streets with high traffic densities. The second urban route (U2) was also approximately 30 km long, had 10 bus stops and included only travel on surface streets (Figure 1). Both urban routes took approximately 1 hour to complete, traveled through inner-city neighborhoods of South LA, and were run during normal school commute times (6:30 in the morning and 15:00 in the afternoon).

In addition to U1 and U2, we selected a third route through low density rural and suburban neighborhoods providing scenarios not encountered in urban areas, including longer periods driving at a constant speed, and reduced idling time and traffic congestion. This rural/suburban route (RS) had little or no heavy-duty truck traffic, no freeways within 1.5 km of the route and low population densities. The route was ~40 km long, corresponding to 1 h of commute time,

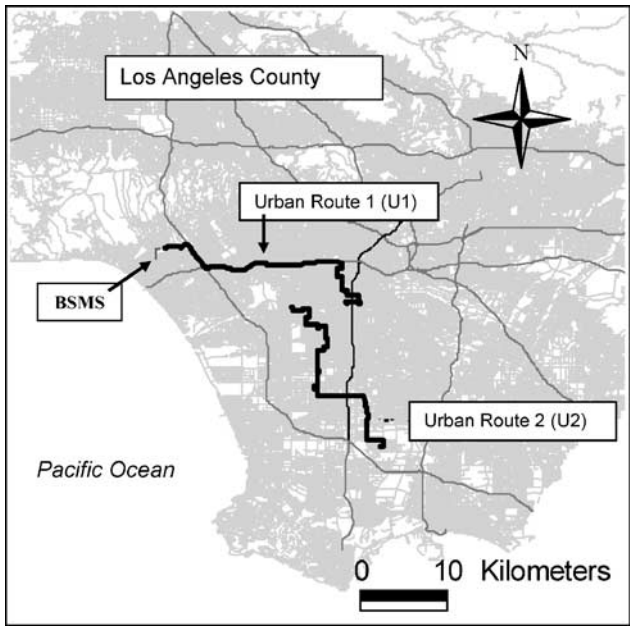

Figure 1. LAUSD urban school bus routes (U1 and U2).

and travelled from rural parts of Riverside county to suburban areas of east LA county.

The majority of bus commutes were completed on U1 (10 morning and 10 afternoon runs). Two morning and 2 afternoon runs were completed on U2, and 7 afternoon runs, one for each bus tested, were completed on RS.

Window Position Tests

The effect of window position on concentrations inside the bus cabin was tested during three additional runs along a north–south stretch of I-405 from Wilshire Blvd. to Century Blvd., and back, for a total sampling time of $\sim$1 h. These runs were conducted immediately following morning bus commutes on one conventional diesel bus (HE3) and the particle trap-outfitted diesel bus (TO1). Owing to relatively uniform traffic densities and stagnant meteorological conditions during these runs, we expected relatively minor pollutant concentration gradients along this route. We alternated between open and closed windows every 8 min during the tests, a short enough period to allow several tests under similar traffic conditions but long enough to allow stabilization of conditions inside the bus. Only real-time instruments were used to measure pollutant concentrations for these runs.

Instrumentation

Real-time black carbon concentrations were measured using Magee Scientific Aethalometers, Model AE-1. Sample air was drawn through a 0.5 cm^2 spot on a quartz fiber filter tape. The decrease of infrared light at 880 nm transmitted through the quartz tape was proportional to the amount of elemental carbon and "heavy" organic molecules collected. The instrument's response to the change in light transmittance was reported as black carbon. EcoChem Model PAS 2000 analyzers were used to measure real-time concentrations of total PB-PAH by UV-photoionization. Real-time NO_2 concentrations were measured by reaction with luminol following gas chromatographic (GC) separation of NO_2 and peroxyacyl nitrates (Fitz et al., 2002).

Integrated measurements of benzene were collected on Tenax cartridges and analyzed by GC, per US EPA TO-1 Method (US EPA, 1989), using a Hewlett Packard HP5890 II GC with a thermal desorber, capillary column and flame ionization detector. Integrated formaldehyde concentrations were measured using a variant of US EPA Method TO-11 (US EPA, 1989) for carbonyls in which 2,4-dinitrophenylhydrazine (DNPH) was impregnated on silica C18 Sep-Pak cartridges (Waters/Millipore Corp., Milford, MA, USA). When ambient air was drawn through the cartridge at 1.0 l/min, carbonyls in the air sample were captured by reacting with DNPH to form hydrazones, which were extracted and then separated and quantified using high-pressure liquid chromatography (Fung and Grosjean, 1981). Accuracy of this method was approximately $\pm$15% for formaldehyde based on comparison with long-path spectroscopy in ambient air (Fung and Wright, 1990; Lawson et al., 1990).

Integrated measurements of $PM_{2.5}$ mass were collected using customized, portable sampling systems, with inlets of the Harvard design (Turner et al., 2000), which have an effective cut point at 2.5 μm while sampling at 20 l/min. A Cahn Model 34 microbalance was used to determine the weight of the filters to $\pm$2 μg before and after sampling. Real-time $PM_{2.5}$ mass was measured using Thermo Systems Inc. Model 8520 DustTrak Aerosol Monitors. Impactors were used to perform the necessary size cut and the particle mass concentration was determined by measuring the intensity of the 90° scattering of light from a laser diode. However, as reported elsewhere (Ramachandran et al., 2000; Chung et al., 2001; Yanosky et al., 2002; Fitz et al., 2003), DustTrak measurements were generally higher than the integrated gravimetric method and to provide absolute concentrations comparable to other studies, $PM_{2.5}$ mass data reported here are from the Harvard Impactors. Data collected with the DustTrak were only used on a relative basis during window position tests, when real-time information was required.

