Vehicle Self-Pollution Intake Fraction: Children's Exposure to School Bus Emissions

JULIAN D. MARSHALL*,† AND EDUARDO BEHRENTZ‡

Energy and Resources Group, University of California, Berkeley, California 94720-3050, and Environmental Science and Engineering Program, School of Public Health, University of California, Los Angeles, California 90095-1772

Vehicle self-pollution occurs when a vehicle's emissions migrate to inside that vehicle's passenger compartment. This paper presents values for two new parameters: vehicle self-pollution intake fraction (iF_{SP}), which is the total fraction of a vehicle's emissions inhaled by all people in the vehicle, and vehicle self-pollution individual intake fraction ($iF_{i,SP}$), which is the fraction of a vehicle's emissions inhaled by an individual in the vehicle. We use results from tracer-gas experiments in California's South Coast Air Basin (SoCAB) to quantify students' iF_{SP} and $iF_{i,SP}$ for school bus emissions. Six buses were studied during nine runs with windows open and seven runs with windows closed. Reported iF_{SP} values (units: per million; min = 10, max = 94, mean = 27) indicate that the total mass of a bus' exhaust inhaled by students commuting on it is comparable in magnitude to the total mass of that bus' exhaust inhaled by all other people in the SoCAB. Reported $iF_{i,SP}$ values (units: per million; min = 0.2, max = 2.4, mean = 0.7) indicate that average per capita inhalation of emissions from any single bus is 10^5–10^6 times greater for a student on that school bus than for a typical resident in the SoCAB. Vehicle self-pollution rate varies with bus window position (open or closed) and bus manufacture year. Our results can be used to develop cost-effective strategies to reduce children's exposure to school bus emissions. Our results indicate, for example, that even if emission reductions were many times more expensive per gram emitted for school buses than for an average vehicle, it would still be less expensive per gram inhaled by a student to reduce emissions from school buses than from an average vehicle.

Introduction

Vehicle emissions are a significant contributor to urban air pollution. Vehicle pollutants believed to cause adverse health impacts include diesel particulate matter (DPM), which include ultrafine particles; criteria pollutants such as NO_2 and carbon monoxide; and organic compounds such as benzene and butadiene (*1*−*5*). DPM has been estimated to cause a majority of the ambient air pollution cancer risk in the South Coast Air Basin (*6*). An important objective of air quality regulations is to reduce exposures, especially for sensitive subpopulations. Children are believed to be especially susceptible to air pollution because of their high inhalation rates and lung surface area per body weight, narrow lung airways, low lung clearance rates, and immature immune systems (*7*−*10*).

Concentrations of vehicle pollutants are higher in and near vehicles than at centrally located monitors (*11*−*15*). It is often assumed that proximity to other vehicles is the reason for elevated in-vehicle concentrations (*14*). Recent work confirms that pollution from other vehicles is important on school buses, especially in explaining short-term variability in on-board concentrations (e.g., particle concentrations increase after passing a diesel truck with visible emissions) (*16*). However, a fraction of the pollution inside a school bus is attributable to the bus itself. This paper investigates this type of pollution, which we term vehicle "self-pollution", for students commuting on a school bus in California's South Coast Air Basin (SoCAB). As a major form of children's transportation, school bus emissions represent a potentially important source of children's exposure to vehicle pollutants.

Intake fraction summarizes the emission-to-inhalation relationship for a specific emission source, pollutant, and population. Intake fraction is the ratio of total attributable intake to total emissions (*17*). Using results from tracer-gas experiments (*18*, *19*), we estimate the fraction of emissions inhaled by the exposed population (the intake fraction, iF) and by an average individual (the average individual intake fraction, iF_i). This information can aid in designing effective exposure reduction strategies.