In order to determine if a significant amount of a bus's own exhaust entered the cabin during commutes, sulfur hexafluoride (SF_6) tracer gas was injected into the bus exhaust system during each run (Behrentz et al., 2004a). SF_6 concentrations were then measured inside the cabin at the front and rear, and just outside the cabin at the front of the bus, with an AeroVironment Model CTA 1000 real-time analyzer using electron capture detection.

Bus location was determined with a Garmin MAP76 global positioning system (GPS) with Wide Area Augmentation System corrections. The GPS system also provided elevation and velocity data. The GPS unit was used as a time reference during this study and the clocks for all instruments were synchronized against the GPS at the beginning of each run. Temperature and relative humidity were measured inside the buses using a Rotronics Model MP101A sensor. Wind speeds during the commutes were obtained by averaging the hourly data from the two SCAQMD air monitoring stations located near the start and end of U1. A Sony DXC-390 video camera was mounted at the front of the buses to record traffic conditions in the lane in which the bus was traveling, as well as the adjacent lanes, during all measurement periods. The video camera clock was synchronized with the GPS master clock prior to each run. In addition to the video camera documentation, field personnel recorded traffic conditions and other observations about vehicles near the bus during each commute.

Instruments that logged data internally were downloaded via a personal computer (PC) following each run. All other real-time instruments had analog or digital inputs connected to a PC that collected data during the run using LabVIEW® software. With the exception of the NO_2 instrument, which recorded 1-min data, all other real-time instruments recorded 1-s data, and the 10-s medians from these data were used for all subsequent analyses.

Results

Typical meteorological conditions for late spring/early summer in Southern California (no rain; light/no wind in the morning, with on-shore flow conditions and higher wind speeds in the afternoon) prevailed for the duration of the 8-week study, with no large differences in meteorology between runs conducted at the same time of day (Table 1). On urban routes, conditions ranged from temperatures of 20 to 27°C and wind speeds from 0.19 to 1.1 m/s in the morning, to temperatures of 24–28°C and wind speeds of 2.4–4.7 m/s in the afternoon. The RS route was only run in the afternoon, with temperatures ranging from 22 to 37°C (no wind data were available for this route).

On urban routes, the mean bus speeds for individual commutes ranged from 20–26 km/h in the morning, and 18–28 km/h in the afternoon. Mean bus speeds on the RS route and during window position tests were higher (33–40 and 39–45 km/h, respectively).

Ventilation Inside the Buses and the Importance of Window Position

Ventilation was reported as the time for 95% of the bus air to exchange with outside air (Table 2). As expected, much faster ventilation was observed when windows were open than closed, and when the buses traveled at higher speeds. With windows closed, ventilation was faster inside older buses compared with newer buses. Relatively fast ventilation was observed for all buses even with the windows closed when traveling at 64 km/h.

While differences in pollutant concentrations inside vehicles may be influenced by the time of day, with higher concentrations typical in the morning compared with the afternoon (Alm et al., 1999; Batterman et al., 2002), differences between morning and afternoon commutes during this study were further enlarged because of the influence of the window position. Consistent with our observations of in-use school buses, all morning commutes had closed windows while all afternoon commutes had every other window partially open, leading to substantially different ventilation rates inside the buses between morning and afternoon commutes. This effect is demonstrated by time series of bus cabin pollutant concentrations (Figure 2). During morning runs with windows closed, pollutant concentrations inside the bus were relatively stable, and increased/decreased only slowly over the commute, with fewer high peak concentrations compared with windows open. By contrast, during afternoon runs with the windows open, we observed lower baseline concentrations due to higher ventilation in the cabin, however, with numerous transient high-peak concentrations.

Table 2. Ventilation response time measured inside six school buses.

Window postion	Bus speed (km/h)	Response time[a] (mm:ss)					
		HE2	HE3	RE1	RE2	TO1	CNG
Closed	0	>60	29:21	>60	>60	>45	>60
	32	4:00	5:36	11:48	10:33	13:54	6:00
	64	2:36	1:54	3:15	6:00	4:06	4:03
Open	0	7:54	9:48	11:51	2:00	6:54	21:00
	32	1:33	2:54	2:24	2:21	1:09	1:18
	64	0:48	1:27	0:51	1:51	0:36	1:09

[a]Time for 95% of the bus air to be exchanged.