Methods

Tracer-Gas Experiment. Tracer-gas experiments were performed on six buses while traveling on an in-use school bus route that covered highly urbanized areas of south-central Los Angeles and suburban areas of west Los Angeles. Measurements were made during seven runs with closed windows and nine runs with open windows in April, May, and June, 2002. Table 1 summarizes the characteristics of these runs. Experimental methods are described elsewhere (*18*, *19*). In each bus run, a mass flow controller metered delivery of a tracer gas, sulfur hexafluoride (SF_6), from a high-concentration cylinder into the bus' exhaust system. On-board SF_6 concentrations were measured at two locations (front and rear) with an electron capture detection analyzer (ECDA) (AeroVironment Model CTA 1000). Model years of the buses are 1975, 1985, 1993, 1998 (two buses), and 2002. These buses included two older (year-1975 and -1985) high-emitting diesel buses, two diesel buses more representative of current fleets, one particle trap-outfitted diesel bus, and one bus powered by compressed natural gas.

Intake Fraction. Intake is the mass of a pollutant that is taken in by an exposed individual or population. For inhalation of air pollution, intake rate (g min^{-1}) is the product of breathing rate (L min^{-1}) and exposure concentration (g L^{-1}). Alternatively, intake rate can be calculated as the product of the emission rate (g emitted per minute) for a specific source and the relevant intake fraction (g inhaled per g emitted) for that source.

We calculate intake fraction for school bus self-pollution, iF_{SP}, using eq 1:

$$iF_{SP} = \frac{Q_B P C}{E} \quad (1)$$

Here, Q_B is the average breathing rate (L person^{-1} min^{-1}), P is the average number of people on a school bus, C is the temporally and spatially averaged on-board SF_6 concentration

* Corresponding author phone: (510)643-7056; fax: (510)642-1085; e-mail: julian@berkeley.edu.

† Energy and Resources Group, University of California.

‡ School of Public Health, University of California.

10.1021/es040377v CCC: $30.25
Published on Web 03/16/2005

TABLE 1. Self-Pollution Intake Fraction and Individual Intake Fraction Results[a]

model year	window position	bus designation	S, front (10^{-9} min L^{-1})	S, rear (10^{-9} min L^{-1})	iF_{SP} (per million)	$iF_{i,sp}$ (per million)
1975	open	high	76	82	46	1.2
1975	closed	high	100	220	94	2.4
1985	open	high	18	28	13	0.33
1985	closed	high	70	100	50	1.3
1993	open	regular	47	8	16	0.40
1993	open	regular	23	22	13	0.33
1993	closed	regular	19	28	14	0.34
1993	closed	regular	14	21	10	0.25
1998	open	regular	83	102	54	1.4
1998	open	regular	17	35	15	0.38
1998	open	trap-outfitted	14	20	10	0.25
1998	open	trap-outfitted	29	27	16	0.41
1998	closed	trap-outfitted	35	44	23	0.58
1998	closed	trap-outfitted	31	35	19	0.48
2002	open	CNG	25	23	14	0.35
2002	closed	CNG	25	41	19	0.48
		average	39	52	27	0.67

[a] High = high emitter diesel school buses; regular = representative diesel school buses; trap-outfitted = particle-trap outfitted diesel school bus; CNG = compressed natural gas school bus; S = self-pollution term, calculated using eq 2 as the ratio of the on-board SF_6 concentration (g L^{-1}) to the SF_6 emission rate (g min^{-1}); iF_{SP} = self-pollution intake fraction; $iF_{i,SP}$ = average self-pollution individual intake fraction. The intake fraction values assume an average population of 40 people on each bus and an average breathing rate of 15 L min^{-1} and are based on the average value of S between front and rear.

during a bus run (g L^{-1}), and E is the experimental SF_6 mass emission rate into the bus' exhaust during a bus run (g min^{-1}).