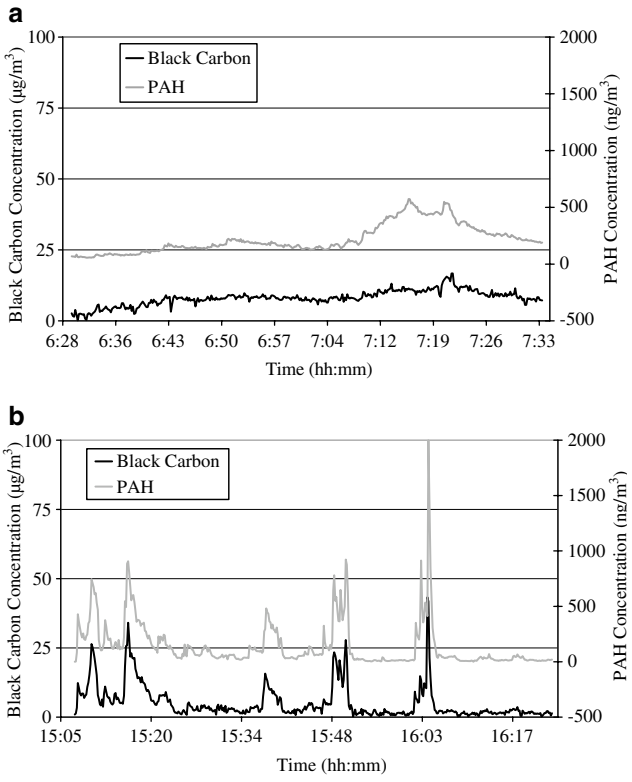

Figure 2. Typical pollutant time series for black carbon and particle-bound PAH measured during (a) Run 31, a morning run with windows closed and (b) Run 33, an afternoon run with windows partially open.

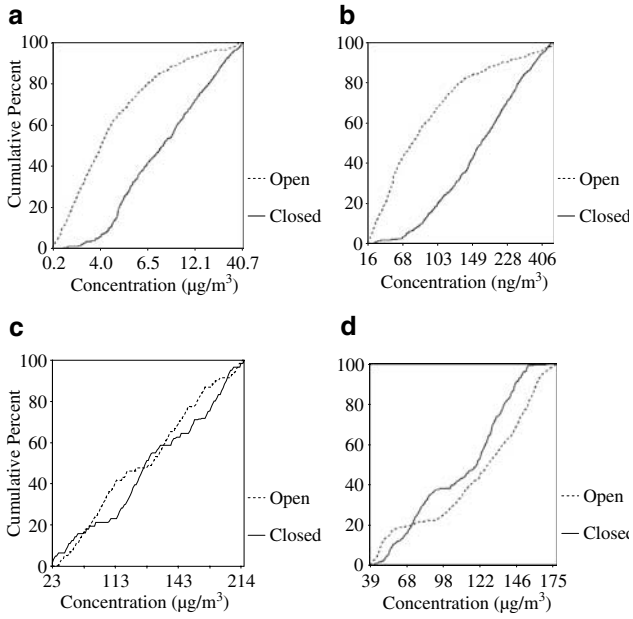

Figure 3. Cumulative frequency distributions during window position tests for (a) black carbon, (b) particle-bound PAH, (c) NO_2 and (d) $PM_{2.5}$ mass.

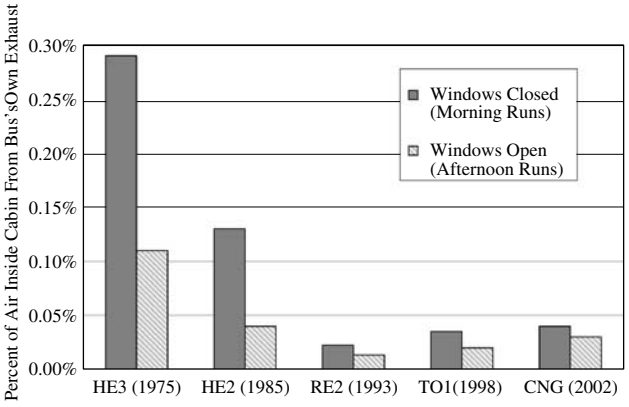

Figure 4. Percent of air inside each bus cabin originating from the bus's own exhaust.

The window position tests provided further evidence of the influence on pollutant concentrations of open vs. closed windows (Figure 3), with higher concentrations of black carbon (BC) and PB-PAH observed inside the bus with windows closed compared with open, while the opposite was true for $PM_{2.5}$ mass. NO_2 concentrations were relatively insensitive to the position of the windows, however, reduced time resolution of the NO_2 data compared with other pollutants may have limited our ability to observe significant differences due to window position on the time scale of these tests (about 8-min cycling between open and closed).

Self-pollution

A detailed description of the measurements of a bus's own exhaust inside the cabin using an SF_6 tracer gas, including the method used to calculate this self pollution, is published in Behrentz et al. (2004a). In summary, (Figure 4), all buses exhibited a degree of self-pollution during every commute; for each bus, the amount of the bus's own exhaust inside the cabin was substantially higher with windows closed compared with open; and compared with newer buses, older buses showed a larger percentage (up to 10 times) of their own exhaust entering the cabin. The mechanisms of exhaust intrusion into bus cabins are a subject of our ongoing research.

Range of Exposures During Bus Commutes

Real-time Data: Table 3 summarizes the range of concentrations of BC, PB-PAH and NO_2 measured inside the buses on each route during morning (windows closed) and afternoon (windows open) commutes. Pollutant concentrations for bus HE1 were not included due to mechanical and power problems during HE1 commutes.