The variables in eq 1 can be grouped into two terms. The first term, Q_BP (L min^{-1}), is the subpopulation breathing rate. The second term, C/E (min L^{-1}), indicates the magnitude of self-pollution, as measured by a tracer gas. We define a self-pollution term, S, as C/E, which is proportional to the mass fraction of emissions that enter the bus (M_f):

$$S = \frac{C}{E} = \frac{M_f \tau}{V} \qquad (2)$$

Here, V is the interior volume of the bus (L), and τ is the mean residence time of air inside the bus (min). The residence time of air inside the bus depends on the rate of air exchange between inside and outside air, which depends on factors such as the window position (opened or closed), vehicle speed, and wind speed (*18*, *20*).

Values for the self-pollution term, S, were calculated from reported tracer-gas experiments for school bus commutes (*18*), as given in Table 1. Concentrations, C, are measured using the ECDA. The SF_6 mass emission rates, E, are calculated as the product of the concentration of SF_6 in the high pressure SF_6 gas cylinder (g L^{-1}) and the flow rate of gas from the cylinder to the bus' exhaust (L min^{-1}). Data on breathing rate and number of passengers are not available for students on a school bus. On the basis of children's metabolic rates at rest and at light activity levels (*21*), we estimate that children's average breathing rate on a school bus is between 7 and 22 L min^{-1}. Our middle estimate, used in the analyses below, is the average of these two values (15 L min^{-1}). We estimate the average number of children on a school bus is 40 and in the range 20−50. The middle estimate equals the number of public school students transported by buses in California during the 2000−2001 school year (964 815 students) divided by the number of buses available (24 497 buses) (*22*).

Results

Table 1 summarizes the SF_6 measurement results and the calculated intake fractions for each bus run (i.e., each row represents a single tracer-gas experiment). Self-pollution is substantial for all six buses.

Bus age and window position affect the magnitude of self-pollution, with older buses and close-windowed buses having higher self-pollution levels. On average, S values are ~2 times higher with windows closed than with windows open. The importance of window position increases with bus age: the difference between open and closed windows is ~20% for the newer buses and a factor of ~3 for the older buses. Also, the importance of bus age increases when windows are closed: the difference in average S value between the oldest (model year 1975) and the newer buses (model year 1993 and later) is a factor of ~2 with windows open and a factor of ~6 with windows closed.

Total intake for school bus emissions has two components: intake by passengers (self-pollution) and intake by all other people (excluding self-pollution). Similarly, intake fraction (iF) is equal to self-pollution intake fraction (iF_{SP}) plus intake fraction excluding self-pollution (iF_{non-SP}). These two components (iF_{SP} and iF_{non-SP}) are presented separately in Figure 1. Values for iF_{SP} are estimated from the tracer-gas experiments (*18*, *19*) analyzed in this work. Values for iF_{non-SP} for primary, nonreactive pollutants are estimated as the fleet-wide average intake fraction for motor vehicle emissions of carbon monoxide in the South Coast Air Basin (46 per million) (*23*). This value accounts for spatial variability in population density and ambient concentrations, temporal variability in concentrations and breathing rates, and microenvironments such as in- and near-vehicles and indoors near a freeway.

Self-pollution intake fraction is estimated in this work from ~90-min tracer-gas experiments, while the estimate of non-self-pollution intake fraction is based on annual exposures in the South Coast. Results from these two methods can be compared because both analyses are independent of exposure duration, which is true for two reasons. First, the periods analyzed are much longer than the residence times of air in the respective environments (i.e., the tracer-gas experiments were performed for much longer than the residence time of air in a bus (*18*), and the South Coast analysis considered a much longer time period than the residence time of air in an air basin (*23*)). Second, in this work, we do not analyze temporal variability in self-pollution intake fraction (i.e., when using eq 1, we incorporate average, rather than time-varying, values for the parameters).

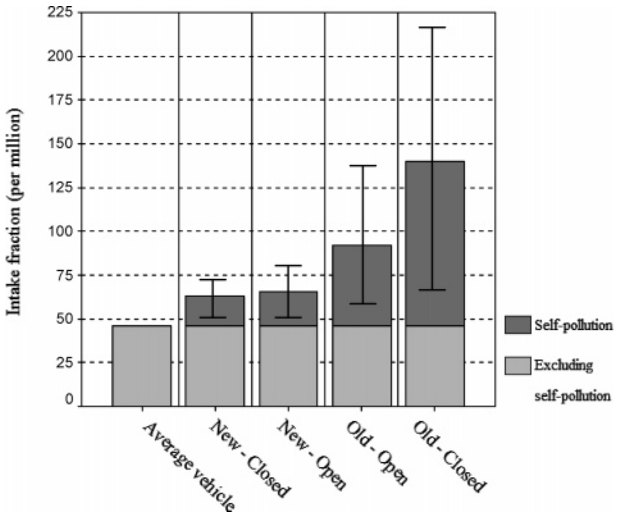

FIGURE 1. Intake fraction for an average vehicle and for school buses in the South Coast Air Basin. Intake fraction is the sum of self-pollution intake fraction and non-self-pollution intake fraction. *X*-axis category labels refer to the buses model year ("new" means 1993 or later; "old" means 1985 or earlier) and the window position (open or closed). The error bars indicate uncertainty in the self-pollution term, owing to uncertainty in the breathing rate and in the number of people on the bus and assuming that uncertainty in these two parameters align to yield the maximum possible uncertainty. These values indicate that if vehicle emissions in the South Coast are reduced by a certain amount, the reduction in the population inhalation intake will be 40−200% greater if the emission reductions come from a school bus than if they come from a typical vehicle.

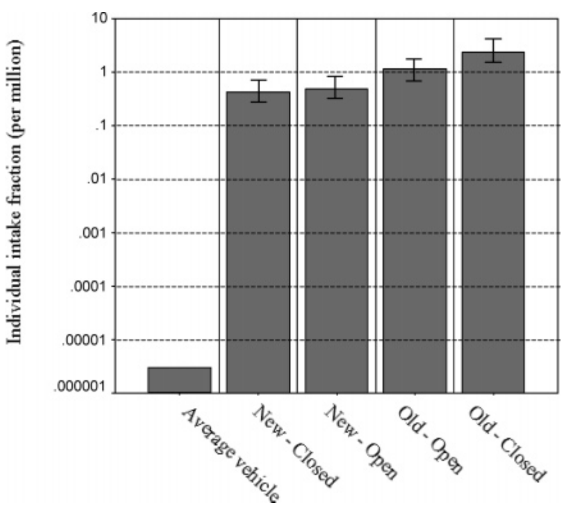

FIGURE 2. Individual intake fraction. The first value is for a typical person's inhalation of emissions from an average vehicle in the South Coast Air Basin. The remaining values are for a student's inhalation of emissions from the school bus on which they commute. Note the log scale. Error bars and *X*-axis labels are analogous to Figure 1. These values indicate that if vehicle emissions in the South Coast are reduced by a certain amount, the reduction in a school child's inhalation intake will be 10^5−10^6 times greater if the emission reductions come from that child's school bus than if they come from a typical vehicle.

Figure 1 and 2 depict intake fraction and average individual intake fraction for primary conserved pollutants (e.g., DPM and benzene). For these figures, results in Table 1 were grouped based on similar values for the self-pollution term. The two groups are the four newer buses (years 1993, 1998 (two buses), and 2002) and the two older buses (years 1975 and 1985). Average values across all bus runs are 27 per million for school bus self-pollution intake fraction (iF_{SP}), 73 per million for school bus intake fraction (iF, which equals $iF_{SP} + iF_{non\text{-}SP}$), and 0.7 per million for school bus self-pollution individual intake fraction ($iF_{i,SP}$).