The range of individual commute mean BC concentrations was 2.5–19 $\mu g/m^3$ on urban routes and 0.9–4.8 $\mu g/m^3$ on the RS route. On urban routes, mean concentrations of BC were 2–3 times higher when windows were closed compared with

Table 3. The range of black carbon, PB-PAH and NO_2 concentrations measured inside school buses during windows closed (morning) and windows open (afternoon) commutes by route.

		n	Arithmetic mean	Standard deviation	Geometric mean	10-s minimum	10-s maximum	Range of run means[a]	Range of ambient concentrations[b]
Black Carbon ($\mu g/m^3$)									
Windows closed	U1	3734	10	6.7	7.9	0.19	44	2.5–19	1.6–7.7
	U2	730	11	4.1	9.7	0.19	27	9.4–12	
Windows open	U1	3798	5.2	7.3	2.9	0.19	51	2.9–9.1	0.7–4.9
	U2	1052	6.0	8.1	3.8	0.19	51	4.9–7.2	
	RS	2345	2.7	3.6	1.8	0.10	51	0.9–4.8	
PAH (ng/m^3)									
Windows closed	U1	3877	200	130	160	19	1000	64–400	15–120
	U2	739	140	81	120	8.3	660	110–160	
Windows open	U1	3971	96	180	38	0.5	2000	32–140	4–72
	U2	1051	81	200	29	1.0	1800	47–120	
	RS	2344	36	77	17	0.2	1000	23–37	
NO_2 ($\mu g/m^3$)									
Windows closed	U1	3627	121	49	112	49	304	64–210	30–83
	U2	702	82	8	81	59	103	77–87	
Windows open	U1	3559	138	60	122	11	373	74–220	23–72
	U2	950	115	52	104	40	268	95–130	
	RS	2002	84	43	73	16	212	44–130	

[a]The lowest and the highest arithmetic means calculated from real-time data for individual runs.
[b]Measured at the start and end of U1.

when they were open. Mean concentrations were twice as high on the urban routes compared with the RS route, while differences between the two urban routes were small (<15%). As noted earlier, for BC, commutes with windows closed generally had higher median concentrations and relatively few high peaks compared with commutes with windows open, which had lower median concentrations but frequent high peaks (Figure 5a). Peak concentrations of BC greater than 50 $\mu g/m^3$ were observed when the windows were open on HE3 (RS), RE1 (U1) and RE2 (U1 and U2), and all urban commutes with windows open had multiple peak concentrations greater than 20 $\mu g/m^3$. These peaks were observed predominantly when following another diesel vehicle, although for the conventional diesel buses, high peaks were also observed while idling. With the windows closed, maximum BC concentrations were typically below 30 $\mu g/m^3$, with a few exceptions, including the highest concentration of 44 $\mu g/m^3$, measured on RE1 (U1).

Mean PB-PAH concentrations for individual runs ranged from 32–400 ng/m^3 on urban routes, and 23–37 ng/m^3 on the RS route. On urban routes, mean concentrations of PB-PAH were approximately 2–4 times higher when the windows were closed compared with when they were open, and higher by 2–3 times compared to the RS route; differences between the two urban routes were small for the same window position. With windows open, the highest real-time PB-PAH concentration was 2000 ng/m^3, while concentrations as high as 1000 ng/m^3 were observed in all buses, with frequent peak concentrations greater than 500 ng/m^3

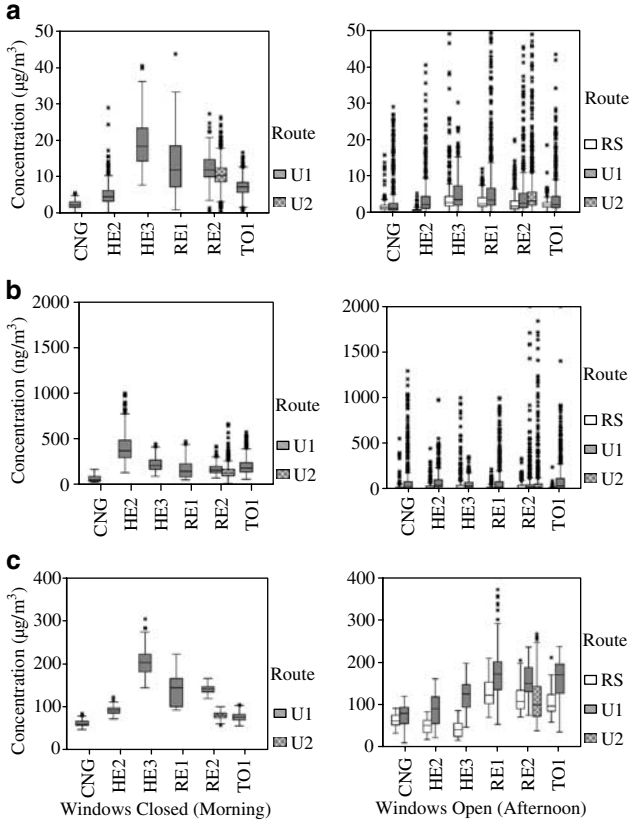

Figure 5. Concentrations from real-time measurements inside school bus cabins during commutes on urban (U1 + U2) and rural/suburban (RS) routes on six buses for (a) black carbon, (b) particle-bound PAH and (c) NO_2.

(Figure 5b). As with BC, these high peaks were observed predominantly when following another diesel vehicle. When the windows were closed, PB-PAH concentrations generally did not exceed 500 ng/m^3, with some exceptions (HE2 on U1, RE2 on U2 and TO1 on U1). It is important to note that the PAH instrument was set to a maximum of 1000 ng/m^3 on buses HE2, HE3 and RE1, while the maximum was increased to 2000 ng/m^3 on buses RE2, TO1 and CNG. Thus, our measurements almost certainly underestimated the maximum PB-PAH concentrations on buses HE2, HE3 and RE1.