Figures 1 and 2 use the arithmetic mean of front and rear S values for the newer buses and for the oldest bus. Error bars assume that uncertainty in the average number of students on a school bus (P) and in students' average breathing rate (Q_B) align to yield the maximum uncertainty in intake fraction and individual intake fraction. The iF values in Figure 1 indicate that for every million grams of a primary conserved pollutant emitted by a school bus, a total of ~46 g are inhaled by the ~15 million people in the South Coast Air Basin who are not riding that bus, and that the passengers inhale an additional 10−54 g for a newer school bus and 13−94 g for an older school bus.

Average individual intake fraction, shown in Figure 2, is calculated as intake fraction divided by the number of people exposed. The left-most bar represents a typical person's exposure to emissions from an average vehicle in the South Coast Air Basin. The remaining values are for a student's exposure to emissions from the school bus on which they commute. For example, for every million grams of a primary, conserved pollutant emitted by an old bus with closed windows, ~2 g are inhaled by the average person on that bus, and $\sim 2 \times 10^{-6}$ g are inhaled by the average person who is not riding on that bus. The difference in intake fraction among the cases in Figure 1 (iF_{SP} for a newer and older bus and iF_{non-SP}) is less than 1 order of magnitude, but the size of the exposed population varies by more than 5 orders of magnitude (~40 people for self-pollution, and ~15 million people for non-self-pollution). Therefore, the difference in individual intake fraction values between self-pollution and non-self-pollution is between 5 and 6 orders of magnitude. That is, the emission-to-individual-intake ratio is 10^5−10^6 times greater for children inhaling their own school bus's emissions than for the average South Coast resident inhaling emissions from a single average school bus.

To use the results in Figures 1 and 2 when estimating the average exposure concentration or the total daily inhalation intake rate attributable to buses and to nonbus vehicles, one would need to incorporate total emissions. Several factors influence vehicle emissions, including engine technology, fuel composition, driving conditions, vehicle size and load, and distance traveled. Because total bus vehicle miles traveled (VMT) represent a small fraction of the total fleet VMT, total pollutant emission rates (kg d^{-1}) are much larger from nonbuses than from buses (*24*).

Discussion

Self-Pollution Intake. The relationship between reductions in emissions and reductions in a child's intake varies significantly among sources. For example, reducing annual DPM emissions by 1 tonne would reduce an average exposed child's annual intake of DPM by 3 μg if the reduction comes from ambient emissions from a typical diesel vehicle, by 470 mg if the reduction comes from the child's school bus if he rides a newer bus, or by 1−2 g if the reduction comes from the child's school bus if he rides an older bus. Because of self-pollution, school buses are more effective than an average vehicle at delivering emissions to children's lungs. Reducing an exposed child's intake by a specific amount would require 5 to 6 orders of magnitude greater emission reductions if control strategies target typical diesel vehicles (e.g., heavy-duty diesel trucks) than if strategies target self-pollution from that child's school bus.

Policy Implications. A main task of air pollution management is to prioritize which emissions should be reduced and by which quantities. Policy makers should prioritize reductions of toxic emissions on the basis of the cost per gram inhaled, rather than per gram emitted, because intake is a better proxy than emissions for attributable health impacts.

A cost-benefit or cost-effectiveness analysis would include both a health risk assessment and the costs of controlling various vehicle emissions sources (*25*). However, on the basis of the individual intake fraction for school children (Figure 2), even if emission reductions were many times more expensive per gram *emitted* for school buses than for an average vehicle, it would still be less expensive per gram *inhaled* by a student to reduce emissions from school buses than from an average vehicle.

Control Strategies. The school bus microenvironment contributes significantly to children's estimated total inhalation intake of DPM. Approximately 90% of school bus fuel consumption is diesel (*26*). On commute days, for newer and year-1975 buses, students commuting on school buses have 34% and 70% higher intakes of DPM than car commuters, respectively (*27*). The daily inhalation intake by a child of emissions from the one school bus on which he or she commutes is between ∼7 and ∼70 times greater than the average daily inhalation intake by a typical South Coast resident of emissions from all school buses.