Mean NO_2 concentrations for individual runs ranged from 44 to 220 μg/m^3, and were slightly higher for open compared with closed windows on urban routes. U1 NO_2 concentrations were 50% higher than U2, and higher than RS by nearly a factor of two, while U2 was 40% higher than RS. The maximum real-time NO_2 concentration with closed windows (300 μg/m^3) was observed on HE3 (U1), while the maximum with open windows (370 μg/m^3) was observed on RE1 (U1). However, between-run variability for NO_2 concentrations was generally greater than differences between routes or between open and closed windows (Figure 5c).

Integrated data: The ranges of integrated $PM_{2.5}$ concentrations measured during each run (Figure 6a) were similar for windows open and closed on U1 (13–56 and 36–60 μg/m^3, respectively), and also similar to the range of concentrations measured on RS with windows open (18–57 μg/m^3). For a given bus on urban routes, $PM_{2.5}$ concentrations were generally higher when windows were closed, except for TO1, which had similar high concentrations (>50 μg/m^3) both with open and closed windows. For a given bus on RS, $PM_{2.5}$ concentrations were typically higher than on U1 with windows open, consistent with the higher background concentrations of $PM_{2.5}$ in the downwind receptor areas of the LA air basin where RS was located, compared with the source-dominated Western basin where the urban routes were located (Hughes et al., 2000). The exceptions were the TO1 and RE2 buses, both of which exhibited slightly higher $PM_{2.5}$ on U1.

Benzene concentrations on U1 were higher when windows were closed, ranging from 5.0 to 11 μg/m^3, compared with 1.6–4.1 μg/m^3 with windows open (Figure 6b). Slightly lower concentrations were observed on U2 (4.2 μg/m^3 with windows closed; 1.7 μg/m^3 with windows open). The TO1 bus had the highest benzene concentrations on urban routes, for both open and closed windows. Benzene concentrations on the RS route were generally low for all buses, ranging from 0.2 to 1.8 μg/m^3.

Formaldehyde concentrations were generally higher with windows closed, ranging from 1.2 to 4.8 μg/m^3 on U1 (Figure 6c). The highest concentration (4.8 μg/m^3) was observed with windows closed on the CNG bus on U1. For windows open, formaldehyde concentrations were similar between buses and between routes, ranging from 0.3 to 2.1 μg/m^3.

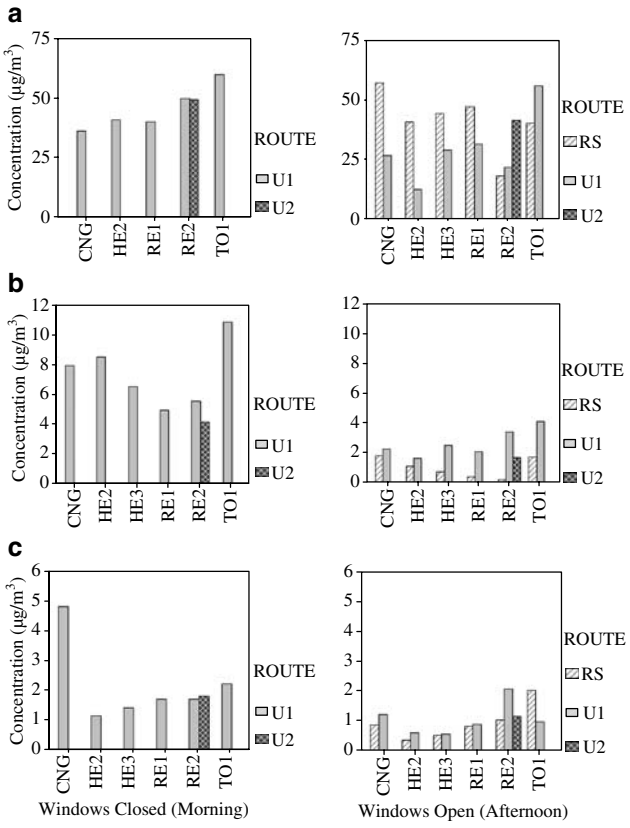

Figure 6. Concentrations from integrated measurements inside school bus cabins during commutes on urban (U1 + U2) and rural/suburban (RS) routes on six buses for (a) $PM_{2.5}$, (b) benzene and (c) formaldehyde.

Ambient Concentration Data

For all pollutants, the mean concentration of all bus commutes was higher than the ambient concentration, both in the morning and in the afternoon, by at least a factor of two (Table 4). When comparing the single highest commute mean concentration with ambient air, differences ranging from almost 4 times as high inside the bus cabin for NO_2 to as much as 12 times higher inside the cabin for formaldehyde were observed.

Discussion

The range of exposures inside bus cabins depended on a number of factors, including window position, self-pollution from a bus's own exhaust, bus type and route type, and these factors varied between pollutants. Black carbon, PB-PAH, NO_2, benzene and formaldehyde, which are all associated with fresh vehicle exhaust emissions, exhibited a different behavior than $PM_{2.5}$, which is not as useful a signature for

Table 4. Comparison of bus commute concentrations on U1 with ambient air concentrations.

	Ratio of mean of all bus commutes to ambient	Ratio of mean of highest bus commute to ambient
Black carbon		
Morning	3.5	6.7
Afternoon	4.0	7.0
PAH		
Morning	5.1	10
Afternoon	5.1	7.6
NO_2		
Morning	2.3	3.9
Afternoon	3.4	5.3
Benzene		
Morning	4.3	7.0
Afternoon	2.1	10
Formaldehyde		
Morning	4.3	12
Afternoon	2.5	8.3

direct emissions from vehicles due to the substantial ''background'' contribution from regional sources and secondary formation (Zhu et al., 2002a, b).