Both emissions and self-pollution intake fraction are higher for old buses than for new buses. The difference between newer (model year 1993 and later) and older buses (model years 1975 and 1985), for windows closed, is a factor of ∼2 for average *iF* values (63 per million versus 140 per million) and ∼5 for average iF_{SP} values (17 per million versus 94 per million). The emission factor difference between newer and older buses, according to EPA's MOBILE6 emission model, is approximately a factor of 10 (*28*). The correlation between vehicle age, vehicle emissions, and both *iF* and iF_{SP} suggests that older buses are a higher emission reduction priority than newer buses. Furthermore, even if emissions from older buses were the same as emissions from newer buses, self-pollution intake would be higher on older buses than on newer buses because of the higher iF_{SP} values.

Inhalation intake equals emissions times intake fraction. Intake control strategies should aim to reduce both emissions and intake fractions. Intake fraction can be reduced, for example, by decreasing the use of older school buses and by decoupling the exhaust flow from air flowing into the bus. Improved understanding of self-pollution mechanisms may suggest additional exposure control strategies. Opening windows, which reduces τ, may reduce self-pollution but increase on-board concentrations attributable to other vehicles.

It is important to identify the mechanism of self-pollution (*29*). Many emission control technologies are end-of-tailpipe. If the dominant mechanism for self-pollution transport is post-tailpipe, then end-of-tailpipe technologies will reduce all attributable exposures, including self-pollution. However, if the dominant mechanism for self-pollution occurs before emissions exit the tailpipe, then end-of-tailpipe technologies will reduce all attributable exposures *except* self-pollution.

Variability and Uncertainty. Relative to other urban areas in the United States, the South Coast Air Basin has a large population size (15 million people) and generally unfavorable atmospheric mixing and pollutant transport conditions (*30*). Annual average iF_{non-SP} for vehicle emissions is typically less than 46 per million in U.S. urban areas. For example, Evans et al. (*31*) reported values in the range 3−18 per million for primary $PM_{2.5}$, and Marshall et al. (*32*) estimated that the mean value among urban areas is in the range 7−21 per million for nonreactive pollutants. Thus, the average self-pollution intake fraction among all bus runs in this study (27 per million) is comparable to, or larger than, non-self-pollution intake fraction for nonreactive vehicle emissions in a typical U.S. urban area. Stated differently, when considering two groups in a typical U.S. urban area—students who ride a school bus and everyone else—the total mass of bus pollution inhaled by bus riders likely exceeds the total bus pollution inhaled by the remaining public, despite bus riders being a relatively small group.

Self-pollution intake fraction will vary on the basis of factors such as the window position, bus speed, wind speed and direction, and the bus' shape and structural integrity. The results presented in this work are averages over the conditions tested. Given the small sample size in the original tracer-gas study (6 buses, 16 runs), our results are not necessarily representative of the entire bus fleet. Additional research is needed to refine and extend our results, for example, by employing additional buses, bus types, and operating conditions.

Variability and uncertainty in breathing rate and number of students on a school bus affect our numeric results but not the conclusions we draw from these results. Uncertainty and variability in SF_6 emission rates and on-board concentrations do not affect our results significantly (*18*, *27*).

Acknowledgments

This work was supported in part by the University of California Toxic Substances Research and Teaching Program and the University of California Transportation Center. The authors thank Professors Arthur M. Winer and William W. Nazaroff for comments on an earlier draft of the manuscript. The primary data for this research was obtained by Fitz et al. (*18*) from a study sponsored by the California Air Resources Board under Contract No. 00-322. David Pankratz provided technical support during the tracer gas experiments.

Literature Cited

(1) *Motor Vehicle-Related Air Toxics Study*; EPA 420-R-93-005. U.S. Environmental Protection Agency: Washington, DC, 1993; available from http://www.epa.gov/otaq/toxics.htm.