Real-time data from the window position tests demonstrated that for BC and PB-PAH, increased ventilation inside the cabin with open windows reduced mean concentrations. In contrast, closed windows allowed these pollutants to build up inside the cabin due to reduced ventilation and greater intrusion of a bus's own exhaust. However, high, transient concentrations from self-pollution when idling, and from nearby diesel vehicles (as documented by videotapes, Fitz et al., 2003) were observed with windows open. Similarly, higher cabin concentrations on urban routes compared with the RS route were likely due to higher roadway concentrations (greater traffic density, including more diesel vehicles) and increased idling time (resulting in reduced ventilation and self-pollution).

While NO_2 is associated with fresh vehicle emissions, it is also a secondary pollutant, and elevated background concentrations are possible (Finlayson-Pitts and Pitts, 2000). Smaller differences observed between open and closed windows, both during window position tests and between morning (closed windows) and afternoon (open windows) commutes could be attributed to the role of NO_2 as both a primary and secondary air pollutant. However, as with black carbon and PB-PAH, higher concentrations were observed on urban routes compared with the RS route, for the same reasons stated above.

Differences between buses for pollutants associated with diesel exhaust were greatest when the windows were closed. With closed windows, concentrations of diesel-related pollutants such as BC, PB-PAH and NO_2 were consistently several times higher on board conventional diesel buses compared to the CNG bus. Results for the trap-outfitted diesel bus were generally in between the conventional diesel buses and the CNG bus, although diesel-related pollutant concentrations on board our specific trap-outfitted bus appeared to be higher than expected, based on emission data reported for other trap-equipped diesel vehicles (Johnson, 2001). Differences between buses with windows closed were at least in part due to self-pollution, as demonstrated by on-board measurements of SF_6, added to each bus's exhaust (Behrentz et al., 2004a). Self-pollution was detected in all buses, with higher rates for older buses. With windows open, rapid ventilation strongly reduced the importance of self-pollution, while the influence of roadway concentrations and nearby diesel vehicles became more pronounced.

For air toxics, such as benzene and formaldehyde, opening the windows significantly lowered concentrations inside the cabin, and reduced differences observed between buses. With closed windows, formaldehyde concentrations were highest inside the CNG bus, consistent with reports of higher emissions of formaldehyde from CNG buses (Ayala et al., 2002). Differences between buses were less distinct for benzene; however, higher concentrations were observed on urban routes compared with the RS route even with the windows open, consistent with higher roadway concentrations due to congested traffic conditions on urban routes.

For $PM_{2.5}$, which has both primary emission sources and substantial secondary formation, closing the windows yielded slightly lower mean concentrations inside the cabin, and fewer high-peak concentrations, although the differences between open and closed windows were generally small. Greater differences were seen between routes, likely due to changing regional background concentrations on different days and the location of the routes. In particular, the relatively high concentrations of $PM_{2.5}$ observed on the RS route, which had little or no traffic during most of the commute, could be attributed to the location of this route in a downwind ''receptor'' area for secondary aerosol formation in the Los Angeles air basin (Hughes et al., 2000).

Comparison to Near-roadway and Ambient Concentrations

Zhu et al. (2002b) measured roadside concentrations of BC along the I-405 in LA, the same freeway traveled during bus commutes on U1 in our study, and found a mean concentration of $5.4\,\mu g/m^3$ next to the freeway, which reduced to $1.3\,\mu g/m^3$ at a site 300 m downwind of the freeway. The 300 m downwind concentration is comparable to the mean ambient BC concentrations we measured near either end of U1 of $1.3–2.9\,\mu g/m^3$. Mean bus cabin concentrations of BC, PB-PAH, NO_2, benzene and formaldehyde on U1 were higher by factors of 2–5 compared with our measurements of nearby ambient concentrations.

Based on these results, we estimate that school bus commutes may contribute more than 30% of a child's exposure to BC and other diesel-related pollutants over a 24-h school day even though the commute represents only about 13% of the day for the longest commute (Behrentz et al., 2004b).

Comparison to Other Studies

The upper end of the range (2.5–19 $\mu g/m^3$) of mean black carbon concentrations measured inside school bus cabins in this study was higher than that reported for other recent school bus studies. Solomon et al. (2001) measured mean concentrations of black carbon inside diesel school buses in LA of approximately 4–10 $\mu g/m^3$, and background concentrations of 2–3 $\mu g/m^3$ (comparable to our ambient measurements of 1–3 $\mu g/m^3$). Wargo et al. (2002) measured black carbon inside diesel school buses in rural Connecticut, and reported mean bus cabin concentrations of approximately 4–9 $\mu g/m^3$ when the windows were closed, while peak concentrations as high as 30 $\mu g/m^3$ were observed when the windows were open. The generally lower mean concentrations observed in these other studies were likely because the bus routes were predominantly low density suburban (Solomon et al., 2001) or rural (Wargo et al., 2002), with reduced traffic congestion, fewer encounters with other diesel vehicles and reduced idling time compared with the often highly congested urban bus routes in the present study.