(2) Lloyd, A. C.; Cackette, T. A. Diesel engines: environmental impact and control. *J. Air Waste Manage. Assoc.* **2001**, *51*, 809−847.

(3) Pope, C. A.; Burnett, R. T.; Thun, M. J.; Calle, E. E.; Krewski, D.; Ito, K.; Thurston, G. D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA, J. Am. Med. Assoc.* **2002**, *287*, 1132−1141.

(4) *National Air Toxics Assessment*; U.S Environmental Protection Agency: Washington, DC, 2002; available from http://www.epa.gov/ttn/atw/nata.

(5) Weinhold, B. Fuel for the long haul? Diesel in America. (Accessed Feb 17, 2005) *Environ. Health Perspect.* **2002**, *110*, A458−A464.

(6) *Multiple Air Toxics Exposure Study (MATES - II)*; South Coast Air Quality Management District: Diamond Bar, CA, 1999; available from http://www.aqmd.gov/matesiidf/matestoc.htm.

(7) Dockery, D.; Speizer, F.; Stramn, D.; Ware, J.; Spengler, J.; Ferris, B. G. Effects of inhalable particles on respiratory health of children. *Am. Rev. Respir. Dis.* **1989**, *139*, 587−594.

(8) Lipsett, M. The Hazards of Air Pollution to Children. In *Environmental Medicine*; Brooks, S. M., Gochfeld, M., Herzstein, J., Schenker, M., Eds.; Mosby: St. Louis, MO, 1995.

(9) Thurston, G. D. *Particulate Matter and Sulfate: Evaluation of Current California Air Quality Standards with Respect to Protection of Children*; New York School of Medicine, 2000; available from http://www.arb.ca.gov/ch/ceh/001207/pmsul.PDF (accessed Feb 17, 2005).

(10) *Public Hearing to Consider Amendments to the Ambient Air Quality Standards for Particulate Matter and Sulfates*; California Air Resources Board: Sacramento, CA, 2002; available from http://www.arb.ca.gov/research/aags/std-rs/pm-final/pm-final.htm.

(11) Wallace, L. A. Personal exposure to 25 volatile organic compounds: EPA's 1987 TEAM study in Los-Angeles, California. *Toxicol. Indus. Health* **1991**, *7*, 203−208.

(12) Flachsbart, P. G. Long-term trends in United States highway emissions, ambient concentrations, and in-vehicle exposure to carbon monoxide in traffic. *J. Expos. Anal. Environ. Epidem.* **1995**, *5*, 473−495.