Rodes et al. (1998) measured pollutant concentrations inside gasoline passenger cars following diesel vehicles in LA and found commute mean concentrations for benzene and formaldehyde of 10–22 $\mu g/m^3$, and below detection to 22 $\mu g/m^3$, respectively. These concentrations were generally higher than our school bus cabin concentrations, in part due to the emphasis on closely following diesel vehicles in the Rodes et al. (1998) chase car study, but also because in LA, as the result of reformulated gasoline and increasingly stringent exhaust and evaporative emission standards for passenger cars, ambient benzene concentrations (and to a lesser extent, formaldehyde concentrations) have decreased since 1997, when the Rodes study was conducted (CARB, 2004).

Fruin et al. (2004) reported mean BC concentrations inside gasoline passenger cars during commutes in LA of 5.9 $\mu g/m^3$, adjusted for representative driving, based on the Rodes et al. (1998) data, which were measured on portions of the same roadways as in the present study. We observed similar BC concentrations inside the school buses on urban routes during commutes with windows open (mean for all buses was 5.2 and 6.0 $\mu g/m^3$ for U1 and U2, respectively). However, when the windows were closed, mean concentrations inside the buses on these routes doubled. Moreover, BC concentrations for diesel bus commutes with windows closed were as high as 19 $\mu g/m^3$. This indicates children riding in diesel school buses with closed windows may be exposed to 2–3 times more BC (and other diesel-related pollutants) than commuters driving in passenger vehicles on the same roadways.

Conclusions

Our study clearly demonstrates that children commuting in congested urban areas such as LA may be exposed to much higher concentrations of vehicle-related pollutants inside school bus cabins than ambient air concentrations measured by central-site monitoring. Two specific types of high exposures to vehicle-related pollutants occurred during our school bus commutes, primarily depending on the position of the windows. Concentrations of BC and PB-PAH exceeding 50 $\mu g/m^3$ and 2000 ng/m^3, respectively, were observed when the bus windows were open, although these high exposures were transient, resulting from intrusion of exhaust plumes from nearby diesel vehicles or the bus itself. The second type of high exposure occurred during commutes with windows closed, and resulted in elevated mean concentrations for the duration of the commute, due to roadway concentrations, reduced ventilation, and build-up of the bus's own exhaust inside the cabin. The two buses with the highest percent of their own exhaust inside the cabin when the windows were closed were the older, high emitting buses (HE2 and HE3). These buses also had the highest mean PB-PAH, BC and NO_2 concentrations, 400 ng/m^3 (HE2), 19 $\mu g/m^3$ (HE3) and 207 $\mu g/m^3$ (HE3), respectively, indicating the importance of self-pollution with windows closed.

We emphasize that bus-to-bus variability was relatively high and therefore with the small number of buses studied, and the limited number of routes covered, the findings of this study should not be viewed as inherently typical for all school buses under all conditions. However, minimizing commute times, using the cleanest buses for the longest bus routes, and reducing bus caravanning and unnecessary idling time would clearly reduce children's exposure to bus-related pollutants and we strongly recommend school districts adopt these policies.

Acknowledgments

We gratefully acknowledge support for this research from the ARB, Contract No. 00-322, and the SCAQMD and US EPA. The statements and conclusions in this document are those of the authors and not necessarily those of these agencies. We appreciate the cooperation of the Brentwood Science Magnet School and the LAUSD. We wish to acknowledge valuable technical support from Kurt Bumiller and Matt Smith of CE-CERT, UC Riverside. We thank our bus driver, Shonna Pierce, and Kenneth Wong and Kathleen Kozawa from the Department of Environmental Health Sciences for their contributions.

References

Alm S., Jantunen M.J., and Vartiainen M. Urban commuter exposure to particle matter and carbon monoxide inside an automobile. *J Exp Anal Environ Epidemiol* 1999: 9: 237–244.

Ayala A.N., Kado R., Okamoto M., Rieger P., Holmen B.A., and Stiglitz K. ARB's study of emission from two "late-model" diesel and CNG heavy-duty transit buses. 12th CRC On-Road Vehicle Emissions Workshop, April 15–17, 2002, San Diego.

Batterman S.A., Peng C.-Y., and Braun J. Levels and composition of volatile organic compounds on commuting routes in Detroit, Michigan. *Atmos Environ* 2002: 36: 6015–6030.

Behrentz E., Fitz D.R., Pankratz D., Sabin L.D., Colome S.D., Fruin S.A., and Winer A.M. Measuring self pollution in school buses using a tracer gas technique. *Atmos Environ* 2004a: 38: 3735–3746.

Behrentz E., Sabin L.D., Winer A.M., Colome S.D., Fitz D.R., Pankratz D.V., and Fruin S.A. Relative importance of school bus-related microenvironments to children's pollutant exposure. *J Air Waste Manage Assoc* 2004b, in press.

Benner B.A., Gordon G.E., and Wise S.A. Mobile sources of atmospheric polycyclic aromatic hydrocarbons: a roadway tunnel study. *Environ Sci Technol* 1989: 23: 1269–1278.

California Air Resources Board (CARB). *The 2004 California Almanac of Emissions and Air Quality*. Air Quality Data Branch: Sacramento, CA, 2004.

Chung A., Chang D.P.Y., Kleeman M.J., Perry K.D., Cahill T.A., Duther D., McDougall E.M., and Stroud K. Comparison of real-time instruments used to monitor airborne particulate matter. *J Air Waste Manage Assoc* 2001: 51: 109–120.

Finlayson-Pitts B.J., and Pitts J.N. *Chemistry of the Upper and Lower Atmosphere*. Academic Press, San Diego, CA, 2000, pp. 4–7, 17–18.