(13) Wallace, L. A. Environmental exposure to benzene: an update. *Environ. Health Perspect.* **1996**, *104*, 1129−1136.
(14) Rodes, C.; Sheldon, L.; Whitaker, D.; Clayton, A.; Fitzgerald, K.; Flanagan, J.; DiGenova, F.; Hering, S.; Frazier, C. *Measuring Concentrations of Selected Air Pollutants inside California Vehicles*; Research Triangle Institute: Research Triangle Park, NC, 1998; available from http://www.arb.ca.gov/research/abstracts/95-339.htm.
(15) Gulliver, J.; Briggs, D. J. Personal exposure to particulate air pollution in transport microenvironments. *Atmos. Environ.* **2004**, *38*, 1−8.
(16) Sabin, L. D.; Behrentz, E.; Winer, A. M.; Lee, S. J.; Fitz, D. R.; Pankratz, D.; Colome., S. D.; Fruin, S. Characterizing the range of children's air pollutant exposure during school bus commutes. *J. Expos. Anal. Environ. Epidem.*, in press. Advanced online publication Dec 8, 2004; doi: 10.1038/sj.jea.7500414.
(17) Bennett, D. H.; McKone, T. E.; Evans, J. S.; Nazaroff, W. W.; Margni, M. D.; Jolliet, O.; Smith, K. R. Defining intake fraction. *Environ. Sci. Technol.* **2002**, *36*, 206a−211a.
(18) Fitz, D. R.; Winer, A. M.; Colome, S.; Behrentz, E.; Sabin, L. D.; Lee, S. J.; Wong, K.; Kozawa, K.; Pankratz, D.; Bumiller, K.; Gemmill, D.; Smith, M. *Characterizing the Range of Children's Pollutant Exposure During School Bus Commutes*; University of California: Riverside, CA, 2003; available from http://www.arb.ca.gov/research/schoolbus/schoolbus.htm.
(19) Behrentz, E.; Fitz, D. R.; Pankratz, D.; Sabin, L. D.; Colome, S. D.; Fruin, S.; Winer, A. M. Measuring self-pollution in school buses using a tracer technique. *Atmos. Environ.* **2004**, *38*, 3735−3746.
(20) Park, J. H.; Spengler, J. D.; Yoon, D. W.; Dumyahn, T.; Lee, K.; Ozkaynak, H. Measurement of air exchange rate of stationary vehicles and estimation of in-vehicle exposure. *J. Expos. Anal. Environ. Epidem.* **1998**, *8*, 65−78.
(21) Layton, D. W. Metabolically consistent breathing rates for use in dose assessments. *Health Phys.* **1993**, *64*, 23−36.
(22) School Transportation News. K-12 Enrollment/Transportation Data, 2002−2003 School Year. In *2002−03 School Transportation News Buyer's Guide*; STN Media, Inc: Redondo Beach, CA, 2003; available from http://www.stnonline.com/stn/schoolbussafety/datastatistics/2002-03_schoolyear.htm.
(23) Marshall, J. D.; Riley, W. J.; McKone, T. E.; Nazaroff, W. W. Intake fraction of primary pollutants: motor vehicle emissions in the South Coast Air Basin. *Atmos. Environ.* **2003**, *37*, 3455−3468.
(24) *Emission Data*; California Air Resources Board: Sacramento, CA, 2004; available from http://www.arb.ca.gov/ei/emissiondata.htm.
(25) Cohen, J. T.; Hammitt, J. K.; Levy, J. I. Fuels for urban transit buses: a cost-effectiveness analysis. *Environ. Sci. Technol.* **2003**, *37*, 1477−1484.
(26) Davis, S. C.; Diegel, S. W. *Transportation Energy Data Book: Edition 23*; ORNL-6970; Oak Ridge National Laboratory: Oak Ridge, TN, 2003; available from http://www-cta.ornl.gov/data.
(27) *ARB Staff Interpretative Summary of Study Results*; California Air Resources Board: Sacramento, CA, 2003; available from http://www.arb.ca.gov/ research/schoolbus/schoolbus.htm.
(28) *MOBILE6.1 Particulate Emission Factor Model Technical Description, Final Report*; EPA/420-R-03-001; U.S. Environmental Protection Agency, Office of Air and Radiation: Washington, DC, 2003.
(29) *Planned Air Pollution Research, Fiscal Year 2003-2004*; California Air Resources Board: Sacramento, CA, 2003; available from http://www.arb.ca.gov/research/apr/apr.htm.
(30) *The 2002 California Almanac of Emissions and Air Quality*; California Air Resources Board: Sacramento, CA, 2002; available from http://www.arb.ca.gov/aqd/almanac/almanac02/almanac02.htm.
(31) Evans, J.; Wolff, S.; Phonboon, K.; Levy, J.; Smith, K. Exposure efficiency: an idea whose time has come? *Chemosphere* **2002**, *49*, 1075−1091.
(32) Marshall, J. D.; Teoh, S.-K.; Nazaroff, W. W. Intake fraction of nonreactive vehicle emissions in US urban areas. *Atmos. Environ.* **2005**, *39* (7), 1363−1371.

Received for review March 9, 2004. Revised manuscript received January 11, 2005. Accepted January 12, 2005.

ES040377V