Fitz D.R., Pankratz D.V., Bumiller K., and Smith M.R. Measurement of NO_2 and PAN by gas chromatography with luminol detection. Air and Waste Management Association Symposium on Air Quality Measurement Methods and Technology. San Francisco, CA, November 13–15, 2002.

Fitz D., Winer A.M., Colome S., Behrentz E., Sabin L.D., Jeong S., Wong K., Kozawa K., Pankratz D., Bumiller K., Gemmill D., and Smith M. Characterizing the Range of Children's Pollutant Exposure During School Bus Commutes, Final Report. Contract No. 00-322. California Air Resources Board, Research Division, Sacramento, CA, 2003.

Fung K., and Grosjean D. Determination of nanogram amounts of carbonyls as 2,4-dinitrophenylhydrazones by high performance liquid chromatography. *Anal Chem* 1981: 53: 168–171.

Fung K., and Wright B. Measurement of formaldehyde and acetaldehyde using 2,4-dinitrophenylhydrazine-impregnated cartridges during the carbonaceous species methods comparison study. *Aero Sci Technol* 1990: 12: 44–48.

Fruin S.A., Winer A.M., and Rodes C.E. Black carbon concentrations in California vehicles and estimation of in-vehicle diesel exhaust particulate matter exposures. *Atmos Environ* 2004: 38: 4123–4133.

Hughes L.S., Allen J.O., Bhave P., Kleeman M.J., and Cass G.R. Evolution of atmospheric particles along trajectories crossing the Los Angeles Basin. *Environ Sci Technol* 2000: 34: 3058–3068.

Johnson T.V. Diesel emission control in review. SAE Technical paper No. 2001-01-0184, 2001.

Kirchstetter T.W., and Harley R.A. Impact of Reformulated Fuel on Particle and Gas-Phase Emissions from Motor Vehicles. Final Report. Contract No. 00-322. California Air Resources Board, Research Division, Sacramento, CA, 1999.

Lawryk N.J., and Weisel C.P. Exposure to volatile organic compounds in the passenger compartment of automobiles during periods of normal and malfunctioning operation. *J Exp Anal Environ Epidemiol* 1995: 5: 511–531.

Lawson D.R., Biermann H.W., Tuazon E.C., Winer A.M., Mackay G.I., Schiff H.I., Kok G.L., Dasgupta P.D., and Fung K. Formaldehyde measurement methods evaluation and ambient concentrations during the carbonaceous species methods comparison study. *Aero Sci Technol* 1990: 12: 64–76.

Lipsett M The Hazards of Air Pollution to Children. In: Brooks S. et al. (Eds). *Environmental Medicine.*. Mosby: St. Louis, MO, 1989.

Ptak T.J., and Fallon S.L. Particulate concentration in automobile passenger compartments. *Particulate Sci Technol* 1994: 12: 313–322.

Ramachandran G., Adgate J.L., Hill N., Sexton K., Pratt G.C., and Bock D. Comparison of short-term variations (15-minute averages) in outdoor and indoor PM2.5 concentrations. *J Air Waste Manage Assoc* 2000: 50: 1157–1166.

Rodes C., Sheldon L., Whitaker D., Clayton A., Fitzgerald K., Flanagan J., DiGenova F., Hering S., and Frazier C. Measuring Concentrations of Selected Air Pollutants Inside California Vehicles. Final Report. Contract No. 95-339. California Air Resources Research Division Board, Sacramento, CA, 1998.

Shikiya D.C., Liu C.S., Hahn M.I., Juarros J., and Barcikowski W. In-Vehicle Air Toxics Characterization Study in the South Coast Air Basin. Final Report. South Coast Air Quality Management District, El Monte, CA, 1989.

Solomon G.M., Campbell T.R., Feuer G.R., Masters J., Samkian A., and Paul K.A. *No Breathing in the Aisles: Diesel Exhaust Inside School Buses*. Natural Resources Defense Council and Coalition for Clean Air, New York, NY, 2001.

Turner W.A., Olson B.A., and Allen G.A. Calibration of sharp cut impactors for indoor and outdoor particle sampling. *J Air Waste Manage Assoc* 2000: 50: 484–487.

U.S. Environmental Protection Agency (US EPA). Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air. Document EPA-600/4-89-017, 1989.

Venkataraman C., Lyons J.M., and Friedlander S.K. Size distributions of polycyclic aromatic hydrocarbons and elemental carbon. 2. Ambient measurements and effects of atmospheric processes. *Environ Sci Technol* 1994: 28: 563–572.

Wargo J., Brown D., Cullen M., Addiss S., and Alderman N. *Children's Exposure to Diesel Exhaust on School Buses*. Environmental and Human Health, Inc., North Haven, CT, 2002.

Wiley J.A., Robinson J.P., Cheng Y.T., Piazza T., Stork L., and Plasden K. Study of Children's Activity Patterns. Contract No. A. 773-149. California Air Resources Board, Research Division, Sacramento, CA, 1991.

Yanosky J.D., Williams P.L., and Macintosh D.L. A comparison of two direct-reading aerosol monitors with the Federal Reference Method for PM2.5 in indoor air. *Atmos Environ* 2002: 36: 107–113.

Zhu Y., Hinds W.C., Kim S., Shen S., and Sioutas C. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmos Environ* 2002a: 36: 4323–4335.

Zhu Y., Hinds W.C., Kim S., and Sioutas C. Concentration and size distribution of ultrafine particles near a major highway. *J Air Waste Manage Assoc* 2002b: 52: 1032–1042.